A Stakeholder-Dependent Ecosystem Service Score for Vertical Green Façades

Ruchira Sharma

MSc Environmental Engineering



A Stakeholder-Dependent Ecosystem Service Score for Vertical Green Façades

Framework Development and Analysis at TU Delft

By

Ruchira Sharma
Student number: 6280161
15th October 2026

Chair: Dr. Marc Ottelé
Mentors:
PhD candidate Jorrit Parmentier
Dr. Nico Tillie
Dr. Ajay Jagadeesh

Cover: Picture of the CEG faculty (2026)

Abstract

Vertical Green Facades (VGF) are increasingly proposed as a nature-based solution for improving the thermal, acoustic, air-quality, and ecological performance of buildings in dense urban environments. However, existing literature evaluates these ecosystem services almost exclusively in isolation, and the few integrated multi-criteria assessments that exist rarely involve the stakeholders who would actually use such evidence, relying instead on fixed, researcher-derived weightings. This thesis addresses that gap by developing a stakeholder-dependent Ecosystem Service Score (ESS) framework for vertical green facades, combining four measurable pillars — thermal regulation, air quality, acoustic performance, and biodiversity — into a composite, auditable scoring structure. The framework connects three VGF typologies (climbing evergreen, climbing deciduous, and living wall), each pillar's quantitative indicator, and priority weights elicited from four stakeholder profiles (a green façade specialist, a landscape architect / urban planner, a building occupant, and an urban ecologist / biodiversity expert) through semi-structured interviews, a questionnaire, and a self-assessment. The framework is designed to be validated against one year of continuous, one-minute-resolution sensor data from an instrumented VGF installation on the CEG building at TU Delft, using a staged rank-correlation procedure. At the time of writing, the framework and its literature grounding are fully developed, and the thermal pillar has been analysed against one seasonal extreme of real sensor data from the CEG installation; validation of the acoustic, air-quality and biodiversity pillars remains outstanding, pending sensor exports for those pillars. This report therefore presents the completed framework and methodology together with thermal-pillar analysis results for the CEG installation; broader applicability to other buildings, orientations, and climates is treated as a question for future testing rather than a claim made here.

Declaration of the Use of Generative AI and AI-assisted Tools

During the preparation of this thesis, generative AI and AI-assisted tools, including ChatGPT and Claude, were used only as supporting tools for language refining, grammar checking, text restructuring, and improving readability. These tools were not used to generate original research ideas, experimental data, sensor measurements, results, interpretations, or conclusions. All AI-assisted output was critically reviewed, edited, and verified by the author.

Acknowledgements

This thesis would not have been possible without the guidance and support of my supervisors, and I would like to thank each of them. I am grateful to Dr. Marc Ottelé, chair of my committee, for his guidance and for the trust he placed in my work. I thank Dr. Nico Tillie and Dr. Ajay Jagadeesh for their time, their careful reading of my drafts, and their thoughtful feedback, which helped me make my arguments clearer and my work stronger.

My special thanks go to Jorrit Parmentier. Jorrit helped me stay on track throughout this journey, and he assisted me whenever I needed it. Whether I was stuck on a problem, unsure about my next step, or running behind, he made time for me and gave clear, practical advice and encouragement. I am deeply grateful for his patience, his generosity with his time, and his support throughout this project.

I am deeply grateful to my family, who supported me on this journey and whose sacrifices over all these years made this master's degree possible. I will always be thankful for their love, their patience and their belief in me. I am thankful to all my friends, who stayed close even from far away. Their messages, calls and encouragement, and their belief that I could finish this, kept me going through the difficult weeks. Thank you for celebrating the small wins with me and for reminding me why I started.

To my flatmates here in the Netherlands, thank you for making this journey so memorable. Your company, your kindness and the everyday moments we shared made a new country feel like home.

Contents

Abstract 3
Declaration of the Use of Generative AI and AI-assisted Tools 4
Acknowledgements 5
List of Acronyms 8
List of Figures and Tables 9
1. Introduction 11
1.1 Scientific Contribution 17
2. Problem Statement 18
3. Aim of the Research 19
3.1 Research Gaps 19
3.2 Research Positioning 19
4. Main Research Question 21
5. Sub-Research Questions 21
5.1 Methodology 21
6. Literature Review 24
6.1 Urbanisation, Climate Change and the Need for Nature-Based Solutions 24
6.2 Vertical Greenery Systems as Urban Nature-Based Solutions 25
6.3 Ecosystem Services and Their Relevance to Vertical Green Facades 28
6.3.1 Scope and Selection of Ecosystem Services Assessed 28
6.4 Thermal Regulation by Vertical Green Facades 32
6.4.1 Shading as the Primary Cooling Mechanism 33
6.4.2 Evapotranspiration and Heat Flux 33
6.4.3 Implications for Building Energy Performance 34
6.5 Urban Heat Island Mitigation 34
6.6 Air Quality Improvement 35
6.6.1 Carbon Sequestration 36
6.7 Acoustic Performance of Vertical Green Facades 36
6.8 Biodiversity Enhancement 37
6.9 Multi-Criteria Assessment of Ecosystem Services 38
7. Stakeholder-Dependent Weighting Framework 42
7.1 Rationale for a Stakeholder-Dependent Approach 42
7.2 Interview Implementation 48
Pairwise comparison matrices and derived weights 49
Building Occupant Self-Assessment 50
7.3 Further Process Steps: Normalisation, Aggregation, and Analysis 53

7.3.1 Multi-Section Process Analysis: Summer (22–30 June 2026) 56
7.3.3 Cross-Section Rank Comparison (Summer) 60
7.3.4 Composite Score Analysis and Sensitivity Check (Thermal Pillar) 60
7.3.5 Three-Way Typology Comparison: Evergreen, Deciduous, and Living Wall (Summer) 62
Each typology against the reference 62
Typologies compared directly against each other 63
7.3.6 Cross-Check Using the Combined-Sensor Dataset, Full Section Groups (Summer) 64
8. Discussion 66
8.1 Interpretation of the Framework 66
8.2 Methodological Limitations 67
8.3 Implications for Practice 69
8.4 Critical Reflection 69
9. Conclusions 73
9.1 Answers to the Sub-Research Questions and Main Research Question 73
9.2 Key Findings 75
10. Recommendations 77
10.1 Practical Guidance for Prospective Users of the Framework 79
10.2 Contribution to Academic Research and Practice 81
References 83
Appendix A: Section-to-Typology Key 86
Appendix B: Stakeholder Pairwise Comparisons and Derived Weights 87
Appendix C: Stakeholder Questionnaire and the Reasoning Behind It 90
Introduction given to respondents 90
Background: the four ecosystem services being assessed 90
Part 1 — Getting the overall view 91
Part 2 — Ranking the four ecosystem services 91
Part 3 — Checking our measurements 91
Part 4 — Looking ahead 92
Appendix D: Raw Stakeholder Questionnaire Responses 93
D.1 Landscape Architect / Urban Planner 93
D.2 Green Façade Specialist 94
D.3 Urban Ecologist / Biodiversity Expert 96

List of Acronyms

VGF	Vertical Green Façade (s)
VGS	Vertical Greenery System (s)
ESS	Ecosystem Service Score
MCDA	Multi-Criteria Decision Analysis
AHP	Analytic Hierarchy Process
CEG	Civil Engineering and Geosciences (TU Delft faculty building)
UHI	Urban Heat Island
PM	Particulate Matter
CO_2	Carbon Dioxide
IL	Insertion Loss (acoustic indicator)
ΔT	Surface temperature differential
VMC	Volumetric Moisture Content
SQ	Sub-Research Question

List of Figures and Tables

Figure 1: Climbing plants used in the CiTG project (Deciduous) 11
Figure 2: Climbing plants used in the CiTG project (Evergreen) 11
Figure 3: Climbing plants used in the CiTG project (Living wall systems) 12
Figure 4: Classification of green infrastructure, Wang et al. (2020) 12
Figure 5: Bare façade, Direct façade greenery, Indirect façade greenery, Living wall (planter boxes), Perini et al. (2011) 13
Figure 6: (a) Bare wall, (b) Direct greening system, and (c) Indirect greening system, showing material layers (Ottelé et al., 2011). 14
Figure 7: Existing sensor network in the CiTG experiment 16
Figure 8: Methodology 23
Figure 9: Classification of vertical greenery systems, adapted from Perini et al. (2011) and Radujković et al. (2024), with the three typologies examined in this thesis highlighted. 26
Figure 10: Vertical greenery system classification, Radujković et al. (2024). 27
Figure 11: The CEG building west façade (June 2026) 29
Figure 12: The CEG building west façade (June 2026) 29
Figure 13: The CEG building west façade (June 2026) 29
Figure 14: Urban Island Heat Effect, Royal Meteorological Society (2017). 35
Figure 15: Input–process–output pipeline for the stakeholder-dependent weighting methodology developed in this chapter 42
Figure 16: Working-hours (09:00–17:00) thermal behaviour relative to the reference location (ΔT = section behind-vegetation probe − Section 4.6 behind-position probe) by section, summer representative week, CEG combined-sensor data. Positive ΔT = section warmer than reference; negative ΔT = section cooler than reference. 60
Figure 17: Working-hours (09:00–17:00) ΔT pattern by typology, dedicated temperature sensors, summer (22–30 June 2026). Positive ΔT = section warmer than reference; negative ΔT = section cooler than reference 64

Table 1: List of Ecosystem services 32
Table 2: Comparison of weighting methods applicable to multi-criteria ecosystem service assessment (Saaty, 1980; Velasquez & Hester, 2013; Bousquet et al., 2023). 40
Table 3a: Ecosystem Service – Stakeholder Weighting Framework (Literature and Stakeholder Interviews) 45
Table 3b: Typology Performance by Data Analysis (Thermal Pillar, Summer, Dedicated Temperature Sensors) 46
Table 4: Saaty's 1–9 pairwise comparison scale (Saaty, 1980) 49
Table 5: Pairwise comparison matrix — Building Occupant self-assessment 50
Table 6: Derived weights — Building Occupant self-assessment (λ_{max} = 4.071, CI = 0.024, CR = 0.026) 50
Table 7: Step 0 of worked example (questionnaire answers to numbers) 51
Table 8: Step 1 of worked example 51
Table 9: Step 2 of worked example 52
Table 10: Step 3 of worked example 52
Table 11: Further Process Steps (Framework Application) 55
Table 12: Summer ΔT 57
Table 13: Step 2 of worked example 57
Table 14: Step 3 of worked example 58
Table 15: Step 4 of worked example 59
Table 16: Summer score ..... **Error! Bookmark not defined.**
Table 17: Typology against reference, working hours (Summer) ..... **Error! Bookmark not defined.**
Table 18: Typology against each other, working hours (Summer) ..... **Error! Bookmark not defined.**
Table 19: Typology against reference, combined sensors, full section groups (Summer, working hours) 64
Table A1: Section-to-typology key (sensor positions, typologies and their role in this report) 86
Table B1: Pairwise comparison matrix — Landscape Architect / Urban Planner 87
Table B2: Derived weights — Landscape Architect / Urban Planner (λ_{max} = 4.300, CI = 0.100, CR = 0.111) 87
Table B3: Pairwise comparison matrix — Green Façade Specialist (qualitative judgments translated to the Saaty scale) 88
Table B4: Derived weights — Green Façade Specialist (λ_{max} = 4.118, CI = 0.039, CR = 0.044) 88
Table B5: Pairwise comparison matrix — Urban Ecologist / Biodiversity Expert 89
Table B6: Derived weights — Urban Ecologist / Biodiversity Expert (λ_{max} = 4.050, CI = 0.017, CR = 0.019) 89
Table C1: The four ecosystem services in plain terms and how each is measured 90

1. Introduction

European cities are increasingly confronted with a cluster of interlinked environmental pressures: rising summer temperatures and urban heat island formation, degraded outdoor air quality, traffic-related noise exposure, and a long-term decline in urban biodiversity. Climate change has intensified each of these pressures, and the trend towards densification has reduced the amount of ground-level space available for conventional green infrastructure such as parks, street trees, and green roofs (Bowler et al., 2010; Santamouris, 2014). Nature-based solutions (NBS) have been put forward as a multifunctional response to this situation, since a single intervention can, in principle, deliver several ecosystem services simultaneously rather than addressing one environmental problem in isolation (Castellar et al., 2021).





Figure 1: Climbing plants used in the CiTG project (Deciduous) Figure 2: Climbing plants used in the CiTG project (Evergreen)



Figure 3: Climbing plants used in the CiTG project (Living wall systems)

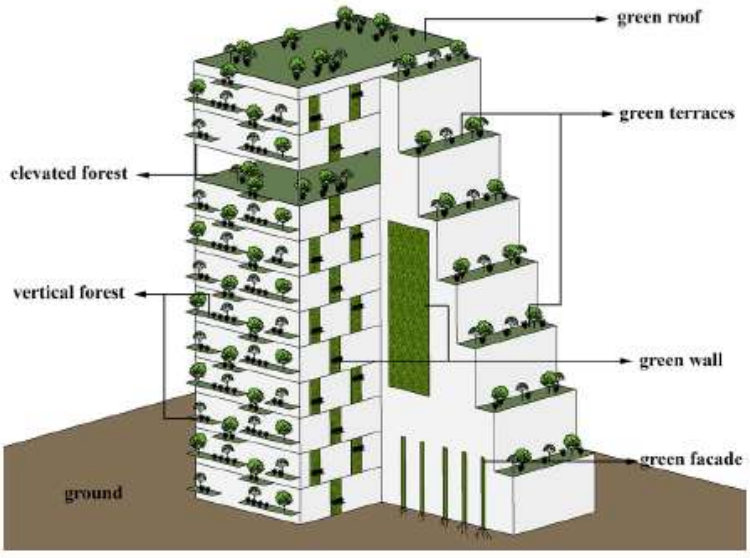
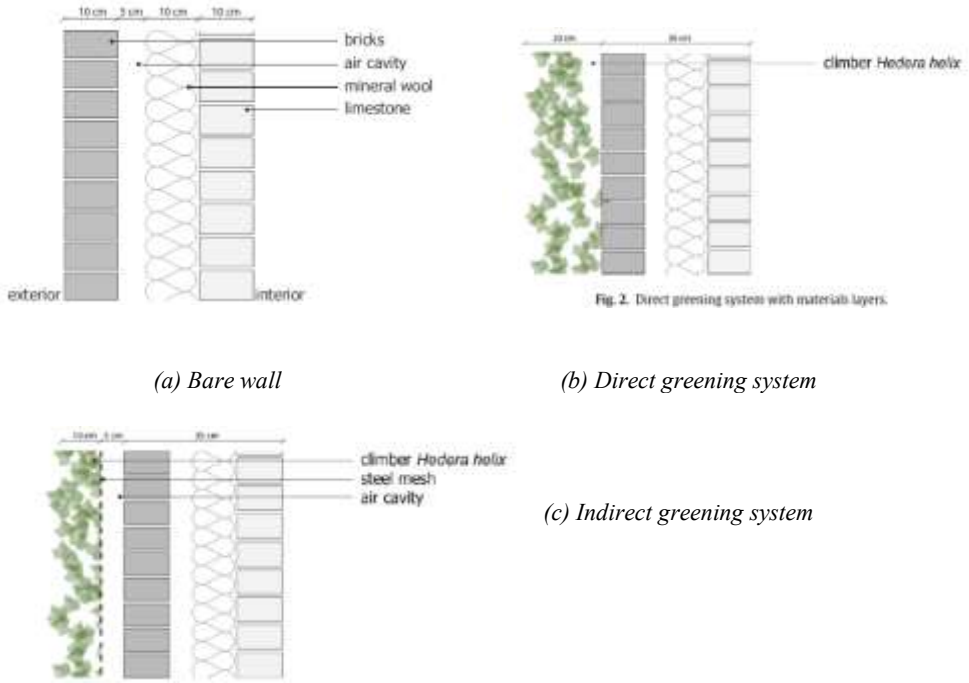


Figure 4: Classification of green infrastructure, Wang et al. (2020).

Vertical greenery systems are one category of NBS that has attracted particular attention in dense urban settings. VGS make use of an existing, largely unused resource – the building façade – and can therefore be retrofitted onto existing structures without requiring additional land. Within the broader VGS family, a distinction is usually made between green façades, in which climbing or trailing plants are grown directly on the wall or on a supporting cable or mesh structure with their root system in the ground or in planters, and living walls, in which a modular substrate-based system is mechanically fixed to the façade and irrigated independently of the ground (Ottelé et al., 2010; Perini et al., 2011). Green façades are generally considered less resource-intensive to install and maintain than living walls (Manso & Castro-Gomes, 2015; Perini et al., 2011), which makes them an attractive option for large-scale retrofitting of existing building stock, including post-war institutional buildings such as the Faculty of Civil Engineering and Geosciences at Delft University of Technology, where the present research is situated.



Figure 5: Bare façade, Direct façade greenery, Indirect façade greenery, Living wall (planter boxes), Perini et al. (2011).



(a) Bare wall

(b) Direct greening system

(c) Indirect greening system

Figure 6: (a) Bare wall, (b) Direct greening system, and (c) Indirect greening system, showing material layers (Ottelé et al., 2011).

Two further points qualify these results. First, the correlation between each section's ΔT and the independent ambient temperature at Weather Station 5.7 is weak throughout ($|r| \leq 0.46$ for all four sections), indicating that a section's departure from the reference is not simply tracking how hot or cold it is outside — a genuine, section-specific effect rather than a shared response to the weather. Second, Sections 3.1 and 3.2 remain warmer than the reference even during office hours (09:00–17:00), but by less than across the full day, so part of their warmer behaviour happens outside working hours. This is more consistent with heat being held behind a denser canopy than with the active daytime shading/evapotranspiration mechanism the framework's thermal pillar is intended to capture; this distinction matters for how these two sections should be interpreted in the composite Ecosystem Service Score and is carried into the Discussion.

The ecosystem services literature attributes a wide range of benefits to VGS, including thermal regulation (Bowler et al., 2010; Wong et al., 2010), acoustic insertion loss (Wong et al., 2010; Bakker et al., 2023), particulate matter capture (Ottelé et al., 2010), carbon sequestration, and biodiversity support (Madre et al., 2015). However, reported magnitudes vary considerably between studies, and most research evaluates these services in isolation rather than within an integrated framework (Ascione et al., 2020; Bakker-den Hartog et al., 2025). These two gaps — measurement variability and the lack of integration — are examined in detail in the Problem Statement (Chapter 2); in brief, they motivate this thesis's development of a sensor-

derived, multi-criteria ecosystem service framework for the green façade installed on the CEG building, using one year of multi-parameter monitoring data collected at one-minute resolution.

