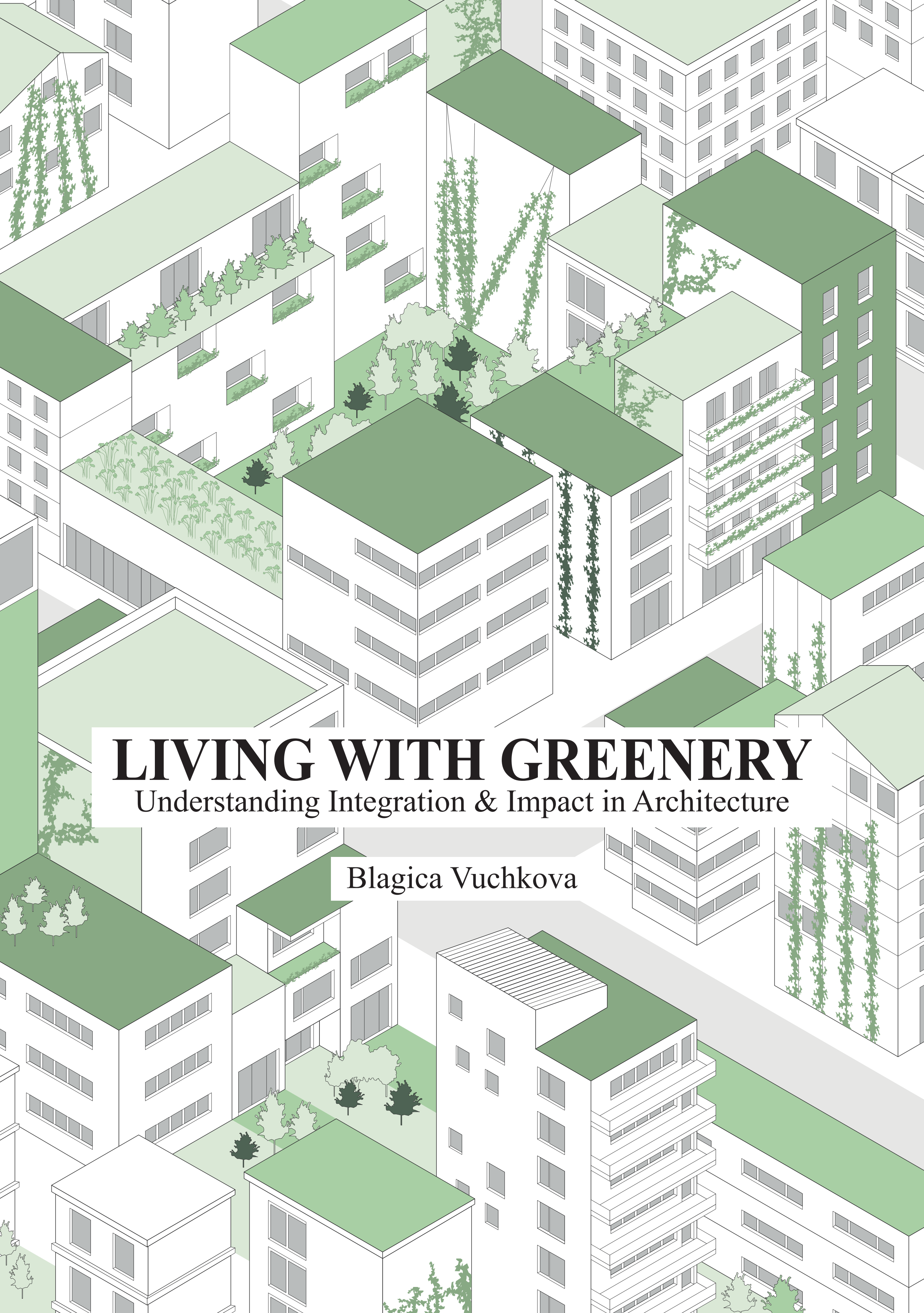

LIVING WITH GREENERY

Understanding Integration & Impact in Architecture

Blagica Vuchkova

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Master's theoretical statement 2024-2025

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1.

INTRODUCTION

1.1 CONTEXT

Cities today are struggling with an interconnected array of challenges spanning human, environmental, and spatial dimensions. Health problems such as rising rates of respiratory diseases, mental health concerns, and lifestyle-related conditions are amplified by the urban environment. They are often driven by factors such as pollution, limited opportunities for physical activity due to overcrowding or insufficient connection with nature.[1,2]

Urban environments are particularly vulnerable to the impacts of climate change, with the Urban Heat Island (UHI) Effect emerging as a major concern. This phenomenon, characterized by elevated surface and air temperatures in cities compared to surrounding rural areas, is driven by factors such as dense urban development, reduced vegetation, and the prevalence of impermeable surfaces. Amplifying these challenges are reduced wind speeds due to urban form, which limit air circulation and restrict nighttime cooling. The result is not only intensified heat stress but also aggravated air pollution. Furthermore, the extensive use of impermeable surfaces, coupled with faster drainage and limited evaporation, contributes to lower humidity levels and degraded urban microclimates.[3]

Global climate change is expected to intensify these challenges further, bringing more frequent and intense heat waves, heavy rainfall, and prolonged droughts in urban areas. These extreme weather events increase risks to human health and pose new challenges for urban infrastructure, from managing heat stress to addressing flooding risks. To address these challenges, implementing urban design and planning solutions is crucial. Strategies such as increasing tree shading, integrating green infrastructure like green roofs and facades, enhancing rainwater management and ventilation can help to adapt to climate change.[4] Simultaneously, the loss of biodiversity due to urban sprawl and habitat destruction threatens ecological balance. Urban ecosystems provide essential services such as clean air, crop pollination, and healthy soil, while also strengthening resilience to climate change and a decline in biodiversity would further expose cities to climate-related risks.[5,6]

1 'Urbanization and Health', *Bulletin of the World Health Organization* 88, no. 4 (1 April 2010): 245–46, https://doi.org/10.2471/BLT.10.010410.

2 Wilhelm Kuttler and Stephan Weber, 'Characteristics and Phenomena of the Urban Climate', *Meteorologische Zeitschrift* 32 (1 June 2023): 36, https://doi.org/10.1127/metz/2023/1153.

3 Wilhelm Kuttler and Stephan Weber, 'Characteristics and Phenomena of the Urban Climate', *Meteorologische Zeitschrift* 32 (1 June 2023): 16, https://doi.org/10.1127/metz/2023/1153.

4 Kuttler and Weber, 41.

5 'Cities and Nature', Resource, accessed 4 January 2025, https://iucn.org/resources/issues-brief/cities-and-nature.

6 'What Is Biodiversity and Why Is It Important to Preserve It?', 10 July 2023, https://www.eea.europa.eu/en/about/contact-us/faqs/what-is-biodiversity-and-why-is-it-important-to-preserve-it.

At the same time, another critical issue is unequal access to green spaces. In Europe, less than half of the population lives within close proximity to such areas.[7] This issue became even more noticeable during the COVID-19 pandemic when homes turned into multi-functional spaces for work, study, and leisure. This extended time indoors heightened our awareness of the need for a "comfortable environment"[8] in our living spaces, one that supports both functionality and well-being. It also highlighted our need for connection with and contact to nature. Personally, spending so much time inside deepened my appreciation for nature, as it became clear how vital it is for our overall well-being. Post-pandemic social trends, such as increased remote working, further highlight the importance of having access to greenery as close as possible by integrating it directly into buildings.

Living With Greenery places the building at the center of the solution, proposing the integration of greenery to design more comfortable living spaces that offer direct access to natural elements, without having to look outside of buildings. The integration takes form in green measures: *Green Facade*, *Green Roof*, *Green Courtyard* and *Green Indoors* and is studied individually and then collectively. These measures are often studied in isolation and evaluated from singular perspectives. However, by addressing environmental, architectural, and human dimensions concurrently, this holistic approach gives a more comprehensive and inclusive integration of greenery, seeking to enhance both functionality and well-being within living spaces in urban zones.

7 World Health Organization. Regional office for Europe, 2016. Urban green spaces and health: A review of evidence. Cited in Weijie Zhong, Torsten Schroeder, and Juliette Bekkering, 'Designing with Nature: Advancing Three-Dimensional Green Spaces in Architecture through Frameworks for Biophilic Design and Sustainability', *Frontiers of Architectural Research* 12, no. 4 (1 August 2023): 2, https://doi.org/10.1016/j.foar.2023.03.001.

8 Ali Sayigh, ed., *Achieving Building Comfort by Natural Means*, Innovative Renewable Energy (Cham: Springer International Publishing, 2022), 291, https://doi.org/10.1007/978-3-031-04714-5.

1.2 METHODOLOGY

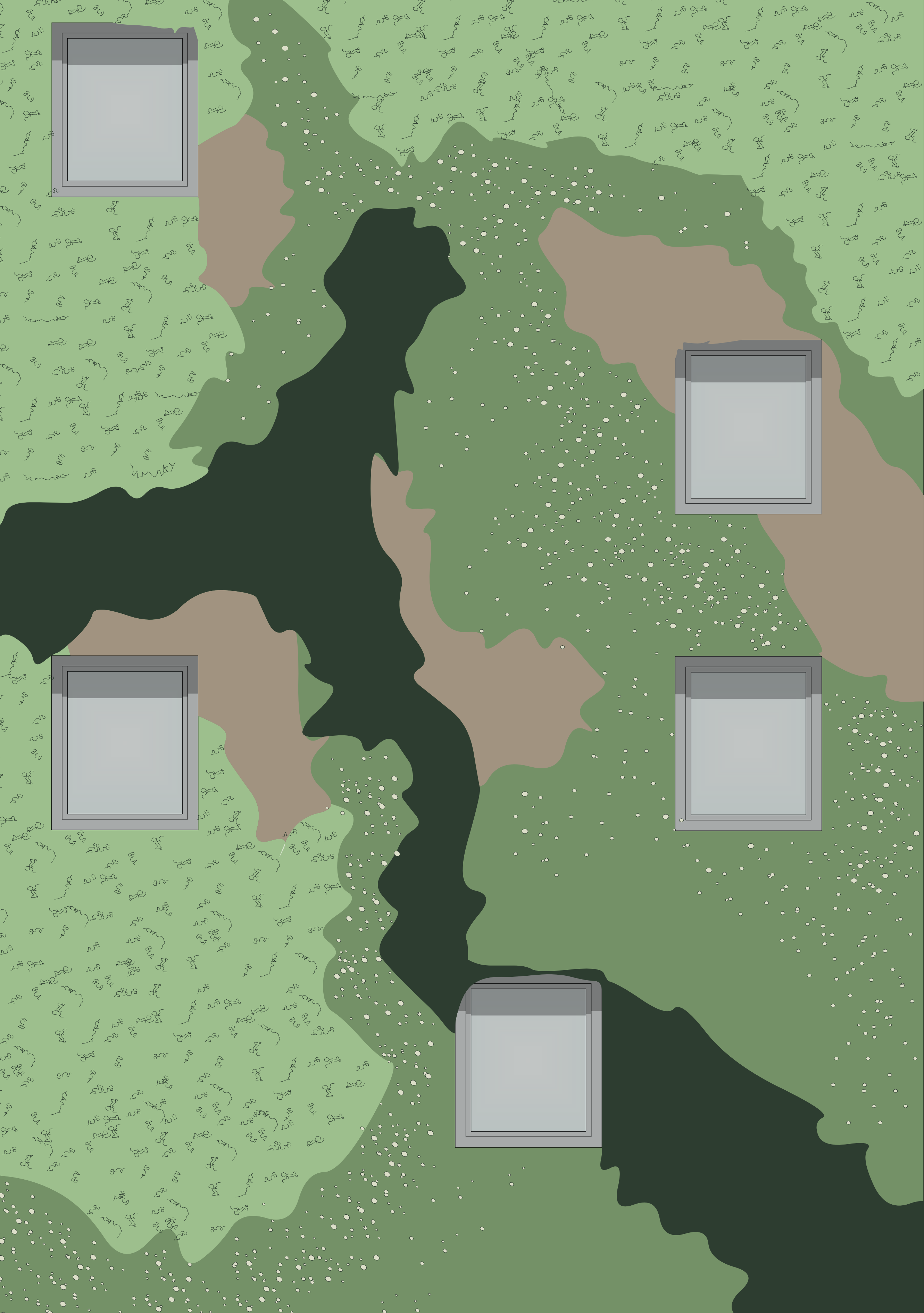
This study aims to investigate the integration of vegetation into architectural design, examining its impact on environmental impact, building performance, and human well-being. It also seeks to identify the challenges and limitations associated with these strategies. The central question is: **how can specific green measures be effectively incorporated into buildings, and what are their implications and constraints for architectural design?**

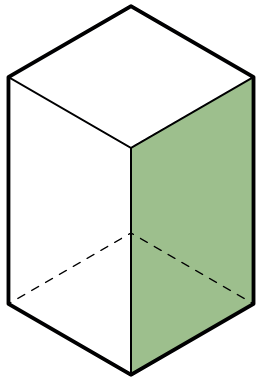
To address this question, the study will be structured into two main parts:
The first part, titled **Individual Analysis**, employs a literature review to examine four primary architectural strategies, collectively referred to as *green measures*: Green Façades, Green Roofs, Green Courtyards, and Green Indoors. Each of these components is thoroughly defined and analysed to evaluate their ecological benefits, impact on building performance, and contribution to enhancing the human experience within urban environments.

The second part, titled **Integrated Analysis**, conducts a comparative evaluation based on insights gained from the literature review in the first part. This evaluation employs environmental, building performance, and human-centred criteria to assess the contributions and limitations of each green measure. Additionally, case studies will be used to support the analysis with examples from 21st-century projects situated in climates of Central Europe.

2.

INDIVIDUAL ANALYSIS





2.1 GREEN FACADES

In this theoretical context, a green facade refers to the greening of a vertical surface of a building through the integration of vegetation. This integration can be partial or complete and may take various forms. For instance, it could involve a living wall that is “a vertical vegetated system with integrated irrigation”[9] or a facade equipped with a secondary structure to support climbing plants. We can argue that green facades have roots in ancient history, from the Hanging Gardens of Babylon to Mediterranean yards adorned with climbing plants like vines. In medieval Europe, climbers such as ivy, vines, or fruiting plants were commonly used on buildings, a practice that continued into the Industrial period and can be seen in traditional architecture, such as Bavaria’s plant-covered balconies. Initially serving ornamental and practical purposes, green facades gained renewed attention in the 1980s with the rise of ecological awareness. Over the past two decades, research has focused on their cooling and insulating properties, dust mitigation, and potential as habitats for wildlife.[10,11]

9 WGIN-mockup, ‘Key Definition: Living Wall’, *World Green Infrastructure Network* (blog), 12 April 2021, https://worldgreeninfrastructurenetwork.org/key-definition-living-wall/.

10 ‘Greening Facades - A Historical Introduction’, Biotope City Journal, 21 January 2023, https://biotope-city.net/en/greening-facades-a-historical-introduction/.

11 Manfred Köhler, ‘Green Facades—A View Back and Some Visions’, *Urban Ecosystems* 11 (1 December 2008): 423–36, https://doi.org/10.1007/s11252-008-0063-x.

2.1.1 Types & Design

To achieve a green façade, there are two possible approaches, depending on the specific goals of the project. The two categories are ground-based greening and wall-based greening.

Ground-Based Greening

In ground-based greening, the plant roots are directly planted in the soil, allowing them to naturally supply themselves with water and nutrients without the need for intervention. The selection of plants in ground-based greening is critical and can greatly influence the desired outcome when greening a façade. Plants should be selected based primarily on their climbing behaviour and growth characteristics (such as height and spread), as well as their seasonal foliage changes. The most critical factor is their climbing behaviour, as it has the greatest impact on the design phase. There are two main types of plants used in this greening technique.

Self-Climbers: Self-climbers are plants that naturally climb vertical surfaces without the need for external support structures. They attach directly to the façade, transferring their weight to the surface. Therefore, the façade must be strong, tear-proof, and free of joints to prevent damage. These plants use clinging roots or tendrils with adhesive pads to secure themselves to the structure. While self-climbers provide a simple, planar surface coverage, they offer limited design flexibility. Additionally, the full aesthetic impact of self-climbers isn’t immediate, often taking between five and twenty years to fully mature.

Guided Climbers: In contrast, guided climbers require external support structures such as nets, ropes, pipes, rods, or grating to direct their growth. These support systems can be arranged in various patterns—vertical, horizontal, or planar—offering more design flexibility compared to self-climbers. The types of plants used as guided climbers include twiners, creepers, and thorn-bearing plants, each with unique climbing habits. The support structure must align with the plant’s growth behaviour: twiners typically need vertical supports, creepers thrive on grid or net-based systems, and thorn-bearing plants also perform best with grid or net supports. Like self-climbers, guided climbers take time to develop their full aesthetic impact, typically requiring three to twelve years to reach maturity.

Both self-climbers and guided climbers offer distinct benefits and challenges, and the choice of plant type and support system should be tailored to the design objectives and the desired long-term outcome for the façade greening project.[12]

12 Nicole Pfoser, ed., *Green Facades*, First edition, DETAIL Practice (München: DETAIL, 2024), 64–73, https://doi.org/10.11129/9783955536213.

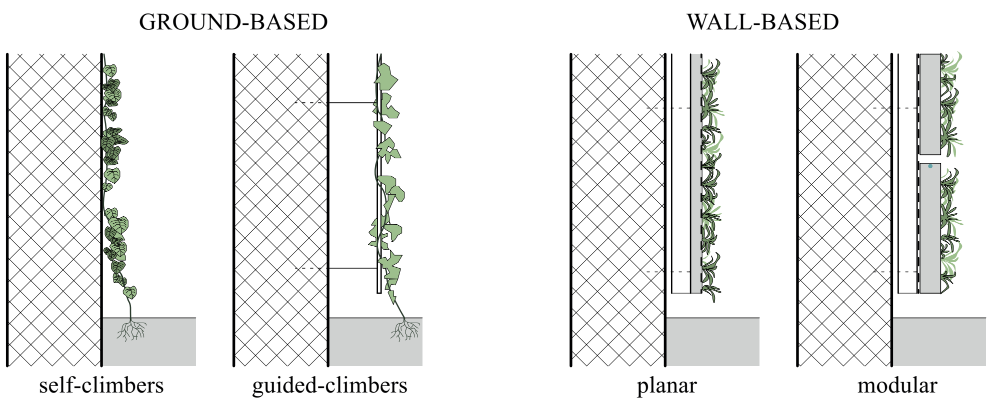
Wall-based greening

Wall-based greening, as the name suggests, involves vegetation growing directly on vertical surfaces. This system is independent of natural ground soil and groundwater, relying instead on artificial supplementation of water and nutrients. It requires careful management of several key elements, including the need for an appropriate substrate, a consistent nutrient supply, and an artificial irrigation system, which can be automated for efficiency.

One of the benefits of wall-based greening is the high degree of design freedom it offers architects. The vegetation can be shaped and arranged on the facade in various patterns, shapes, and designs according to the architect's vision. The selected plant species significantly impact the overall appearance, influencing aspects like texture, colour, and the overall visual uniformity or contrast.

When designing wall-based greening, there are two primary systems to consider:
Modular Systems: These systems use prefabricated units that contain plants, each with its own substrate and irrigation system. Modular systems are easy to construct and maintain since individual modules can be replaced or adjusted without affecting the entire facade.
Planar Construction: This method involves growing plants on a continuous vertical surface supported by a geotextile, which offers a more seamless appearance. However, planning and maintenance are more complex.

When selecting plants, careful consideration is essential, particularly if multiple species are used. The plants must have compatible needs for water, sunlight, and nutrients to ensure they can coexist on the green facade. An advantage of wall-based greening compared to ground-based methods is the ability to pre-cultivate plants. This allows for an immediate aesthetic impact, as the greenery will already be established when installed.[13]



3. *Green facade details*

13 Pfoser, 65–66.

Green facades have practical purposes in the urban landscape, acting as orientation and identification tools, they create distinct markers within the city. They can influence the spatiality by offering privacy, separating spaces, and adding a secondary layer that acts as a filter. Moreover, green facades have the ability to modify and enhance the proportions of a building by rhythmic the facades design. Additionally, the seasonal changes in the plants contribute to a dynamic appearance, keeping the facade lively and colourful throughout the year. Thus, incorporating greenery into facades can be a valuable aspect of architectural design.[14]

2.1.2 Maintenance

In architecture involving vertical greening systems, planning and maintenance are crucial to ensuring both the functionality and longevity of the structure. While initial design is essential, ongoing upkeep must also be considered, particularly in terms of time commitment and costs.

Among the various facade greening types discussed, ground-based self-climbing systems are the simplest to maintain. In these systems, plants naturally grow upward, drawing water and nutrients from the ground, with minimal intervention required. The main maintenance task for self-climbers involves basic plant care, such as pruning and managing growth. For guided climbers, which grow along a supporting structure, there is slightly more maintenance involved. Beyond standard plant care, regular inspections are needed to ensure that the plants remain properly attached to their guiding structure. This helps prevent plants from detaching, damaging the building, or growing uncontrollably. Typically, ground-based greening requires only one care session per year.