The present research forms part of the Green Facade Research Project at Delft University of Technology, an interdisciplinary initiative led by the Faculty of Civil Engineering and Geosciences to investigate the environmental performance of Vertical Greenery Systems under real operating conditions. The project involves the installation of a full-scale vertical green facade on the west façade of the CEG building, and it enables long-term field monitoring of a functioning green facade integrated into an occupied university building. The research installation incorporates multiple facade typologies, including climbing plant systems with both evergreen and deciduous species, as well as modular living wall systems containing different plant compositions. The vegetation has been intentionally distributed across several floors and facade sections to enable comparative analysis of different planting strategies, vegetation densities, and species combinations under identical climatic conditions. The project therefore provides a unique opportunity to investigate how facade design influences ecosystem service delivery within the same urban environment. To support comprehensive environmental monitoring, the facade has been equipped with an extensive sensor network that continuously measures air temperature, relative humidity, carbon dioxide concentration, particulate matter, surface temperature, heat flux, solar irradiance, wind speed and direction, and environmental noise. A dedicated weather station records background meteorological conditions, enabling measured environmental changes to be interpreted within the context of prevailing weather conditions. The integrated monitoring system generates high-resolution datasets that capture the dynamic interactions between vegetation, building surfaces, and the surrounding microclimate.

This installation is the main body of a research project led jointly by researchers from the Faculty of Civil Engineering and Geosciences and the Faculty of Architecture and the Built Environment, with PhD researchers actively involved (FaçadeWorld, 2026). It is designed as a living lab on the west façade of building 23, equipped with advanced sensors, and tests three kinds of system under real conditions: climbing plants on cables or mesh, a living wall with planter boxes and irrigation, and a combination of both (TU Delft Campus, n.d.). The supplier, Mobilane, reports that two of its systems were installed: the modular MobiPanel living wall, which has integrated irrigation, and the WallPlanter plant-container system (Mobilane, 2025). The project measures the insulating properties of the greenery and the resulting energy savings, temperature reduction at the façade, air quality and water management, biodiversity, and the impact on health and well-being. Its planned outputs are an open database of measurement data, design tools, educational material, upscaling recommendations, and a catalogue for various building types, primarily existing ones (TU Delft Campus, n.d.; FaçadeWorld, 2026). According to the project's published planning, the façades were installed in summer 2025, data collection runs from September 2025 until the end of 2027,

and results are to be evaluated and published in the first quarter of 2028 (TU Delft Campus, n.d.). This thesis therefore draws on the first summer of a multi-year monitoring programme: it is an early analysis within that programme, not a final evaluation of the installation.



Figure 7: Existing sensor network in the CiTG experiment

Within this broader research initiative, this thesis focuses on developing a quantitative framework for assessing the ecosystem service performance of the installed vertical green façade. While the Green Façade Research Project primarily generates environmental measurements through its sensor infrastructure, this research develops the methodology required to translate these heterogeneous datasets into meaningful ecosystem service indicators. Specifically, the study integrates measurements related to thermal regulation, air quality improvement, carbon sequestration, acoustic performance, and biodiversity into a unified multi-criteria assessment framework. By converting individual environmental measurements into standardized performance scores and aggregating them into a composite ecosystem service index, the proposed framework provides a systematic method for evaluating the overall environmental contribution of the façade. The research therefore complements the Green Façade Research Project by transforming raw environmental monitoring data into an evidence-based decision-support framework that can be applied to evaluate the multifunctional performance of Vertical Greenery Systems. Beyond assessing the TU Delft installation, the framework is intended to support future research, building performance evaluations, and the design of Nature-Based Solutions; its scope as a single-case proof-of-concept and what that means for transferability is discussed in full in the Discussion.

1.1 Scientific Contribution

The scientific contribution of this thesis is a stakeholder-dependent ecosystem service assessment framework for vertical greenery systems that combines objective sensor-derived performance indicators with stakeholder-specific weighting to support building-scale decision-making. Its novelty lies in bringing together three elements that the existing literature has so far kept apart: weights elicited from real stakeholders using the Analytic Hierarchy Process (Saaty, 1980) rather than fixed by the research team; indicators derived from continuous sensor monitoring rather than design-stage assumptions; and a composite score reported per stakeholder profile rather than as a single researcher-fixed value.

Positioned against the most closely related work, no single existing study closes this gap. Bakker-den Hartog et al. (2025) developed the closest ecosystem-service-based multi-criteria framework for vertical greenery systems, but did not elicit its weights from real stakeholders or validate them against continuous sensor data; Bousquet et al. (2023), reviewing 124 MCDA studies, found stakeholder involvement in weighting to be the exception rather than the norm; Adem Esmail and Geneletti (2018) noted that expert-derived weights are rarely validated against empirical performance; Cook and Larsen (2021) called for performance-based green-infrastructure models but did not implement stakeholder-elicited weighting for VGS; and Perini et al. (2011) characterises VGS typologies without integrating them into a stakeholder-facing decision score. On completion, this thesis therefore adds knowledge that does not currently exist: a working, auditable method for scoring a vertical greenery system's ecosystem service performance that is at once grounded in measured data and responsive to whose priorities are being served, rather than collapsing these into a single, undifferentiated answer.

2. Problem Statement

Despite substantial advances in Vertical Greenery Systems research, four interconnected problems limit the practical usefulness of existing knowledge for engineers and decision-makers. First, the majority of published studies focus on a single ecosystem service, particularly thermal regulation, while comparatively fewer studies investigate air quality improvement, biodiversity enhancement, or acoustic performance simultaneously (Perini et al., 2011; Manso & Castro-Gomes, 2015). Second, reported performance values vary considerably due to differences in climate, plant species, leaf area index, façade orientation, irrigation practices, and measurement methodologies, limiting direct comparison between studies and highlighting the need for standardised performance indicators (Susorova et al., 2013). Third, relatively few empirical studies have investigated operational Vertical Greenery Systems using continuous sensor measurements under real building conditions, with most research relying on laboratory experiments, numerical simulations, or short-term monitoring campaigns. Fourth, although integrated ecosystem service frameworks have recently been proposed (Bakker-den Hartog et al., 2025), their application to real, continuously monitored façades remains limited, and there is a clear need for case studies that combine field measurements with multi-criteria assessment methodologies capable of producing transparent, reproducible ecosystem service evaluations.

3. Aim of the Research

The aim of this research is to develop a multi-criteria performance framework that integrates the thermal, acoustic, air-quality, and biodiversity-related ecosystem services of a vertical green façade into a single, interpretable performance structure, using a stakeholder-dependent weighting approach informed by scientific literature, professional/grey literature, and semi-structured expert interviews. Rather than fixing a single set of pillar weights, the framework is designed to accommodate the differing priorities of three relevant stakeholder profiles (a green façade specialist, a landscape architect / urban planner, and a building occupant), making explicit how the relative importance of thermal regulation, air quality, acoustic performance, and biodiversity shifts depending on whose perspective is being represented. The framework is intended to translate the four ecosystem service pillars, together with the specific Vertical Greenery System typologies installed on the CEG building, into a structured relational table that can subsequently be populated and tested against the one year of continuous, multi-sensor monitoring data collected from the CEG green façade.

3.1 Research Gaps

Despite substantial advances in Vertical Greenery Systems research, several important knowledge gaps remain. First, the majority of published studies focus on a single ecosystem service, particularly thermal regulation. Comparatively fewer studies investigate air quality improvement, biodiversity enhancement, or acoustic performance, and very few simultaneously evaluate multiple ecosystem services within a unified framework (Perini et al., 2011; Manso & Castro-Gomes, 2015).

Second, reported performance values vary considerably because of differences in climate, plant species, Leaf Area Index, facade orientation, irrigation practices, and measurement methodologies. This variability limits direct comparison between studies and highlights the need for standardised performance indicators and assessment procedures (Susorova et al., 2013).

Third, relatively few empirical studies have investigated operational Vertical Greenery Systems using continuous sensor measurements under real building conditions. Much existing research relies on laboratory experiments, numerical simulations, or short-term monitoring campaigns. Finally, although integrated ecosystem service frameworks have recently been proposed (Bakker-den Hartog et al., 2025), their application remains limited. There is a clear need for case studies that combine field measurements with multi-criteria assessment methodologies capable of producing transparent, reproducible ecosystem service evaluations.

3.2 Research Positioning

The present research directly addresses the four gaps identified above by developing a quantitative ecosystem service assessment framework for the Vertical Green Façade installed on the CEG building at TU Delft. Unlike previous studies that evaluate individual ecosystem services in isolation, this research integrates thermal regulation, air quality improvement, acoustic performance, and biodiversity enhancement within a unified Multi-Criteria Decision Analysis framework applied to one year of

continuously monitored, sensor-derived data from an operational building façade. This approach responds to the call by Bakker-den Hartog et al. (2025) for case studies that validate integrated ecosystem service frameworks under real operational conditions rather than relying solely on design-stage assumptions or short-term monitoring campaigns. By combining field measurements with a structured multi-criteria assessment, the study contributes both methodological and practical knowledge to the rapidly expanding field of Nature-Based Solutions. What this transferability claim does and does not cover is addressed in the Discussion (Critical Reflection).

4. Main Research Question

How can a stakeholder-dependent ecosystem service assessment framework for vertical greenery systems be developed, applied using sensor-derived performance indicators, and analysed against measured typology performance, in order to support building-scale decision-making?

5. Sub-Research Questions

1. How can a vertical green facade system be characterized, and what environmental data are required to comprehensively assess its ecosystem service performance?

2. How can environmental data be processed and converted into reliable indicators that quantify the ecosystem services of a vertical green facade?

3. How can ecosystem service indicators be standardized and integrated into a multi-criteria decision-making framework, using stakeholder-dependent weighting derived from literature and expert interviews, to evaluate the overall performance of a vertical green facade?

4. How can the multi-criteria framework be validated against experimental data collected from the CEG vertical green façade, and to what extent does this validation confirm the reliability and robustness under real operational conditions?

5. How can the developed evaluation framework be used to interpret ecosystem service performance, identify trade-offs and synergies, and support decision-making for vertical green facades?

5.1 Methodology

The methodological approach adopted in this study follows a four-phase sequential pipeline, illustrated in the figure below, with terminology aligned throughout this report to the Phase 1–4 labelling shown in the figure. In Phase 1 (System Characterisation and Data Acquisition), the physical, structural, and environmental boundary conditions of the CEG green façade are characterised, including vegetation typology, façade orientation, and sensor placement (Jonckheere et al., 2004; Manso & Castro-Gomes, 2015). Continuous measurements are collected across five ecosystem service domains — thermal, acoustic, air quality, biodiversity, and carbon — using the installed sensor network and supplementary visual surveys. Phase 2 (Data Processing and Indicators) involves cleaning, gap detection, and environmental flagging of raw sensor data, followed by indicator quantification: raw measurements are converted into ecosystem service indicators such as surface temperature differential (ΔT), insertion loss (IL), particulate matter concentration reduction (PM), and indicative CO_2 uptake (Susorova et al., 2013; Wong et al., 2010; Shannon, 1948). Phase 3 (MCDA Framework) comprises three sequential and explicitly ordered steps (Section 7.1): first, stakeholder weight elicitation, in which relative weights for the four ecosystem service pillars are established on a stakeholder-dependent basis through semi-structured interviews with at least three to four relevant stakeholder groups, supported by scientific and professional/grey literature; second, min–max normalisation of all indicators to a common dimensionless scale between zero and one (Ascione et al., 2020); and third, weighted additive aggregation of the normalised indicators, using the stakeholder-elicited weights, into a composite Ecosystem Service

Performance Index calculated separately for each stakeholder profile (Velasquez & Hester, 2013). Framing stakeholder weight elicitation as the first explicit step of Phase 3, rather than as an incidental detail folded into the aggregation step, reflects the stakeholder-dependent framework described in Section 7.1. Phase 4 (Analysis, Interpretation and Output) examines trade-offs, synergies, and seasonal variability across ecosystem services, while a ±20% weight sensitivity analysis tests the robustness of the composite score against variations in the assigned weights (Bousquet et al., 2023). This phase also synthesises the findings into framework conclusions and considers, cautiously, what would be required to test the methodology's transferability to other VGS installations, without claiming such transferability from this single case. The feedback loops embedded in the pipeline ensure that quality issues identified at any phase are resolved before moving forward rather than being carried into the final score. The detailed procedure for analysing this framework against the CEG sensor dataset is set out in full in Section 7.3.

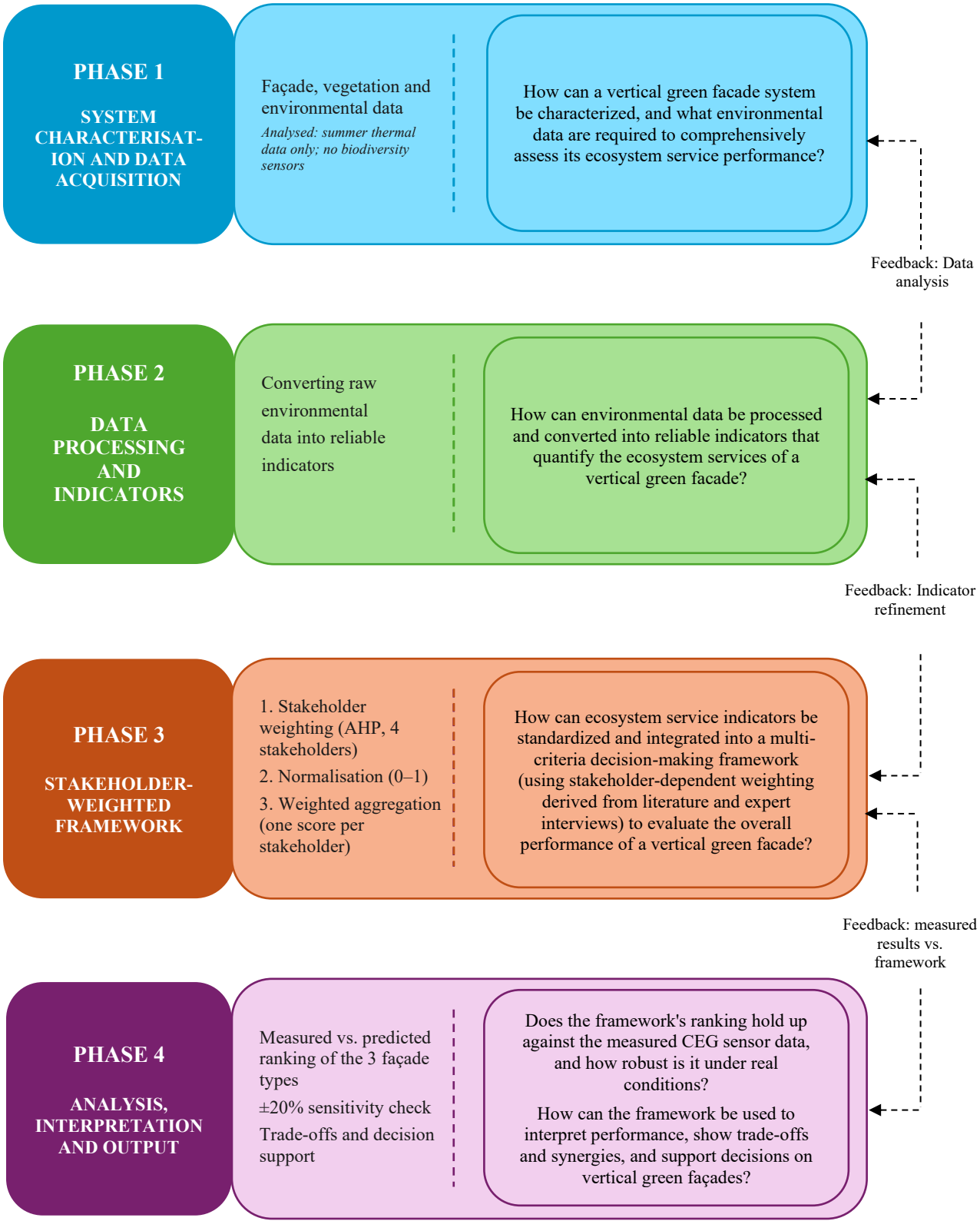


Figure 8: Methodology

6. Literature Review

6.1 Urbanisation, Climate Change and the Need for Nature-Based Solutions

Urbanisation has become one of the defining global trends of the twenty-first century. According to the IPCC (2023), more than half of the world's population currently resides in urban areas, and this proportion is expected to continue increasing over the coming decades. While cities function as centres of economic development, innovation, and social interaction, they are also major contributors to greenhouse gas emissions and are particularly vulnerable to climate-related hazards. Dense building configurations, extensive impervious surfaces, limited vegetation cover, and anthropogenic heat emissions collectively intensify environmental challenges such as the Urban Heat Island effect, deteriorating air quality, increased stormwater runoff, biodiversity loss, and elevated environmental noise (Santamouris, 2014).

The transformation of natural landscapes into built environments fundamentally alters the surface energy balance of cities. Impervious materials including concrete, asphalt, steel, and glass possess high thermal mass and low albedo, allowing them to absorb and store significant amounts of solar radiation during the day before gradually releasing heat during the night. This process contributes to persistent increases in urban temperatures compared with surrounding rural areas, commonly referred to as the Urban Heat Island effect (Oke, 1982; Bowler et al., 2010). Elevated urban temperatures increase cooling energy demand, intensify heat stress, reduce outdoor thermal comfort, and negatively affect human health, particularly among vulnerable populations such as the elderly and individuals with pre-existing medical conditions (Santamouris, 2014).

Beyond thermal impacts, urbanisation has contributed to declining ecosystem functioning. The replacement of vegetated surfaces with impermeable infrastructure disrupts ecological connectivity, reduces habitats for flora and fauna, decreases carbon sequestration capacity, and limits natural mechanisms for pollutant removal (Millennium Ecosystem Assessment, 2005). These environmental changes are accompanied by increasing concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides, ozone, and other atmospheric pollutants, all of which are associated with adverse respiratory and cardiovascular health outcomes (European Environment Agency, 2023). Furthermore, increasing traffic density and urban activity generate continuous noise pollution that affects psychological well-being, cognitive performance, and overall quality of life (World Health Organization, 2018).

Conventional engineering solutions have historically addressed these environmental issues individually through technological interventions such as mechanical cooling systems, air purification devices, or noise barriers. While these approaches often provide immediate benefits, they generally require substantial energy consumption, financial investment, and maintenance while offering limited multifunctionality. Consequently, there has been growing recognition that sustainable urban development requires solutions capable of simultaneously addressing multiple environmental challenges while enhancing ecosystem resilience (Castellar et al., 2021).

Nature-Based Solutions (NBS) have emerged as an integrated approach to addressing complex urban environmental problems by utilising natural processes and ecosystem functions. According to the European Commission (2021), Nature-Based Solutions are actions inspired and supported by nature that simultaneously provide environmental, social, and economic benefits while increasing resilience. Unlike traditional grey infrastructure, NBS utilise vegetation, soil, and ecological interactions to regulate environmental conditions. These solutions include urban forests, green roofs, green corridors, constructed wetlands, rain gardens, and Vertical Greenery Systems.