In contrast, wall-based greening systems are more complex and require more intensive maintenance efforts.[15] While care for the plants is similar with two maintenance sessions a year; one in autumn for pruning, plant health, removing dead plants and in autumn for rejuvination pruning,[16] there are additional concerns due to the direct interaction between vegetation and the building facade. These additional controls can be: structural verifications, to ensure that the wall is still attached, corrosion protection, when there is a metal structure or facade protection from moisture infiltration and root penetration. These extra layers of maintenance contribute to higher long-term costs compared to simpler systems like ground-based climbers. Therefore, when implementing wall-based greening, it’s essential to weigh these factors and allocate resources accordingly to ensure the system’s success and longevity.

14 Pfoser, *Green Facades,* 50–52.

15 Katia Perini and Paolo Rosasco, ‘Cost–Benefit Analysis for Green Façades and Living Wall Systems’, *Building and Environment* 70 (1 December 2013): 111, https://doi.org/10.1016/j.buildenv.2013.08.012.

16 Pfoser, *Green Facades*, 70–76.

Irrigation is a critical aspect of maintenance, and automation can simplify this process. An automatic irrigation system equipped with sensors can detect rainfall and connect to meteorological stations to adjust watering based on weather conditions. This makes it cost-efficient by reducing labour needs and conserving water. However, the system still requires management, with checks recommended twice a year.[17]

Neglecting proper maintenance or design can significantly reduce the system's life cycle and lead to the degradation of the green facade, ultimately compromising its functionality and aesthetic appeal. Adequate planning and regular care are vital to preserving the integrity and sustainability of these systems.[18]

2.1.3 Environmental Impact

Temperature regulation

Green facades are highly effective in regulating exterior temperatures, playing a role in reducing the urban heat island effect. This cooling happens through a combination of processes that naturally lower the temperature around buildings. One of the key processes is **evapotranspiration**, where plants release water vapour through their leaves. This process absorbs heat from the surrounding air, creating a cooling effect. The more vegetation present, the greater the cooling impact on the environment. Another important factor is **shading**. When building materials are exposed to direct sunlight, they absorb and store heat, causing temperatures to rise. However, when a facade is covered with plants, the vegetation acts as a natural barrier, reducing the amount of sunlight that reaches the building's surface. This prevents the building materials from storing excessive heat during the day. As a result, at night, when these materials would normally release stored heat, the facade stays cooler, emitting far less stored heat back into the environment.[19]

This process of reduced heat absorption during the day and lower heat emission at night helps regulate temperatures not only around individual buildings but also in the surrounding urban area. A simulation study conducted in Germany demonstrated that greening a facade can lower temperatures around a building by 0.5°C to 3°C, highlighting the cooling potential of green facades in urban environments.[20] Through these mechanisms, green facades offer an effective natural solution to reduce overall urban temperatures and address the urban heat island effect.[21]

17 Pfoser, 76–77.

18 Flavie Mayrand and Philippe Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation: A Contribution to Urban Connectivity?', *Sustainability* 10, no. 4 (April 2018): 6, https://doi.org/10.3390/su10040985.

19 Pfoser, *Green Facades*, 26–27.

20 Xin Chen Pan and Yi Xuan Xiao, 'Simulation Analysis of Building Green Facade Eco-Effect', *Applied Mechanics and Materials* 548–549 (April 2014): 1701–5, https://doi.org/10.4028/www.scientific.net/AMM.548-549.1701.

21 Mehdi Rakhshandehroo, Mohd Johari Mohd Yusof, and Meysam Deghati Najd, 'Green Façade (Vertical Greening): Benefits and Threats', *Applied Mechanics and Materials* 747 (1 March 2015), https://doi.org/10.4028/www.scientific.net/AMM.747.12.

Urban Air Pollution Reduction

The natural composition of air can be altered by pollutants such as smoke, dust or gases that are influenced by factors like heavy traffic, increased heating during winter, and local topography. Air pollution has a negative impact on human health particularly in densely populated urban areas.

Green facades offer an effective solution to air pollution. Plants naturally possess properties that help purify the air by absorbing pollutants. Through photosynthesis, vegetation takes in gases like CO_2, SO_2 and other harmful substances, releasing oxygen esential for human-life.[22] Additionally, certain plants, known as accumulators, have rough or textured surfaces that can trap dust and airborne particles, acting as natural air filters. For enhanced filtration, a two-layered green facade can be used, where the back leaves capture most particles, making the system even more efficient.[23] By capturing pollutants in the plant leaves and soil in the case for wall based greening alongside buildings and filtering them, green facades prevent these impurities from re-entering the atmosphere.[24]

Thus, green facades in cities can improve air quality through the natural processes of plants, especially because they create large plant surfaces and sections that provide extensive filtration and trapping of pollutants. Some studies have even found that a green facade can absorb more CO_2 and produce more oxygen than the same size surface of a mature tree, making them even more beneficial for the environment.[25]

Urban Noise Reduction

Today's cities endure noise pollution, affecting millions of people daily and potentially leading to serious health issues such as hearing loss, high blood pressure, and elevated stress levels. Additionally, it disrupts wildlife, altering their behaviour and habitats.[26] In urban environments, noise pollution primarily originates from transportation, construction, and industrial activities.[27] However, green facades hold promising potential in reducing this urban noise. Modular living walls have been shown to possess sound absorption capacity, with studies confirming that green walls offer effective sound insulation. In fact, they provide similar or even superior acoustic absorption compared to some commercial sound-absorbent-materials.[28] Indeed, in wall-based greening the substrate plays an essential role in sound

22 M. Ottele, 'The Green Building Envelope: Vertical Greening', 2011, 33, https://www.semanticscholar.org/paper/The-green-building-envelope%3A-Vertical-greening-Ottele/fd79a695e5c67eec5659169c6646f8a8eb46d39c.

23 Pfoser, *Green Facades*, 30–33.

24 Ottele, 'The Green Building Envelope', 33–34.

25 Ottele, 34.

26 'Noise Pollution', accessed 12 October 2024, https://education.nationalgeographic.org/resource/noise-pollution.

27 'Noise Pollution Is Still Widespread across Europe, but There Are Ways to Reduce the Volume', accessed 12 October 2024, https://www.eea.europa.eu/signals-archived/signals-2020/articles/noise-pollution-is-still-widespread.

28 Z. Azkorra et al., 'Evaluation of Green Walls as a Passive Acoustic Insulation System for Buildings', *Applied Acoustics* 89 (1 March 2015): 46–56, https://doi.org/10.1016/j.apacoust.2014.09.010.

absorption. An experiment conducted at Delft University of Technology highlighted that the substrate is responsible for most of the sound absorption. The research found that thicker substrates enhance the sound absorption coefficient, particularly at lower frequencies, with a minimum thickness of 8 to 10 cm being optimal for a good range of sound absorption.[29] In ground-based green structures, where there is no soil, the plants themselves are more important for reducing noise. The denser the plants, the better they reduce noise. However, since wall-based green structures have soil, they generally absorb sound better than ground-based ones. This difference can be reduced by using plants with thicker leaves in ground-based green structures.[30]

Biodiversity Enhancement

In our cities, opportunities for creating new green spaces are limited, reducing the available habitat for animals, birds, insects, and plants. Green facades can help address this issue by providing homes for various species, offering essential shelter in urban areas dominated by concrete and buildings.[31] The choice of plants is especially important; native plants are better suited to existing ecosystems and more likely to thrive, especially when considering their resistance to local conditions. We can enhance this further by adding nesting aids and creating spaces that encourage sheltering.[32]

Birds and bats are particularly drawn to climbing plants, where they can have safe nesting sites. In fact, a green facade can host up to five times more birds compared to one without greenery. Moreover, these facades serve as a food source for insects, making them essential contributors to urban ecosystems.[33] As a result, facade greening not only supports wildlife but also strengthens biodiversity and, with thoughtful planning, can help enhance urban ecosystems.

Rainwater Management

Paved surfaces in cities prevent rainwater from naturally absorbing into the ground, causing it to flow directly into sewer systems. This often overwhelms the infrastructure, increasing the risk of flooding during heavy rainfall. Instead of letting this valuable water escape the city, it could be retained and stored in urban areas for later use. For instance, the stored water could be used to irrigate green spaces during hot, dry periods. This approach not only eases the burden on sewer systems but also ensures a continuous water supply, managing amore healthier urban environment.[34]

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29 M.J.M. Davis et al., 'More than Just a Green Facade: The Sound Absorption Properties of a Vertical Garden with and without Plants', *Building and Environment* 116 (May 2017): 64–72, https://doi.org/10.1016/j.buildenv.2017.01.010.

30 Feng Yan et al., 'A Review of the Application of Green Walls in the Acoustic Field', *Building Acoustics* 29, no. 2 (1 June 2022): 303–6, https://doi.org/10.1177/1351010X221096789.

31 Mayrand and Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation', 2.

32 Pfoser, *Green Facades*, 38–41.

33 Ottele, 'The Green Building Envelope', 36.

34 Pfoser, *Green Facades*, 34–47.

Green facades contribute to rainwater management by allowing plants to absorb and retain water, thereby reducing the volume of runoff reaching paved surfaces and sewer systems. A significant portion of the absorbed water is also evaporated through the plants, further mitigating excess runoff.[35] Wall-based greening systems have a substrate layer and are more effective in regulating water flow compared to ground-based systems. The combination of substrate and plants retains more water than plants alone and provides additional benefits, such as filtering pollutants from rainwater.[36]

To enhance this approach, we can adopt blue-green architecture, which combines the principles of green infrastructure with water-sensitive urban development on a project level; water and vegetation become central elements of architectural design. This can include water retention systems, such as cisterns and floodplains, that store rainwater for irrigating green facades. Furthermore, facade vegetation can be integrated into purification systems, where plants help filter and clean the water.[37]

2.1.4 Building Impact

As highlighted in the environmental impact section, green facades help cool buildings through shading and the evapotranspiration mechanism. Additionally, they provide **insulation properties**, further enhancing the building's energy efficiency. This means that in winter, the transmission or loss of heat from the building is reduced. In summer, the opposite occurs: heat is blocked from passing through the vegetation due to the shading effect and the plants' evaporative mechanism, preventing the building from overheating. This natural cooling effect allows buildings to reduce the need for artificial cooling and heating, leading to **energy savings**. Additionally, green facades block UV light, which is known to have damaging effects on building materials. By protecting the building from UV exposure, green facades reduce maintenance costs and **increase durability** of building materials over time.[38,39]

However, it is important to note a significant **difference** between wall-based greening and ground-based greening due to the presence of soil. In terms of insulation properties, wall-based greening offers higher thermal resistance as it creates a thicker barrier. Both systems are effective for cooling, but soil-based systems retain moisture, enhancing their cooling potential compared to non-soil alternatives.[40]

35 Pfoser, *Green Facades* 29.

36 Wen Wang et al., 'Vertical Green Wall Systems for Rainwater and Sewage Treatment', *Sustainability* 16, no. 17 (January 2024): 7593, https://doi.org/10.3390/su16177593.

37 Pfoser, *Green Facades*, 34–47.

38 Ottele, 'The Green Building Envelope', 37–41.

39 Pfoser, 26–29.

40 Marc Ottelé et al., 'Comparative Life Cycle Analysis for Green Façades and Living Wall Systems', *Energy and Buildings* 43, no. 12 (1 December 2011): 3419–29, https://doi.org/10.1016/j.enbuild.2011.09.010.

To further increase energy savings, by integrating controlled **natural ventilation** into the building's design, air conditioning units can potentially be eliminated. Introducing a strategically planned ventilation layer between the green facade and the building creates a multifunctional space that amplifies key benefits: it humidifies and purifies the air, strengthens the previously mentioned buffer effect, and provides natural cooling. This integrated system allows the building to harness natural cooling and ventilation, resulting in a more sustainable, energy-efficient environment that also improves indoor air quality and comfort. Additionally, incorporating photovoltaic panels into the green facade can provide renewable energy, further increasing energy savings and contributing to the building's overall sustainability.[41]

2.1.5 Human centred Impact

Physical well-being

In the Environmental Impact section, several positive effects were outlined. First, green facades can significantly reduce air pollution by filtering particulate matter, a major air contaminant linked to various health issues. In addition, green facades help remove harmful gases from the atmosphere while increasing oxygen levels. Given that air pollution is a major contributor to illnesses and even deaths, improving air quality through green facades can improve public health.[42,43] Secondly, we highlighted that green facades have the ability to ease the urban heat island effect and lower indoor temperatures through evapotranspiration and shading. As they are similar to green spaces, which reduce excessive heat in the environment and contribute to lowering the risk of cardiovascular diseases, green facades offer equivalent benefits.[44] Additionally, studies show that when indoor temperatures rise to 33°C, health consultations increase by 15%. By reducing indoor temperatures, green facades minimise the need for medical visits, contributing to fewer health issues overall.[45]

Although there is no measurable direct link between green facades and specific health outcomes, the **indirect benefits**, such as improved air quality and reduced heat, create conditions that encourage better physical well-being, though further research is needed to quantify these effects. The potential health risks of green facades include exposure to allergenic pollen, and transmission of animal diseases. Living with a green facade brings close contact with nature, which may also mean increased presence of animals and insects.[46]

41 Pfoser, *Green Facades*, 26–29.

42 Marcel Cardinali et al., 'Green Walls and Health: An Umbrella Review', *Nature-Based Solutions* 3 (1 December 2023): 11, https://doi.org/10.1016/j.nbsj.2023.100070.

43 Fernando Fonseca, Marina Paschoalino, and Lígia Silva, 'Health and Well-Being Benefits of Outdoor and Indoor Vertical Greening Systems: A Review', *Sustainability* 15, no. 5 (January 2023): 7, https://doi.org/10.3390/su15054107.

44 Cardinali, Marcel, Alvaro Balderrama, Daniel Arztmann, and Uta Pottgiesser. 'Green Walls and Health: An Umbrella Review'. *Nature-Based Solutions* 3 (1 December 2023): 100070, 11. https://doi.org/10.1016/j.nbsj.2023.100070.

45 Fonseca, Paschoalino, and Silva, 'Health and Well-Being Benefits of Outdoor and Indoor Vertical Greening Systems', 8.

46 Åsa Ode Sang, Petra Thorpert, and Ann-Mari Fransson, 'Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach', *Frontiers in Ecology and Evolution* 10 (29 April 2022): 12, https://doi.org/10.3389/fevo.2022.804500.

Mental well-being

Noise and air pollution have been increasingly linked to mental health issues, and research on this connection is ongoing. One study, which used a questionnaire to investigate the impact of residential noise and air pollution on students' mental health, found that higher levels of continuous noise were associated with poorer mental well-being. Noise exposure heightened annoyance, making the neighbourhood feel less calming, which in turn reduced physical activity and worsened mental health. Additionally, the increased irritation led to more frequent sleep disturbances, further exacerbating mental health problems.[47,48] Other studies have similarly linked air pollution to deteriorating mental health.[49] Green facades could be a potential solution to these environmental challenges. Their sound-absorbing properties help reduce noise pollution, while their ability to improve air quality by reducing air pollution could also benefit mental health. By addressing both noise and air pollution, green facades may play a role in easing the mental health problems associated with these environmental stressors.

Another positive impact green facades could have on mental well-being is their **restorative effect**; the process by which individuals recover from mental, physical, or emotional stress through exposure to natural environments[50], in this case, green facades. This restorative effect is facilitated by the comfort created through visual and auditory contact with the green wall.[51]

One study explored this effect by examining the responses of 25 students during a stressful exam period. The students were exposed to two different scenarios: a standard building wall and a green wall. Researchers used physiological measures such as brain activity, heart rate variability, and skin conductance, alongside psychological assessments, to evaluate the impact of the green wall. The results indicated that the green facade had a clear positive effect. The green wall was associated with enhanced cerebral activity, fostering a more comfortable and relaxing environment. This, in turn, led to improved mood, increased focus, and reduced stress among the students. These findings suggest that green facades can effectively promote mental well-being, especially during periods of high stress.[52]

47 Angel M. Dzhambov et al., 'Pathways Linking Residential Noise and Air Pollution to Mental Ill-Health in Young Adults', *Environmental Research* 166 (1 October 2018): 458–65, https://doi.org/10.1016/j.envres.2018.06.031.

48 Angel Dzhambov et al., 'Residential Road Traffic Noise and General Mental Health in Youth: The Role of Noise Annoyance, Neighborhood Restorative Quality, Physical Activity, and Social Cohesion as Potential Mediators', *Environment International* 109 (1 December 2017): 1–9, https://doi.org/10.1016/j.envint.2017.09.009.

49 Lilian Tzivian et al., 'Effect of Long-Term Outdoor Air Pollution and Noise on Cognitive and Psychological Functions in Adults', *International Journal of Hygiene and Environmental Health* 218, no. 1 (1 January 2015): 1–11, https://doi.org/10.1016/j.ijheh.2014.08.002.

50 Marc G. Berman and Katherine M. Krpan, 'Restorative Natural Environments', in *Encyclopedia of Quality of Life and Well-Being Research*, ed. Alex C. Michalos (Dordrecht: Springer Netherlands, 2014), 5550–55, https://doi.org/10.1007/978-94-007-0753-5_3963.

51 Cardinali et al., 'Green Walls and Health', 11.

52 Mohamed Elsadek, Binyi Liu, and Zefeng Lian, 'Green Façades: Their Contribution to Stress Recovery and Well-Being in High-Density Cities', *Urban Forestry & Urban Greening* 46 (1 December 2019): 126446, https://doi.org/10.1016/j.ufug.2019.126446.

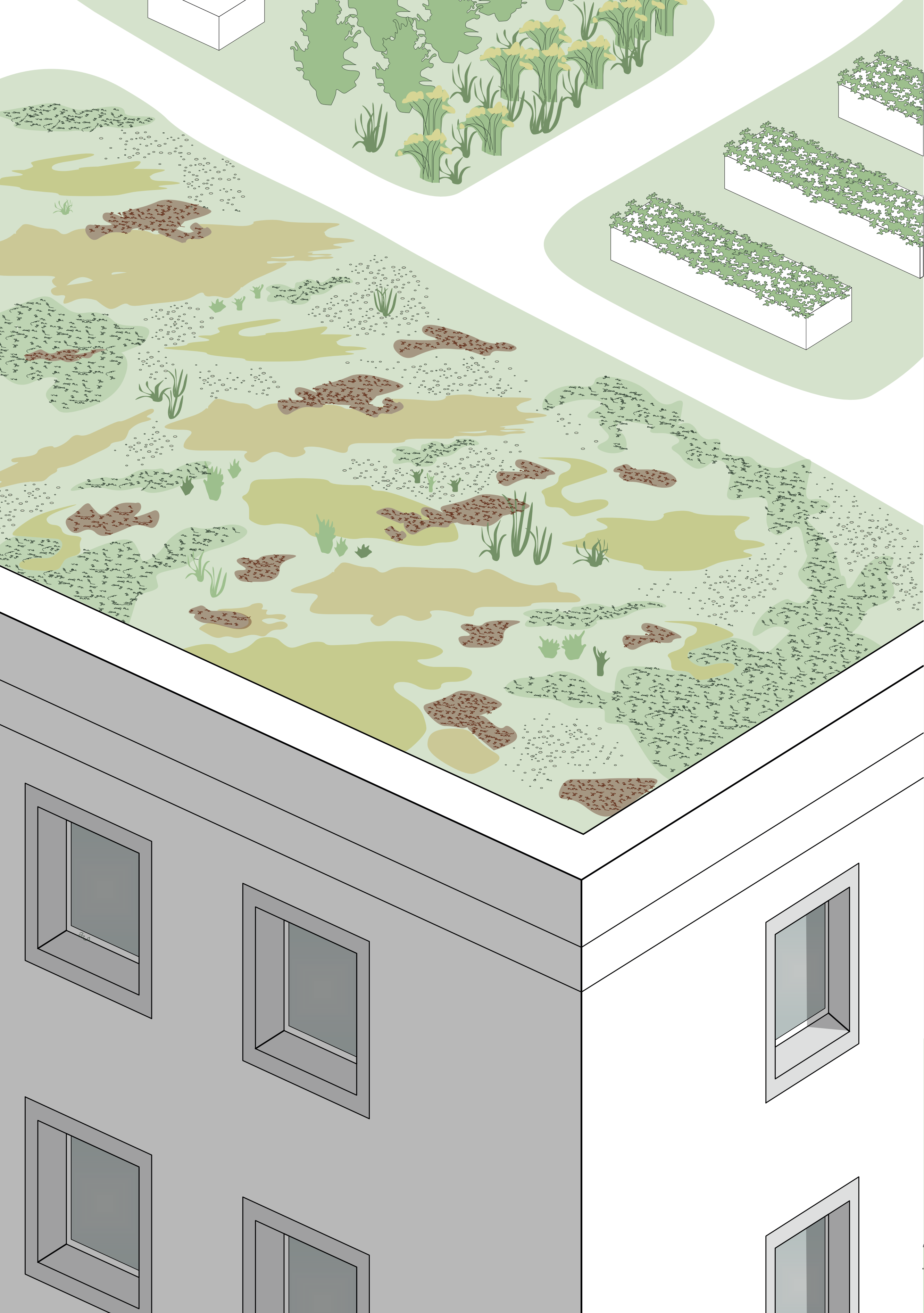
A negative impact on mental well-being is **discomfort** from animal presence; some individuals may feel uneasy around insects, birds, or other wildlife attracted by green facades. This discomfort could make green facades unsuitable for certain living environments, potentially leading to inadequate conditions for those sensitive to close contact with nature.[53]

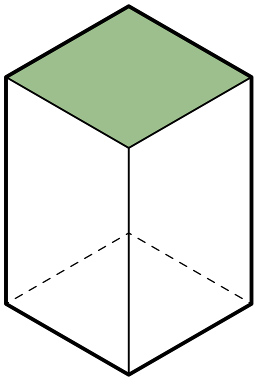
Social well-being

Many people pause when they encounter a green façade, and for good reason. Green facades stand out against the city's concrete walls and glass surfaces, creating a contrast that captures attention. Beyond their aesthetic appeal, green facades also have an **inviting quality**, drawing people in and encouraging interaction with their surroundings. Social well-being, in this context, is closely linked to mental well-being. When individuals are in a positive mental state, experiencing reduced stress and improved mood, as green facades can help promote, they are more likely to engage socially and experience a greater sense of social well-being.