One of the principal advantages of Nature-Based Solutions lies in their multifunctionality. Rather than addressing a single environmental objective, NBS simultaneously contribute to climate adaptation, climate mitigation, biodiversity enhancement, improved human health, and enhanced ecosystem resilience (Castellar et al., 2021). This multifunctional character distinguishes them from conventional engineering interventions and has contributed to their increasing incorporation into urban planning and sustainability policies worldwide.

Despite their recognised potential, the implementation of Nature-Based Solutions continues to face several challenges. Performance varies considerably depending on climatic conditions, vegetation characteristics, maintenance practices, and local environmental contexts. Furthermore, many studies evaluate individual ecosystem services independently, making it difficult to understand the overall environmental contribution of specific Nature-Based Solutions. Consequently, researchers increasingly emphasise the need for integrated assessment frameworks capable of quantifying multiple ecosystem services simultaneously using standardised methodologies (Bakker-den Hartog et al., 2025).

6.2 Vertical Greenery Systems as Urban Nature-Based Solutions

Among the various Nature-Based Solutions available for densely built environments, Vertical Greenery Systems have attracted increasing research interest due to their ability to introduce vegetation without requiring additional ground space. As urban land becomes increasingly scarce, particularly within historic city centres and high-density developments, building facades represent an underutilised surface capable of supporting vegetation while improving environmental performance (Perini et al., 2011).

Vertical Greenery Systems encompass a range of technologies designed to establish vegetation on building envelopes. Broadly, these systems are classified into green facades and living walls. Green facades utilise climbing or cascading plant species that grow directly on building surfaces or on supporting structures such as cables, trellises, or mesh systems. Within green facades, a further distinction is made between direct systems, where the plant clings straight to the wall surface with no intervening structure, and indirect systems, where the plant climbs a trellis, cable, or mesh mounted a short distance off the wall, leaving an air gap between vegetation and building surface that alters the balance between shading and insulation (Ottelé et al., 2011; see Figures 5–6). Living walls, in contrast, incorporate

engineered modular panels containing artificial growing media and irrigation systems that support a wide variety of herbaceous and ornamental plant species (Manso & Castro-Gomes, 2015).

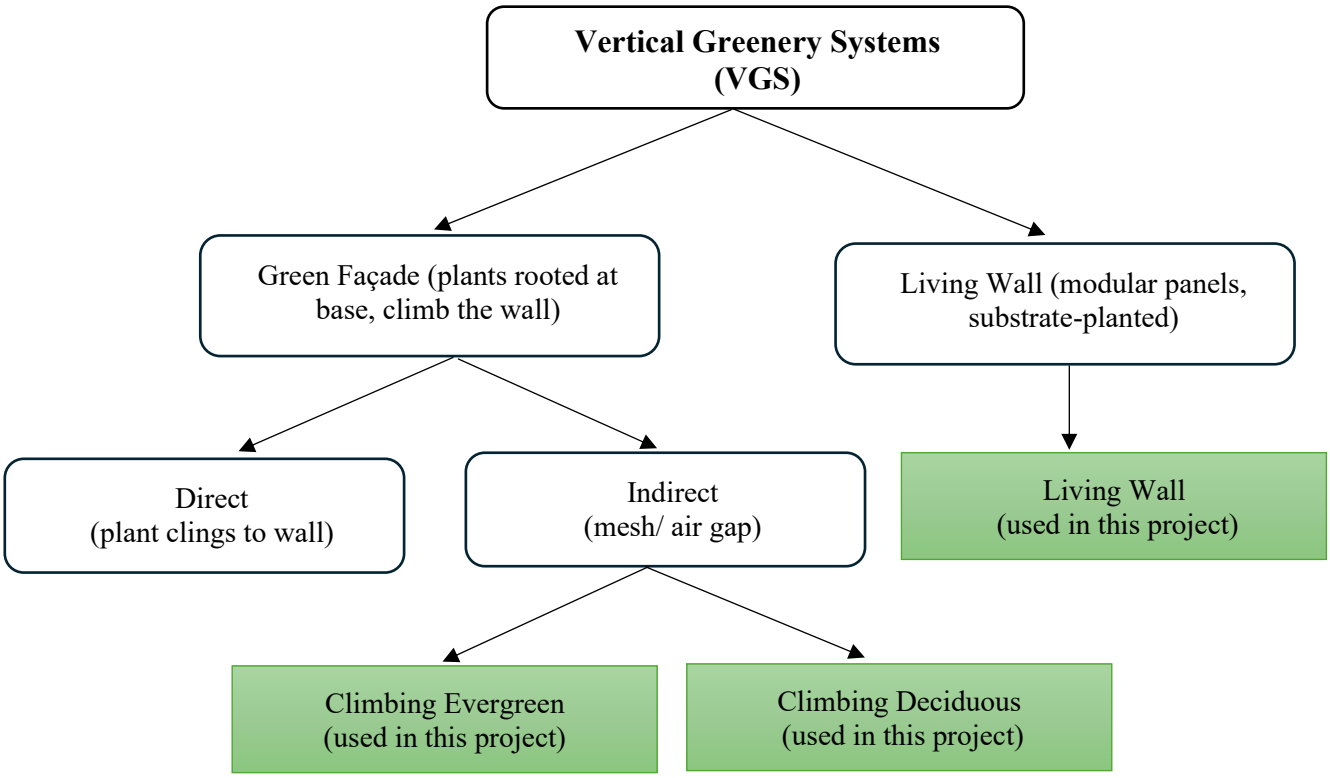


Figure 9: Classification of vertical greenery systems, adapted from Perini et al. (2011) and Radujković et al. (2024), with the three typologies examined in this thesis highlighted.

Of the typologies shown in Figure 9, this thesis examines three: climbing evergreen, climbing deciduous, and living wall, all installed on the same west-facing façade of the CEG building at TU Delft (Figures 11–13). This selection was made for four reasons. First, it spans the practical range of what is actually installed on buildings today, from the comparatively low-cost, low-maintenance green façade approach to the more engineered, higher-performing but costlier living wall system (Perini et al., 2011), allowing the framework to be tested across genuinely different levels of technological complexity rather than within one narrow category. Second, installing all three typologies on the same building, orientation, and climate removes confounding variables that complicate comparisons across the wider literature (Susorova et al., 2013), so that differences observed in Chapter 6 can be attributed to typology rather than site conditions. Third, including both an evergreen and a deciduous climbing species allows this thesis to test whether seasonal leaf behaviour, and the associated seasonal change in leaf area index and canopy density, measurably affects thermal, acoustic, and biodiversity performance (Jonckheere et al., 2004), a distinction the general classification literature acknowledges but rarely quantifies directly. Fourth, and practically, all three typologies are already instrumented within the CEG sensor network, which is what makes the sensor-based analysis described in Section 7.3 possible at all. The project's own design reflects the same logic: it tests climbing plants on cables or mesh and a living wall with planter boxes and irrigation side by side on one façade (TU Delft Campus, n.d.), so the climbing and living-wall typologies examined here are

two of the project's core system types rather than a selection imposed by this thesis. Together, these three typologies allow the stakeholder-dependent framework developed later in this thesis (Chapter 7) to be evaluated across a realistic and directly comparable range of vertical greenery options.

Although living walls often achieve greater plant diversity and immediate visual impact, they require significantly higher installation costs, irrigation demands, structural support, and maintenance requirements. Green facades are generally considered more economically feasible and environmentally sustainable because climbing plants are rooted directly in the ground, reducing both water consumption and embodied energy associated with artificial substrates (Perini et al., 2011). Consequently, green facades have become an attractive solution for retrofitting existing buildings where structural modifications must remain minimal.

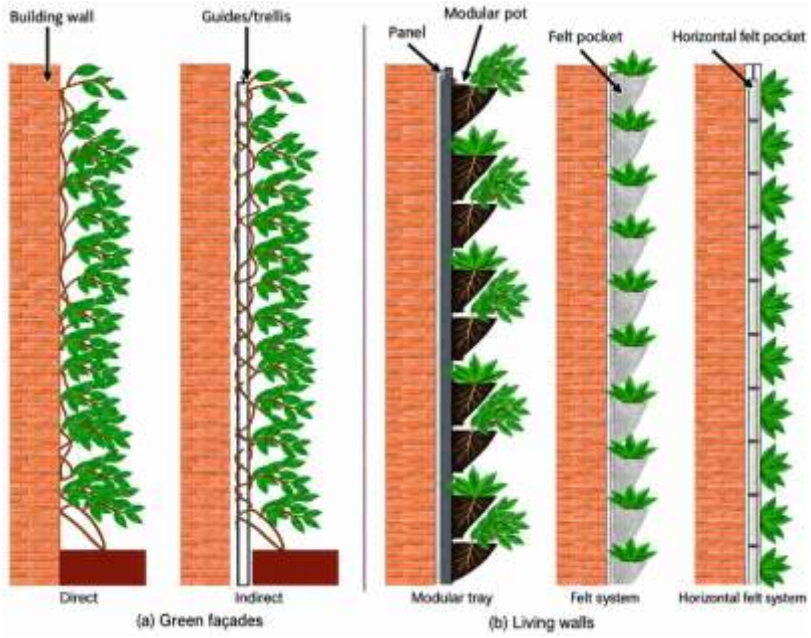


Figure 10: Vertical greenery system classification, Radujković et al. (2024).

The environmental performance of Vertical Greenery Systems is governed by complex interactions between vegetation characteristics, building geometry, climatic conditions, and facade orientation. Factors such as plant species selection, leaf morphology, canopy density, Leaf Area Index (LAI), plant-wall distance, and maintenance practices all influence ecosystem service delivery (Susorova et al., 2013). Consequently, reported performance values vary substantially across published studies.

Leaf Area Index has emerged as one of the most influential vegetation parameters. LAI represents the total one-sided leaf surface area per unit ground area and directly affects solar interception, evapotranspiration capacity, aerodynamic resistance, and pollutant deposition (Jonckheere et al., 2004). Higher LAI values generally improve shading effectiveness and increase evapotranspiration, leading to greater thermal regulation. Similarly, dense vegetation can enhance particulate matter capture by increasing the total available leaf surface area while simultaneously providing additional habitat complexity that supports urban biodiversity. Facade orientation also plays a critical role in determining

system performance. South- and west-facing facades generally receive higher levels of solar radiation and therefore exhibit greater potential for reducing solar heat gain through vegetation. However, local wind conditions, building height, surrounding structures, and seasonal variations influence both microclimatic conditions and vegetation growth, making performance highly site-specific (Susorova et al., 2013).

Despite these complexities, a growing body of literature consistently demonstrates that Vertical Greenery Systems contribute to improved environmental performance through multiple ecosystem services including thermal regulation, air quality improvement, carbon sequestration, stormwater management, biodiversity enhancement, acoustic modification, and aesthetic improvement (Ottelé et al., 2010; Perini et al., 2011; Manso & Castro-Gomes, 2015). Nevertheless, most studies evaluate these ecosystem services independently rather than collectively.

6.3 Ecosystem Services and Their Relevance to Vertical Green Facades

6.3.1 Scope and Selection of Ecosystem Services Assessed

The CEG green façade at TU Delft is the object of a broader, ongoing monitoring project that spans a wider range of environmental and ecological functions than are addressed here. This thesis is scoped more narrowly: it is not an evaluation of the CEG green façade project as a whole, and does not examine every function that project monitors. For example, nitrogen oxide (NOx) capture is monitored as part of the wider CEG project but falls outside the scope of this thesis, since it is not one of the four ecosystem service pillars developed in the ESS framework. This distinction matters because the ESS framework's completeness claims apply only to the four pillars explicitly scoped below, not to the full set of environmental functions the CEG installation is capable of supporting.



Figure 11: The CEG building west façade (June 2026)



Figure 12: The CEG building west façade (June 2026)



Figure 13: The CEG building west façade (June 2026)

The ecosystem service list in Table 1 below is synthesised primarily from the Millennium Ecosystem Assessment (2005) classification, cross-checked against VGS-specific service inventories reported by Perini et al. (2011) and Bakker-den Hartog et al. (2025), rather than drawn from a single source. Several ecosystem services applicable to vegetated surfaces in principle — including stormwater retention, wind regulation, and pollination support — are deliberately excluded from the framework developed in this thesis. The reason for exclusion is practical rather than conceptual: none of these services is currently instrumented within the CEG sensor network, so including them in a quantitative multi-criteria framework would require either new field data collection outside this thesis's timeline or an unsupported literature-only estimate that could not be analysed against the CEG dataset in the way the four included pillars can. The four pillars retained — thermal regulation, air quality, acoustic performance, and biodiversity — are therefore the services for which both an evidence base and a measurable, testable data source exist within the current scope of this research.

The ecosystem services provided by green facades that will be examined in this thesis (as distinct from the wider CEG monitoring project introduced above) include the following:

include the following:

1. Thermal insulation capacity
2. Rainwater retention and management
3. Evaporative cooling (transpirational and evaporative processes)
4. Shading-induced cooling
5. Acoustic absorption and noise attenuation
6. Particulate matter (PM) capture
7. Nitrogen oxide (NOx) capture
8. Carbon dioxide (CO2) sequestration
9. Enhancement of urban biodiversity (including both flora and invertebrate fauna)
10. Aesthetic and visual amenity contributions

The concept of ecosystem services provides an important theoretical framework for understanding the environmental benefits delivered by Nature-Based Solutions. The Millennium Ecosystem Assessment (2005) defines ecosystem services as the direct and indirect benefits that humans obtain from ecosystems. These services are commonly classified into provisioning, regulating, supporting, and cultural services. For Vertical Greenery Systems, regulating ecosystem services represent the most extensively investigated category. These include thermal regulation through shading and evapotranspiration, air pollutant removal, carbon sequestration, stormwater retention, and noise attenuation. Supporting services primarily include habitat creation and biodiversity enhancement, while cultural services encompass aesthetic improvement, psychological well-being, and increased visual quality within urban environments (Bakker-den Hartog et al., 2025).

Among these ecosystem services, thermal regulation has received the greatest scientific attention due to its direct relationship with Urban Heat Island mitigation and building energy performance. Air quality improvement and biodiversity enhancement have also received increasing attention because of growing

concerns regarding urban health and ecological resilience. Acoustic performance has historically been less studied, largely because measurable improvements are typically smaller and more difficult to isolate under real-world environmental conditions (Wong et al., 2010).

An important limitation within existing literature concerns the fragmented evaluation of ecosystem services. Many studies focus exclusively on thermal performance, while others investigate biodiversity, air pollution removal, or acoustic effects independently. Although these studies provide valuable insights into individual mechanisms, they fail to capture the multifunctional nature of Vertical Greenery Systems. Since ecosystem services frequently interact through shared ecological processes, evaluating them separately may underestimate the overall environmental contribution of green infrastructure (Castellar et al., 2021). Recent research has therefore shifted towards integrated ecosystem service assessment frameworks capable of simultaneously evaluating multiple performance dimensions. Bakker-den Hartog et al. (2025) argue that future research should move beyond isolated performance indicators towards multi-criteria decision frameworks that integrate environmental, ecological, and engineering perspectives. Such approaches enable more comprehensive comparisons between different Vertical Greenery Systems while supporting evidence-based decision-making for urban planners, architects, and policymakers.

The present research directly addresses this identified gap by developing an integrated quantitative framework that combines thermal regulation, air quality improvement, acoustic performance, and biodiversity enhancement into a single ecosystem service assessment. Unlike many previous studies that investigate only one environmental function, this research adopts a multi-criteria approach capable of capturing the multifunctionality of an operational vertical green facade under real building conditions.

Table 1 provides an overview of ecosystem service categories as defined by the Millennium Ecosystem Assessment (2005), mapped against the services applicable to Vertical Greenery Systems and the specific services investigated in the present study.

Sr. No.	Ecosystem Service	Category	Applicable to VGS	Investigated in this study
1.1	Food production	Provisioning	No	No
1.2	Water supply		No	No
1.3	Raw materials		No	No
2.1	Thermal regulation / UHI mitigation	Regulating	Yes	Yes
2.2	Air pollutant removal		Yes	Yes
2.3	Carbon sequestration		Yes	Yes
2.4	Stormwater retention		Yes	No
2.5	Noise attenuation / acoustic scattering		Yes	Yes
2.6	Wind regulation		Yes	No
3.1	Biodiversity / habitat provision	Supporting	Yes	Yes
3.2	Nutrient cycling		Partially	No
3.3	Soil formation		No	No
4.1	Aesthetic and visual amenity	Cultural	Yes	No
4.2	Psychological well-being		Yes	No
4.3	Educational and research value		Yes	No

Table 1: List of Ecosystem services

As shown, Vertical Greenery Systems are most directly associated with regulating and supporting ecosystem services. Of the applicable services, this study focuses on four that are directly measurable through the installed sensor network: thermal regulation, air quality improvement (particulate matter and carbon sequestration), acoustic performance, and biodiversity enhancement. Services such as biodiversity, stormwater retention and wind regulation, while applicable to VGS in principle, fall outside the scope of this study due to the absence of corresponding sensors in the current monitoring infrastructure.

6.4 Thermal Regulation by Vertical Green Facades

Thermal regulation is widely regarded as the most significant ecosystem service provided by Vertical Greenery Systems, primarily because of its direct contribution to reducing building cooling loads, mitigating Urban Heat Island effects, and improving outdoor thermal comfort. Consequently, thermal performance has become the most extensively investigated aspect of green facade research over the past two decades (Perini et al., 2011; Santamouris, 2014).

Unlike conventional building facades, vegetated facades modify the energy balance of building envelopes through several interconnected physical mechanisms. Rather than functioning as passive insulation alone, vegetation actively alters heat exchange between the building surface and the surrounding atmosphere by reducing incoming solar radiation, increasing latent heat transfer through evapotranspiration, modifying airflow within the boundary layer, and reducing long-wave radiation exchange (Susorova et al., 2013). These mechanisms operate simultaneously, making the thermal behaviour of green facades considerably more complex than that of conventional building materials.

6.4.1 Shading as the Primary Cooling Mechanism

Among the various cooling mechanisms, solar shading is generally considered the dominant contributor to temperature reduction. Vegetation intercepts incoming short-wave solar radiation before it reaches the building surface, thereby limiting heat absorption by external wall materials. Instead of allowing solar energy to be converted into sensible heat within the facade, a substantial proportion of the intercepted radiation is either reflected or utilised by plants during photosynthesis and evapotranspiration (Alexandri & Jones, 2008).

The effectiveness of shading depends strongly on vegetation characteristics, particularly leaf density, canopy thickness, Leaf Area Index (LAI), and plant morphology. Jonckheere et al. (2004) demonstrated that increasing LAI substantially increases radiation interception while simultaneously reducing radiation penetration through vegetation canopies. Consequently, dense vegetation generally provides greater thermal protection than sparse vegetation.

Perini et al. (2011) investigated climbing plant systems installed on building facades and observed surface temperature reductions ranging between 5°C and 12°C during summer conditions. Similar findings were reported by Susorova et al. (2013), who demonstrated that reductions varied considerably depending on facade orientation, plant coverage, and climatic conditions. South- and west-facing facades consistently exhibited the greatest thermal improvements because of their higher solar exposure.