While green facades can positively influence social well-being through their visual appeal, the atmosphere they create and the mental well-being effects, their impact remains somewhat **limited to these observable effects**, as they do not serve a functional purpose as usable spaces.

53 Ode Sang, Thorpert, and Fransson, 'Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach', 12.





2.2 GREEN ROOF

A green roof, sometimes referred to as the *fifth facade*, is a type of roof that integrates vegetation into its structure.[54] In urban areas, roofs make up about 40-50% of all impermeable surfaces, representing a significant portion of the city's landscape.[55] This makes green roofs an appealing solution for achieving multiple environmental and urban benefits. Traces of green roofs can be found in ancient cities like Pompeii and Italian palaces from the 15th century. They are also part of traditional architecture in some cultures, such as Norwegian vernacular design, where soil and plants were used on roofs for practical purposes, including insulation, rot prevention, and rain damage mitigation.[56] During the late 19th century, the development of building materials like reinforced concrete and advancements in flat roof construction made green roofs more feasible.[57] Their adoption has since been strengthened by ecological movements advocating for sustainable and environmentally friendly design.

54 WGIN-mockup, 'Key Definition: Green Roof', *World Green Infrastructure Network* (blog), 12 April 2021, https://worldgreeninfrastructurenetwork.org/key-definition-green-roof/.

55 Virginia Stovin, 'The Potential of Green Roofs to Manage Urban Stormwater: The Potential of Green Roofs to Manage Urban Stormwater', *Water and Environment Journal* 24, no. 3 (September 2010): 192, https://doi.org/10.1111/j.1747-6593.2009.00174.x.

56 'A BRIEF HISTORY OF ROOF GARDENS – Heather Shimmin Photography', accessed 5 November 2024, https://www.heathershimmin.com/a-brief-history-of-roof-gardens.

57 'Historical Green Roofs: Their Development until the Invention of the Iron Concrete | TU Berlin Fachgebiet Landschaftsarchitektur Und Freiraumplanung', accessed 4 January 2025, https://fg.freiraum.tu-berlin.de/en/historical-green-roofs-their-development-until-the-invention-of-the-iron-concrete-2/#.

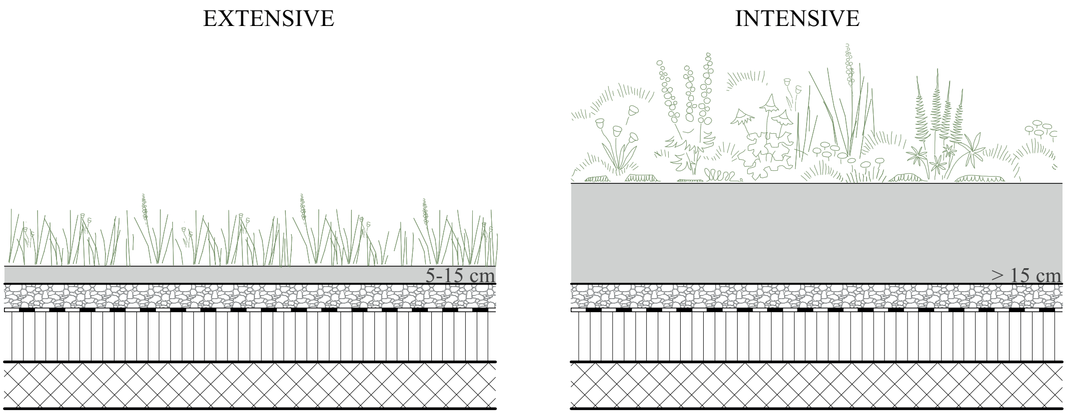
4. *Green roof axonometries*

2.2.1 Types & Design

Green roofs generally come in two main types, distinguished by the depth of the substrate:

Extensive system
These roofs have a substrate depth of up to 15 cm, which supports only low-growing plants such as “sedum species”[58], grasses and mosses. Due to their shallow substrate, extensive green roofs are lightweight, easy to install, and suitable for structures that cannot bear heavy loads. They can be flat or slightly inclined, though the angle is limited. The plant variety is restricted by the shallow soil layer, which limits design options. While the limited soil depth restricts plant variety and design flexibility, extensive green roofs are typically cost-effective, low-maintenance, and don’t require any irrigation systems.[59,60,61]

Intensive system
They have a deeper substrate, exceeding 15 cm, allowing for a much wider range of plants, from “lawn, low-lying shrubs and coppices [to][..] large trees”.[62] This depth provides greater design flexibility, allowing for features like green terraces or paved sections, and even the option to pre-cultivate plants before installation. However, the substantial weight of intensive green roofs requires a stronger, flat roof structure, making them more costly to install compared to extensive systems.[63,64,65]



5. *Green roof details*

58 W. C. Li and K. K. A. Yeung, ‘A Comprehensive Study of Green Roof Performance from Environmental Perspective’, *International Journal of Sustainable Built Environment* 3, no. 1 (1 June 2014): 128, https://doi.org/10.1016/j.ijsbe.2014.05.001.

59 Richard K. Sutton, ed., *Green Roof Ecosystems*, vol. 223, Ecological Studies (Cham: Springer International Publishing, 2015), 6–7, https://doi.org/10.1007/978-3-319-14983-7.

60 Pfoser, *Green Facades*, 82–85.

61 Sara Wilkinson and Timothy J. Dixon, eds., *Green Roof Retrofit: Building Urban Resilience*, Innovation in the Built Environment (Chichester, West Sussex, United Kingdom: Wiley, 2016), 64, https://doi.org/10.1002/9781119055587.

62 Li and Yeung, ‘A Comprehensive Study of Green Roof Performance from Environmental Perspective’, 128.

63 Sutton, *Green Roof Ecosystems*, 223:6–7.

64 Pfoser, *Green Facades*, 82–85.

65 Wilkinson and Dixon, *Green Roof Retrofit*, 16; 64.

Special applications

In addition to the primary green roof systems, some special applications offer unique functionality and environmental benefits. Intensive green roofs can include walkable zones that transform rooftops into communal spaces, such as gardens where residents grow food, seating areas, or terraces. Biodiverse green roofs enhance ecological diversity by incorporating water features, deadwood, and native plants, creating habitats for local wildlife. Green roofs can also be paired with solar or photovoltaic panels, generating clean energy while benefiting from the cooling effect of the vegetation, which improvessolar efficiency.[66]

When designing green roofs, several aspects must be considered to ensure a successful outcome:

<u>Structural support:</u> The roof must be capable of bearing the added weight of the green roof, especially for intensive systems.

<u>Orientation and sun exposure:</u> The amount of sunlight the roof receives, along with any shading from adjacent buildings or taller structures, plays a major role in plant health and selection. Areas exposed to consistent sunlight are suited for sun-loving plants, while shaded areas require shade-tolerant species.

<u>Building Height and Wind Exposure:</u> The height of the building impacts its exposure to wind, with taller buildings facing more intense wind conditions. This can affect both the health of the plants and the stability of the substrate.

<u>Waterproofing:</u> Effective waterproofing is essential to prevent leaks, which could damage the building's structure and compromise the entire green roof system.[67,68]

<u>Access:</u> To ensure proper maintenance of the green roof, planning for access during the design phase is vital.[69] However, care must be taken during access to avoid damaging the waterproofing membrane, as this could compromise the roof's integrity.[70]

<u>Plants selection:</u> The choice of plants is influenced by sun exposure, shading, wind and structural capacity. Green roofs create a challenging environment for plants due to factors like temperature fluctuations, drought, and high winds, which can stress vegetation.[71] Therefore, selecting plant species adapted to these conditions is essential for establishing a resilient green roof system. Research in this field supports the use of diverse mixtures of native plant species from different evolutionary backgrounds to improve the overall performance of green roofs.[72] Native plants are naturally adapted to the local climate and environmental conditions, making them easier to maintain with reduced water or fertiliser needs and also known to insects and animals.[73]

66 Pfoser, *Green Facades*, 82–85.
67 Wilkinson and Dixon, *Green Roof Retrofit*, 26.
68 Sutton, *Green Roof Ecosystems*, 223:6–7.
69 Wilkinson and Dixon, *Green Roof Retrofit*, 24.
70 Sutton, *Green Roof Ecosystems*, 223:8.
71 Sutton, 223:194.
72 Sutton, 223:204.
73 Li and Yeung, 'A Comprehensive Study of Green Roof Performance from Environmental Perspective', 128–29.

2.2.2 Maintenance

Green roofs demand ongoing monitoring and maintenance to ensure long-term functionality and health. Regular upkeep, such as plant care, weed control, waterproofing controls or drainage checks, is essential to prevent issues like roof damage or plant deterioration.[74] Additional activities include regular inspections for pests and diseases, as well as assessments of plant health after periods of extreme heat or drought, and at the beginning and end of each growing season.[75]

To facilitate maintenance, green roofs should be designed with **access** to the roof like pathways or areas that allow workers to perform inspections and repairs as needed. Thoughtful design that considers plant selection, structural stability, and waterproofing can reduce the overall maintenance burden and extend the roof's lifespan.

Irrigation isn't always necessary for plants to survive, but it can affect how well green roofs work by supporting plant growth, plant health, and summer cooling. It also influences soil moisture levels and stormwater drainage measurements.[76] Additionally, it can improve aesthetics (growth, flowering, canopy coverage) and increase vegetation diversity and composition, allowing a wider range of plant species to grow.[77] Extensive green roofs typically do not require irrigation under normal conditions. In contrast, intensive green roofs often depend on irrigation to maintain their ecosystem services and aesthetic qualities.[78]

The way a green roof is composed also impacts maintenance. A single, continuous substrate layer is simpler to install, but modular trays holding soil and plants make upkeep easier, as problematic sections can be swapped out as needed.[79]

In terms of **cost**, green roofs tend to be more expensive than conventional roofing systems, with costs influenced by several "components, including the growing medium, type of roofing membrane, quantity of plants and drainage system".[80] The type of green roof selected, extensive or intensive, also plays a role in cost variation. Extensive green roofs, which are shallower and typically planted with low-maintenance vegetation, are generally less costly "in terms of installation as well as maintenance".[81] Intensive green roofs, with their thicker

74 Wilkinson and Dixon, *Green Roof Retrofit*, 25.

75 Sutton, *Green Roof Ecosystems*, 223:9.

76 Sutton, 223:35.

77 Sutton, 223:97.

78 Erica Oberndorfer et al., 'Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services', *BioScience* 57, no. 10 (1 November 2007): 825, https://doi.org/10.1641/B571005.

79 Sutton, *Green Roof Ecosystems*, 223:7.

80 Li and Yeung, 'A Comprehensive Study of Green Roof Performance from Environmental Perspective', 132.

81 Li and Yeung, 128.

soil layers that support a wider range of plant species, require a more reinforced structure to handle the additional weight, resulting in higher installation and maintenance expenses.

Maintenance expenses for intensive green roofs can be up to 10 to 20 times higher than those for extensive systems[82], which may discourage the use of green roofs or favour extensive over intensive options. Research shows a greater prevalence of studies and applications for extensive green roofs, likely due to their lower costs and reduced maintenance needs.[83]

2.2.3 Environmental Impact

Temperature regulation

Green roofs have the ability to cool temperatures, helping to mitigate the urban heat island effect in cities. As discussed previously in the section on *green facade*, plants provide cooling through **evapotranspiration**, a process where water vapour is released and cools the air, and through **shading**, which covers building materials that typically store heat. Soil also plays an important role in cooling by holding water and heat. The storage of heat affects surface temperature, which is influenced by sunlight reflectivity; the more sunlight reflected, the lower the surface temperature. The type, form, diversity and the biomass of plants can enhance the cooling effect and increase this reflectivity and, thus, reduce **surface temperature**.[84,85] Intensive roofs, for example, with their higher vegetation, are more effective in temperature regulation than extensive ones.[86] Additionally, the **height and orientation** of buildings significantly affect cooling performance. According to a study by Lilliana L. H., Peng, and C. Y. Jim, the most effective cooling configurations in a neighbourhood are low-rise buildings in low-density areas that align with the wind direction.[87] Beyond temperature reduction, green roofs can also improve thermal comfort by r**educing hot periods**; extensive roofs can reduce these periods by 6-9 hours and intensive ones can do so by 9-11 hours.[88]

In urban areas, building roofs occupy substantial ground space and there is “less space for greening at ground level”[89]. Green roofs bay may be a solution for more urban green spaces. Research links green spaces to mitigation of the urban island effect, suggesting

82 Li and Yeung, ‘A Comprehensive Study of Green Roof Performance from Environmental Perspective’, 132.

83 Li and Yeung, 128.

84 Umberto Berardi, AmirHosein GhaffarianHoseini, and Ali GhaffarianHoseini, ‘State-of-the-Art Analysis of the Environmental Benefits of Green Roofs’, *Applied Energy* 115 (February 2014): 416–17, https://doi.org/10.1016/j.apenergy.2013.10.047.

85 Li and Yeung, 128–29.

86 Lilliana L. H. Peng and C. Y. Jim, ‘Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation’, *Energies* 6, no. 2 (February 2013): 598–618, https://doi.org/10.3390/en6020598.

87 Peng and Jim, 615–16.

88 Peng and Jim, 615–16.

89 Wilkinson and Dixon, *Green Roof Retrofit*, 41.

that the adoption of green roofs could also help reduce urban temperature.[90] Moreover, implementing green roofs on a large scale could lower surrounding temperatures,[91] even by 2 to 3°C.[92] For example, according to Rosenzweig et al., as summarised in Bianchini and Hewage, putting green roofs on 50% of roofs in New York City could reduce the urban temperature difference by 0.8°C.[93] Another example of the cooling effects of green roofs shows temperature reductions ranging from 0.1 to 2.1°C at rooftop and pedestrian levels, illustrating slight differences between the top and ground floors. Vertically, these cooling benefits extend to building occupants, lowering temperatures on the top and ground floors by as much as 1.6°C.[94]

Urban Air Pollution Reduction

This environmental impact is similar to what was discussed in the green facade section. Plants and soil function similarly across environments, helping to reduce air pollution by absorbing CO_2 and other harmful gases through photosynthesis. In addition, green roofs help stabilise temperature fluctuations, which indirectly lowers CO_2 emissions by reducing the need for heating and cooling in buildings. This decrease in energy demand also contributes to a reduction in air pollution. This concept will be further explored in the Building Impact section.[95,96]

Urban Noise Reduction

Green roofs reduce noise through the sound-absorbing properties of their porous soil layer. The effectiveness of this noise reduction depends on both the thickness and type of materials used in the green roof.[97] Research indicates that green roofs achieve the best noise reduction with a substrate layer around 15 to 20 cm thick. Adding more thickness beyond 20 cm does not enhance effectiveness. Therefore, for optimal acoustic attenuation, an extensive green roof with a maximum depth of 15-20 cm or an intensive green roof is most beneficial.[98]

Further supporting this, Berardi and GhaffarianHoseini found that green roofs can reduce noise by 5-13 decibels at low frequencies and 2-8 decibels at high frequencies. However, for this noise reduction to be effective, the buildings need to be relatively low. This is because

90 Amir Mahdiyar et al., 'INVESTIGATING THE ENVIRONMENTAL IMPACTS OF GREEN ROOF INSTALLATION', *Jurnal Teknologi (Sciences & Engineering)* 76, no. 1 (27 August 2015): 269, https://doi.org/10.11113/jt.v76.3975.

91 Sutton, *Green Roof Ecosystems*, 223:4.

92 Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 423.

93 Fabricio Bianchini and Kasun Hewage, 'How "Green" Are the Green Roofs? Lifecycle Analysis of Green Roof Materials', *Building and Environment* 48 (1 February 2012): 58, https://doi.org/10.1016/j.buildenv.2011.08.019.

94 Peng and Jim, 'Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation', 615–16.

95 Mahdiyar et al., 'INVESTIGATING THE ENVIRONMENTAL IMPACTS OF GREEN ROOF INSTALLATION', 270.

96 Bianchini and Hewage, 'How "Green" Are the Green Roofs?', 59.

97 Sutton, *Green Roof Ecosystems*, 223:5.

98 T. Van Renterghem and D. Botteldooren, 'Numerical Evaluation of Sound Propagating over Green Roofs', *Journal of Sound and Vibration* 317, no. 3–5 (November 2008): 796–97, https://doi.org/10.1016/j.jsv.2008.03.025.

the green roof must be in direct exposure to the noise source for effective absorption.[99] For instance, green roofs are effective in attenuating noise from overhead sources, such as airplanes, reducing sound levels by up to 10 decibels.[100]

Biodiversity Enhancement

Green roofs support biodiversity in urban environments by creating new habitats for both plants and animals.[101,102] Underground animals live in the soil, while the vegetation layer attracts insects.[103] A study done in Switzerland showed "that 91 out of the 532 species (17%) known in Switzerland are represented on green roofs"[104].

Native plants are an effective tool for attracting animals, birds, and insects, as these species are naturally adapted to them.[105] Additionally, plant diversity on green roofs influences animal diversity, and animal diversity, in turn, supports plant diversity. This mutual diversity also helps with disease resistance, as a variety of species can limit the spread of diseases. However, selecting plant species for green roofs is complex; choices cannot be random due to the high costs of installation and maintenance. Moreover, the ecosystems found on green roofs differ from those in natural environments mainly because they are artificially created by humans and exist within a constructed setting.[106]

Extensive and intensive green roofs support distinct ecosystems due to their structural and environmental differences. Extensive roofs stand out for their rare urban conditions, featuring shallow soil and low fertilization. They create a challenging environment that favors stress-tolerant species that are adapted to survive under harsh conditions.[107] Extensive green roofs can host diverse arthropod communities, similar to those found in urban ground-level habitats like road verges, brownfields, or dry meadows. They also support specialist species, such as ground-nesting bees, which rely on rare urban resources like bare soils or sandy patches, key features of extensive roofs.[108]

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99 Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 422–23.

100 Sutton, *Green Roof Ecosystems*, 223:5.

101 Sutton, 223:5.

102 Mayrand and Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation', 3.

103 Li and Yeung, 'A Comprehensive Study of Green Roof Performance from Environmental Perspective', 133.

104 Pétremand, G.; Chittaro, Y.; Braaker, S.; Brenneisen, S.; Gerner, M.; Obrist, M.K.; Rochefort, S.; Szallies, A.; Moretti, M. Ground Beetle (Coleoptera: Carabidae) Communities on Green Roofs in Switzerland: Synthesis and Perspectives. Urban Ecosyst. 2017, 1–14. Cited in Mayrand and Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation', 3.

105 Li and Yeung, 'A Comprehensive Study of Green Roof Performance from Environmental Perspective', 128–29.

106 Sutton, *Green Roof Ecosystems*, 223:199–205.

107 Oberndorfer et al., 'Green Roofs as Urban Ecosystems', 825–27.

108 Mayrand and Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation', 6–7.

One remarkable difference between green roofs and natural settings is height. The building's elevation affects biodiversity, as it must be accessible. The surrounding environment is also crucial; without nearby natural habitats or existing ecosystems, animals, insects, and birds are less likely to be attracted to the roof. This lack of connectivity can lead to the green roof becoming isolated, with limited interaction with other green spaces. [109]

Rainwater Management

Rainwater management is one of the key environmental benefits of green roofs.[110] Studies show that extensive green roofs can reduce runoff by up to 60%, while intensive green roofs can mitigate it by as much as 100%.[111,112]

On a conventional roof, rainwater flows off quickly, while on a green roof, it enters into a complex system.[113,114] Indeed, green roofs have a high **retention** capacity, meaning that rainwater drains more slowly into city sewer systems. This controlled release reduces the volume of runoff, helping to lower the risk of flooding.[115,116] The retention amount depends mainly on two components of the green roof. The substrate plays a critical role in water retention and its composition and volume influence the capacity to absorb and store water.[117,118]. Then, vegetation also contributes, though to a lesser extent. Water is retained "on and within plants"[119], and different types of plants vary in their ability to absorb and hold water.[120] Green roofs not only slow runoff but also reduce its overall volume. With the help of plants and soil a part of the water is evaporated in the atmosphere.[121,122]

In addition to controlling runoff quantity, green roofs can enhance runoff **quality**. Soil and plants act as natural filters, absorbing and storing pollutants from runoff water. However,

109 Mayrand and Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation', 9.

110 Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 421.

111 Virginia Stovin, Gianni Vesuviano, and Hartini Kasmin, 'The Hydrological Performance of a Green Roof Test Bed under UK Climatic Conditions', *Journal of Hydrology* 414–415 (11 January 2012): 148–61, https://doi.org/10.1016/j.jhydrol.2011.10.022.

112 DeNardo, J.C., A.R. Jarrett, H.B. Manbeck, D.J. Beattie, and R.D. Berghage. 'Stormwater Mitigation and Surface Temperature Reduction by Green Roofs'. Transactions of the American Society of Agricultural Engineers 48, no. 4 (2005): 1491–96. Cited in: Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 421.

113 Sutton, *Green Roof Ecosystems*, 223:81.

114 Bianchini and Hewage, 'How "Green" Are the Green Roofs?', 58.

115 Mahdiyar et al., 'INVESTIGATING THE ENVIRONMENTAL IMPACTS OF GREEN ROOF INSTALLATION', 270.

116 Bianchini and Hewage, 'How "Green" Are the Green Roofs?', 58.

117 Sutton, *Green Roof Ecosystems*, 223:93.

118 Li and Yeung, 'A Comprehensive Study of Green Roof Performance from Environmental Perspective', 130.

119 Sutton, *Green Roof Ecosystems*, 223:82.

120 Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 422.

121 Wilkinson and Dixon, *Green Roof Retrofit*, 89.

122 Sutton, *Green Roof Ecosystems*, 223:82.

they can also raise phosphorus levels due to the usage of fertilisers, which may affect water quality downstream.[123,124]

Finally, rainwater management can be further optimised by incorporating ponds and cisterns to store rainwater for later use. This approach strengthens control over runoff into sewer systems but also provides a sustainable water source for irrigation or other needs.[125]

2.2.4 Building Impact

At the building level, the additional layers of vegetation and substrate on green roofs have **insulating properties**. In winter, these layers help retain interior heat, while in summer, they reduce heat entering the building. Additionally, through evapotranspiration heat is dissipated, and the shading effect from plants prevents heat absorption by building materials. Through these processes, green roofs effectively moderate temperature fluctuations, protecting the building from external temperature shifts. This means that the energy consumption of cooling and heating are reduced.[126,127,128]

Estimates for **energy consumption** reduction with green roofs vary across studies. Some report reductions of up to 80%[129], while others suggest a more moderate reduction of up to 14.5%, primarily observed in top-floor units.[130] In terms of insulation effects, one study shows that green roofs can reduce winter heat loss by 10% to 30% and decrease summer solar heat gain by 70% to 90%.[131] Green roofs offer impacts beyond just energy savings; they also **extend the lifespan** of the roof itself. Conventional roofs are typically exposed to UV radiation, rain, and other elements, limiting their lifespan to about 20-25 years. Green roofs, however, provide a protective barrier that shields the underlying materials from these harsh conditions, potentially doubling the roof's lifespan and reducing lifespan costs.[132,133]

123 Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 422.

124 Li and Yeung, 'A Comprehensive Study of Green Roof Performance from Environmental Perspective', 133.

125 Sutton, *Green Roof Ecosystems*, 223:4.

126 Wilkinson and Dixon, *Green Roof Retrofit*, 80–81.

127 Berardi, GhaffarianHoseini, and GhaffarianHoseini, 'State-of-the-Art Analysis of the Environmental Benefits of Green Roofs', 416–17.

128 Sutton, *Green Roof Ecosystems*, 223:4–5.

129 Peng, L. L. and Jim, C. Y. (2013) 'Green roof effects on neighborhood microclimate and human thermal sensation', Energies, 6, 598–618. Cited in: Wilkinson and Dixon, *Green Roof Retrofit*, 42.

130 Ascione, F., Bianco, N., de' Rossi, F., Turni, G., Vanoli, G. P. 2013. Green Roofs in European Climates. Are Effective Solutions for the Energy Savings in Air-conditioning? Appl Energy. 104: 845-859. doi:10.1016/j.apenergy.2012.11.068. Cited in: Mahdiyar et al., 'INVESTIGATING THE ENVIRONMENTAL IMPACTS OF GREEN ROOF INSTALLATION', 268.

131 Ascione, F., Bianco, N., de' Rossi, F., Turni, G., Vanoli, G. P. 2013. Green Roofs in European Climates. Are Effective Solutions for the Energy Savings in Air-conditioning? Appl Energy. 104: 845-859. doi:10.1016/j.apenergy.2012.11.068. Cited in: Mahdiyar et al., 267.

132 Wilkinson and Dixon, *Green Roof Retrofit*, 20.

133 Sutton, *Green Roof Ecosystems*, 223:4–5.

Finally, green roofs do have some limitations. First, they are more **costly to install** than traditional roofs due to the need for additional structural support, drainage systems, and specialised materials. Second, the insulating properties of green roofs may be less impactful in buildings that are already insulated, in such cases, the primary advantage may be environmental rather than building-specific. Moreover, the effectiveness and impact of green roofs vary by climate[134], making it challenging to determine their suitability for specific buildings.

2.2.5 Human centred Impact

Physical well-being

Similar to green facades, green roofs help address urban health issues like respiratory and cardiovascular problems linked to air pollution and the urban heat island effect. By absorbing pollutants and particulate matter, green roofs improve air quality (Chapter 2.2.3) and, consequently, enhance urban well-being. Additionally, green roofs mitigate the urban heat island effect through evapotranspiration, shading, and by reducing the duration of extreme heat, positively impacting health issues related to urban heat. A study across four European cities even found that green roofs could significantly reduce heatwave-related deaths in warmer urban areas.[135]

However, potential health downsides include runoff water contamination from pesticides and fertilisers, as well as exposure to pollen or animal diseases. Discomfort concerns are minimal, as direct contact is generally avoidable with green roofs.[136]

Mental well-being

Green roofs contribute to mental well-being in various ways including noise reduction, visual restorative effects and overall healthy mental state.

Noise pollution can negatively impact health by causing annoyance, sleep disturbances, and stress.[137] Green roofs help mitigate these effects by absorbing sound; however, there are some limitations (Chapter 2.2.3). For noise reduction to be effective, the noise exposure must be direct, and since green roofs are typically located on top of buildings, their impact on street-level noise can be limited.

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134 Berardi, GhaffarianHoseini, and GhaffarianHoseini, ‘State-of-the-Art Analysis of the Environmental Benefits of Green Roofs’, 421.

135 Antonino Marvuglia, Rembrandt Koppelaar, and Benedetto Rugani, ‘The Effect of Green Roofs on the Reduction of Mortality Due to Heatwaves: Results from the Application of a Spatial Microsimulation Model to Four European Cities’, *Ecological Modelling* 438 (15 December 2020): 10, https://doi.org/10.1016/j.ecolmodel.2020.109351.

136 Ode Sang, Thorpert, and Fransson, ‘Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach’, 11–12.

137 Ode Sang, Thorpert, and Fransson, 11.

A study using neuroscience tests on 150 students found that viewing a 40-second scene of a green roof with flowers, as opposed to a concrete roof, was associated with an attention boost and restorative mental effects.[138] Another study in Helsinki showed similar outcomes, with the green roof providing visitors with refreshing and positive experiences.[139] Another questionnaire-based study on residents with green roofs in Malaysia found that green roofs help preserve a healthy mental state. The residents reported an awareness of the positive emotional impact that green roofs have on their well-being.[140] However, it's important to recognize that green roofs are not universally visible and their visual benefits are primarily experienced from higher stories or specific vantage points.

Social well-being

Accessible green roofs enhance social well-being by creating **shared spaces** for building residents to connect and engage with nature. Studies, including one conducted through an online survey, indicate that green roofs are primarily used for relaxation and socialising, with users feeling an increased attachment to the space as they visit more frequently. Additionally, longer visits to green rooftops contribute to greater social well-being, showing the value of these spaces in creating social and emotional bonds within the building community.[141]

Additionally, green roofs actively might encourage **community-building** through activities centred on food cultivation, such as communal gardening and urban farming. These roof garden spaces provide shared areas for events, social networking, participation, and knowledge sharing, which contribute to broad community benefits.[142]

While the social impact of green roofs is notable, it is limited to **intensive systems**, which are accessible because of the roof's structure and can be designed for communal use. In contrast, **extensive green roofs,** with some accessible exceptions, are generally inaccessible and thus lack the capacity to deliver similar community-oriented benefits.

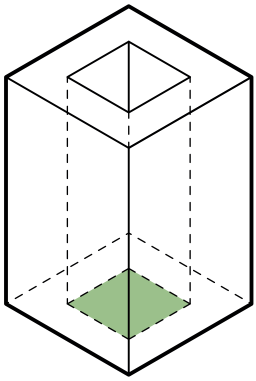
138 Kate E. Lee et al., '40-Second Green Roof Views Sustain Attention: The Role of Micro-Breaks in Attention Restoration', *Journal of Environmental Psychology* 42 (1 June 2015): 182–89, https://doi.org/10.1016/j.jenvp.2015.04.003.

139 Marja Mesimäki, Kaisa Hauru, and Susanna Lehvävirta, 'Do Small Green Roofs Have the Possibility to Offer Recreational and Experiential Benefits in a Dense Urban Area? A Case Study in Helsinki, Finland', *Urban Forestry & Urban Greening*, Urban green infrastructure – connecting people and nature for sustainable cities, 40 (1 April 2019): 114–24, https://doi.org/10.1016/j.ufug.2018.10.005.

140 Hanisah Abd Rahman, Nurul Syakima Mohd Yusoff, and Mustafa Omar, 'Perception of Green Roof Users with Their Mental Well-Being', *IOP Conference Series: Earth and Environmental Science* 1274, no. 1 (December 2023): 012036, https://doi.org/10.1088/1755-1315/1274/1/012036.

141 Hoai-Anh Nguyen Dang et al., 'Social Impact of Green Roofs', *Frontiers in Built Environment* 8 (10 November 2022), https://doi.org/10.3389/fbuil.2022.1047335.

142 Wilkinson and Dixon, *Green Roof Retrofit*, 189–215.



2.3 GREEN COURTYARD

In this context, a green courtyard refers to an open-air garden situated at ground level, enclosed by a building or a group of buildings. Courtyards have existed since ancient times and have been a prominent architectural typology across many civilizations, spanning regions from North Africa to China. Over centuries, they became integral elements in the built environments of cultures such as ancient Greece, Rome, and the Islamic world.[143] The origins of the courtyard can be linked to the Persian garden, a meticulously designed, enclosed space created to bring life and comfort to the harsh, arid climates of the region. These gardens, bounded by protective walls, fostered a microclimate that provided shade, greenery, and water, offering respite from the extreme external conditions.[144] In a contemporary context, courtyards can be found in a variety of settings across the world, each adapted to the local climate, culture, and architectural style.

143 Mohammad Taleghani, Martin Tenpierik, and Andy van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', *Journal of Green Building* 7, no. 2 (1 April 2012): 121, https://doi.org/10.3992/jgb.7.2.113.

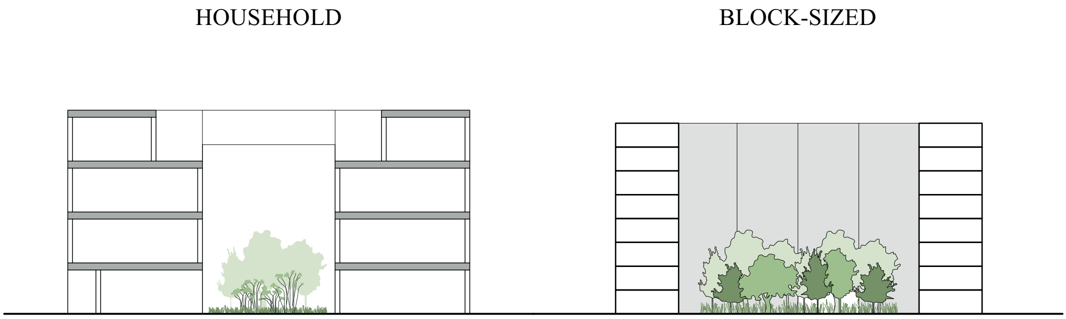
144 Hamed Khosravi, 'GEOPOLITICS OF TABULA RASA: PERSIAN GARDEN AND THE IDEA OF CITY', *JOURNAL OF ARCHITECTURE AND URBANISM* 38, no. 1 (28 March 2014): 42, https://doi.org/10.3846/20297955.2014.897017.

6. *Green courtyard perspective & axonometry*

2.3.1 Types & Design

We can distinguish two primary types of courtyards, differentiated by their size, though many other variations exist. **Household** courtyards are small, private spaces found within a single building or house. They can be centrally located or exist in multiple areas within the property, often serving as garden-like retreats. In contrast, **block-sized** courtyards, common in Europe, are much larger and span multiple buildings, functioning as shared open spaces for an entire block or community.

Courtyards are distinctive in how their function and the building's needs change with seasons and climates. In summer, they serve as outdoor living spaces, while in winter, they provide sheltered areas that protect against wind.[145] To meet specific environmental and functional goals, elements such as orientation, proportions, form and natural features are adjusted based on the climate, as each produces different outcomes.[146,147,148] For instance, in some climates, the courtyard functions as protection from the sun, while in others, it acts as a collector of sunlight.[149]



7. Green courtyards sections

2.3.2 Maintenance

Since courtyards are open-air spaces often featuring vegetation, their upkeep is similar to that of gardens and does not directly impact the structural layers of the building. As a result, only standard gardening maintenance is required.

145 Ferrer Forés and Jaime Jose, 'Courtyard Housing: Environmental Approach in Architectural Education', 2010, 840, https://upcommons.upc.edu/handle/2117/12880.

146 Zahra Zamani, Shahin Heidari, and Pirouz Hanachi, 'Reviewing the Thermal and Microclimatic Function of Courtyards', *Renewable and Sustainable Energy Reviews* 93 (October 2018): 580, https://doi.org/10.1016/j.rser.2018.05.055.

147 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 122–23.

148 Horizon Research Publishing(HRPUB) Kevin Nelson, 'Courtyard: A Look at the Relevance of Courtyard Space in Contemporary Houses', *Civil Engineering and Architecture*, 1 January 2021, 2268, https://www.academia.edu/65426294/Courtyard_A_Look_at_the_Relevance_of_Courtyard_Space_in_Contemporary_Houses.

149 Zamani, Heidari, and Hanachi, 'Reviewing the Thermal and Microclimatic Function of Courtyards', 586.

2.3.3 Environmental Impact

Temperature regulation

It is evident that temperature regulation is one of the most significant impacts of courtyards, as they have been used for centuries in hot and arid climates to effectively mitigate heat.[150] Courtyards regulate the temperature with three means:

Shading from the sun is a crucial factor in reducing heat. In hot areas or climates, small courtyards with high walls provide extensive shade throughout the day, creating a cooler environment.[151] A study conducted in Spain evaluated the heat mitigation effects of small courtyards and found that courtyards with greater height-to-width ratios act as effective thermal buffers, reducing temperatures during heat waves by 7 to 14°C.[152]

Natural elements such as plants, soil, and water are vital in enhancing the functionality of courtyards by improving thermal comfort. Plants, through the process of evapotranspiration, increase humidity levels and contribute to significant heat reduction. This process helps cool the surrounding air and enhances comfort within the courtyard. Additionally, the foliage of plants provides essential shading, further amplifying their cooling effect.[153] Vegetation, in particular, is often more effective at mitigating heat compared to water elements.[154] For instance, a study in Northern Italy assessed the impact of trees in block-sized courtyards and found that their cooling effects, driven by evapotranspiration, significantly reduced outdoor temperatures and alleviated heat stress. This highlights the importance of vegetation as a key element in courtyards for effective heat mitigation.[155]

In humid climates, the role of natural elements in courtyard design is influenced by the need to manage moisture and maintain comfortable conditions. Water features, such as pools or fountains, are typically avoided because they can increase humidity levels, which are already high in such environments. Instead, design efforts focus on elements that help cool the space without exacerbating the humidity like the usage of few evergreen trees. Conversely, in colder climates, the functional role of natural elements shifts due to differing priorities. The primary focus is on maximising sunlight exposure during winter to provide warmth and light, while shading requirements during the short summer months are minimal.

150 Zamani, Heidari, and Hanachi, 580.

151 Zamani, Heidari, and Hanachi, 586.

152 Walter Leal Filho and Evangelos Manolas, eds., *Climate Change in the Mediterranean and Middle Eastern Region*, Climate Change Management (Cham: Springer International Publishing, 2022), 413–31, https://doi.org/10.1007/978-3-030-78566-6.

153 Shuang Liu et al., 'The Role of Outdoor Courtyard Design Variables in Microclimate Performance: A Review', *Architectural Science Review*, 17 July 2024, 6, https://doi.org/10.1080/00038628.2024.2376582.

154 Zamani, Heidari, and Hanachi, 'Reviewing the Thermal and Microclimatic Function of Courtyards', 593.

155 Lia Marchi, Jacopo Gaspari, and Kristian Fabbri, 'Outdoor Microclimate in Courtyard Buildings: Impact of Building Perimeter Configuration and Tree Density', *Buildings* 13, no. 11 (November 2023): 2687, https://doi.org/10.3390/buildings13112687.

Instead, courtyards in these climates often are small courtyards to minimise heat loss and maximise sun exposure, and reduced vegetation density to allow sunlight to penetrate both the courtyard and adjacent interiors during colder seasons. [156]

The third method by which courtyards help mitigate heat is through the **Air circulation** into the building.[157] In hot climates, the rising hot air within the courtyard exits at night, allowing cooler air to replace it. During the day, this influx of cool air helps lower indoor temperatures. In humid climates, effective cross-ventilation is essential for maintaining comfortable indoor conditions by promoting airflow and reducing humidity. That's why courtyards are usually narrow with tall buildings that enhance cross-ventilation while avoiding excess vegetation to prevent increased humidity.[158] In addition, s*trategic openings on the exterior side of buildings could enhance this effect.*[159] However, in colder climates, airflow between the interior and courtyard is typically limited to retain warmth and prevent excessive heat loss.[160]

This method primarily impacts the courtyard and the building itself rather than the broader urban environment. However, block-sized courtyards, due to their larger scale, may have a greater impact on urban heat mitigation.

Urban Air Pollution Reduction

Air pollution is mitigated by the plants in the courtyard, though the extent of this effect depends on plant density and design. We could argue that block-sized courtyards are more efficient than household courtyards due to their larger size, which allows for greater functionality and impact. One article suggests that the cross circulation of air from exterior to courtyards may be efficient in reducing pollution.[161] Additionally, the energy savings achieved through the passive design strategies inherent in courtyards may indirectly lower urban air pollution by decreasing emissions associated with energy production. This aspect is explored further in discussions on building impact.

156 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 126–29.

157 Forés and Jose, 'Courtyard Housing', 852–53.

158 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 129.

159 Liu et al., 'The Role of Outdoor Courtyard Design Variables in Microclimate Performance', 13.

160 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 122.

161 Zamani, Heidari, and Hanachi, 'Reviewing the Thermal and Microclimatic Function of Courtyards', 588.

Urban Noise Reduction

While literature on this subject is limited, the layout of courtyards suggests noise attenuation from the exterior; "surrounding buildings or from the street".[162] This typology provides a quiet outdoor space, with household courtyards offering privacy and block-sized courtyards offering semi-private, communal spaces.

Biodiversity Enhancement

While specific studies on biodiversity in courtyards are scarce, green courtyards designed as gardens can support biodiversity by providing habitats for birds, insects, and other wildlife. This is more related to block-sized courtyards, which are larger and less isolated, offering more space for diverse plant life. The impact on biodiversity depends on the design and warrants further study.

Rainwater Management

Although literature on rainwater management specific to courtyards is limited, we can infer their potential benefits. Courtyards with permeable surfaces, such as soil or gravel, facilitate rainwater infiltration into the ground, reducing runoff into storm drains and mitigating urban flooding. The vegetation within courtyards further aids in managing water by absorbing a portion of it and promoting evaporation, much like green facades and roofs. Additionally, integrating water features into courtyard designs enhances their utility, allowing for the collection and storage of rainwater for future use.

162 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 121.