However, it is important to recognise that shading effectiveness is highly dynamic rather than constant throughout the day. Maximum cooling generally occurs during periods of peak solar radiation, whereas thermal differences diminish during nighttime as radiative heat exchange becomes the dominant process (Susorova et al., 2013). Consequently, evaluating hourly temperature variations rather than single maximum values provides a more comprehensive understanding of thermal performance.

6.4.2 Evapotranspiration and Heat Flux

Although shading provides immediate protection against solar heating, evapotranspiration represents the second major cooling mechanism associated with green facades. During transpiration, plants transport water from the soil through their vascular tissues before releasing it into the atmosphere via leaf stomata. The evaporation of this water consumes latent heat energy, thereby cooling both leaf surfaces and the surrounding air (Bowler et al., 2010).

Santamouris (2014) describes evapotranspiration as one of the principal natural cooling processes within urban ecosystems. Unlike mechanical cooling systems, which consume electrical energy, evapotranspiration utilises solar energy to drive water evaporation, producing passive cooling without increasing greenhouse gas emissions. The magnitude of evapotranspiration depends upon several environmental variables including solar radiation intensity, air temperature, relative humidity, wind

speed, soil moisture availability, and plant physiology. Consequently, identical green facade systems may exhibit substantially different cooling performance under varying meteorological conditions.

Because direct measurement of evapotranspiration requires specialised instrumentation such as lysimeters or eddy covariance systems, many field studies—including the present research—employ relative humidity differences as indirect indicators of evaporative cooling. Although humidity measurements cannot quantify evapotranspiration directly, they provide useful evidence of enhanced moisture exchange near vegetated surfaces.

6.4.3 Implications for Building Energy Performance

The thermal benefits of green facades extend beyond surface temperature reduction and directly influence building energy consumption. Reduced solar heat gain lowers cooling requirements during summer months while stabilised wall temperatures decrease conductive heat transfer through building envelopes. Ottelé et al. (2010) demonstrated that vegetated facades reduce thermal stress on external wall materials while simultaneously improving insulation performance. Similarly, Pérez et al. (2011) concluded that vegetation contributes to measurable reductions in cooling demand, particularly in warm climates where solar gains dominate annual energy consumption.

However, reported energy savings vary considerably across published studies because of differences in building construction, climate, vegetation type, irrigation practices, and simulation methodologies. Consequently, many authors caution against generalising numerical energy savings without considering local environmental conditions (Manso & Castro-Gomes, 2015).

A concurrent, unpublished field experiment on the same CEG building provides a directly relevant real-world precedent for these mechanisms (Parmentier, Ottelé, & van den Dobbelsteen, in preparation). During the Dutch heatwave of 18–29 June 2026, four installed VGS typologies — three climbing green façade support structures and one living wall system — were compared against an unshaded reference and automated external solar blinds. All vegetated systems significantly reduced local afternoon air temperature relative to the unshaded reference (mean reduction 3.3–6.6°C, maximum reduction 4.5–8.4°C; Holm-adjusted $p < 0.05$), and the climbing façade systems also outperformed the mechanically shaded reference by 0.9–1.3°C on average, consistent with the shading and evapotranspiration mechanisms discussed above.

This section has addressed part of SQ1 (system characterisation and data requirements) and SQ2 (indicator quantification) as they apply to thermal regulation: the literature indicates that surface temperature differential (ΔT) and heat flux are the appropriate quantitative indicators for this pillar, and that shading and evapotranspiration are the two mechanisms that must be characterised at the CEG façade to interpret them correctly.

6.5 Urban Heat Island Mitigation

The Urban Heat Island effect represents one of the most significant environmental consequences of urbanisation. Oke (1982) first described the phenomenon as the systematic increase in urban air temperatures relative to surrounding rural environments resulting from altered land cover, anthropogenic heat emissions, and modified surface energy balances. Bowler et al. (2010) conducted one of the earliest systematic reviews evaluating the effectiveness of urban greening for UHI mitigation. Their review concluded that vegetation consistently reduces local temperatures through shading and

evapotranspiration, although the magnitude of cooling varies considerably depending on vegetation configuration and climatic context.

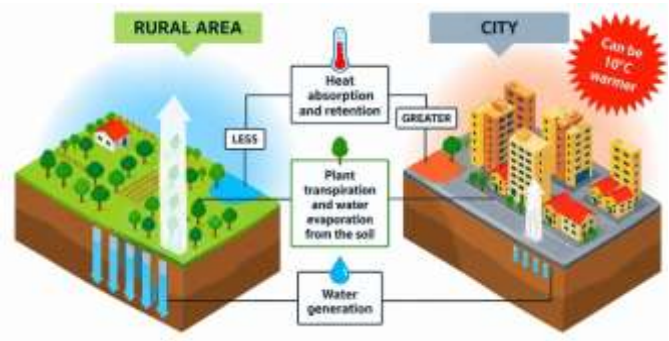


Figure 14: Urban Island Heat Effect, Royal Meteorological Society (2017).

Vertical Greenery Systems contribute to UHI mitigation primarily at the building and street scales rather than the city-wide scale. Unlike urban forests or large parks, green facades influence microclimatic conditions within immediate pedestrian environments by reducing radiant temperatures, lowering wall temperatures, and improving thermal comfort. Santamouris (2014) argues that although individual green facades produce relatively localised cooling effects, widespread implementation across urban districts could collectively contribute to meaningful reductions in urban temperatures. Consequently, green facades should be viewed as complementary components within broader urban climate adaptation strategies rather than standalone solutions.

For SQ1, this confirms that the CEG façade's thermal indicators should be interpreted at both building and pedestrian scale, since the same ΔT and heat flux measurements feeding the ESS framework also carry city-scale UHI-mitigation relevance beyond the composite score itself.

6.6 Air Quality Improvement

Urban air pollution remains one of the leading environmental risks to human health worldwide. Fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}), nitrogen dioxide, ozone, and volatile organic compounds contribute to respiratory diseases, cardiovascular disorders, and premature mortality (European Environment Agency, 2023). Vegetation improves air quality primarily through pollutant deposition onto leaf surfaces. Airborne particles collide with leaves through gravitational settling, Brownian diffusion, inertial impaction, and turbulent interception before remaining attached to wax layers or microscopic leaf structures (Nowak et al., 2006).

Compared with horizontal vegetation, green facades occupy vertical surfaces located immediately adjacent to emission sources such as roads and pedestrian corridors. This positioning potentially enhances pollutant interception within street canyons where pollutant concentrations are often highest. Research indicates that deposition efficiency depends strongly upon leaf morphology. Rough leaves possessing hairs, grooves, and waxy surfaces generally capture greater quantities of particulate matter than smooth leaves (Sæbø et al., 2012). Consequently, plant species selection represents an important determinant of air purification performance.

Despite growing interest in green infrastructure for pollution control, reported pollutant removal rates remain highly variable. Variability arises from differences in local meteorology, pollution concentrations, vegetation density, rainfall frequency, and measurement methodologies. Therefore, many authors

recommend expressing pollutant removal using deposition velocities rather than absolute pollutant mass because deposition velocity provides greater comparability across studies.

6.6.1 Carbon Sequestration

Carbon sequestration constitutes another important regulating ecosystem service provided by Vertical Greenery Systems. Through photosynthesis, climbing plants absorb atmospheric carbon dioxide and incorporate carbon into leaves, stems, roots, and supporting tissues. Although carbon storage by individual green facades is relatively modest compared with urban forests, widespread implementation across densely built cities could collectively contribute to urban carbon mitigation strategies (Perini et al., 2011).

Carbon sequestration capacity depends upon plant species, growth rate, biomass accumulation, maintenance practices, and climatic conditions. Fast-growing climbing species generally exhibit higher annual carbon uptake than slower-growing ornamental vegetation, although long-term sequestration depends upon plant longevity and biomass management. Ottelé et al. (2010) emphasise that life-cycle assessment should accompany carbon sequestration analysis because installation materials, irrigation systems, fertilisers, and maintenance activities also contribute embodied carbon emissions. Consequently, evaluating net environmental benefits requires consideration of both operational ecosystem services and life-cycle impacts. Current research increasingly recommends integrating carbon sequestration with other ecosystem services rather than evaluating carbon removal independently. Such integrated approaches better reflect the multifunctional contribution of green infrastructure to sustainable urban development.

While thermal regulation, air quality improvement, and carbon sequestration represent the most extensively investigated ecosystem services, Vertical Greenery Systems also influence urban sound environments and ecological functioning. However, these ecosystem services remain comparatively under-researched, and standardised assessment methodologies are still emerging. The following section examines the literature on acoustic performance, biodiversity enhancement, and integrated multi-criteria ecosystem service assessment, highlighting the research gaps that directly motivate the present study.

For SQ2, this indicates that particulate matter concentration reduction is the primary directly-measurable air quality indicator available from the CEG sensor network, while carbon sequestration is retained in the framework as an indicative rather than a precisely quantified pillar component, given the life-cycle caveats raised above.

6.7 Acoustic Performance of Vertical Green Facades

Compared with thermal regulation and air quality improvement, the acoustic performance of Vertical Greenery Systems has received considerably less scientific attention. This imbalance is largely attributed to the relatively modest acoustic benefits provided by climbing vegetation and the inherent complexity of measuring sound propagation under outdoor conditions. Nevertheless, environmental noise has become a major public health concern in urban areas, making noise mitigation an increasingly relevant ecosystem service provided by green infrastructure (World Health Organization, 2018).

Road traffic remains the dominant source of environmental noise in most European cities, contributing to sleep disturbance, cardiovascular disease, reduced cognitive performance, and diminished psychological well-being (WHO, 2018). Traditional mitigation strategies rely primarily on rigid noise barriers or engineered sound-absorbing materials. Although effective, these interventions often occupy valuable

urban space, require considerable financial investment, and provide limited ecological benefits. Consequently, vegetation-based approaches have attracted increasing attention as multifunctional alternatives capable of simultaneously improving environmental quality while contributing to biodiversity and urban aesthetics.

Unlike engineered acoustic insulation materials, climbing vegetation contributes only minimally to sound absorption because of its relatively low mass and density. Instead, the primary acoustic mechanism associated with green facades is sound scattering. Leaves, stems, and supporting structures create irregular surfaces that disrupt specular sound reflection, diffusing acoustic energy across multiple directions rather than reflecting it directly toward receivers (Wong et al., 2010). This process can reduce perceived sound intensity within pedestrian environments despite relatively small reductions in measured sound pressure levels.

Field experiments by Wong et al. (2010) demonstrated measurable differences in insertion loss between vegetated and non-vegetated facades, although reductions generally remained below those achieved by specialised acoustic barriers. Similar observations have been reported in subsequent studies investigating facade greening systems, where vegetation primarily modified sound reflection characteristics rather than acting as a substantial sound absorber (Van Renterghem & Botteldooren, 2014). The effectiveness of sound scattering depends on vegetation density, leaf morphology, facade geometry, and sound frequency. High-frequency sounds interact more readily with relatively small vegetation elements, whereas low-frequency sound waves possess wavelengths considerably larger than leaves and branches, limiting their attenuation potential (Van Renterghem & Botteldooren, 2014). Consequently, reported acoustic improvements vary substantially depending upon measurement frequency ranges and experimental configurations.

Another important challenge concerns measurement methodology. Outdoor acoustic experiments are particularly sensitive to meteorological conditions, including wind speed, atmospheric stability, humidity, and background environmental noise. Even relatively small changes in weather conditions can influence measured sound pressure levels, making repeatability difficult to achieve. As a result, many researchers recommend conducting controlled field measurements using standardised sound sources and reference surfaces while carefully documenting environmental conditions (Kang, 2007). Although the magnitude of acoustic improvement provided by green facades is generally smaller than their thermal benefits, the literature increasingly recognises acoustic modification as one component of the broader ecosystem service portfolio delivered by urban vegetation. Rather than evaluating noise mitigation independently, researchers advocate integrating acoustic performance within multifunctional ecosystem service assessments capable of capturing cumulative environmental benefits.

For SQ2, this establishes insertion loss (IL) as the acoustic indicator adopted in this framework, with the caveat, noted above, that outdoor acoustic measurement is more sensitive to confounding weather conditions than the thermal or air-quality indicators.

6.8 Biodiversity Enhancement

Urbanisation has resulted in extensive habitat fragmentation, reduced ecological connectivity, and declining biodiversity across cities worldwide. The replacement of natural vegetation with buildings, roads, and other impermeable infrastructure has substantially reduced habitat availability for insects, birds, and other organisms that contribute to ecosystem functioning (Millennium Ecosystem Assessment,

2005). Nature-Based Solutions have therefore become increasingly important not only for climate adaptation but also for biodiversity conservation within urban environments. Among these interventions, Vertical Greenery Systems provide additional habitat without requiring ground-level land, making them particularly valuable in compact cities where horizontal green space is limited (Madre et al., 2015).

Unlike thermal regulation or pollutant removal, biodiversity enhancement represents a supporting ecosystem service, meaning that it indirectly contributes to numerous other ecosystem functions. Pollination, biological pest regulation, nutrient cycling, and ecosystem resilience all depend upon healthy and diverse biological communities. Consequently, increasing habitat availability through facade vegetation may generate cascading ecological benefits extending beyond the immediate building environment (Bakker-den Hartog et al., 2025). Several studies have demonstrated that vegetated facades support diverse assemblages of arthropods, pollinating insects, spiders, and occasionally bird species. Madre et al. (2015), investigating living walls in urban France, reported significantly greater invertebrate abundance and species richness compared with adjacent non-vegetated walls. Similar observations have been reported for climbing plant systems, although biodiversity outcomes depend strongly on vegetation composition, maintenance practices, surrounding landscape structure, and seasonal conditions.

Species richness alone, however, provides only a partial representation of ecological quality. Communities dominated by a single abundant species may exhibit high richness but low ecological stability. Consequently, ecologists frequently employ diversity indices that incorporate both species richness and species evenness.

Despite growing interest in biodiversity associated with Vertical Greenery Systems, significant knowledge gaps remain. Most ecological investigations have been conducted over relatively short monitoring periods, frequently lasting only a single growing season. Such studies provide valuable snapshots of ecological communities but may not capture longer-term seasonal dynamics, successional changes, or interannual variability (Francis & Lorimer, 2011).

Additionally, biodiversity outcomes are influenced by numerous external factors beyond vegetation itself, including surrounding land use, proximity to parks, local climate, and urban connectivity. Thus, isolating the ecological contribution of individual green facades remains methodologically challenging. For these reasons biodiversity assessments within engineering-focused studies often employ relatively simple quantitative indicators such as species richness, vegetation coverage, and qualitative habitat observations. Although these indicators cannot fully represent ecosystem complexity, they provide practical measures capable of being integrated alongside engineering performance metrics.

For SQ1 and SQ2, it must be stated plainly that biodiversity is the one ecosystem service pillar in this framework without a continuous sensor source: the CEG monitoring network does not instrument biodiversity. This is treated in this thesis as an explicit scope limitation, biodiversity is retained as a scored pillar using literature-derived and survey-based qualitative values.

6.9 Multi-Criteria Assessment of Ecosystem Services

Although extensive research has demonstrated that Vertical Greenery Systems provide multiple ecosystem services, most investigations continue to evaluate these services independently. Thermal studies typically report temperature reductions or energy savings, ecological studies focus on biodiversity indicators, while air quality research quantifies particulate matter deposition. This fragmented research

landscape limits the ability of planners and decision-makers to compare overall system performance or prioritise design alternatives. The concept of ecosystem service integration has therefore gained increasing importance within Nature-Based Solutions research. Rather than evaluating environmental functions individually, integrated assessment frameworks recognise that ecosystem services interact through shared ecological processes and should therefore be considered collectively (Castellar et al., 2021).

One of the most influential developments in this area has been the application of Multi-Criteria Decision Analysis (MCDA). Multi-criteria methods enable diverse environmental indicators measured in different physical units to be converted into comparable dimensionless scores before aggregation into composite performance indices (Ascione et al., 2020). MCDA has been widely applied in sustainable building design, energy retrofit optimisation, environmental planning, and infrastructure management because it accommodates both quantitative measurements and qualitative expert judgement. Unlike single-indicator assessments, multi-criteria frameworks explicitly recognise that environmental performance involves trade-offs among multiple objectives.

Adem Esmail and Geneletti (2018), in a systematic review of twenty years of MCDA applications to nature conservation, found that AHP remains the most frequently applied weighting method across environmental studies, largely because it is transparent, mathematically well-founded, and capable of handling both qualitative and quantitative inputs simultaneously. Their review further identified a consistent methodological gap: most applications rely on expert elicitation for weight derivation without validating those weights against empirical performance data, a limitation directly relevant to the present thesis. More recently, Bousquet et al. (2023), reviewing 124 MCDA studies applied specifically to urban green spaces and Nature-Based Solutions between 2000 and 2022, confirmed that expert involvement in the weighting phase remains the dominant practice, and highlighted that the choice of weighting method materially influences final rankings, reinforcing the need for sensitivity analysis alongside any composite score. For Vertical Greenery Systems, Bakker-den Hartog et al. (2025) proposed one of the first ecosystem-service-based multi-criteria frameworks specifically developed for facade greening, identifying the need for integrated assessment approaches capable of combining regulating, supporting, and cultural ecosystem services into coherent decision-support tools, while also acknowledging that additional empirical case studies are required to validate such frameworks under real operational conditions.

A common feature of MCDA involves three sequential steps: normalisation, weighting, and aggregation. Normalisation converts indicators measured in different units — including degrees Celsius, decibels, particulate concentrations, and biodiversity indices — onto a common scale. Among available techniques, min–max normalisation remains one of the most widely applied because it preserves proportional relationships while producing dimensionless values between zero and one (Ascione et al., 2020). This approach enables direct comparison among indicators that would otherwise remain incompatible.

Following normalisation, indicators must be assigned weights representing their relative contribution to overall environmental performance. The literature distinguishes between three broad categories of weighting approach, each with distinct advantages and limitations, summarised in Table 2 below.

Subjective methods derive weights from human judgement. The Analytic Hierarchy Process (AHP), originally developed by Saaty (1980), is the most widely used: decision-makers perform pairwise

comparisons between criteria on a nine-point scale, from which mathematically consistent weights are derived alongside a consistency ratio that flags internally incoherent judgements. AHP is particularly well suited to contexts where criteria cannot be meaningfully ranked from data alone and where the relative importance of different ecosystem services must reflect research priorities and environmental policy. However, AHP is susceptible to subjectivity and inconsistency when used by a single assessor rather than a panel (Velasquez & Hester, 2013). Direct rating and SMART/SWING methods similarly rely on expert assignment but require less structured pairwise elicitation, making them faster but less rigorous.