2.3.4 Building Impact

Courtyards are particularly effective in using natural methods to create **comfort** in living spaces. They enhance the building's performance, whether for cooling or heating, provide natural ventilation for the interior, and serve as a source of daylight.[163,164,165] For instance, studies on courtyard houses in Malaysia's hot-humid climate reveal significant temperature modulation, with indoor temperatures reduced by 0.3 to 1.7°C during the day and elevated by 0.8 to 1.9°C above outdoor temperatures at night.[166] Similarly, incorporating trees into courtyard designs in hot climates enhances wind flow, further reducing indoor temperatures and improving thermal comfort in adjacent rooms.[167] These findings highlight how courtyards with vegetation enhance both thermal comfort and natural ventilation. Courtyards also provide an efficient means of introducing **natural light** into buildings. In colder climates where sunlight is scarce, they maximise daylight penetration and heat gain, contributing significantly to indoor comfort[168]

The **orientation** of courtyard buildings also plays a significant role in building's performance. With four differently oriented sides, each is suited to specific seasonal and climatic needs. For example, a study in the Netherlands showed that in summer, the eastern and western sides of block-sized courtyards experience more indoor thermal discomfort due to solar angles, particularly on higher floors.[169] To address these challenges in hot-arid climates, buildings are often designed with longer facades facing east-west and narrower widths to optimise shading and minimise solar gain.[170] Conversely, in cold climates, the northern block is designed to be the largest, taking advantage of increased sunlight during winter.[171] Finally, through these passive strategies, courtyards significantly **reduce energy** demands for heating, cooling, ventilation, and lighting.[172] For instance, a study in Dubai's hot-arid climate demonstrated a 6.9% reduction in total annual energy consumption when a conventio-

163 Taleghani, Tenpierik, and van den Dobbelsteen, 121.

164 Zamani, Heidari, and Hanachi, 'Reviewing the Thermal and Microclimatic Function of Courtyards', 580.

165 Zahra Zamani, Mohammad Taleghani, and Seied Hoseini, 'Courtyards as Solutions in Green Architecture to Reduce Environmental Pollution', *Energy Education Science and Technology Part A: Energy Science and Research* 30 (1 October 2012): 388.

166 Zakaria MA, Kubota T, Toe DHC. The Effects of Courtyards on Indoor Thermal Conditions of Chinese Shophouse in Malacca. Procedia Eng 2015;121:468–76. http://dx.doi.org/10.1016/j.proeng.2015.08.1094. Cited in Zamani, Heidari, and Hanachi, 'Reviewing the Thermal and Microclimatic Function of Courtyards', 589.

167 Hao Sun et al., 'Numerical Investigation of the Influence of Vegetation on the Aero-Thermal Performance of Buildings with Courtyards in Hot Climates', *Energies* 14 (30 August 2021): 5388, https://doi.org/10.3390/en14175388.

168 Forés and Jose, 'Courtyard Housing', 840.

169 Mohammad Taleghani, Martin Tenpierik, and Andy Van Den Dobbelsteen, 'Indoor Thermal Comfort in Urban Courtyard Block Dwellings in the Netherlands', *Building and Environment* 82 (December 2014): 566–79, https://doi.org/10.1016/j.buildenv.2014.09.028.

170 Zamani, Taleghani, and Hoseini, 'Courtyards as Solutions in Green Architecture to Reduce Environmental Pollution', 395.

171 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 126.

172 Nelson, 'Courtyard', 2269.s.

nal six-story building was redesigned with a courtyard layout.[173] These benefits underscore the role of courtyards as a sustainable design strategy in diverse climates.

2.3.5 Human centred impact

Physical well-being

Courtyards in buildings provide natural views, light, and ventilation, all of which significantly contribute to overall well-being. Additionally, courtyards help improve indoor air quality by facilitating natural ventilation and allowing plants to filter out pollutants, creating a healthier living environment.[174] Small courtyards, and especially block-sized courtyards, offer valuable spaces for exercise in urban areas, promoting better physical health and fitness through physical activity.

Mental well-being

Green courtyards, whether small or block-sized, seamlessly integrate nature into urban spaces, providing daily access to natural views. This connection to nature has a proven healing effect, enhancing emotional well-being and fostering positive emotions. They also have a restorative impact, reducing stress, lifting mood, and promoting mental balance.[175] For instance, a survey conducted in a hospital courtyard garden in Malaysia (spanning 2,100 sqm) revealed that over 80% of participants felt more relaxed, less stressed, refreshed, pleased, calmer, and safe.[176] Furthermore, courtyards help mitigate noise pollution by orienting openings within the courtyard and by providing a secluded outdoor space. This setup has been shown to counteract the negative effects of noise on mental health, enhancing their benefits for overall mental well-being.[177]

Small courtyards contribute significantly to mental well-being by providing a private and tranquil outdoor space. In cultures where visual privacy is highly valued, such as in Islamic traditions, courtyards fulfil this essential requirement, offering a secluded area shielded from external views. This sense of privacy extends to feelings of safety and security, as courtyards are physically separated from the outside world, creating a protective environment. Together, these attributes foster a sense of mental comfort, promoting relaxation and

173 N. Al-Masri and B. Abu-Hijleh, “Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate,” Renew. Sustain. Energy Rev., vol. 16, no. 4, pp. 1892–1898, 2012, doi: 10.1016/j.rser.2012.01.008. Cited in Nelson, 2268.

174 Fawzi Al-Zamil, ‘Interior Courtyard and Its Impact on the Well-Being of Inhabitants’, *International Design Journal* 8, no. 1 (1 January 2018): 77, https://doi.org/10.21608/idj.2018.86214.

175 Al-Zamil, 77.

176 Madihah Mat Idris, Magda Sibley, and Karim Hadjri, ‘Users’ Perceptions, Experiences and Level of Satisfaction with the Quality of a Courtyard Garden in a Malaysian Public Hospital’, *Environment-Behaviour Proceedings Journal* 3, no. 9 (22 November 2018): 71, https://doi.org/10.21834/e-bpj.v3i9.1534.

177 Al-Zamil, ‘Interior Courtyard and Its Impact on the Well-Being of Inhabitants’, 84.

psychological well-being for occupants.[178,179] Additionally, smaller courtyards can be personalized, and this sense of control over the environment adds to greater psychological satisfaction and comfort.[180]

However, a potential drawback is that in urban areas, private outdoor spaces may lose their integrity due to taller buildings with visual access, compromising the privacy and tranquility that courtyards provide.[181]

Social well-being

From a social perspective, green courtyards provide valuable outdoor spaces that offer a variety of benefits. The nature of these benefits differs between small and block-sized courtyards. Small, private courtyards foster family-focused activities and intimate social interactions within the household. On the other hand, block-sized courtyards function as shared community spaces, encouraging interaction among neighbors and strengthening a sense of belonging. These larger courtyards can host collaborative work, workshops, or social gatherings, bringing residents together. They also serve as spaces for leisure activities such as gardening, food cultivation, or providing a safe area for children to play. When designed thoughtfully and enriched with greenery, these communal courtyards become valuable green spaces that promote social cohesion and collective engagement.[182,183] Finally, a study that employed eye-tracking techniques to investigate block-sized courtyards with vegetation found that people tend to fixate longer on green courtyards, highlighting the general interest and appeal of shared courtyards enriched with greenery.[184]

178 Nelson, 'Courtyard', 2266.

179 Taleghani, Tenpierik, and van den Dobbelsteen, 'ENVIRONMENTAL IMPACT OF COURTYARDS—A REVIEW AND COMPARISON OF RESIDENTIAL COURTYARD BUILDINGS IN DIFFERENT CLIMATES', 121.

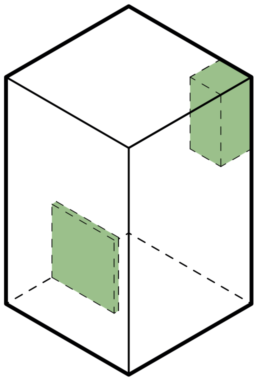
180 Al-Zamil, 'Interior Courtyard and Its Impact on the Well-Being of Inhabitants', 77.

181 Al-Zamil, 74–75.

182 Nelson, 'Courtyard', 2269.

183 Al-Zamil, 'Interior Courtyard and Its Impact on the Well-Being of Inhabitants', 76.

184 Nadezhda Kerimova et al., 'Visual Processing of Green Zones in Shared Courtyards during Renting Decisions: An Eye-Tracking Study', *Urban Forestry & Urban Greening* 68 (1 February 2022): 127460, https://doi.org/10.1016/j.ufug.2022.127460.



2.4 GREEN INDOORS

Green Indoors refers to the integration of greenery systems, such as potted plants, living walls, or indoor gardens, within interior spaces. The domestication of plants dates back to ancient civilizations like the Egyptians, Romans, and Greeks. In the 16th century, colonization introduced exotic plants to Europe, where they became a point of interest for the nobility. By the 19th century, during the Victorian era, indoor plants also gained popularity among the middle class. This trend experienced a resurgence during the COVID-19 pandemic as more people incorporated plants into their living spaces.[185] In the 2000s, indoor green installations gained increased interest, driven by the growing focus on biophilia and the well-being benefits of natural elements.

185 David Watson, 'Cultural History of House Plants' 11, no. 3 (2022).

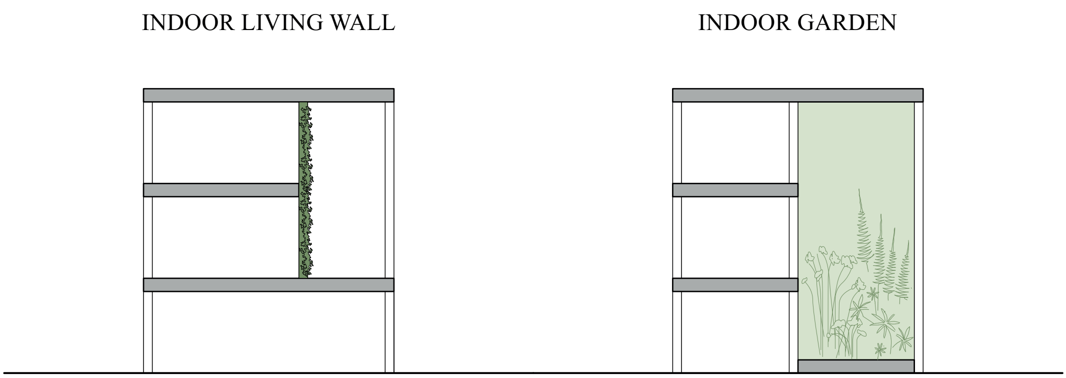
8. *Green indoors interior perspective & axonometr*

2.4.1 Types & Design

This greening method stands apart from others because it focuses on plant-based installations integrated directly into building interiors. While there are numerous options for indoor greenery, this discussion will highlight the most common examples without differentiating their environmental and building impacts. The most common and widely studied type of indoor greenery is the indoor living wall, a vertical installation of plants often with air circulation integrated. Another popular example is the indoor garden, usually situated in atriums, which creates a three-dimensional green space that transforms the volume and atmosphere of the area.

Design plays a crucial role in the success of indoor greening systems, both in terms of functionality and spatial impact. Integrating greenery within buildings presents challenges, particularly with ensuring adequate light and air circulation for plant health.[186] Additionally, selecting appropriate plants is critical, as choices must align with climate conditions, growth mediums, and light availability.[187] For this reason, it is essential to incorporate green systems into the design process from the outset, allowing for the creation of fully functional and sustainable installations.

Beyond functionality, green systems significantly influence spatiality. They can transform interior spaces by fostering unique interactions, enhancing aesthetic appeal, and shaping architectural design. Thoughtfully designed green installations not only serve environmental and practical purposes but also contribute to creating dynamic and engaging indoor environments.



9. *Green indoors sections*

186 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 12.

187 Tatiana Armijos Moya et al., 'A Review of Green Systems within the Indoor Environment', *Indoor and Built Environment* 28, no. 3 (March 2019): 8, https://doi.org/10.1177/1420326X18783042.

2.4.2 Maintenance

When integrating greenery into a building, several key considerations must be addressed to ensure long-term success and minimize risks. High humidity levels, resulting from plant transpiration and irrigation, can promote mold growth, deteriorating building materials and compromising structural integrity.[188] Additionally, irrigation systems or water leaks may damage building structures, potentially shortening the lifespan of the indoor greenery over time. In some cases, indoor greenery may also attract insects, which could pose further challenges within the building.[189]

Regular maintenance is also essential to ensure the health and aesthetics of the plants. Tasks such as "cleaning of leaves"[190] and removing debris are crucial for maintaining a clean, vibrant appearance and supporting the plants' overall health.

2.4.3 Environmental Impact

Since *Green Indoors* is situated within buildings, their primary impact is focused on the indoor environment of the building, with minimal direct influence on the external environment. However, it can contribute to rainwater management by utilizing collected rainwater to sustain indoor vegetation, thereby reducing the volume entering sewer systems and delaying runoff.[191]

188 Moya et al., 8–9.

189 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 13.

190 Moya et al., 'A Review of Green Systems within the Indoor Environment', 9.

191 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 8–9.

2.4.4 Building Impact

Interior greenery can positively influence buildings' indoor comfort by acting as a thermal buffer. In winter, it aids in preheating spaces, while in summer, it promotes cooling through evaporation. These effects lead to energy savings by reducing the demand for heating and cooling systems.[192] A study conducted in Wyoming tested an indoor greenery system and concluded that it enhances thermal comfort and increases occupant satisfaction. This approach has the potential to address challenges associated with rising temperatures and energy efficiency, making it an intriguing solution for future building design and sustainability.[193]

Additionally, greenery contributes to sound insulation through three mechanisms: reflection of sound by plants, absorption within vegetation, and sound dampening by the growth medium.[194] These properties enhance living spaces by reducing indoor noise levels and improving privacy, creating more comfortable and functional environments.

However, the potential downsides must also be considered. These include higher initial construction costs for incorporating greenery, increased maintenance expenses, and potential additional material and energy consumption during installation and upkeep.[195]

192 Zhong, Schroeder, and Bekkering, 8–9.

193 Emmanuel Iddio and Liping Wang, 'INDOOR GREENERY SYSTEMS: HOW DO THEY IMPACT OCCUPANT THERMAL COMFORT?', in *2024 ASHRAE Winter Conference* (2024 ASHRAE Winter Conference, ASHRAE, 2024), https://doi.org/10.63044/w24idd88.

194 Moya et al., 'A Review of Green Systems within the Indoor Environment', 7.

195 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 17.

2.4.5 Human centred Impact

Physical well-being

Integrating green installations within interior spaces offers a range of physical health benefits, with one of the most notable being their ability to enhance **indoor air quality**, an essential factor given that people spend approximately 80% of their time indoors.[196] These installations purify the air through the pollutant-absorbing properties of foliage and soil, effectively reducing indoor air pollution. Additionally, they help regulate **humidity** levels, enhance natural **ventilation**, and improve thermal comfort by lowering ambient temperatures and maintaining balanced humidity.[197]

Research on indoor air quality highlights the efficacy of indoor living walls in enhancing air purification. These systems demonstrate notable reductions in CO_2 and particulate matter, with removal rates ranging from 12% to 17% for CO_2 and 8% to 14% for PM2.5. Additionally, they contribute to a modest yet meaningful increase in indoor humidity, ranging from 3.1% to 6.4%,[198] and can remove volatile organic compounds (VOCs) in the root zones of plants.[199] This synergy of pollutant reduction and humidity regulation underscores the ability of indoor living walls to foster healthier and more comfortable indoor environments.

Moreover, green installations within buildings have been shown to positively influence the indoor microbiome and support the immune system. Studies reveal that air-circulating green walls can improve microbiome diversity, with office workers experiencing noticeable benefits within two weeks. These systems foster the growth of beneficial skin microbiota, such as Lactobacillaceae, which play a crucial role in enhancing skin health by mitigating issues like sunburn, oxidative stress, and hyperpigmentation.[200]

By reducing air pollution, regulating environmental conditions, and promoting microbiological diversity, green installations can significantly enhance indoor health, making them a valuable addition to modern spaces. However, some studies stress the importance of realistic design considerations. The scale of vegetation must be carefully planned to ensure he intended benefits are effectively realized.[201]

196 Fonseca, Paschoalino, and Silva, 'Health and Well-Being Benefits of Outdoor and Indoor Vertical Greening Systems', 8.

197 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 7–9.

198 Yiming Shao et al., 'The Impact of Indoor Living Wall System on Air Quality: A Comparative Monitoring Test in Building Corridors', *Sustainability* 13, no. 14 (14 July 2021): 7884, https://doi.org/10.3390/su13147884.

199 Moya et al., 'A Review of Green Systems within the Indoor Environment', 4–6.

200 L. Soininen et al., 'Indoor Green Wall Affects Health-Associated Commensal Skin Microbiota and Enhances Immune Regulation: A Randomized Trial among Urban Office Workers', *Scientific Reports* 12 (20 April 2022): 6518, https://doi.org/10.1038/s41598-022-10432-4.

201 D. Llewellyn and Mike Dixon, 'Can Plants Really Improve Indoor Air Quality?', *Comprehensive Biotechnology* 4 (31 December 2011): 331–38, https://doi.org/10.1016/B978-0-08-088504-9.00325-1.

Additionally, it is essential to account for potential challenges, such as dust accumulation and allergens, which could inadvertently contribute to respiratory issues for certain individuals.[202]

Mental well-being

Green systems bring the essence of nature into indoor environments, creating a harmonious atmosphere that reconnects individuals with their evolutionary bond to the natural world. This connection profoundly benefits mental well-being, influencing emotional balance, healing, performance, and our sense of connection to our surroundings.

Emotional Regulation: The integration of greenery in living and working spaces plays a vital role in regulating emotions. The calming presence of plants helps to alleviate stress and anxiety, fostering a tranquil and positive environment. This soothing influence promotes emotional stability, making spaces feel more inviting and comfortable.[203]

Healing and Restoration: Green systems go beyond aesthetic enhancement; they actively contribute to creating restorative environments. By purifying the air, improving thermal comfort, and mitigating noise, these systems support physical and mental well-being. Additionally, access to views of greenery or natural features has been shown to promote relaxation and healing. The color green, symbolizing renewal and calmness, further reinforces this restorative impact, making such installations beneficial for recovery and stress reduction.[204]

Performance: The visual presence of greenery not only enhances satisfaction by creating a pleasant and hospitable ambiance but also contributes to performance improvements. Green systems help alleviate fatigue, restore attention, and boost concentration, leading to increased productivity and mental clarity in indoor spaces.[205,206]

Connection: The presence of green systems fosters a deeper sense of fulfillment and attachment to a space. They strengthen an innate connection to nature, enhancing feelings of belonging and contentment in indoor environments.[207,208]

202 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 13.

203 Zhong, Schroeder, and Bekkering, 7–9.

204 N. Safitri, A. A. S. Fajarwati, and I. Rachmayanti, 'Indoor Greenery Effect as Anxiety Reduction to Improve Human Health and Wellbeing' (1ST INTERNATIONAL CONFERENCE ON ACHIEVING THE SUSTAINABLE DEVELOPMENT GOALS, Istanbul, Turkey, 2023), 2–5, https://doi.org/10.1063/5.0113721.

205 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 7–9.

206 Safitri, Fajarwati, and Rachmayanti, 'Indoor Greenery Effect as Anxiety Reduction to Improve Human Health and Wellbeing', 4–5.

207 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 7–9.

208 Safitri, Fajarwati, and Rachmayanti, 'Indoor Greenery Effect as Anxiety Reduction to Improve Human Health and Wellbeing', 4–5.

Research highlights the profound impact of green systems on mental health. For instance, a study involving university students examined the psychological effects of indoor green walls. Results showed that small green walls significantly reduced mental stress and fatigue compared to plain walls. Conversely, large green walls were linked to increased stress levels, possibly due to overstimulation or a sense of confinement. These findings suggest that smaller-scale greenery offers a more balanced and effective design choice for promoting mental well-being.[209] Similarly, a survey-based study conducted in China revealed that vertical greenery significantly enhances visual satisfaction and the restorative quality of indoor environments. These insights emphasize the potential of green systems to transform interiors into spaces that not only look appealing but also actively support mental and emotional health.[210]

However, indoor green systems may also introduce challenges. For example, their presence can sometimes evoke negative emotions due to concerns about insects in the living space that may be attracted to the plants.[211]

Social well-being

In shared living or working spaces, green installations contribute to social inclusion. For instance, an interior green wall can serve as an aesthetically pleasing feature that enhances the value of buildings. Similarly, a green garden provides a functional and welcoming space, ideal for social gatherings, conversations, and communal activities.[212] While these benefits primarily enhance interactions within a single building or community, they demonstrate how thoughtfully designed green systems can transform spaces into hubs of connection and cooperation.

209 Seungkeun Yeom, Hakpyeong Kim, and Taehoon Hong, 'Psychological and Physiological Effects of a Green Wall on Occupants: A Cross-over Study in Virtual Reality', *Building and Environment* 204 (15 October 2021): 108134, https://doi.org/10.1016/j.buildenv.2021.108134.