Objective methods derive weights entirely from the data itself, without human judgement. The Entropy weighting method assigns higher weights to indicators with greater variability in the dataset, on the premise that more variable indicators carry more discriminating information. The CRITIC method (Criteria Importance Through Inter-criteria Correlation) extends this by also penalising highly correlated indicators to avoid double-counting redundant information. While these methods are free from subjective bias, they are sensitive to the specific dataset used: a single anomalous monitoring period can disproportionately inflate the weight of a noisy indicator, and weights may shift considerably if the monitoring window changes (Velasquez & Hester, 2013).

Hybrid methods combine both approaches, for example using AHP to set initial expert-based weights that are then corrected or validated using entropy-derived objective weights from the monitoring data. This approach preserves the theoretical grounding of expert judgement while incorporating empirical evidence from the actual dataset (Bousquet et al., 2023; Adem Esmail & Geneletti, 2018).

Method	Category	Basis	Advantage	Limitation
AHP	Subjective	Pairwise expert comparison	Transparent, consistency-checked	Susceptible to single-assessor bias
Direct rating	Subjective	Direct score assignment	Simple, fast	No internal consistency check
Entropy weighting	Objective	Data variability	No expert input needed	Sensitive to dataset characteristics
CRITIC	Objective	Variability + correlation	Reduces redundancy	Complex, dataset-dependent
AHP-Entropy hybrid	Hybrid	Expert + data combined	Balances subjectivity and evidence	More complex to implement

Table 2: Comparison of weighting methods applicable to multi-criteria ecosystem service assessment (Saaty, 1980; Velasquez & Hester, 2013; Bousquet et al., 2023).

For the present study, AHP is adopted as the primary weighting method, for three reasons. First, the four ecosystem service pillars — thermal regulation, air quality, acoustic performance, and biodiversity — are not equally well-represented in the sensor dataset: biodiversity is not measured and carbon sequestration

cannot be directly quantified from available instruments. Objective data-driven methods would therefore produce weights reflecting sensor density and data variability rather than genuine ecosystem service importance. Second, AHP allows the weighting to reflect the scientific evidence base reviewed in this literature review — particularly the well-established thermal dominance of green façade performance — while retaining an explicit, auditable structure rather than an arbitrary numerical assignment. Third, the ±20% weight perturbation sensitivity analysis incorporated into this study's analysis workflow partially compensates for the subjectivity of AHP by testing how much the composite score changes under modified weight assumptions, providing the kind of robustness check that Bousquet et al. (2023) recommend as standard practice alongside any expert-elicited weighting scheme.

Weighted indicators are aggregated using a weighted additive (linear) model to generate a composite performance index that facilitates comparison across monitoring periods, seasons, and façade sections. Composite indices simplify complex environmental information into interpretable performance scores while maintaining transparency regarding individual indicator contributions, provided that the normalisation bounds, weights, and aggregation formula are all reported alongside the final score (Castellar et al., 2021; Bakker-den Hartog et al., 2025).

7. Stakeholder-Dependent Weighting Framework

Contribution statement. As stated in Section 1.1, this thesis's scientific contribution is the development of a stakeholder-dependent ecosystem service assessment framework for vertical greenery systems that combines objective sensor-derived performance indicators with stakeholder-specific weighting to support building-scale decision making. Concretely, rather than a single, researcher-fixed weighting scheme, the relative importance of the four ecosystem service pillars is elicited directly from stakeholders using the Analytic Hierarchy Process (AHP), producing a family of defensible, auditable composite scores — one per stakeholder profile — rather than one score claiming universal validity. Figure 15 summarises the full pipeline this chapter implements, from stakeholder input through to the framework's output, with the thermal pillar of that output tested against measured data later in this chapter.

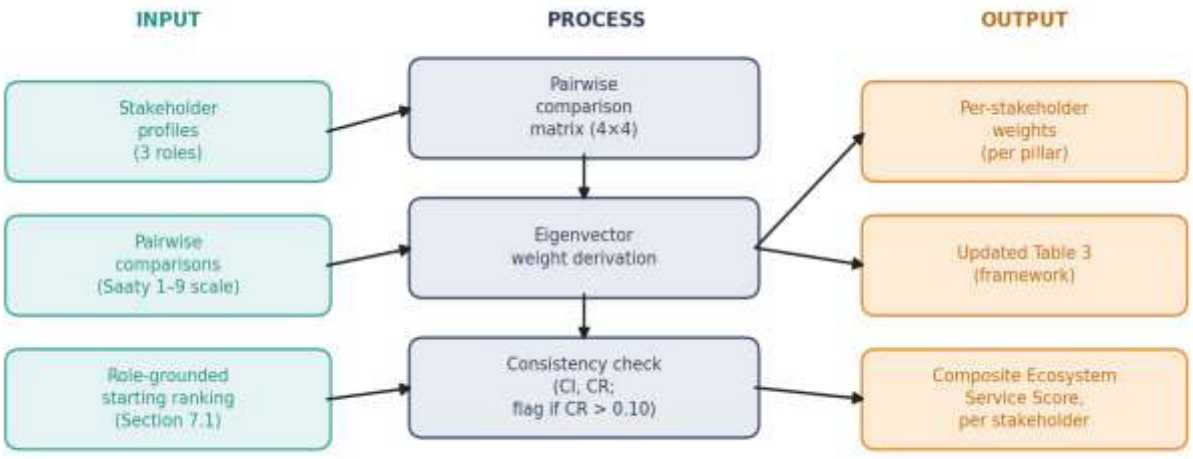


Figure 15: Input–process–output pipeline for the stakeholder-dependent weighting methodology developed in this chapter

7.1 Rationale for a Stakeholder-Dependent Approach

Building on the rationale established earlier in this thesis for adopting the Analytic Hierarchy Process (AHP) as the primary weighting method, this study adopts a stakeholder-dependent weighting approach rather than a single, fixed set of pillar weights. Bousquet et al. (2023) note that the vast majority of MCDA applications to urban green space and Nature-Based Solutions planning are conducted by the research team alone, with only a minority of studies meaningfully involving external stakeholders in the weighting phase; the same review argues that involving multiple stakeholder types produces a more representative and defensible weighting outcome than a single expert-derived scheme. Different stakeholders interacting with a vertical green façade — a green façade specialist, a landscape architect or urban planner, and a building occupant, among others — are expected to value the four ecosystem service pillars differently depending on their professional priorities, and making this variation explicit, rather than collapsing it into a single fixed weighting, better reflects how such a façade would actually be evaluated in practice.

Four stakeholder profiles are used in this thesis, each corresponding to a real respondent interviewed, questionnaired, or (for the building occupant) self-assessed in the relevant professional capacity. To preserve respondent confidentiality, each stakeholder is identified by professional role only, and no individual names are used. The four profiles — a green façade specialist, a landscape architect / urban

planner, a building occupant, and an urban ecologist / biodiversity expert — are expected to weight the four ecosystem service pillars differently according to their professional priorities.

Stakeholder 1: Green Façade Specialist. A green façade specialist is concerned primarily with the material performance and ecological function of the vegetated envelope itself — the durability of the system, its thermal behaviour, and the habitat value of the planting. This profile is expected to weight Biodiversity & Aesthetics and Thermal Regulation relatively highly, reflecting a focus on the living system and its physical performance (Perini et al., 2011; Manso & Castro-Gomes, 2015; Madre et al., 2015), with Air Quality & Carbon and Acoustic Performance weighted lower. The weights for this profile are derived from a semi-structured interview (Section 7.2).

Stakeholder 2: Landscape Architect / Urban Planner. A landscape architect or urban planner is concerned with how the façade contributes to the wider urban landscape and to city-scale environmental and public-health objectives, including greening, biodiversity connectivity, air quality and heat mitigation (Santamouris, 2014; European Environment Agency, 2023; Madre et al., 2015). This profile is expected to weight Biodiversity & Aesthetics highly, alongside Thermal Regulation for its relevance to urban heat, with Air Quality & Carbon and Acoustic Performance weighted lower. The weights for this profile are derived from a semi-structured interview (Section 7.2).

Stakeholder 3: Building Occupant. A building occupant experiences the façade directly through indoor thermal comfort, noise, and the visual amenity of the planting. This profile is expected to weight Thermal Regulation and Acoustic Performance most heavily, reflecting everyday comfort near the façade (Wong et al., 2010; Susorova et al., 2013), with Biodiversity & Aesthetics weighted moderately for perceived amenity and Air Quality & Carbon lower as its benefits are less immediately perceptible. The weights for this profile are a self-assessment completed by the author as a genuine daily occupant of the CEG building. This is stated explicitly and prominently here: this column is one illustrative occupant perspective, not independent stakeholder evidence, and should not be read as representative of building occupants generally (Section 7.2).

Stakeholder 4: Urban Ecologist / Biodiversity Expert. An urban ecologist or biodiversity expert is concerned primarily with the façade's habitat value rather than with its material or thermal performance as such: species richness, structural layering, a flowering-and-fruiting sequence that spans the season, and physical connectivity to the ground-level green system. This profile is expected to weight Biodiversity & Aesthetics most heavily, reflecting a specialist ecological perspective in which thermal performance is comparatively substitutable by other building measures (insulation, shading, shutters) whereas habitat value is not, with Air Quality & Carbon and Acoustic Performance weighted lower still (Perini et al., 2011; Madre et al., 2015). The weights for this profile are derived from a structured stakeholder questionnaire completed by the respondent in their professional capacity (Section 7.2).

Each of the four profiles above is treated as a provisional, role-grounded starting point that is then tested against the respondent's actual interview or self-assessment weights in Section 7.2. This keeps the weighting explicit and auditable, as recommended by Adem Esmail & Geneletti (2018) and Bousquet et al. (2023).

Scope of the stakeholder selection. These four profiles were selected to span the design–ecology–occupant axis most directly relevant to how a vertical green façade performs and is experienced: one respondent focused on the vegetated system itself, one on its role in the wider urban landscape, one on the

lived experience of the building, and one specifically on the façade's ecological and habitat function. This choice was also shaped by a practical constraint — within the thesis timeline, access was limited to graduation-committee members who could act as expert proxies in these capacities, and to the author as a genuine daily occupant — rather than by a claim that these four exhaust the relevant perspectives. They deliberately do not cover the full decision-making chain involved in commissioning, financing, and operating a VGS in practice. Several stakeholder types that would participate in a real implementation were therefore not included, among them building owners, facility managers, housing corporations, investors, municipalities, and property developers. These were excluded not because their priorities are judged unimportant — several would very plausibly weight the pillars quite differently, for example prioritising maintenance cost, asset value, regulatory compliance, or return on investment, none of which map neatly onto the four ecosystem service pillars used here — but because no interviews with them were feasible within this thesis's scope and timeline, and because the aim at this stage is to develop and demonstrate the framework rather than to conduct a comprehensive stakeholder study. The current set is thus suitable for framework development but is not a representative sample of the real decision-making chain; the implications of this for the weighting outcomes and for the framework's practical applicability are discussed under Methodological Limitations in the Discussion.

The stakeholder columns of Table 3a report the interview-derived weights (green façade specialist, landscape architect / urban planner, and urban ecologist / biodiversity expert) and the self-assessed weights (building occupant) established in Section 7.2, expressed as a 1–5 score per pillar that follows the size of each stakeholder's weights.

The core framework developed by this thesis is presented below as two linked tables, reflecting the two distinct sources of evidence behind it. Table 3a connects the four ecosystem service pillars to their literature-derived performance rating, their sensors and indicators, and each stakeholder's elicited priority; it is the structure that every subsequent stakeholder-weighting step in this report operates on. Table 3b reports the three VGS typologies — climbing evergreen, climbing deciduous, and living wall (Section 6.3.1) — rated solely on the summer thermal data analysis (Section 7.3.5); it is typology-agnostic by design and does not treat the living wall as a default case. Table 3a's ratings remain literature- and interview-derived only, since the acoustic, air-quality and biodiversity pillars are not yet sensor-tested; Table 3b's ratings are derived entirely from this thesis's own summer sensor analysis and are not informed by literature. The two tables are read together rather than merged, so that a reader can see clearly which claims rest on published literature and stakeholder judgement, and which rest on this thesis's own measured evidence.

In summary, Tables 3a and 3b each draw on a different, clearly identifiable source of evidence, consistent with this thesis's auditability principle of making explicit where every number comes from (Adem Esmail & Geneletti, 2018; Bousquet et al., 2023). In Table 3a, the Rating column draws on the published literature for all four pillars; the Sensors and Indicator columns state which physical instrument and which measured quantity stand behind each pillar, again grounded in the literature reviewed in Sections 6.4–6.9; and the Stakeholders column draws on the semi-structured interviews, questionnaire, and self-assessment reported in Section 7.2 — the literature also informed the initial rationale for what each stakeholder profile was expected to prioritise (Section 7.1), but the stakeholder scores shown in the table itself are worked out directly from each respondent's own pairwise judgements, not assumed from literature. The Stakeholder Rating, Final Rating and Final Ranking columns then combine the two sources, as explained

below the table. In Table 3b, every column — the Rating, the measured ΔT, and the Wilcoxon p-value — is drawn entirely from this thesis's own summer sensor data analysis (Section 7.3.5), with no literature or stakeholder input at all.

Table 3a: Ecosystem Service – Stakeholder Weighting Framework (Literature and Stakeholder Interviews)

This table brings together, for each of the four ecosystem service pillars, how well the literature says a vertical green façade delivers that service (Literature Rating), how important each of the four stakeholders considers it (Score), which sensors would measure it, and which indicator those sensors measure. The last three columns combine the literature and the stakeholders into one result. Every rating, score and ranking in this table uses the same 1–5 scale, where 1 is the lowest and 5 is the highest. None of the values in this table comes from this thesis's own sensor data, which is reported separately in Table 3b.

Ecosystem Service	Literature Rating (1–5)	Stakeholders		Sensors	Indicator	Stakeholder Rating (1–5)	Final Rating (out of 10)	Final Ranking (1–5, 5 = highest)
		Stakeholder	Score (1–5)					
Thermal Regulation	**5**	Green Façade Specialist	5	Heat flux; surface temp.; ambient temp.	ΔT, heat flux	**3.9**	**8.9**	**4.5**
		Landscape Architect	2.3					
		Building Occupant	5					
		Urban Ecologist	3.3					
Acoustic Performance	**3**	Green Façade Specialist	1	Noise	Insertion loss / noise level (dB)	**1.2**	**4.2**	**2.1**
		Landscape Architect	1.2					
		Building Occupant	1.6					
		Urban Ecologist	1					
Air Quality & Carbon	**3**	Green Façade Specialist	1.1	CO_2; PM2.5, PM10	PM reduction; CO_2 uptake (indicative)	**1.5**	**4.5**	**2.3**
		Landscape Architect	1					
		Building Occupant	2.7					
		Urban Ecologist	1.1					
Biodiversity & Aesthetics	**5**	Green Façade Specialist	3.0	None (manual survey only)	Visual / manual survey	**3.5**	**8.5**	**4.3**
		Landscape Architect	5					
		Building Occupant	1					
		Urban Ecologist	5					

1 = Red (lowest)	2 = Purple	3 = Orange	4 = Blue	5 = Green (highest)

Colour legend. Every value in this table uses the same colours, where 1 is the lowest and 5 is the highest: 1 = red, 2 = purple, 3 = orange, 4 = blue and 5 = green. Values with a decimal are coloured by the nearest whole number (halves round up). The Final Rating is out of 10, so each colour there covers two points: 9–10 green, 7–8.9 blue, 5–6.9 orange, 3–4.9 purple and below 3 red.

How to read this table. Each row is one ecosystem service. The Literature Rating shows how well published studies say a green façade delivers that service. The Score column shows how much weight each of the four stakeholders gave that service in the AHP questionnaire (Section 7.2 and Appendix B), placed on the same 1–5 scale as the rest of the table. For each stakeholder, the service they weighted highest scores 5, the one they weighted lowest scores 1, and the other two are placed in proportion to where their weight falls between those two. For example, the building occupant gave Air Quality 26% of the weight, which lies about 43% of the way from their lowest weight (12%) to their highest (45%), so it scores $1 + 4 \times 0.43 = 2.7$. This keeps not only each stakeholder's order of priorities but also how strongly they prefer one service over another. The Sensors and Indicator columns show how the service would be measured on the CEG façade. The last three columns then bring the literature and the stakeholders together in three simple steps. First, the four stakeholders' scores are averaged to give the Stakeholder Rating. For example, Thermal Regulation scored 5, 2.3, 5 and 3.3, which gives $(5 + 2.3 + 5 + 3.3) \div 4 = 3.9$. Second, the Final Rating adds the Literature Rating (5) and the Stakeholder Rating (3.9) together, giving 8.9 out of 10. Third, the Final Ranking halves that score ($8.9 \div 2 = 4.5$) so that it sits back on the same 1–5 scale as the rest of the table, with 1 the lowest and 5 the highest. Literature and stakeholders therefore have an equal say in the result.

What the table means. Two services clearly come out on top. Thermal Regulation scores highest (4.5 out of 5): the literature rates it strongly, and every stakeholder gave it either their highest or their second-highest weight, including the building occupant and the green façade specialist, who both rank it first. Biodiversity & Aesthetics follows closely (4.3): the literature rates it just as strongly, and it is the top priority for two of the four stakeholders — the landscape architect / urban planner and the urban ecologist / biodiversity expert — though the building occupant weights it lowest of all four services. Air Quality & Carbon (2.3) and Acoustic Performance (2.1) sit well behind and almost level: the literature gives both only moderate ratings, and three of the four stakeholders gave these two services much smaller weights than the others; only the building occupant gave air quality a noticeably higher weight. In plain terms, the framework says that, for this façade and these four stakeholders, a green façade is valued first for the cooling it gives the building and for the living habitat it provides — the two are very close — and much less for cleaning the air or reducing noise. The gap between the top two services is small (0.2), so their order could plausibly swap under slightly different stakeholder weighting, while the gap between the top two and the bottom two is large, so that split is a stable result. The difference between Air Quality and Acoustic Performance (0.2) is too small to be read as a real difference in priority.

Table 3b: Typology Performance by Data Analysis (Thermal Pillar, Summer, Dedicated Temperature Sensors)

This table reports the three VGS typologies examined in this thesis — climbing evergreen, climbing deciduous, and living wall — rated solely on the summer thermal data analysis reported in Section 7.3.5 (Table 17), restricted to working hours (09:00–17:00) and using the dedicated single-channel temperature

sensors at Sections 3.1, 3.2, and 2.3 respectively. No literature or stakeholder input is reflected here. Ratings use the same 1–5 scale and colours as Table 3a, where 1 is the lowest and 5 is the highest: the typology that stayed coolest in summer compared with the reference location is rated 5, and the one that ran warmest is rated 1. Because this table has only one source of evidence, the measured data, the Final Ranking is the same as the measured rating.

Typology	Rating (1–5)	Working-hours (09:00–17:00) mean ΔT vs. reference	Wilcoxon p	Verdict	Final Ranking (1–5, 5 = highest)
Living Wall	**5**	−2.72°C	0.004	Favourable — significant cooling benefit	**5**
Evergreen	**2**	−0.82°C	0.027	Favourable — significantly cooler than reference (smaller benefit)	**2**
Deciduous	**1**	−0.35°C	0.074	Cooler direction, not statistically significant (weakest)	**1**

1 = Red (lowest)	2 = Purple	3 = Orange	4 = Blue	5 = Green (highest)

Colour legend. 1 = red (lowest), 2 = purple, 3 = orange, 4 = blue and 5 = green (highest).

What the table means. The living wall scores 5, the highest possible, because it stayed by far the coolest of the three relative to the reference during working hours: about 2.7°C cooler on average, on all nine days ($p = 0.004$). The evergreen climber scores 2 and the deciduous climber 1: the evergreen was about 0.8°C cooler than the reference ($p = 0.027$), a smaller but still significant benefit, while the deciduous was only about 0.4°C cooler, which is not statistically significant ($p = 0.074$). In plain terms, during working hours in the summer week analysed, all three typologies ran cooler than the bare reference, the living wall by a wide margin; only the living wall and the evergreen climber show a statistically confirmed benefit. This result covers one summer week and the thermal pillar only, so it does not yet say anything about noise, air quality, biodiversity or winter performance.

Note. Table 3b is based solely on the summer sensor data analysis (Section 7.3.5); winter data collection coincided with a period when the climbing façade vegetation had not yet established sufficient canopy coverage to produce a reliable seasonal signal, and is therefore excluded from this version of the framework and reported instead as a scope limitation (Discussion) and a direction for future work (Recommendations). Genuine statistical validation of this framework — for example, against a full annual cycle of data, additional façade orientations, or independent replication — remains future work; the results reported here and in Section 7.3 constitute a data analysis of the available summer measurements, not a completed validation of the framework. A cross-check using the original combined CO_2/temperature/humidity sensors, averaged across the full section groups per typology (Section 7.3.6), agrees with the ranking and with the Living Wall result shown here, but finds the two climbing typologies about level with, or warmer than, the reference rather than cooler; this is reported as an instrument-dependent finding rather than incorporated into the ratings above.

Table 3a's literature ratings (1–5 scale, colour-coded from green to red) are qualitative, literature-derived judgements of how well a vertical greenery system delivers each ecosystem service; none of Table 3a's ratings are informed by this thesis's own sensor data. Table 3b's ratings, by contrast, are derived entirely from the summer working-hours (09:00–17:00) thermal data analysis for the three typologies (climbing evergreen, climbing deciduous, living wall), drawn from Section 7.3.5, and are not informed by literature: Living Wall is rated highest, reflecting its large, significant cooling effect during summer working hours; Evergreen is rated second, with a smaller but significant cooling effect, and Deciduous is rated lowest, with the weakest and not statistically significant effect, which gives final rankings of 5 for the living wall, 2 for the evergreen climber and 1 for the deciduous climber (1 = lowest, 5 = highest). A winter result is not yet available for any typology (Section 7.3.3), so Table 3b reflects summer performance only; extending it to a winter rating, once representative winter data is available, is identified as a priority for future work (Recommendations). Stakeholder weight priorities in Table 3a are the finalized ranks for each of the four profiles, derived from the interviews, questionnaire, and self-assessment reported in Section 7.2 rather than from literature alone. Robustness of the resulting composite scores will subsequently be tested via ±20% weight-perturbation sensitivity analysis (Bousquet et al., 2023). All four stakeholder columns in Table 3a report real, non-provisional weights: the green façade specialist, the landscape architect / urban planner, and the urban ecologist / biodiversity expert weights are interview- or questionnaire-derived AHP weights, and the building occupant weights are a self-assessment by the author (Section 7.2), each reported in the table as a score on the 1–5 scale (5 = the pillar they weighted highest, 1 = the one they weighted lowest, and the others placed in proportion to their weight); the underlying weights are given in Section 7.2 (building occupant) and Appendix B (the other three profiles).

7.2 Interview Implementation

This section reports the outcomes of the stakeholder weight elicitation for the four profiles defined in Section 7.1. To preserve confidentiality, respondents are identified by professional role only. Three profiles were elicited through semi-structured interviews or a structured questionnaire following the protocol in Section 7.1: a green façade specialist, a landscape architect / urban planner and a biodiversity expert, each interviewed in their respective professional capacity, who completed the same pairwise-comparison protocol as a written questionnaire; each is treated as a distinct stakeholder profile. For the building occupant profile, no independent third-party interview was feasible within this thesis's timeline; the questionnaire was instead completed by the author as a genuine daily occupant of the CEG building. This is disclosed explicitly as a self-assessment rather than an independent respondent and is treated as a limitation on that specific column's independence. Each respondent completed six pairwise comparisons across the four ecosystem service pillars using the Analytic Hierarchy Process (AHP; Saaty, 1980), on the standard 1–9 scale summarised in Table 4 below. The full questionnaire, together with the reasoning behind each question, is given in Appendix C.

This 1–9 range is not an arbitrary convention: Saaty grounded it in Miller's (1956) finding that people can reliably and consistently distinguish only about seven, plus or minus two, categories when making a judgement by feel rather than by precise measurement. A finer scale, such as 1–100, would ask a respondent to distinguish differences of preference they cannot reliably or repeatably perceive, producing an illusion of precision rather than a genuine measurement; a coarser scale, such as 1–5, would collapse real differences of preference — for instance, between "clearly more important" and "extremely more

important" — that a respondent can meaningfully distinguish. The 1–9 scale is therefore the range within which a stakeholder's pairwise judgement is both fine enough to be informative and coarse enough to be given consistently.

Scale value	Interpretation
1	The two pillars are of equal importance
3	One pillar is moderately more important than the other
5	One pillar is strongly more important than the other
7	One pillar is very strongly more important than the other
9	One pillar is extremely more important than the other
2, 4, 6, 8	Intermediate values between the judgments above

Table 4: Saaty's 1–9 pairwise comparison scale (Saaty, 1980)

Pairwise comparison matrices and derived weights

For each respondent, the six pairwise judgments were assembled into a 4×4 reciprocal comparison matrix (criterion i vs. criterion j, with the reciprocal entered automatically at j vs. i), and weights were derived using the principal eigenvector method: the matrix's dominant eigenvalue (λ_{max}) and its associated eigenvector were computed, and the eigenvector was normalised to sum to one to give the final weight per pillar. Consistency was checked using Saaty's consistency ratio, CR = CI / RI, where CI = (λ_{max} − n) / (n − 1) and RI is the random-index benchmark for a matrix of size n (RI = 0.90 for n = 4); a CR below 0.10 is conventionally taken to indicate acceptably consistent judgments (Saaty, 1980).

The full pairwise comparison matrices and derived weights for the other three stakeholders — the landscape architect / urban planner, the green façade specialist, and the urban ecologist / biodiversity expert — are given in Appendix B (Tables B1–B6), with the underlying interview questions and full verbatim answers reproduced in Appendix C. Two of the three — the landscape architect / urban planner and the urban ecologist / biodiversity expert — put Biodiversity first and Thermal Regulation second; the third, the green façade specialist, puts Thermal Regulation first and Biodiversity second, consistent with their own stated summary ranking ("Thermal regulation > Biodiversity > Air quality ≈ Acoustic performance", Appendix C.2). The landscape architect / urban planner held their Biodiversity-first view most strongly (weight 0.656), and their answers came out slightly less consistent than the usual 0.10 threshold (CR = 0.111); this is reported as it is rather than corrected. The green façade specialist's and urban ecologist's answers were both well within the consistency threshold (CR = 0.044 and 0.019 respectively). Only the building occupant is kept in the main text, below, together with a step-by-step worked example, so that a reader can follow exactly how one set of answers turns into the scores shown in Table 3a.

Three distinct stakeholder profiles, hence three distinct columns. Because the three interviewed or questionnaired respondents represent three different professional profiles, their weight vectors are kept as separate stakeholder entries in Table 3a rather than aggregated into one. Aggregating them would average away exactly the between-stakeholder variation the framework is designed to expose, so no cross-

respondent geometric-mean step is applied. Two of the three profiles — the landscape architect / urban planner and the urban ecologist / biodiversity expert — independently place Biodiversity first (weights 0.656 and 0.455 respectively) and Thermal Regulation second; the green façade specialist instead places Thermal Regulation first (weight 0.449) and Biodiversity second (weight 0.288), consistent with their own stated summary ranking. Where the profiles agree on ordering, they still differ in the strength of that preference and in the ordering of the lower-weighted pillars, and these differences are preserved in their respective columns.

Building Occupant Self-Assessment

As no independent Building Occupant interview was feasible within this thesis's timeline, the same questionnaire and pairwise comparison protocol was completed by the author, reflecting her own perspective as a genuine daily occupant of the CEG building. This is reported here as a self-assessment, not as an independent third-party respondent; it is a real but limited data point, and the consequences of its lack of independence are discussed under Methodological Limitations.

	Thermal	Air Quality	Acoustic	Biodiversity
Thermal	1	2	3	3
Air Quality	1/2	1	2	2
Acoustic	1/3	1/2	1	2
Biodiversity	1/3	1/2	1/2	1

Table 5: Pairwise comparison matrix — Building Occupant

Pillar	Derived weight	Rank	Score in Table 3a (1–5)
Thermal Regulation	0.451	1	5
Air Quality & Carbon	0.261	2	2.7
Acoustic Performance	0.169	3	1.6
Biodiversity & Aesthetics	0.119	4	1

Table 6: Derived weights — Building Occupant (λ_{max} = 4.071, CI = 0.024, CR = 0.026)

This matrix is well within the consistency threshold (CR = 0.026). The resulting ranking is Thermal > Air Quality > Acoustic > Biodiversity. This only partly matches what was expected for this profile in Section 7.1: thermal comfort does come first, but air quality comes second rather than acoustic comfort, and biodiversity comes last. On Thermal Regulation coming first, this matches the green façade specialist among the three interview- or questionnaire-based profiles discussed above, though not the landscape architect / urban planner or the urban ecologist / biodiversity expert, both of whose rankings placed Biodiversity first. This result should be read cautiously given the self-assessment limitation stated above:

the author's own priorities as an occupant may not represent the range of views held by other building occupants (see also the reflection on the author's own background in the Discussion).

Worked example: how the Building Occupant's answers became the scores in Table 3a

This box walks through, in plain terms, how the building occupant's pairwise judgments in Table 5 turn into the weights in Table 6 and, from there, into the scores shown for the building occupant in Table 3a. It uses a simple shortcut that can be worked out by hand instead of the full principal eigenvector method described above. The figures in Tables 3a, 5 and 6 use the full method, which gives almost the same result for a consistent (low-CR) matrix such as this one.

Step 0 — turn the questionnaire answers into numbers. Questions 3–8 of the questionnaire (Appendix C) each compare two pillars. For each pair, the respondent says which one matters more and by roughly how much, using Saaty's 1–9 scale (Table 4). That number is written into Table 5 in the row of the pillar that matters more. The mirror cell, in the row of the other pillar, gets the upside-down value (for example, 2 becomes 1/2): if Thermal matters twice as much as Air Quality, then Air Quality matters half as much as Thermal. The diagonal of Table 5 is always 1, because every pillar is exactly as important as itself. The building occupant's six answers were:

Q	Pair compared	Answer	Number	Where it goes in Table 5
Q3	Thermal vs Air Quality	Thermal matters slightly more	2	Thermal row: 2; Air Quality row: 1/2
Q4	Thermal vs Acoustic	Thermal matters moderately more	3	Thermal row: 3; Acoustic row: 1/3
Q5	Thermal vs Biodiversity	Thermal matters moderately more	3	Thermal row: 3; Biodiversity row: 1/3
Q6	Air Quality vs Acoustic	Air quality matters slightly more	2	Air Quality row: 2; Acoustic row: 1/2
Q7	Air Quality vs Biodiversity	Air quality matters slightly more	2	Air Quality row: 2; Biodiversity row: 1/2
Q8	Acoustic vs Biodiversity	Acoustic matters slightly more	2	Acoustic row: 2; Biodiversity row: 1/2

Table 7: Step 0 of worked example (questionnaire answers to numbers)

Step 1 — start from the table built in Step 0. For each of the four pillars, take its row of judgments from Table 5 and multiply the four numbers together:

Pillar	Row of judgments (from Table 5)	Row multiplied together
Thermal Regulation	1 × 2 × 3 × 3	= 18
Air Quality & Carbon	1/2 × 1 × 2 × 2	= 2
Acoustic Performance	1/3 × 1/2 × 1 × 2	= 0.333
Biodiversity & Aesthetics	1/3 × 1/2 × 1/2 × 1	= 0.083

Table 8: Step 1 of worked example

Step 2 — undo the inflation from multiplying. Multiplying four numbers together inflates the result, so each row's product is brought back down to a comparable size by taking its 4th root (4th, because four pillars were multiplied together):

Pillar	4th root of the row product
Thermal Regulation	18^(1/4) = 2.060
Air Quality & Carbon	2^(1/4) = 1.189
Acoustic Performance	0.333^(1/4) = 0.760
Biodiversity & Aesthetics	0.083^(1/4) = 0.537

Table 9: Step 2 of worked example

Step 3 — turn these into percentages that add up to 100%. Add the four numbers from Step 2 (2.060 + 1.189 + 0.760 + 0.537 = 4.546), then divide each one by that total:

Pillar	Calculation	Result	Score in Table 3a (1–5)
Thermal Regulation	2.060 ÷ 4.546	45.3%	5
Air Quality & Carbon	1.189 ÷ 4.546	26.2%	2.7
Acoustic Performance	0.760 ÷ 4.546	16.7%	1.6
Biodiversity & Aesthetics	0.537 ÷ 4.546	11.8%	1

Table 10: Step 3 of worked example

Step 4 — turn the shares into scores on the 1–5 scale. The pillar with the largest share scores 5 and the one with the smallest share scores 1. Each of the other two is placed in proportion to where its share falls between those two: score = 1 + 4 × (its share − smallest share) ÷ (largest share − smallest share). For Air Quality this gives 1 + 4 × (26.2 − 11.8) ÷ (45.3 − 11.8) = 1 + 4 × 14.4 ÷ 33.5 = 2.7, and for Acoustic Performance 1 + 4 × (16.7 − 11.8) ÷ 33.5 = 1.6. These are the scores shown for the building occupant in Table 3a (last column of Table 10). Unlike a simple ranking, this keeps the size of the gaps between the pillars: Air Quality sits clearly below Thermal, and Acoustic only a little above Biodiversity. In plain terms: as a daily occupant of the CEG building, thermal comfort matters most to this respondent (about 45%), air quality comes a clear second (about 26%), acoustic comfort third (about 17%), and biodiversity — valued, but seen as less urgent than a comfortable and healthy indoor environment — comes last (about 12%).

Check — do the answers fit together? Before the weights are used, AHP checks whether the six answers are consistent with each other. For example, if Thermal matters more than Air Quality, and Air Quality matters more than Biodiversity, then Thermal should also matter more than Biodiversity, and by a bigger margin than either of those two. The consistency ratio (CR) measures how far a set of answers strays from this kind of logic. A CR below 0.10 is treated as consistent; a higher value means some answers contradict each other and should be looked at again. The building occupant's CR is 0.026, so the six answers fit together well.

What happens next. These four scores are not used on their own. In Table 3a they are averaged with the scores of the other three stakeholders to give the Stakeholder Rating for each pillar, then added to the

Literature Rating to give the Final Rating (out of 10), and finally halved to give the Final Ranking on the 1–5 scale (see "How to read this table" under Table 3a).

Table 3a reflects these self-assessed scores for the building occupant, alongside the interview- or questionnaire-derived scores for the green façade specialist, the landscape architect / urban planner, and the urban ecologist / biodiversity expert, whose full calculations are given in Appendix B. All four stakeholder entries are therefore based on real elicited data; there is no literature-only stakeholder, and the urban-ecologist profile is included on the basis of a completed stakeholder questionnaire.

7.3 Further Process Steps: Normalisation, Aggregation, and Analysis

Following weight assignment, the study proceeds through the remaining stages of the multi-criteria framework outlined in the Methodology section:

1. **Normalisation.** All raw indicators (ΔT, insertion loss, PM concentration reduction) are converted to a common 0–1 scale using min–max normalisation, preserving proportional relationships between measurements taken in incompatible physical units (Ascione et al., 2020). Because min–max normalisation rescales each indicator against the minimum and maximum observed within this specific dataset, the resulting 0–1 scores are relative to the four sections and two measurement weeks analysed here, not an absolute measure of ecosystem-service performance; a section scoring 1.0 is the best performer among these four sections in this dataset, not a fixed benchmark that would carry over unchanged to a different set of sections, buildings, or monitoring periods. This has a direct bearing on transferability (Discussion, Critical Reflection): the normalised scores in Section 7.3.4 cannot be read as portable performance values outside the CEG dataset they were computed from.

2. **Weighted aggregation.** The normalised indicators are combined using a weighted additive (linear) model, applying the stakeholder-dependent weighting scheme confirmed through interviews (Table 3a), to produce a distinct composite Ecosystem Service Performance Index for each stakeholder profile, monitoring period, and façade section (Velasquez & Hester, 2013).

3. **Sensitivity analysis.** To test the robustness of the composite index against the inherent subjectivity of AHP-derived weights, a ±20% perturbation is systematically applied to each pillar weight in turn, and the resulting change in composite score and façade ranking is recorded. This follows the sensitivity-testing practice recommended by Bousquet et al. (2023) as a standard companion to any expert-elicited weighting scheme.

4. **Analysis of experimental data.** Given the constrained timeline, analysis of the framework against the CEG sensor dataset is designed as a bounded, staged procedure instead of an open-ended statistical exploration of the full one-year, one-minute-resolution dataset. This approach follows the general precedent of analysing predictive vegetated-envelope models against extensive field or sensor data, as demonstrated for green roof heat and mass transfer models by Tabares-Velasco et al. (2012), and is consistent with the performance-based design philosophy proposed by Cook and Larsen (2021), who argue that green infrastructure co-benefits should be linked to quantifiable physical processes and tested against measured performance rather than assumed from design intent alone. The strategy prioritises testing whether the framework's ranking logic holds against measured data, since that is both the claim the framework actually makes and the most time-efficient thing to test.

Calibration versus analysis data. A necessary condition for this analysis to be meaningful is that the data used to develop the framework is kept separate from the data used to test it, in the same sense that a predictive model must be validated on data distinct from whatever calibrated it (Khan, Neda'a, & Munawer, 2026). In this thesis, the literature ratings in Table 3a (Section 7.1) are derived entirely from literature, not from the CEG sensor dataset; no sensor readings were used, directly or indirectly, in setting those illustrative ratings or in eliciting the stakeholder weights (Section 7.2). The CEG sensor exports used in Sections 7.3.1–7.3.4 therefore function as an independent analysis set against the literature-derived prediction, rather than as an input the framework was tuned to reproduce. This separation is what allows a divergence between the predicted and measured rankings (Sections 7.3.1–7.3.3) to be read as a genuine finding about the framework's predictive validity, rather than as evidence recycled from the same source it is being checked against.