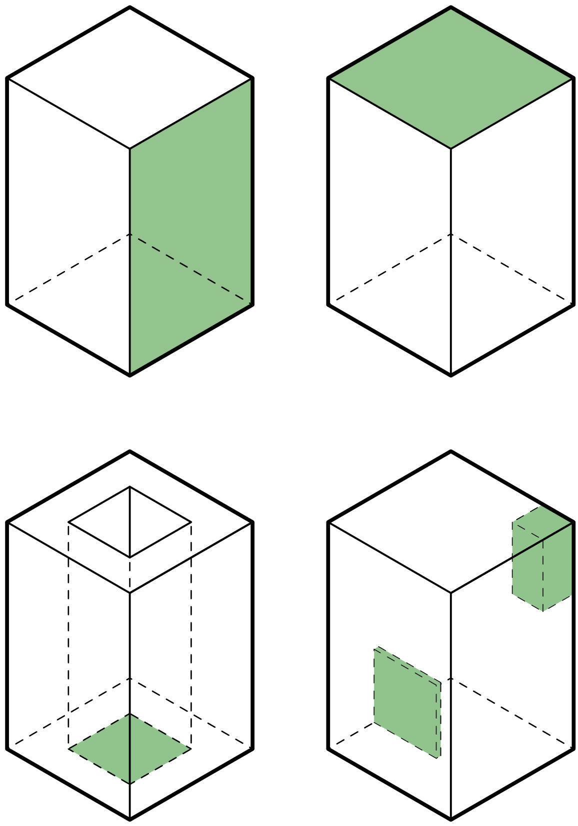
210 Lei Xiao et al., 'Study on the Relationship between Restoration Benefit and Visual Satisfaction of LONG-PLAN's Indoor Vertical Greenery', *Buildings* 12, no. 8 (19 August 2022): 1267, https://doi.org/10.3390/buildings12081267.

211 Zhong, Schroeder, and Bekkering, 'Designing with Nature', 7–9.

212 Zhong, Schroeder, and Bekkering, 7.

3.

INTEGRATED ANALYSIS



3.1 DESIGN

Design plays a crucial role in the successful integration of green measures in architecture. In this chapter, we examine three key aspects of design: complexity, opportunity, and feasibility. These perspectives help us understand the challenges and potential of integrating green facades, roofs, courtyards, and indoor greenery, while also addressing the complexity of each measure and comparing their strengths in different aspects.

3.1.1 Design Complexity

The design complexity of green measures involves the degree of difficulty in planning and integrating these systems while maintaining the integrity of the building or managing additional loads. Green facades, particularly wall-based systems, require careful planning because facade layers are involved and should remain intact and functional. Similarly, green roofs face likewise challenges, such as ensuring effective waterproofing. However, intensive systems add an extra constraint; the need to support significantly greater structural loads. Green indoors is the most challenging in itself because it accommodates plants within interior spaces, demanding a careful balance between greenery and the building's operational needs. Critical design considerations include ensuring adequate sunlight, proper ventilation, and selecting suitable plants. Compared to these three measures, green courtyards seem less complex because the focus is mainly on designing appropriate proportions and layouts that suit the local climate and regional characteristics thus require less technological complexity.

3.1.2 Design Opportunity

Here the opportunity lies in both the added aesthetic value of these measures and their potential spatial use or influence in the interior space. In regard to aesthetic value, it is safe to say green facades dominate because they add value to buildings and are visible from the street, serving as the face of the building. This is especially true for wall-based systems, as the aesthetic effect is immediate with pre-cultivation. For roofs, intensive ones should be highlighted, as they support taller vegetation, are more visible, and, most importantly, can serve as outdoor spaces for residents, an advantage green facades lack. While extensive roofs contribute aesthetically and can in some cases be used as outdoor spaces, their visibility often depends on being viewed from taller buildings. However, if we look at green courtyards, these also offer outdoor usability and influence spatiality of building mostly when it's the case of a household courtyard. Courtyards impact building typology but are not designed for street visibility; instead, their aesthetic value serves a more private purpose. Lastly, indoor greenery combines usability (3D gardens) and spatial influence, along with an aesthetic that adds value to the building's interior space.

The *Municipal Office* in Venlo designed by Kraaijvanger Architects exemplifies a well executed design opportunity by integrating all four greening measures. This approach not only achieves aesthetic value but also enhances spatial usage and functionality. The green facade, as the most prominent feature, defines the building's identity. Indoor greenery, including living walls and a greenhouse, adds visual appeal while serving practical purposes, such as the functional use of the greenhouse. The semi-courtyard provides an outdoor usable space, and parts of the green roof are designed as terraces, giving additional functionality and a visual connection with the offices overlooking the green roofs. This project stands out for its design due to its combination of all four greening measures.[213]

213 See Annexe: 5.1 *Municipal Office* in Venlo

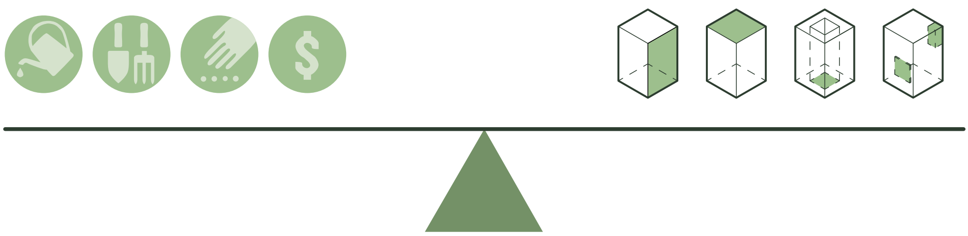
Fig.1 *Municipal Office's green facade* © Ronald Tilleman Fig. 2 *Green roof and courtyard* © C2C Expolab

Fig. 3 *Interior* © Ronald Tilleman Fig. 4 *Interior* © Ronald Tilleman

3.1.3 Feasibility

Assessing the feasibility of these four greening measures in an urban context is crucial to understanding their applicability and potential constraints. Among them, extensive green roofs are the most feasible for urban environments due to their lightweight systems and adaptability to existing buildings, making retrofitting a possibility. Intensive green roofs are feasible but face challenges due to their significant weight, which requires more careful structural considerations. Green facades are also practical, particularly ground-based systems, which are easier to implement compared to wall-based systems. They can still be implemented effectively with proper planning and structural support. Green courtyards, on the other hand, pose some feasibility challenges in urban areas. Their reliance on ground-level space, often limited in densely populated cities, constrains their applicability, especially for household courtyards that cannot meet needed density. One solution is the concept of semi-courtyards, as demonstrated in the *Municipal Office* project in Venlo. These offer a compromise between full courtyards and limited urban space. However, larger, block-sized courtyards can be more suitable for urban areas, offering greater utility and ecological benefits.

When considering the limitation of ground space, which is predominantly occupied by buildings, roofs offer significant potential for future greening. Intensive green roofs, in particular because of their load bearing capability, could serve as a solution by transforming unused roof areas into additional outdoor spaces with park-like environments.



3.2 MAINTENANCE

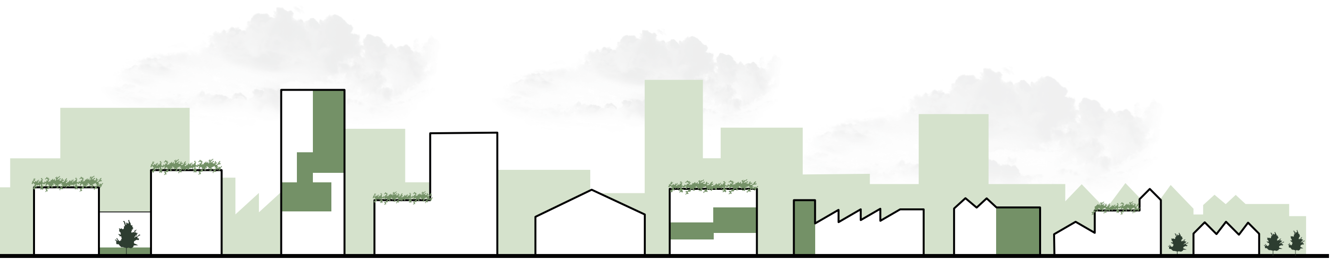
Maintenance is a significant challenge when incorporating green measures in architectural design. Plants require ongoing care as they grow, evolve over the years, and respond to seasonal changes. This dynamic process can sometimes be a drawback, influencing design choices and limiting the feasibility of certain green measures. In this subchapter, the maintenance aspects of each green measure will be evaluated, focusing on plant care and inspection, as well as the need for irrigation.

3.2.1 Plant care & inspection

This is the fundamental plant care associated with green measures, with varying levels of intensity depending on the type. The simplest options include ground-based facade greening, extensive roofs, and green courtyards, as they require only basic plant maintenance. In contrast, wall-based green facades, intensive roofs, and interior green systems are more complex due to more dense and diverse vegetation. Neglecting proper maintenance can lead to degradation, compromising the effectiveness of these green measures. These systems also demand additional inspections to ensure structural integrity, effective waterproofing, and, for indoor systems, to maintain the building's integrity by managing risks such as mold, humidity, and insect infestations.

3.2.2 Irrigation

The need for irrigation not only raises installation costs but also increases maintenance requirements, as these systems must be regularly monitored and controlled. Greening measures that depend on irrigation include intensive roofs, wall-based facades, and all indoor systems. Green indoors is the most complex, especially since they are located within buildings where leaks can pose significant risks. The other measures require less irrigation and can function independently without it.



3.3 ENVIRONMENTAL IMPACT

Understanding the environmental impact of green measures is essential, as they directly affect both buildings and the cities we live in. These measures offer practical solutions to many common urban problems. Integrating greenery in buildings can help regulate temperatures, improve air quality, reduce noise, support biodiversity, and manage rainwater. In addition to solving environmental issues, these efforts create healthier and more livable cities. This subchapter looks at the environmental benefits of green measures, focusing on how they address challenges like the heat island effect, air pollution, noise, and water management.

3.3.1 Temperature Regulation

One of the most important considerations in the face of global warming is the need to plan buildings with future temperature conditions in mind. Green roofs and facades contribute similarly to cooling through shading and evapotranspiration, with intensive roofs proving more effective than extensive roofs, and wall-based greening outperforming ground-based systems. Green facades primarily affect street-level environments and spaces between buildings, while green roofs influence rooftop levels and have a broader impact on the urban scale.[214] This means that combining both green facades and green roofs on a building allows for temperature regulation at both street level, where people typically spend their time, and at the roof level, contributing to overall heat reduction across the urban area. Block-sized green courtyards regulate temperature at an environmental level, leveraging shading, natural elements, and improved air circulation to help mitigate the urban heat island effect. When combined with a green roof, this strategy can potentially achieve a "maximum reduction (14%) in the number of discomfort hours."[215] But what if all these three greening measures were combined? Research on combinating measures lack and further studies are needed to explore the combined effects of these strategies, which individually and in pairs perform well but could potentially have a much greater impact on temperature regulation and urban climate resilience when integrated all together.

The *25 Verde* residential project, designed by Luciano Pia, exemplifies the successful integration of these three green measures into architecture: a block-sized courtyard, green roofs, and green facades. With 50 trees in the courtyard and 150 tall trees planted in large vases on the terraces and roof, the building significantly contributes to urban cooling. The trees provide shading, regulate humidity levels, and enhance natural ventilation through evapotranspiration, while the water elements on the ground floor further aid in cooling. Additionally, the building's typology itself creates natural shading during the summer months, showcasing how a combination of greenery and thoughtful design can effectively mitigate heat and improve environmental comfort.[216]

3.3.2 Urban Air Pollution Reduction

As previously discussed, vegetation plays a crucial role in mitigating urban air pollution, with its effectiveness being enhanced when combined with soil, which also helps trap particulate matter. This is particularly evident in green roofs and green façades, especially concerning wall-based structures. One of the key advantages of green façades is their direct presence on street levels, where they can filter pollutants right at the source, particularly in

214 Wilkinson and Dixon, *Green Roof Retrofit*, 41–42.

215 Ode Sang, Thorpert, and Fransson, 'Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach', 12.

216 See Annexe: 5.2 *25 Verde* in Turin

areas impacted by vehicle emissions. The plants and soil in green façades capture particulate matter as it advances along the street, trapping it before it spreads further. Block-sized courtyards also can contribute to improving air quality, particularly when they are densely vegetated. These courtyards can enhance air circulation, helping to «push» polluted air out of the area. However, the extent of their impact depends on the density and type of vegetation, which determines how effectively they can trap pollutants and support air circulation. A good example for a densely vegetated courtyard is the *25 Verde* project that was mentioned previously, which includes 50 trees and 150 more trees integrated into the building. This large amount of greenery in the urban area helps reduce air pollution by capturing particulate matter and improving air circulation. The project "absorbs approximately 200,000 litres of carbon dioxide an hour"[217] demonstrating the potential of combining green facades, roofs, and courtyards to enhance air quality in cities.

Fig. 5 *25 Verde's Green Facade* © Beppe Giardino

Fig.6 *Courtyard* © Beppe Giardino

Fig.7 *Green courtyard* © Beppe Giardino

217 Jon Astbury, '25 Verde in Turin by Luciano Pia', *The Architectural Review* (blog), 14 May 2015, https://www.architectural-review.com/today/25-verde-in-turin-by-luciano-pia.

3.3.3 Urban Noise Reduction

In this aspect, green façades are most effective at reducing noise when soil is present. Their impact is specifically efficient in street canyons. Green roofs, while similar in their noise-absorbing qualities, are more effective when the noise originates above roof level. However, their impact is more limited at street level, even though most urban noise is generated by street traffic.[218] Green courtyards, in contrast, serve as sound buffers, giving outdoor protected space from noise especially in areas with high noise levels from traffic and other urban activities. The *Municipal Office* in Venlo incorporates all three green measures and is efficient in urban noise reduction. Situated in a busy traffic zone and next to a railroad, the building effectively mitigates noise through its design. The wall-based green facade directly absorbs street traffic noise, the green roofs address noise from higher levels, and the semi-courtyard offers a quiet outdoor space.[219]

3.3.4 Biodiversity Enhancement

Green façades, roofs, and courtyards create additional natural spaces in urban environments, which is inherently beneficial for biodiversity. Green façades, in particular, attract a variety of animals, insects, birds, and bats. One of their advantages over green roofs is that they are more accessible from the ground, making them more attractive to a wider range of species. Both intensive and extensive green roofs contribute to biodiversity. Intensive green roofs, with their higher plant diversity and density, support a broader range of species. Extensive green roofs, while offering fewer plant species, provide important urban resources that may be rare in the city. To reduce the isolation of green roofs and enhance biodiversity, a practical solution is to use green façades as «vertical corridors,»[220] improving connectivity between different green spaces and allowing species to move more freely throughout the urban environment. Some notable projects exemplify these principles. The *Municipal Office* features a wall-based green façade with over 100 plant species, linked to green roofs above. Similarly, the *Wagnis 4* residential project in Munich showcases a green roof system with diverse vegetation, nesting boxes, and insect hotels. Although the façade here is smaller and ground-based, it effectively connects to the rich biodiversity of the roof. Both the Municipal Office and Wagnis 4 integrate courtyards into their designs, further enhancing biodiversity. These courtyards provide additional habitats and resources for various species and function much like small parks. Larger, block-sized courtyards are less isolated compared to smaller ones. By combining green façades, roofs, and courtyards, these projects show how design can create connected spaces that support biodiversity in urban areas.[221, 222]

218 Ode Sang, Thorpert, and Fransson, 'Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach', 11–12.

219 See Annexe: 5.1 *Municipal Office* in Venlo

220 Mayrand and Clergeau, 'Green Roofs and Green Walls for Biodiversity Conservation', 8.

221 See Annexe: 5.1 *Municipal Office* in Venlo

222 See Annexe: 5.3 *Wagnis 4* in Munich

Fig.8 *Wagnis 4 green roof view* © Bernhard Rohnke

3.3.5 Rainwater Management

All measures influence rainwater management through natural processes like evaporation and absorption. These processes affect not only runoff but also filtration, with varying degrees of effectiveness depending on the system. Among these measures, green roofs, especially intensive ones, are particularly effective. They directly receive rainwater, absorbing and significantly delaying runoff. The thicker the substrate layer, the greater the delay. Additionally, intensive green roofs can store water, making it available for use during drier periods. Green facades share similarities with green roofs but lack the capacity for water storage. Courtyards, by contrast, can include water storage features but filtration properties weren't found in literature. Their contribution to rainwater management depends heavily on design specifics. The least effective option is indoor greenery, which can use rainwater but does not include storage or filtration capabilities, only usage of water.

In the case of *25 Verde*, the roof features an intensive system with soil depths ranging from 60 cm to 100 cm. This substrate absorbs rainwater, filters it, delays runoff, and stores it in ground-floor ponds. Trees within the building further absorb and evaporate water. The captured rainwater is used to irrigate the project's trees and plants, ensuring a balance of delay, filtration, storage, and usage. This system effectively manages heavy precipitation, preventing flooding while providing stored water for drier periods.[223] The *Municipal Office*

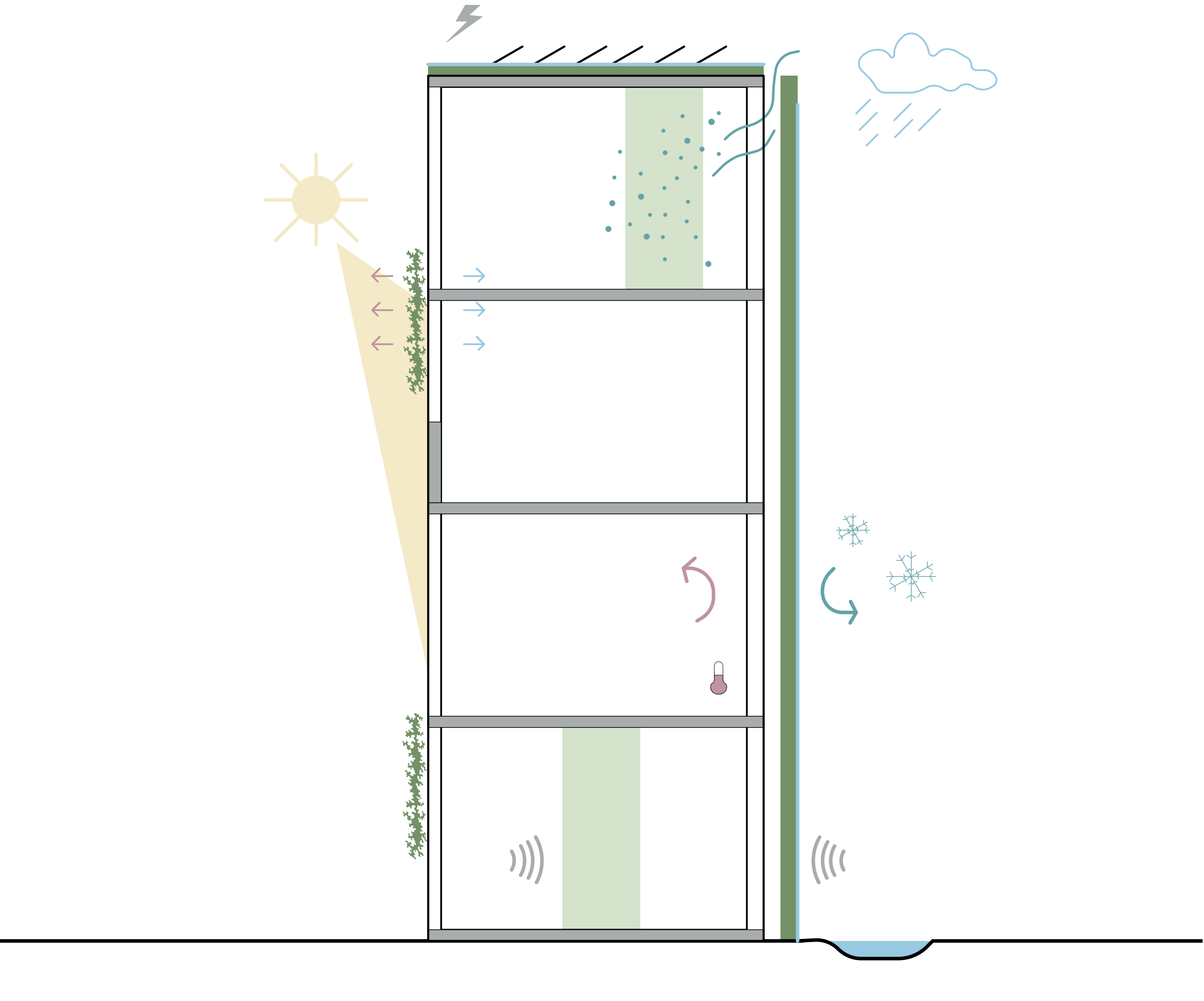
223 See Annexe: 5.2 *25 Verde* in Turin

in Venlo demonstrates an even more advanced approach. In addition to collecting water through its green roofs and wall-based green facade, rainwater is directed to the courtyard, where a pond and helophyte filter further purify it. The filtered water is then reused for irrigating the green facade and flushing toilets.[224] Both projects exemplify effective rainwater management by delaying runoff, reducing rainwater through evaporation, and providing stored water for use during hotter days or daily activities.

Fig.9 *25 Verde's ground-floor water storage*
© Beppe Giardino

Fig.10 *Municipal Office's Courtyard with water pond*
© Kraaijvanger Architects

224 See Annexe: 5.1 *Municipal Office* in Venlo



3.4 BUILDING IMPACT

Since we spend much of our time indoors, ensuring comfort in the indoor environment is essential, both for our well-being today and for the future as we need to adopt more passive design strategies. This subchapter examines the impact of integrating greenery into buildings, emphasizing their potential to enhance thermal comfort, air quality, noise reduction, energy efficiency, and structural durability. By analyzing and comparing the four green measures, we evaluate how these approaches contribute to improving a building's overall performance.