Step 1 — Aggregation. Rather than working with raw one-minute sensor data, all thermal, acoustic, and air-quality time series are first resampled to daily office-hours means (09:00–17:00, to focus on peak summer conditions while the building is in use) and weekly means per VGS typology. One representative summer week, capturing peak thermal load, is used for the analysis reported here. A winter window was originally collected in parallel but is excluded from this analysis (Section 7.3.3), since the façade vegetation had not yet established sufficient canopy coverage during that period to produce a representative winter signal. Analysis against a full annual dataset, including a winter window collected once the vegetation is established, is treated as a priority for future work (Recommendations) rather than as part of the current analysis.

Step 2 — Per-pillar rank analysis. For each measurable pillar, the framework's literature-derived typology ranking (Table 3a) is tested against the aggregated sensor data using a Spearman rank correlation (Spearman, 1904) between predicted and observed typology performance: Thermal Regulation (predicted Living Wall > Climbing Evergreen > Climbing Deciduous, tested against measured ΔT and heat flux), Acoustic Performance (tested against measured insertion loss), and Air Quality & Carbon (tested against measured PM and CO_2 indicators). A rank-correlation approach is chosen over significance testing on the full distribution because it directly answers the question the framework depends on — does the relative ordering of typologies hold — without requiring the more time-intensive assumption-checking that formal inferential statistics on high-frequency sensor data would demand.

Step 3 — Composite analysis. The stakeholder-weighted composite Ecosystem Service Score ranking (per stakeholder profile, from Table 3a) is compared against the composite measured-performance ranking using the same rank-correlation logic, to test whether the stakeholder-weighted framework — not just the individual indicators — reproduces a defensible ordering of typologies.

Step 4 — Sensitivity check. The ±20% weight-perturbation analysis described above is run on the analysed composite ranking to confirm whether typology ordering is robust to reasonable variation in stakeholder-derived weights.

Biodiversity — scope limitation. As established in Section 6.8, the CEG sensor network does not include biodiversity instrumentation. The Biodiversity & Aesthetics pillar is therefore assessed only against the literature-derived qualitative scores already established in Table 3a, and is explicitly excluded from the sensor-based rank analysis described in Steps 2–4 above. This is stated as a scope limitation

rather than a gap, and is revisited in the Recommendations as a direction for future instrumentation of the CEG installation.

This analysis step addresses the core methodological gap identified in the problem statement — namely, that most existing MCDA frameworks for VGS are built from literature-derived or expert-elicited values rather than tested against real, noisy, gap-containing sensor data (Bakker-den Hartog et al., 2025). Where a pillar's predicted and measured rankings do not align, this is reported and discussed as an informative finding in its own right, consistent with the Recommendations set out at the end of this report, rather than silently adjusted.

Stage	Process Step	Method / Tool	Output
1	Stakeholder Weight Elicitation	Semi-structured interviews with graduation committee members (facility management, ecology, planning perspectives) + literature/professional sources	Confirmed or revised stakeholder-dependent weights for the four ecosystem service pillars
2	Normalisation	Min–max normalisation of raw indicators to 0–1 scale	Dimensionless, comparable indicator values
3	Weighted Aggregation	Weighted additive (linear) model using stakeholder-dependent weights (Table 3a)	Composite Ecosystem Service Performance Index, per stakeholder profile
4	Sensitivity Analysis	±20% perturbation applied to each stakeholder-derived weight in turn	Robustness check on composite score and facade ranking, per stakeholder
5	Analysis	Rank-comparison analysis (Spearman ρ) of predicted vs. measured typology ranking, per pillar and composite, on aggregated summer/winter windows; ±20% sensitivity check on the analysed ranking; biodiversity excluded (literature-only, see Section 6.8)	Confirmation of framework reliability under real operational conditions

Table 11: Further Process Steps (Framework Application)

7.3.1 Multi-Section Process Analysis: Summer (22–30 June 2026)

Reference-based comparison method. Section 4.6 functions as the unshaded reference location rather than as a ranked vegetated section. For each vegetated section, the thermal buffering indicator is computed by comparing that section's behind-vegetation probe (position 2) against the reference location's equivalent behind-position probe (4.6.2). This reference-based approach is consistent with the method used in the concurrent CEG field study by Parmentier, Ottelé, and van den Dobbelsteen (in preparation) and standard practice in comparable vertical-greenery field experiments (Wong et al., 2010; Bakhshoodeh, Ocampo, & Oldham, 2023). The results below are computed directly from the raw 15-minute sensor exports under this definition.

This subsection reports the first cross-section analysis step, using nine days of continuous CEG sensor data (22–30 June 2026, 15-minute resolution). To focus on peak summer conditions at the times the building is actually in use, the analysis is restricted to office hours: only readings taken between 09:00 and 17:00 are used (32 readings per day, 288 per probe over the nine days). Four instrumented green façade sections (3.1, 3.2, 4.1 and 4.3) are compared against the unshaded reference location (Section 4.6), rather than against a section-specific paired probe. For each vegetated section, the thermal buffering indicator is computed as ΔT = T(behind-vegetation, section) − T(behind, reference location), so that a positive ΔT means the vegetated section runs warmer than the reference at the equivalent position, and a negative ΔT means it runs cooler — i.e. a genuine cooling benefit attributable to the vegetation rather than to the wall or cavity alone. Ambient outdoor conditions are taken from the dedicated weather station (Section 5.7) rather than from any section's own probe. Statistical significance of each section's office-hours mean ΔT against zero is assessed using a Wilcoxon signed-rank test on the nine daily office-hours means, which avoids treating autocorrelated 15-minute readings as independent observations. The final column reports the Spearman rank correlation between each section's 15-minute ΔT readings and the concurrent ambient air temperature recorded at Weather Station 5.7. Unlike the other columns, this check is computed across all 863 paired readings (all hours of the day); it checks whether a section's departure from the reference simply tracks how hot or cold it is outside, rather than reflecting a genuine, section-specific effect.

The results are mixed. During office hours, only one of the four sections shows a statistically significant cooling benefit relative to the reference: Section 4.3 runs 0.73 °C cooler than the reference on average (Wilcoxon $p = 0.020$), consistent with an active shading and evapotranspiration effect. Section 4.1 shows no detectable difference from the reference (mean +0.00 °C, $p = 0.734$). Sections 3.1 and 3.2, by contrast, run significantly warmer than the reference during office hours (+1.46 °C, $p = 0.004$, and +1.03 °C, $p = 0.008$). For these two sections the office-hours difference is smaller than over the full 24-hour day (+2.36 °C and +1.66 °C), so part of their warmer behaviour happens outside working hours. This is more consistent with heat being held behind a denser canopy and released slowly than with an active cooling mechanism.

Summer ΔT relative to the reference location (Section 4.6) during office hours (09:00–17:00), 22–30 June 2026, n = 9 daily office-hours means per section:

Section	Section temp. (°C)	Reference temp. (°C)	Mean ΔT, office hours	Wilcoxon p	corr(ΔT, WS5.7), all hours
Section 3.1	31.71	30.25	+1.46 °C	0.004	-0.04
Section 3.2	31.28	30.25	+1.03 °C	0.008	+0.31
Section 4.1	30.25	30.25	+0.00 °C	0.734	-0.35
Section 4.3	29.51	30.25	−0.73 °C	0.020	+0.09

Table 12: Summer ΔT

What Table 12 shows. For each section, the second and third columns give the average temperature measured behind the vegetation and at the bare reference location during office hours, over the nine days. The fourth column is simply the difference between the two (ΔT): a positive value means the section was warmer than the reference, a negative value means it was cooler. The Wilcoxon p-value shows how likely it is that a difference this consistent could have happened by chance; a value below 0.05 is treated as a real difference. In plain terms, during working hours in this hot June week, only Section 4.3 kept the wall behind its planting cooler than the bare reference, by about 0.7 °C (29.51 °C against 30.25 °C). Section 4.1 made no measurable difference at all. Sections 3.1 and 3.2 were actually warmer than the reference, by about 1.5 °C and 1.0 °C. The last column is weak for every section (between −0.35 and +0.31), which means these differences are not simply following the outdoor weather.

Worked example: how Table 12's office-hours mean ΔT and Wilcoxon p were calculated

This box illustrates, using Section 3.1's summer result as a concrete example, exactly how each value in Table 12 was derived from the raw 15-minute sensor exports. The same procedure was applied to every other section analysed in this chapter.

Step 1: at every 15-minute timestamp between 09:00 and 17:00, ΔT is computed as Section 3.1's behind-vegetation probe reading minus the reference location's equivalent probe reading. On 22 June, for example, this gave +0.8°C at 09:00, +0.7°C at 09:15 and +0.7°C at 09:30, peaking at +1.3°C at 10:45 and falling back to 0.0°C by 16:45 — 32 such readings were logged during office hours that day.

Step 2: each day's 32 office-hours readings are averaged to a single office-hours mean. For 22 June, the 32 readings summed to 14.9, and 14.9 ÷ 32 = 0.466°C. Repeating this for all nine days of the summer week gives nine daily office-hours means:

Date	Office-hours mean ΔT, 09:00–17:00 (°C)
22 Jun	0.466
23 Jun	0.387
24 Jun	1.059
25 Jun	2.106
26 Jun	1.541
27 Jun	2.884
28 Jun	2.787
29 Jun	1.216
30 Jun	0.725

Table 13: Step 2 of worked example

Summing these nine values gives 13.17; dividing by 9 gives 13.17 ÷ 9 = 1.46°C, the office-hours mean ΔT reported in Table 12. In plain terms, Section 3.1 was warmer than the reference during working hours on every one of the nine days: by as little as 0.4°C on 23 June and by almost 2.9°C on 27 June, the hottest part of the week.

Step 3: the Wilcoxon p-value tests whether the nine office-hours means (from Step 2) are reliably different from zero. For each day, the table below shows the average temperature behind Section 3.1's planting and at the reference location during office hours, and the difference between them (ΔT). The days are then ranked by the size of that difference, ignoring whether it is positive or negative:

Date	Section 3.1 (°C)	Reference (°C)	ΔT (°C)	Rank	Sign
23 Jun	29.98	29.59	+0.387	1	+
22 Jun	29.56	29.10	+0.466	2	+
30 Jun	28.72	27.99	+0.725	3	+
24 Jun	32.34	31.28	+1.059	4	+
29 Jun	29.09	27.88	+1.216	5	+
26 Jun	34.36	32.82	+1.541	6	+
25 Jun	32.83	30.73	+2.106	7	+
28 Jun	33.95	31.17	+2.787	8	+
27 Jun	34.58	31.70	+2.884	9	+

Table 14: Step 3 of worked example

What Table 14 shows. Each row is one day of the summer week. The second and third columns are the average temperatures during office hours behind Section 3.1's planting and at the bare reference location; the fourth is the difference between them. Section 3.1 was warmer than the reference on every day, from about 0.4°C warmer on 23 June to almost 2.9°C warmer on 27 June, one of the hottest days of the week (about 34.6°C behind the planting against 31.7°C at the reference). The Rank column simply orders the days from the smallest difference to the largest, which is the first step of the Wilcoxon test.

All nine days are positive, so the rank sum on the positive side is 1+2+...+9 = 45, and the rank sum on the negative side is 0. The test statistic W is the smaller of these two sums, W = 0 — the most one-sided result possible for nine paired values.

The exact p-value is obtained by considering every possible way nine independent positive/negative signs could have occurred by chance ($2^9 = 512$ equally likely combinations under the null hypothesis of no real effect), and counting how many of those 512 combinations are at least as one-sided as the observed result. Only two combinations qualify — all nine days positive, or all nine days negative — giving p = 2 ÷ 512 = 0.0039, which rounds to the p = 0.004 reported in Table 12. This exact enumeration, rather than a formula-based approximation, is appropriate given the small sample size (Wilcoxon, 1945).

In plain terms: if Section 3.1 made no real difference, it would be expected to be warmer than the reference on some days and cooler on others, more or less at random. Instead, it was warmer on all nine days, and the chance of that happening by luck alone is only about 4 in 1,000. This is why the result is treated as a real, if unfavourable, effect.

Step 4: the final column, corr(ΔT, WS5.7), checks whether Section 3.1's departure from the reference simply tracks how hot or cold it was outside that day, using a Spearman rank correlation between the full series of 15-minute ΔT readings and the concurrent ambient temperature at Weather Station 5.7 (n = 863

paired readings). Unlike Steps 1–3, this check uses all hours of the day rather than office hours only. Each series is first converted to ranks (1st coolest to 863rd coolest), and for every timestamp the difference between the two ranks (d) is recorded and squared:

Time	ΔT	ΔT rank	WS5.7	WS5.7 rank	d	d²
00:15	3.0	550.5	21.7°C	286.0	264.5	69,960
00:30	3.0	605.5	21.5°C	272.0	333.5	111,222
00:45	2.9	533.5	21.3°C	254.5	279.0	77,841

Table 15: Step 4 of worked example

Summing d^2 across all 863 paired readings (not just the three shown above) gives $\Sigma d^2 = 111,857,104$. This total is then substituted into the Spearman formula:

$\rho = 1 - [6\Sigma d^2 \div n(n^2 - 1)]$

With $n = 863$: $\rho = 1 - [(6 \times 111,857,104) \div (863 \times (863^2 - 1))] = 1 - [671,142,624 \div 642,734,784] = 1 - 1.044 = -0.044$, which rounds to the −0.04 reported in Table 12.

A value this close to zero indicates the two rankings are essentially unrelated: Section 3.1's ΔT is not simply mirroring the ambient weather, so the unfavourable summer result identified in Steps 1–2 reflects a genuine, section-specific effect rather than an artefact of a particularly hot or cold day within the sampling window.

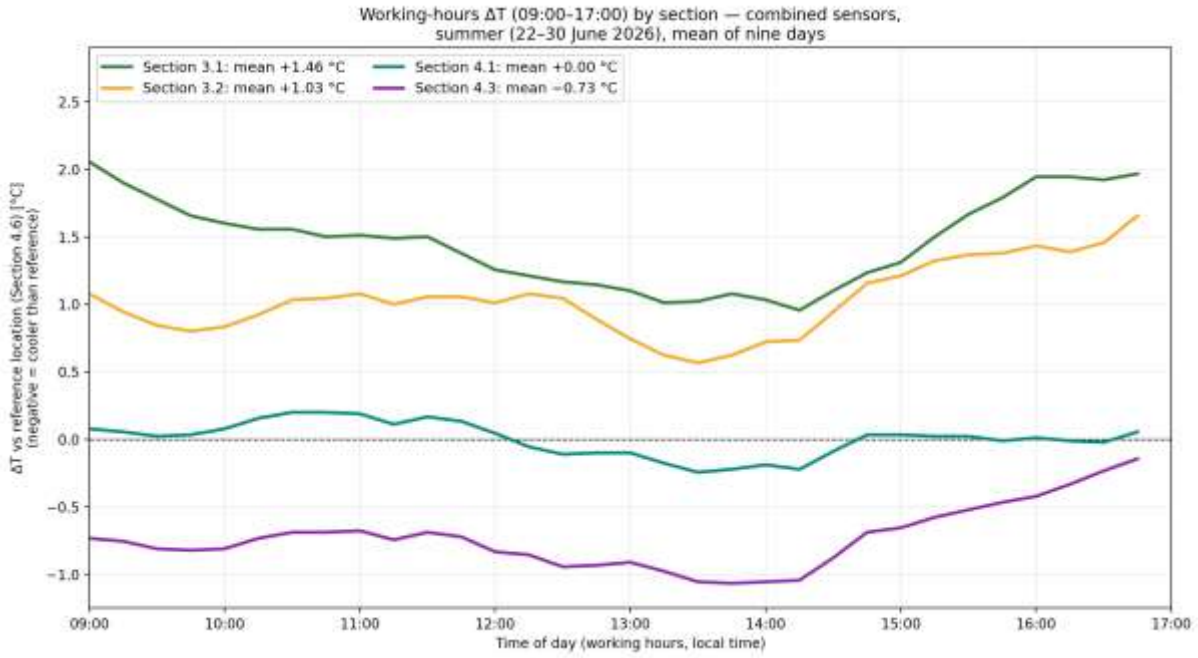


Figure 16: Working-hours (09:00–17:00) thermal behaviour relative to the reference location (ΔT = section behind-vegetation probe − Section 4.6 behind-position probe) by section, summer representative week, CEG combined-sensor data. Positive ΔT = section warmer than reference; negative ΔT = section cooler than reference.

7.3.3 Cross-Section Rank Comparison (Summer)

With the analysis restricted to the summer window (Section 7.3.1), this subsection compares the four sections' ranked performance directly, to establish whether the framework's central claim — that façade sections can be meaningfully ranked by measured thermal performance — holds against real data.

Only Section 4.3 shows a statistically significant favourable result during office hours: 0.73°C cooler than the reference ($p = 0.020$). Section 4.1 shows no significant difference from the reference ($p = 0.734$). Sections 3.1 and 3.2 both run significantly warmer than the reference ($p = 0.004$ and $p = 0.008$), which is unfavourable in summer. This means that, of the four sections analysed, only one shows a confirmed cooling benefit during working hours; the remaining three either show no confirmed effect or a confirmed unfavourable effect.

Scope and status of this analysis. This is a genuine cross-section rank comparison of the thermal pillar against a defined reference condition for the summer window: four vegetated sections are compared against the reference location on measured data, using a consistent, corrected indicator definition. Two limitations remain and are carried into the Discussion. First, this analysis covers the thermal pillar only — the acoustic, air-quality and biodiversity pillars are not addressed by these temperature-probe exports and remain at the status described in Sections 6.6–6.8. Second, with only four sections and a single nine-day window, the sample is small, which limits how confidently these section-level results can be generalised to typology-level claims (Section 7.3.5) or to conditions outside this specific summer extreme.

Winter data was originally collected in parallel (3–11 January 2026) but is excluded from this analysis. At the time of the winter measurement window, the climbing façade vegetation had not yet established sufficient canopy coverage following its first growing season, so any thermal signal recorded during that period would reflect an immature, partially bare support structure rather than a representative winter condition for an established green façade. This is consistent with the project's published planning, which places the installation of the façades in summer 2025 and the start of data collection in September 2025 (TU Delft Campus, n.d.): the January 2026 window therefore fell only a few months after planting, before the vegetation could have reached full coverage. Reporting that data alongside the summer results risked implying a seasonal comparison the underlying vegetation state could not actually support. This is treated as a scope limitation of the present analysis (Discussion, Methodological Limitations) rather than a finding in its own right, and winter-season validation, once the vegetation has matured through at least one further growing season, is identified as a priority direction for future work (Recommendations).