3.4.1 Insulating Properties

Green facades contribute to cooling buildings in summer and reducing heat transfer in winter, an effect that is enhanced when soil is involved, as seen in both wall-based greening and green roofs. While indoor greenery does not provide insulation in the traditional sense, it acts as a thermal buffer, improving thermal comfort within interior spaces. Courtyards are particularly effective in regulating temperatures through their layout, proportions and natural elements, aiding in heating during winter and cooling in summer. However, their benefits can be unevenly distributed; some parts of the building may receive insufficient sunlight in winter, while others might experience excessive heat in summer due to greater sun exposure. Similarly, green roofs are most effective in non-isolated buildings, with their insulating properties predominantly benefiting the upper floors. The *Municipal Office* highlights these dynamics. Its green façade and roof contribute to the building's insulation, but the courtyard is only partial and lacks the full shading benefits that a larger courtyard could provide in summer. An interesting feature, however, is the green indoors in the form of a greenhouse that is located on the upper floors. Heated by the sun in winter, the greenhouse distributes warmth throughout the building via atriums and voids, enhancing the thermal comfort.[225]

3.4.2 Ventilation & Air Quality

Green indoors and green courtyards emerge as the most efficient in this aspect. Green indoors, being directly located within the indoor environment, significantly enhance air quality through the plants' air-purifying properties, humidity regulation, and support for natural ventilation. These features have a direct impact on indoor air quality. Green courtyards, on the other hand, function differently by enabling cross-ventilation through their open typology, coupled with the humidity effects of natural elements present in the courtyard space. Green facades are less effective overall but can contribute to natural ventilation when a ventilation layer is integrated, allowing fresh air to flow into the building. When compared to outdoor green facades, indoor systems have a greater impact on indoor air quality.[226] In contrast, green roofs are the least effective in this regard, with no literature found linking them to improvements in natural ventilation.

The *Municipal Office* project illustrates an integrated approach to improving interior air quality. Its green facade not only enhances the building's aesthetics but actively purifies the surrounding air that enters the building, reducing fine dust and CO_2 levels by up to 30% within a 500-meter radius. Within the building, a combination of indoor greenery, the green façade, and water storage systems work together to purify and humidify the air. The design of voids, atriums, and a solar chimney, which drives air outside using heat, complements

225 See Annexe: 5.1 *Municipal Office* in Venlo

226 Shao et al., 'The Impact of Indoor Living Wall System on Air Quality', 1.

these features and enhances natural ventilation. Together, these elements improve indoor air quality while reducing reliance on mechanical systems.[227]

3.4.3 Interior Noise Reduction

The most effective green measure for reducing interior noise is indoor greenery. Plants and soil have sound absorption properties that help lower noise levels inside, creating a quieter and more comfortable living space. Green courtyards also play a role in supporting a quiet indoor environment by providing an outdoor space isolated from external noise. Adding a green roof alongside a courtyard could further enhance the tranquility of the environment by blocking noise from above. Additionally, green facades can absorb sound in the outdoor environment, potentially reducing noise transmission into buildings. While their impact is mainly external, they still offer indirect benefits that improve indoor sound conditions.

3.4.4 Energy Savings

Heating and cooling energy savings are among the most common benefits of green systems, with wall-based green facades being particularly effective, alongside intensive and extensive green roofs. Ground-based facades also contribute to energy savings, although to a lesser extent due to their comparatively lower insulating qualities. Green roofs are especially impactful in summer, as they have direct exposure to sun and greening helps significantly reduce heat gain while also reducing a part of heat loss in winter. This makes them highly efficient in hot periods. Courtyards, on the other hand, contribute to energy savings across multiple areas. They reduce energy consumption for heating, cooling, and ventilation, while also bringing natural lighting, making them an efficient design feature for capturing passive energies. Indoor systems act as thermal buffers, enhancing thermal comfort and potentially reducing energy demand. However, their energy-saving potential is uncertain, as these systems often rely on infrastructure like extensive ventilation to operate effectively.

An example that shows an energy-efficient design that integrates green indoor systems is the *Municipal Office*. This building uses only one-third of the energy consumed by the city's former municipal offices. Key to this performance is its combination of natural ventilation (via green indoors, green façade, and water elements), insulating features (including the greenhouse, green façade, and green roof), and a water reuse system that supports multiple functions, contributing to its overall energy efficiency.[228]

227 See Annexe: 5.1 *Municipal Office* in Venlo

228 See Annexe: 5.1 *Municipal Office* in Venlo

3.4.5 Longevity

Green roofs provide the most protection for buildings because roofs are constantly exposed to UV light or other weather conditions. According to research, covering roofs with vegetation can double their lifespan. Green facades offer similar benefits, but their impact is less significant since they are not as exposed as roofs. The type of green facade is also crucial, as ground-based greening with self-climbers is not as effective in this regard. However, wall-based or ground-based with guided climbers can extend a facade's lifespan by up to 15 years.[229] On the other hand, green courtyards have little effect on building durability because they are not directly attached to the structure and are more of a design feature. Similarly, green indoor spaces do not enhance building durability and may even lead to deterioration if not properly maintained. Any measure, including green roofs, facades, courtyards, or indoor spaces, can lead to deterioration if not properly designed, installed, and maintained.

229 Perini and Rosasco, 'Cost–Benefit Analysis for Green Façades and Living Wall Systems', 115.

3.5 HUMAN CENTRED IMPACT

Studying green measures for their environmental and building-related impact is essential, but it's equally important to investigate their effect on humans. While they contribute to energy efficiency or rainwater management, they also play a significant role in enhancing well-being. In this investigation, we define health not merely as the absence of illness but as «a state of complete physical, mental, and social well-being».[230] In this subchapter we explore and compare how the four green measures contribute to human well-being, focusing on their ability to improve physical comfort, mental health, and social environments.

230 'Constitution of the World Health Organization', accessed 16 October 2024, https://www.who.int/about/governance/constitution.

14. *Human centred scheme*

3.5.1 Physical Well-being

Green measures contribute to physical well-being through both indirect and direct benefits. Indirectly, they improve the overall urban environment by reducing air pollution and mitigating urban heat island effects, positively impacting public health. Measures like green roofs, facades, and courtyards are particularly effective in this regard. There are also direct benefits that come from enhancing indoor environments. Green courtyards influence indoor spaces by supporting natural ventilation and cooling, while indoor greenery directly improves air quality and contributes additional benefits, such as supporting the skin microbiome. For example, the *Municipal Office* project illustrates the physical health advantages of green measures. As mentioned earlier, indoor air quality and ventilation are enhanced by the green façade and indoor greenery. Notably, within the first year of operation, sick leave among employees was reduced, demonstrating the positive impact of these green features on workplace health.[231] Moreover, some green measures provide opportunities for physical activity. Courtyards and, in some cases, intensive green roofs can offer areas for exercise, encouraging healthier lifestyles. However, these benefits must be weighed against potential drawbacks. Green roofs, facades, and indoor systems can introduce allergens, dust or attract insects, while the use of pesticides and fertilizers in green roofs and potentially facades risks contaminating water supplies.

3.5.2 Mental Well-being

Green measures provide indirect benefits to mental well-being, mainly through improved air quality and noise reduction. All green measures contribute to this in different ways. For example, indoor greenery specifically enhances the indoor environment. The most significant benefit to mental well-being, however, comes from the visual impact of greenery. Green courtyards are especially effective in providing views of nature from inside the home, as are well-designed indoor green spaces. Viewing nature has healing effects, helps regulate emotions by reducing stress and anxiety, and improves concentration and performance. The direct connection to nature in living spaces offered by indoor greenery and courtyards is particularly beneficial. However, the design of these spaces plays a key role; for instance, block-sized courtyards provide views but may not create as strong a sense of connection to nature as smaller courtyards. Similarly, the placement of indoor greenery, whether in every individual apartment or if in shared communal spaces, affects its impact. Green roofs provide visual appeal as well, but their effect is limited to taller buildings, meaning those who can see them from above. In contrast, green facades offer less consistent benefits since they are typically visible only from outside. However, project-specific designs can overcome this limitation.

231 'Venlo City Hall – C2C Expolab', accessed 17 December 2024, https://www.c2cexpolab.eu/en/references/venlo-city-hall/.

For instance, the residential *Garden Tower* in Wabern, designed by Buchner Bründler Architekten, incorporates a green facade with a ground-based system, where substrate is situated on the concrete slabs. The building's open apartment layout gives a visual connection between the interior spaces and the green facade. In contrast, wall-based greening systems, like the green facade in the *Municipal Office*, often obstruct views from inside due to the placement of substrates. Systems using metal mesh to guide climbing plants, as in the Wabern Tower, preserve visual transparency, enhancing the mental health benefits of greenery by maintaining a strong indoor-outdoor connection.[232,233]

Fig.11 *Wabern Tower's interior view* © Bruno Helbling

Fig.12 *Wabern Tower's facade* © Michael Blaser

Lastly, potential drawbacks should be noted, with the most common being discomfort caused by insects in green facades that can enter indoor spaces or balconies and in indoor greenery. This weaker aspect can be more easily avoided in roofs and courtyards.

232 See Annexe: 5.4 *Garden Tower* in Wabern

233 See Annexe: 5.1 Municipal Office in Venlo

3.5.3 Social Well-being

Social well-being refers to the quality of interactions among individuals, which green measures can support by providing spaces for activities or gatherings. For instance, green roofs, especially intensive ones, often provide shared outdoor spaces that encourage interaction among building residents. Similarly, courtyards can foster social connections, with smaller courtyards creating more intimate spaces and block-sized ones accommodating broader community interactions beyond just the building's occupants. A notable example is the *Wagnis 4* residential project in Munich, which features both a courtyard, an intensive-extensive rooftop garden and some climbing-plants on the facade. The rooftop serves as a place for social activities such as vegetable gardening, recreation, and gatherings, while the mid-sized courtyard offers additional usable outdoor space. Residents were actively involved in the design and construction process and now maintain the rooftop themselves, fostering a strong sense of community.[234] If we compare this project to *25 Verde*, both incorporate similar green measures, such as the courtyard and green roof. However, in *Wagnis 4*, the courtyard and especially the rooftop garden serve as usable spaces for the community, fostering social interactions. This is a notable difference, as *25 Verde* lacks this aspect where rooftop gardens are private and courtyards aren't usable spaces, making social well-being a weaker element of its design.

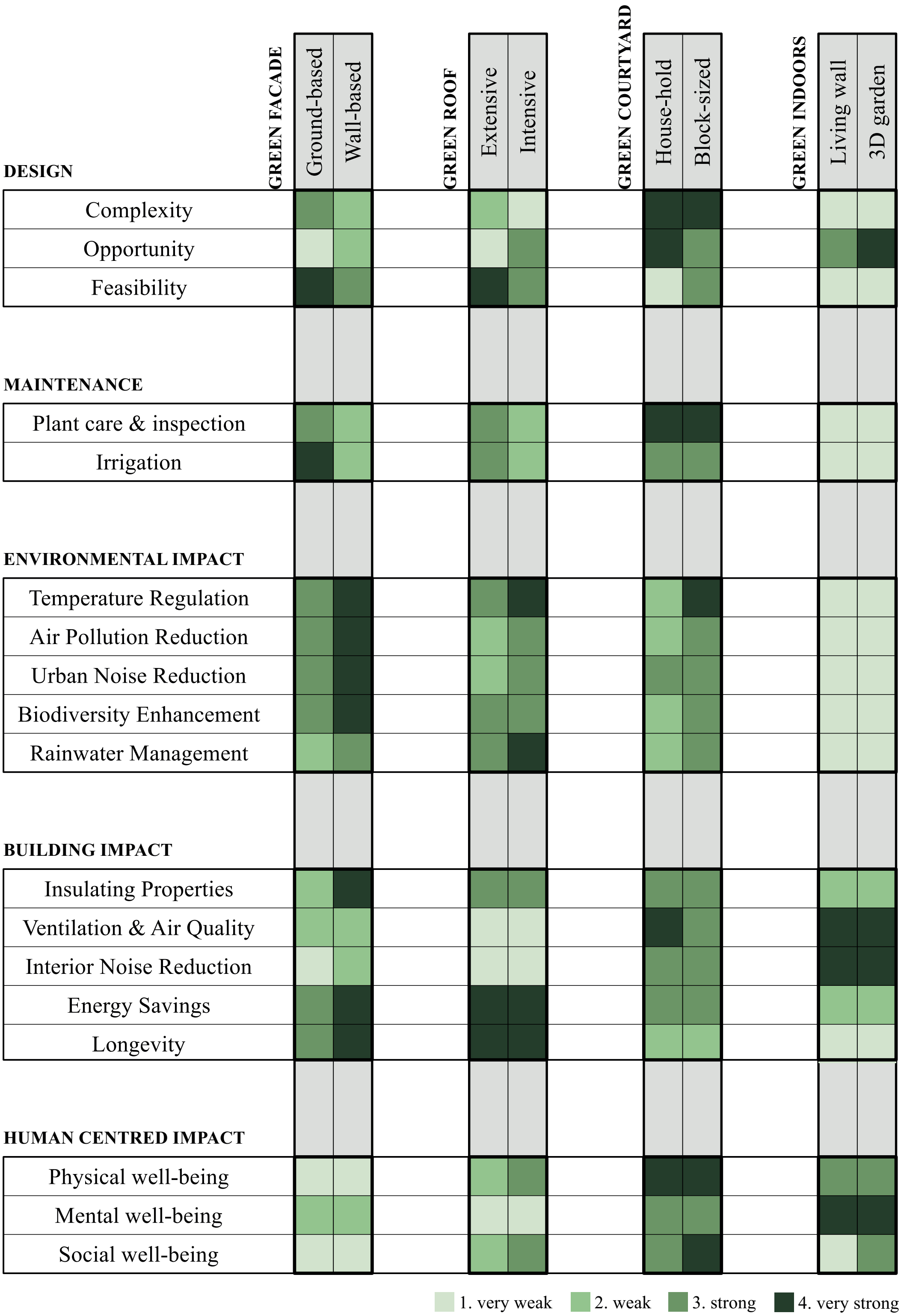
Fig.13 *Wagnis 4's courtyard and green facade* © Bundesverband GebäudeGrün e. V.

234 See Annexe: 5.3 *Wagnis 4* in Munich

Fig.14 *Wagnis 4 Roof gardening*
© Bernhard Rohnke

Fig.14 *Wagnis 4 collective work* © Rudi Hassenstein

Furthermore, indoor greenery can also contribute to social well-being when it includes shared, usable spaces within the building. However, if the greenery has no usable space, such as green walls or facades, the interaction is limited to only visual observation of the installation. Among all the measures, green roofs stand out as having the greatest potential. In cities where green spaces are scarce and roofs dominate much of the available space, green roofs emerge as a future and feasible solution to enhance social well-being while optimizing urban space.


GREEN FACADE
Ground-based
Wall-based
GREEN ROOF
Extensive
Intensive
GREEN COURTYARD
House-hold
Block-sized
GREEN INDOORS
Living wall
3D garden
DESIGN
Complexity
Opportunity
Feasibility
MAINTENANCE
Plant care & inspection
Irrigation
ENVIRONMENTAL IMPACT
Temperature Regulation
Air Pollution Reduction
Urban Noise Reduction
Biodiversity Enhancement
Rainwater Management
BUILDING IMPACT
Insulating Properties
Ventilation & Air Quality
Interior Noise Reduction
Energy Savings
Longevity
HUMAN CENTRED IMPACT
Physical well-being
Mental well-being
Social well-being
1. very weak
2. weak
3. strong
4. very strong

3.6 RESULTS

This final subchapter summarizes the findings from the *Integrated Analysis*, presented in a comprehensive table. The table highlights the strengths and weaknesses of each green measure, drawing from the literature review in *Individual Analysis* and the comparative analysis conducted in the *Integrated Analysis*. The evaluation considered specific criteria grouped under five categories: Design, Maintenance, Environmental Impact, Building Impact, and Human-Centered Impact. Each measure and its types were rated on a performance scale from 1 to 4, where 1 is very weak, 2 is weak, 3 indicates strong and 4 is very strong. It is important to note that the scores represent generalized assessments based on common findings rather than evaluations of specific cases, as individual applications may vary.

15. *Comparative table*

The table reveals that no single greening measure is universally superior; each has distinct strengths and weaknesses across different categories. Green courtyards are the most balanced overall, contributing to design, environmental impact, building performance, and human-centered benefits. Green indoors, for instance, have weaker environmental impact scores compared to the other three measures. However, they excel in building-related criteria such as ventilation and air quality, as well as interior noise reduction, performing better than green roofs and façades in these aspects. In human-centered impacts, green indoors also stand out due to their integration within interior spaces, fostering close interaction with users. Although the environmental benefits are less pronounced because the measure operates within the building, its influence on human-centered impacts and interior space quality is significant.

Green façades, on the other hand, are strong in environmental impacts like air pollution reduction and biodiversity enhancement but rank weaker in human-centered benefits and interior space performance (air quality, ventilation, and noise reduction). Nevertheless, they perform well in areas such as energy savings and insulation, contributing to building efficiency. When compared to green roofs, façades show similar overall results, with the main distinction being the added functionality of roofs as usable spaces. Furthermore, ground-based façades and extensive green roofs tend to be less effective due to minimal or absent soil layers, while wall-based façades and intensive roofs perform better with more substantial soil systems.

Maintenance requirements are influenced by the system's complexity. Ground-based façades and extensive green roofs are easier to maintain, while more intricate systems like green indoors face greater challenges. In design considerations, courtyards excel, though household courtyards are less feasible in high-density contexts. Overall, the results emphasize that the suitability of each measure depends on context and priorities, whether they are environmental, design-oriented, or human-centered.

4.

CONCLUSION

In conclusion, urban areas today face a spectrum of interconnected challenges, from climate change and loss of biodiversity to limited access to green spaces and growing health concerns. These problems require innovative solutions that can simultaneously enhance environmental resilience, building performance, and human well-being. This study highlights the potential of green measures, Green Facades, Green Roofs, Green Courtyards, and Green Indoors, as key strategies for addressing these pressing urban challenges.

While no single measure emerges as universally optimal, each green measure offers unique advantages based on context and priorities. If one measure were to be considered the most well-rounded across design, maintenance, environmental impact, building performance, and human-centered impact, it would be the household green courtyard. However, its feasibility in dense urban areas is often constrained by limited space.

When focusing on human well-being, green indoors prove particularly beneficial. Their direct integration into interior spaces, where people spend most of their time, significantly improves physical and mental health while enhancing building quality in areas like air quality and noise attenuation.

To address environmental challenges, green roofs and facades, especially wall-based facades and intensive green roof systems, perform well in aspects like rainwater management, temperature regulation, and air pollution reduction. These two measures also strengthen building performance through better insulation, energy savings, and longevity. When combined, green roofs and facades offer amplified environmental and building benefits. Individually, they address different areas, rooftops, street levels, or building exteriors, impacting factors like noise attenuation, temperature regulation or insulating properties. Together, they create a multi-level approach that promotes connectivity for biodiversity while enhancing social well-being, with green roofs offering parklike outdoor spaces for communal use.

In terms of design, green facades are to choose if the aim is to enhance the building's exterior appearance. For creating a green interior atmosphere, green indoors or courtyards work better as the first provides indoor systems and the second sheltered outdoor spaces within the building, offering a direct connection to nature.

While greening measures positively contribute to building performance, thoughtful design remains crucial for maximizing outcomes. The *Municipal Office*, for example, combines multiple green systems with design features like atriums, a solar chimney, water reuse systems, and solar panels to achieve superior performance and circularity. Each type of measure and its performance in all categories strongly varies from one case to another and to do a comparative analysis it was necessary to generalize and choose the most common variations. In addition, climate and geographical conditions impact greening measures performance in aspects.

Incorporating greenery into buildings presents some difficulties, particularly in terms of maintenance and cost. Green measures like green indoors, wall-based facades, and intensive roofs require more care, and poor upkeep risks degradation, shortening building lifespans. The initial cost is higher when integrating greening measures than for normal buildings; for green roofs, intensive are much more expensive in installation but also maintenance. The architect behind *25 Verde* highlighted that the inclusion of greenery resulted in “double of the average cost for a standard building” and greenery accounted for 10-15% of the total cost, compared to an average of 3-5% for a standard building.[235]

This research emphasizes the necessity of a holistic approach to integrating greenery into architectural design. By bridging the gaps often found in studies that focus exclusively on environmental, building-related, or human-centered impacts, the study considers all these aspects together and offers a comprehensive understanding of the potential and limitations of these measures. With the challenges cities face today, such as climate change and limited access to green spaces, the integration of greenery directly within a housing project in the urban context of Lausanne would be a valuable focus for the master project. This approach provides direct access to nature, enhancing well-being for residents, but also serves as an effective response to the evolving urban climate. By incorporating greenery in the forms of green facades, green roofs, green indoors, and green courtyards as core design elements, buildings can be transformed into spaces that could meet future standards and well-being but also redefine urban living, making it healthier and more adaptable to the challenges of tomorrow.

235 ‘Living in a Tree House in Torino (Italy): Combining Adaptation and Mitigation Measures to Improve Comfort’, accessed 16 December 2024, https://climate-adapt.eea.europa.eu/en/metadata/case-studies/living-in-a-tree-house-in-torino-italy-combining-adaptation-and-mitigation-measures-to-improve-comfort.

5.

ANNEXES: MENTIONED PROJECTS

5.1 Municipal Office in Venlo

Architects | Kraaijvanger Architects, Rotterdam
Landscape architects | Copijn
Structural engineering | Envo Groep BV, Laudy construction
Completion | 2012 - 2016
Location | Venlo, The Netherlands

The council office project in Venlo is a showcase of circular design principles, featuring the use of recycled concrete and self-generated energy. The building integrates greenery in multiple ways, including a green roof, indoor greenery, a patio (which resembles a courtyard), and a green façade, the largest of its kind in the world. This wall-based green façade features over 100 plant species, providing a habitat for insects and birds and enhancing biodiversity. Located next to busy traffic and a railway, it filters fine dust and gases like CO_2, while also absorbing sound from the noisy surroundings. Indoor greenery is strategically placed in the building, where circulation occurs (voids, atriums), as well as on the top floor, which houses a greenhouse for growing regional products. This tall green house is the heat source for the entire building. The indoor greenery, green facade, and water storage systems purify and humidify the air within the building. Additionally, the voids and atrium support natural ventilation, aided by the solar chimney, which draws air out due to captured heat. Water management is another key feature. The green roof collects rainwater and is directed to the patio/courtyard where rainwater and wastewater is purified through the helophyte filter and then used for flushing toilets and watering the green facade. The water in the courtyard also helps with heat stress and biodiversity as well as providing a place for relaxation.[236,237,238,239]

Finally, compared to the former municipal offices, this building uses only one-third of the energy. The green façade purifies 30% of fine dust and CO2 within a 500-meter radius, while also improving the interior air quality to levels better than the external air. Additionally, in the first year of operation, there was a noticeable decrease in sick leave among employees.[240]

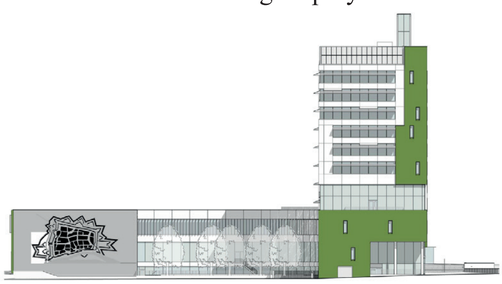


Fig.16 *Eastern facade,*© Kraaijvanger Architects

236 ‘Municipal Office Venlo | Kraaijvanger’, accessed 17 December 2024, https://www.kraaijvanger.nl/en/projects/city-hall-venlo.

237 ‘Stadskantoor Venlo / Kraaijvanger Architects’, ArchDaily, 27 May 2017, https://www.archdaily.com/872129/stadskantoor-venlo-kraaijvanger-architects.

238 *Development of Venlo Municipal Offices - Veldhoen + Company*, 2011, https://www.youtube.com/watch?v=FWDG-goTLYGA.

239 *C2C Stadskantoor, Documentaire Engels*, 2017, https://www.youtube.com/watch?v=a8dsIBwdiLM.

240 ‘Venlo City Hall – C2C Expolab’.

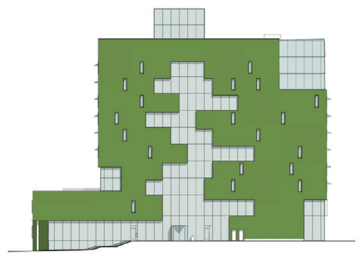


Fig.17 *Northern Facade,* © Kraaijvanger Architects

Fig.18 *Section,* © Kraaijvanger Architects

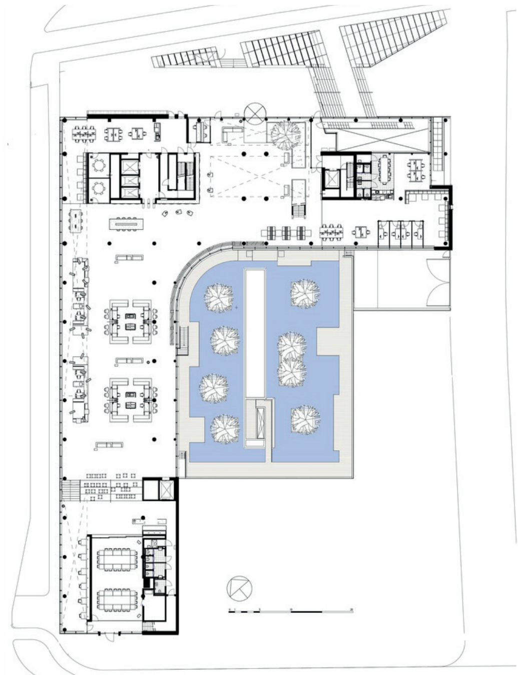


Fig.19 *Ground floor plan,* © Kraaijvanger Architects

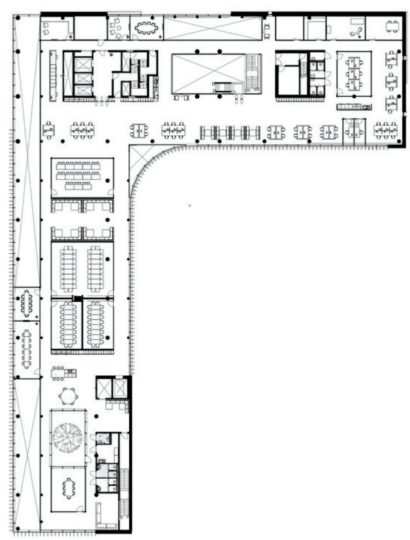


Fig. 20 *First Floor plan,* © Kraaijvanger Architects

Fig. 21 *Floor Plan, Levels 4 and 8,* © Kraaijvanger Architects

5.2 *25 Verde* in Turin

Architects | Luciano Pia
Landscape architects | LineeVerdi
Structural engineering | Giovanni Vercelli
Completion | 2010-2023
Location | Turin, Italy

This housing project stands out for its exceptional design, resembling a giant treehouse with 200 trees seamlessly incorporated into its architecture. The U-shaped building features a central courtyard with 50 trees, acting as a filter between the internal living spaces and the surrounding streets, while the terraces host another 150 tall trees planted in large vases. These trees represent a diverse mix of species, ranging in height from 2.5 to 8 meters, and showcasing colorful leaves and vibrant flowers. The trees significantly improve the building's environmental performance by purifying the air, reducing noise pollution, creating shade, promoting natural ventilation, and stabilizing indoor temperatures. The top floor is covered with private green roofs using an intensive system, with a soil depth of 60 to 100 cm. Rainwater is captured on the rooftop gardens and directed to a pond at ground level, which enhances the ambiance, provides summer cooling, and supplies irrigation for the plants.

The building's structure combines brick walls, thick floor slabs, and steel supports designed to mimic tree trunks, enhancing its natural aesthetic. Continuous thermal insulation and a ventilated facade further enhance energy efficiency, while wide glass surfaces provide optimal natural lighting and facilitate winter solar gain. Designed with durability in mind, the structure has an expected lifetime of "50 years with only ordinary maintenance".[241] The project also integrates geothermal energy through heat pumps, enhancing its renewable energy systems. Combined with water reuse, natural cooling strategies, and effective sun protection, these features contribute significantly to the building's energy efficiency.[242,243,244,245]

241 'Living in a Tree House in Torino (Italy)'.

242 'Architetto Luciano Pia » 2007-2012 – "25 Green" (25 Verde)', accessed 16 December 2024, https://www.lucianopia.it/opere-e-progetti/2007-2012-25-green-25-verde/.

243 'Living in a Tree House in Torino (Italy)'.

244 '25Verde Apartment Jungle Is an Ecosystem of 150 Trees, 60+ Apartments', **faircompanies* (blog), 16 January 2022, https://faircompanies.com/videos/forest-condominium-is-ecosystem-of-150-trees-60-apartments/.

245 Astbury, '25 Verde in Turin by Luciano Pia'.

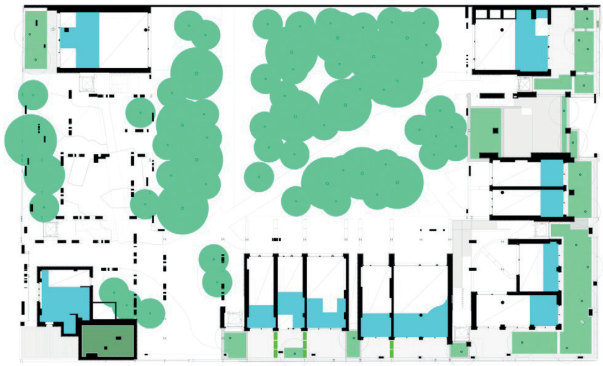


Fig. 22 *Level 0* © Luciano Pia

Fig. 23 *Elevation* © Luciano Pia

Fig. 24 *Section* © Luciano Pia

5.3 *Wagnis 4* in Munich

Architects | a2 freising architekten + stadtplaner, Kai Krömer and Stefan Lautner, Freising
Landscape architects | Wamsler Rohloff Wirzmüller FreiRaumArchitekten, Regensburg
Structural engineering | Bauart Ingenieure, Munich
Completion | Summer 2014
Location | Munich, Germany

This residential complex has around 55 apartments arranged in a U-shaped floor plan and built with a concrete-timber hybrid structure. A standout feature is its green spaces, including a rooftop garden, a central courtyard with trees and climbing plants on the facade. The rooftop, accessible by an elevator, has three zones: two wings for gardening and recreation (intensive system) and a third for a photovoltaic system (extensive) that enables self-generated energy for the building. Gardening areas include vegetable beds shared by 2-3 families, a greenhouse built and maintained by residents, an unheated winter garden, and other retreat spaces. In the courtyard, a small watercourse runs along the pathway, and a climbing wall complements the covered outdoor seating area. On a more environmental side, paved surfaces are to a minimum and this intensive-extensive roof helps with rainwater management, cooling and biodiversity with its diverse vegetation, nesting boxes and insect hotels. Community involvement is at the heart of the project, with residents engaged in planning, construction, maintenance and most importantly profit of these green spaces.[246,247,]

246 Pfoser, *Green Facades*, 104–7.

247 ‘wagnis 4 München’, *solid UNIT* (blog), accessed 13 December 2024, https://www.solid-unit.de/projekte/wagnis-4-muenchen/.

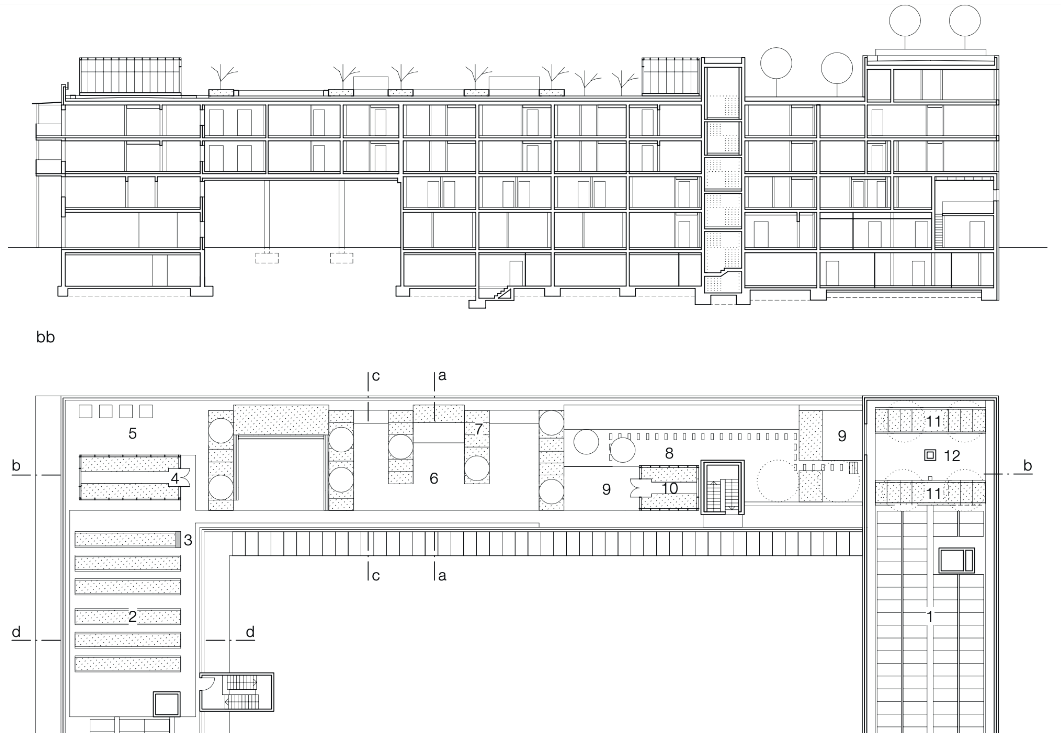


Fig. 25 *Section & Roof plan* © a2 freising architekten + stadtplaner, Kai Krömer and Stefan Lautner

5.4 *Garden Tower* in Wabern

Architects | Buchner Bründler Architekten, Basel
Landscape architects | Nipkow Landschaftsarchitektur AG
Structural engineering | Schnetzer Puskas Ingenieure AG
Completion | 2014-2016
Location | Wabern (BE), Switzerland

Located in Wabern, this 54-meter-tall residential tower with 184 apartments is part of five projects in Bächtelen, each focusing on a unique design theme. This project has the theme of «living with a view.» Designed as a polygonal tower, it features projecting concrete slabs and a metal mesh that has openings and blends with the natural landscape. A defining element of the design is the vertical garden, supported by the metal mesh that encircles the building. This feature serves a dual purpose: providing shade and enhancing aesthetic appeal, with vibrant greenery that turns vivid in autumn. Along the slab edges, a substrate layer supports plant growth, integrating nature into the structure. The open apartment layouts offer panoramic views of the surrounding landscape, emphasizing a strong connection between the building and its environment. [248,249,250]

Fig. 26 *Ground floor* © Buchner Bründler Architekten

248 Pfoser, *Green Facades*, 100–103.

249 'Garden Tower', accessed 15 December 2024, https://bbarc.ch/en/garden-tower?cat=Bau.

250 'Climbing Plants and Asymmetric Balconies Surround Buchner Bründler's Garden Tower', Dezeen, 24 February 2017, https://www.dezeen.com/2017/02/24/climbing-plants-asymmetric-balconies-buchner-brundler-garden-tower-architecture-switzerland/.

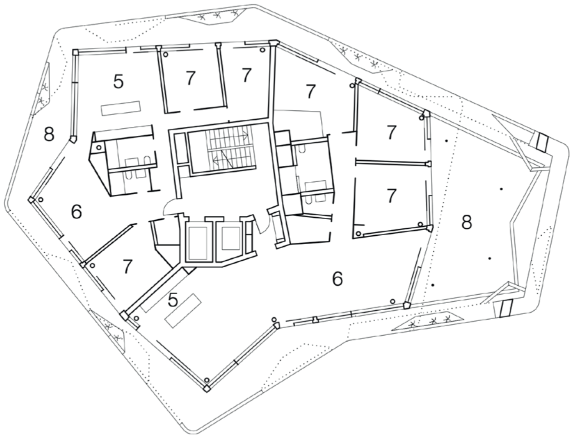


Fig. 27 *Fifteenth floor* © Buchner Bründler Architekten

Fig. 28 *Section* © Buchner Bründler Architekten

6.

ILLUSTRATIONS

Fig. 1: *Green facade* © Ronald Tilleman, Kraaijvanger Architects
Source: ArchDaily. 'Stadskantoor Venlo / Kraaijvanger Architects', 27 May 2017. Accessed 19 December 2024. https://www.archdaily.com/872129/stadskantoor-venlo-kraaijvanger-architects.

Fig. 2: *Green roof and courtyard* © C2C Expolab
Source: 'Venlo City Hall – C2C Expolab'. Accessed 19 December 2024. https://www.c2cexpolab.eu/en/references/venlo-city-hall/.

Fig 3: *Interior* © Ronald Tilleman, Kraaijvanger Architects
Source: ArchDaily. 'Stadskantoor Venlo / Kraaijvanger Architects', 27 May 2017. Accessed 19 December 2024. https://www.archdaily.com/872129/stadskantoor-venlo-kraaijvanger-architects.

Fig 4: *Interior* © Ronald Tilleman, Kraaijvanger Architects
Source: ArchDaily. 'Stadskantoor Venlo / Kraaijvanger Architects', 27 May 2017. Accessed 19 December 2024. https://www.archdaily.com/872129/stadskantoor-venlo-kraaijvanger-architects.

Fig 5: *Green Facade* © Beppe Giardino
Source: ArchDaily. '25 Green / Luciano Pia', 13 March 2015. Accessed 19 December 2024. https://www.archdaily.com/609260/25-green-luciano-pia.

Fig 6: *Courtyard* © Beppe Giardino
Source: ArchDaily. '25 Green / Luciano Pia', 13 March 2015. Accessed 19 December 2024. https://www.archdaily.com/609260/25-green-luciano-pia.

Fig 7: *Green courtyard* © Beppe Giardino
Source: ArchDaily. '25 Green / Luciano Pia', 13 March 2015. Accessed 19 December 2024. https://www.archdaily.com/609260/25-green-luciano-pia.

Fig 8: *Wagnis 4 green roof view* © Bernhard Rohnke
Source: 'Dachgarten wagnis 4'. Accessed 16 December 2024. https://www.competitionline.com/de/projekte/64235.

Fig 9: *25 Verde ground-floor water storage* © Beppe Giardino
Source: ArchDaily. '25 Green / Luciano Pia', 13 March 2015. Accessed 19 December 2024. https://www.archdaily.com/609260/25-green-luciano-pia.

Fig 10: *Interior* © Kraaijvanger Architects
Source: 'Epea'. Accessed 7 January 2025. https://www.epea.com/en/references/venlo-city-hall.

Fig 11: *Wabern Tower's interior view* © Bruno Helbling
Source: Nicole Pfoser, ed., Green Facades, First edition, DETAIL Practice (München: DETAIL, 2024), 102, https://doi.org/10.11129/9783955536213.

Fig 12: *Wabern Tower's facade* © Michael Blaser
Source: 'Garden Tower | Schnetzer Puskas'. Accessed 16 December 2024. https://www.schnetzer-puskas.com/en/projects/3107-garden-tower.

Fig 13: *Wagnis 4's courtyard and green faade* © Bundesverband GebäudeGrün e. V.
Source: solid UNIT. 'wagnis 4 München'. Accessed 13 December 2024. https://www.solid-unit.de/projekte/wagnis-4-muenchen/.

Fig 14: *Wagnis 4's Roof gardening* © Bernhard Rohnke
Source: 'Dachgarten wagnis 4'. Accessed 16 December 2024. https://www.competitionline.com/de/projekte/64235.

Fig 15: *Wagnis 4 collective work* © Rudi Hassenstein
Source: 'Dachgarten wagnis 4'. Accessed 16 December 2024. https://www.competitionline.com/de/projekte/64235.

Fig.16: *Eastern facade,*© Kraaijvanger Architects
Fig.17: *Northern Facade,* © Kraaijvanger Architects
Fig.18: *Section,* © Kraaijvanger Architects
Fig.19:*Ground floor plan,* © Kraaijvanger Architects
Fig. 20: *First Floor plan,* © Kraaijvanger Architects
Fig. 21: *Floor Plan, Levels 4 and 8,* © Kraaijvanger Architects
Source: ArchDaily. 'Stadskantoor Venlo / Kraaijvanger Architects', 27 May 2017. Accessed 19 December 2024. https://www.archdaily.com/872129/stadskantoor-venlo-kraaijvanger-architects.

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Source: ArchDaily. '25 Green / Luciano Pia', 13 March 2015.Accessed 19 December 2024.https://www.archdaily.com/609260/25-green-luciano-pia.

Fig. 25: *Section & Roof plan* © a2 freising architekten + stadtplaner, Kai Krömer and Stefan Lautner
Source: Nicole Pfoser, ed., Green Facades, First edition, DETAIL Practice (München: DETAIL, 2024), 105, https://doi.org/10.11129/9783955536213.

Fig. 26:*Ground floor* © Buchner Bründler Architekten
Fig. 27: *Fifteenth floor* © Buchner Bründler Architekten
Fig. 28: *Section* © Buchner Bründler Architekten
Source: Nicole Pfoser, ed., Green Facades, First edition, DETAIL Practice (München: DETAIL, 2024), 101, https://doi.org/10.11129/9783955536213.

All drawings in this work were created by the author, with the exception of those found in the annexes (Chapter 5).

1: Cover - *City Axonometry*
2: *Green facade elevation & axonomentry*
3: *Green facade details*
4: *Green roof amonometries*
5: *Green roof details*
6: *Green courtyard perspective & axonometry*
7: *Green courtyards sections*
8: *Green indoors interior perspective & axonometry*
9: *Green indoors sections*
10: *Green measures axonometries*
11: *Maintenance scheme*
12: *City section*
13: *Building section*
14: *Human centred scheme*
15: *Comparative table*

7.

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