7.3.4 Composite Score Analysis and Sensitivity Check (Thermal Pillar)

This subsection carries out Steps 3 and 4 of the process specified in Table 11 — composite score analysis and ±20% weight-perturbation sensitivity check — which are distinct from the per-pillar indicator analysis in Sections 7.3.1–7.3.3. Those sections establish what the measured thermal indicator itself shows; this subsection instead runs the thesis's own framework — normalisation, stakeholder weighting, and aggregation, as specified in Section 7.3 — on that measured indicator, and asks whether the resulting composite score behaves as intended. This tests the framework's own output, not only the raw

measurement; genuine statistical validation of the framework, as distinct from this analysis, remains future work (Recommendations).

Step 3 — Composite score. Each vegetated section's summer office-hours mean ΔT (Section 7.3.1) is min–max normalised to a 0–1 scale, such that the best-performing section scores 1 and the worst scores 0 (Ascione et al., 2020), then multiplied by each stakeholder's thermal-pillar weight from Table 3a to give a partial composite score. This is a partial rather than full composite, since the acoustic, air quality and biodiversity pillars do not yet have section-level sensor data (Sections 6.6–6.8) and are therefore not included here. Section 2.3 (Living Wall) is added as a fifth row using its combined-sensor office-hours mean ΔT (+0.33°C, Section 7.3.6); this lies within the range of the other four sections, so their normalised scores are unchanged. Because the Living Wall sections are measured at probe position 1 rather than position 2, and because the dedicated sensors place Section 2.3 far lower (−2.72°C, Section 7.3.5), the Section 2.3 row should be read as instrument-dependent.

Partial (thermal-only) composite score by stakeholder profile and section, summer:

Section	Green Façade Specialist	Landscape Architect/Planner	Building Occupant	Urban Ecologist
Section 3.1	0.000	0.000	0.000	0.000
Section 3.2	0.088	0.046	0.089	0.060
Section 4.1	0.299	0.154	0.300	0.205
Section 4.3	0.449	0.232	0.451	0.308
Section 2.3 (Living Wall)	0.232	0.120	0.233	0.159

Table 16: Summer score

Interpretation. Because the thermal pillar is currently the only pillar with section-level sensor data, the composite ranking is identical for all four stakeholder profiles: Section 4.3 ranks best for every profile, regardless of how heavily each profile weights the thermal pillar. This is an expected mathematical property, not a finding about stakeholder preferences: multiplying a single ranked indicator by any positive weight preserves its order, so a single-pillar composite cannot yet differentiate between stakeholders. Section 2.3 ranks third, after Sections 4.3 and 4.1, for every profile; with its dedicated-sensor value it would rank first, which shows how strongly the composite depends on the instrument. Genuine stakeholder-differentiated rankings — the actual purpose of the framework — will only emerge once at least one more pillar with section-level data is added, since differentiation requires combining pillars on which sections perform differently, weighted differently by different stakeholders.

Step 4 — Sensitivity check. The ±20% weight-perturbation analysis specified in Table 11 tests whether a composite ranking changes under reasonable disagreement about the elicited weights. Applied to the thermal-only composite above, perturbing any stakeholder's thermal weight by ±20% leaves every section's rank unchanged (verified numerically for all four profiles): a positive weight applied to a single indicator cannot reorder it, so this test is uninformative at the single-pillar stage and will only become a meaningful check once a second pillar is added and the two pillars can trade off against each other. A cross-seasonal robustness check — comparing this composite ranking against an equivalent winter analysis — was originally planned as a complementary sensitivity check, but is not available in this version of the report because winter data collection coincided with immature façade vegetation (Section

7.3.3); this check is identified as a priority for future work once a winter dataset from an established façade is available (Recommendations).

Status. This subsection demonstrates that the framework's own normalisation, weighting and aggregation machinery (Steps 3–4) runs correctly on real measured data, which is a necessary and previously missing piece of the analysis this thesis provides. What it does not yet show is stakeholder-differentiated output, which requires the acoustic, air-quality and biodiversity pillars to be populated with section-level sensor data (Sections 6.6–6.8) and, ideally, a larger sample of sections and monitoring windows than the five sections and single nine-day week used here. Completing this, together with winter-season and full statistical validation of the framework, is set out as the top priority in the Recommendations.

7.3.5 Three-Way Typology Comparison: Evergreen, Deciduous, and Living Wall (Summer)

This subsection reports a typology-level comparison — Evergreen, Deciduous, and Living Wall, each benchmarked against the unshaded reference location, for the summer window and restricted to working hours (09:00–17:00), as in Sections 7.3.1–7.3.4 — using one representative section per typology (3.1, 3.2, and 2.3 respectively) instrumented with dedicated, single-channel temperature sensors, distinct from the combined CO_2/temperature/humidity sensors used for the four-section analysis in Sections 7.3.1–7.3.4. This dedicated-sensor dataset is treated as the primary basis for the typology-level ratings in Table 3b, since it instruments all three typologies directly rather than requiring the Living Wall typology to be inferred from sections outside the original four-section CO_2-sensor analysis; the corresponding result using the combined CO_2 sensors, averaged across the full section groups per typology, is reported as a cross-check in Section 7.3.6. Winter data is excluded from this comparison for the reasons stated in Section 7.3.3 and revisited in the Discussion and Recommendations.

Method note. Table 17's figures are calculated by the identical procedure set out in the worked example following Table 12 — raw 15-minute ΔT readings averaged to nine daily means, then tested with a Wilcoxon signed-rank test — applied here to the dedicated temperature sensor rather than the combined CO_2/temperature/humidity sensor, and to the same office hours (09:00–17:00, 32 readings per day). For Evergreen (Section 3.1), for example, the nine daily ΔT means (22–30 June) are −0.294, −0.847, −2.469, −1.788, −1.863, −0.272, −0.119, 0.256, and 0.044°C; these sum to −7.35 and average to −0.82°C, the Mean ΔT reported in Table 17. Ranking these nine values by absolute size and summing ranks by sign gives a positive-side sum of 4 against a negative-side sum of 41 (seven of the nine days are negative), producing the Wilcoxon p = 0.027 shown in the same table — a less one-sided split than Table 12's result, and therefore a less extreme p-value, but still below the 0.05 threshold.

Each typology against the reference

Typology	Working-hours mean ΔT vs. reference	Wilcoxon p	Significant?
Evergreen	−0.82°C	0.027	Yes — cooler (favourable)
Deciduous	−0.35°C	0.074	No (cooler direction)
Living Wall	−2.72°C	0.004	Yes — cooler (favourable)

Table 17: Typology against reference, working hours (Summer)

During working hours all three typologies run cooler than the reference on average. Living Wall shows by far the largest effect ($p = 0.004$) and Evergreen a smaller but significant one ($p = 0.027$), while Deciduous is cooler by only a few tenths of a degree, which is not statistically significant ($p = 0.074$).

Typologies compared directly against each other

Comparison	Mean difference	Wilcoxon p
Evergreen vs. Deciduous	−0.46°C (Evergreen cooler)	0.027
Evergreen vs. Living Wall	+1.90°C (Evergreen warmer)	0.004
Deciduous vs. Living Wall	+2.37°C (Deciduous warmer)	0.004

Table 18: Typology against each other, working hours (Summer)

Evergreen is significantly cooler than Deciduous ($p = 0.027$), and Living Wall is significantly cooler than both ($p = 0.004$ in each comparison): the three typologies form a clear order, with Living Wall first, Evergreen second and Deciduous third. Figure 17 shows that this order holds through the working day. Living Wall stays well below the reference from mid-morning onwards, with its largest gap in the early afternoon (just over 5°C at 14:00), while Evergreen and Deciduous stay close to the reference at the start and end of the day and dip below it around midday. A likely reason for the Living Wall's larger effect is its greater mass, because its panels hold growing medium and water, which lets it provide cooling more readily than the thinner climbing plants; this is discussed in Section 8.1.

Taken together, Living Wall shows the strongest summer thermal benefit of the three typologies during working hours and is significantly cooler than both climbing typologies directly. Evergreen shows a smaller but significant cooling effect, and Deciduous a cooler direction that is not statistically confirmed. This pattern should be read together with the section-level findings in Sections 7.3.1 and 7.3.3, which use a different instrument and probe position and find Sections 3.1 and 3.2 warmer than the reference, the limitations stated there, and the exclusion of winter data discussed above — particularly the fact that each typology here is represented by a single instrumented section rather than the multi-section groups used in Sections 7.3.1–7.3.4, and that this comparison currently reflects one season only.

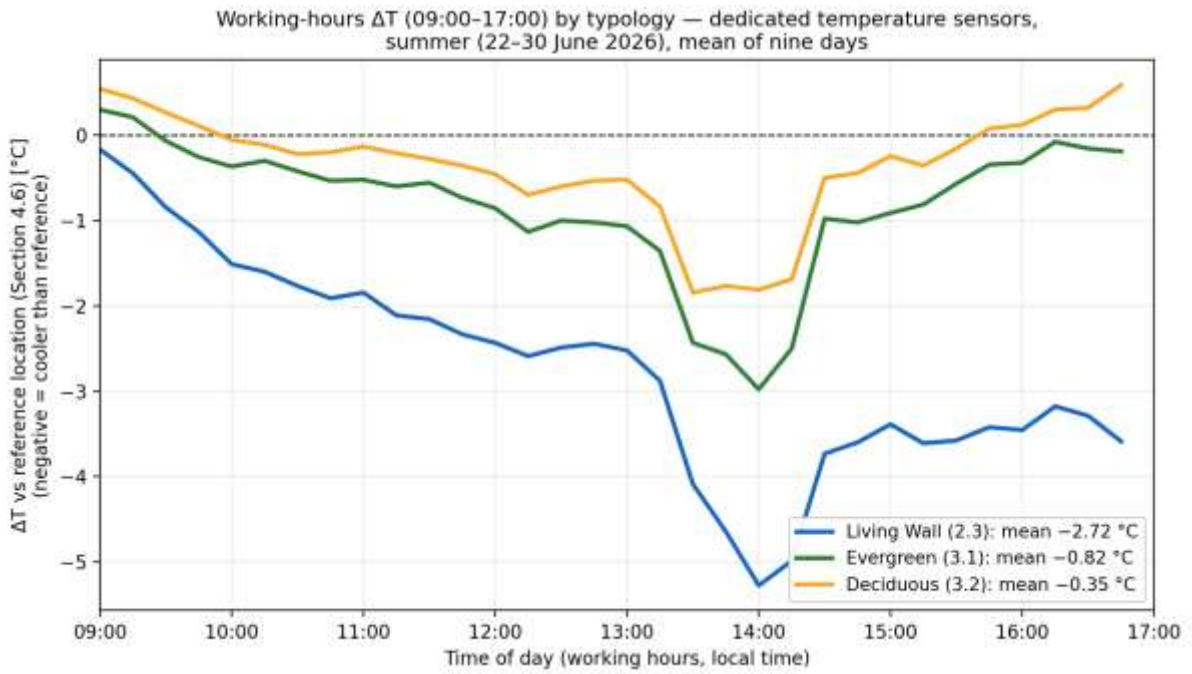


Figure 17: Working-hours (09:00–17:00) ΔT pattern by typology, dedicated temperature sensors, summer (22–30 June 2026). Positive ΔT = section warmer than reference; negative ΔT = section cooler than reference.

7.3.6 Cross-Check Using the Combined-Sensor Dataset, Full Section Groups (Summer)

As a cross-check on Section 7.3.5's primary, single-section-per-typology result, the same three typologies are compared here, over the same working hours (09:00–17:00), using the original combined CO_2/temperature/humidity sensors, averaged across the full section groups defined in Appendix A: Evergreen as the mean of Sections 3.1, 4.1 and 4.3; Deciduous as Section 3.2 alone; and Living Wall as the mean of Sections 2.3 and 3.3. This is the same dataset and grouping used in Sections 7.3.1–7.3.4.

Typology	**Mean ΔT vs. reference**	**Wilcoxon p**	**Significant?**
Evergreen (3.1, 4.1, 4.3 mean)	+0.24°C	0.359	No
Deciduous (3.2)	+1.03°C	0.008	Yes — warmer (unfavourable)
Living Wall (2.3, 3.3 mean)	−0.57°C	0.020	Yes — cooler (favourable)

Table 19: Typology against reference, combined sensors, full section groups (Summer, working hours)

This cross-check agrees with Section 7.3.5 on the typology ranking — Living Wall most favourable, Deciduous least — and on the Living Wall result itself, which runs significantly cooler than the reference in both datasets ($p = 0.004$ and $p = 0.020$). It does not agree on the climbing typologies. The dedicated sensors find Evergreen significantly cooler than the reference and Deciduous cooler but not significantly; the combined sensors find Evergreen about level with the reference (+0.24°C, $p = 0.359$) and Deciduous significantly warmer (+1.03°C, $p = 0.008$). The disagreement is clearest for a single section: for Section 3.1, the combined-sensor analysis in Table 12 finds +1.46°C during working hours ($p = 0.004$), whereas the dedicated sensor finds −0.82°C ($p = 0.027$). The two instrument types also differ in probe position for

the climbing sections (position 1 for the dedicated sensors, position 2 for the combined sensors), which is one candidate explanation that has not been tested. It cannot be the whole explanation: for Section 2.3, which both instrument types measure at probe position 1, the dedicated sensor finds −2.72°C ($p = 0.004$) and the combined sensor +0.33°C ($p = 0.164$), so the Living Wall group mean of −0.57°C rests mainly on Section 3.3 (−1.47°C, $p = 0.004$). The Section 3.3 export used here is a temperature-sensor file rather than a combined-sensor file, and its instrument type should be confirmed before this cross-check is relied on. Both datasets are reported in full, side by side, rather than merged into a single number, so that a reader can see precisely where the two agree and where they do not. Reconciling the two instrument types is identified as a priority for future work (Recommendations).

8. Discussion

This chapter interprets what the framework developed in Chapters 6 and 7 means in relation to the wider literature, and reflects honestly on the limitations of the work at this stage of the research, with thermal-pillar sensor analysis complete and the remaining pillars still pending.

8.1 Interpretation of the Framework

The shift from a single fixed weighting scheme to a stakeholder-dependent one (Chapter 7) is the central methodological move of this thesis, and it changes what the composite Ecosystem Service Score actually means. Rather than a single number claiming to represent "the" performance of a VGS typology, the framework produces a family of scores, one per stakeholder profile, each reflecting a different, defensible set of professional priorities. This is a more honest representation of how a real façade would be evaluated in practice, consistent with the gap identified by Bousquet et al. (2023), but it also means the framework cannot produce a single "best typology" answer independent of who is asking. Table 3a makes this trade-off explicit rather than hiding it behind an aggregated figure, which is itself a contribution: it gives decision-makers an auditable structure rather than a black-box score, in keeping with Cook and Larsen's (2021) call for green infrastructure design to move toward explicit, process-linked, performance-based models rather than design recommendations disconnected from measurable outcomes. The real sensor evidence gathered in Sections 7.3.1 and 7.3.3 reinforces this point directly, once compared correctly against the reference location rather than within each section alone. The measured summer evidence shows that thermal performance relative to the reference is highly section-specific: of the four instrumented sections, only Section 4.3 shows a statistically significant cooling benefit (−0.73 °C during office hours, $p = 0.020$). Sections 3.1 and 3.2 run significantly warmer than the reference ($p = 0.004$ and $p = 0.008$), which is unfavourable in summer, and Section 4.1 shows no significant benefit relative to the reference ($p = 0.734$). This means the framework cannot yet claim that any single section, or by extension any typology (Section 7.3.5), reliably delivers the thermal benefit the framework's illustrative ratings assume. A single, untested thermal score would in any case have obscured this section-by-section variation; the corrected finding is one of largely absent or inconsistent benefit relative to the reference within the summer window analysed, and is revisited in the Methodological Limitations below.

A same-building precedent refines this picture further. A concurrent field study on the same CEG installation offers an important refinement to the living wall's highest rating in Table 3b, and underlines why the framework should not privilege that typology. Parmentier et al. (in preparation) found that, during the June 2026 heatwave, the living wall system achieved the largest reduction in local air temperature of the four typologies tested, but its surface temperature was not significantly different from that of automated external solar blinds, whereas the climbing green façade systems were significantly cooler than the blinds at the surface and achieved lower maximum surface temperatures than the living wall itself (31.9–32.9°C versus 36.5°C). This divergence — living wall strongest on air temperature, climbing façades strongest on surface temperature — indicates that a single rating per typology, as used in Table 3b, may obscure a real trade-off between which specific thermal indicator is prioritised. It further suggests that this thesis's own ΔT and heat flux indicators (Section 7.3.1–7.3.3), which are surface-referenced, may be more favourable to the climbing façade typologies than an air-temperature-based indicator would be — a genuine, indicator-dependent sensitivity consistent with the Critical Reflection on indicator dependence discussed below.

A likely reason the living wall cools more is its greater mass. During working hours the living wall cooled the façade more than the evergreen and deciduous climbers (Section 7.3.5). A likely explanation is that the living wall carries more mass: its modular panels hold growing medium and water (the MobiPanel system has integrated irrigation; Mobilane, 2025), which gives it more material to take up heat and to evaporate water from, so it can provide cooling more readily, in a shorter period of time, than a thin layer of climbing plants. This fits the pattern in Figure 17, where the living wall's gap to the reference opens up from mid-morning, while the climbers stay close to the reference at the start and end of the day. This explanation was not tested in this study, because the mass, water content and evaporation of the panels were not measured, so it should be read as a hypothesis for future work rather than a finding.

The literature review (Sections 6.1–6.9) shows that thermal regulation has both the strongest evidence base and the most directly measurable indicator (ΔT, heat flux) of the four pillars, which is consistent with it being the most extensively studied ecosystem service for VGS generally (Perini et al., 2011; Santamouris, 2014). Acoustic performance and biodiversity, by contrast, sit at the weaker end of both the evidence base and the measurement infrastructure: acoustic measurement is acknowledged in the literature to be highly sensitive to weather conditions, and biodiversity is not measured by the CEG sensor network at all. This asymmetry across pillars is not a flaw introduced by this thesis; it reflects a genuine imbalance in how mature the underlying measurement science is for each ecosystem service, and the framework is designed to make that imbalance visible (via the analysis scope limitation in Section 7.3) rather than to paper over it with an equally weighted or equally confident treatment of all four pillars.

8.2 Methodological Limitations

Several limitations qualify the framework at this stage of the research, and together they mean it should be read as a single-case proof-of-concept rather than a tested, transferable tool. The evidential base is narrow on five axes simultaneously: one façade, on one building (the CEG building at TU Delft), in one climate (the Dutch maritime climate), at one façade orientation (west-facing), and with a very limited stakeholder sample. Because these constraints compound rather than acting independently, section-level comparisons across the three VGS typologies are internally valid for this installation, but the absolute magnitude of any pillar score — and indeed the elicited weights and indicator thresholds — should not be generalised to other buildings, orientations, climates, or stakeholder groups without further testing of the kind proposed by Castellar et al. (2021) and Enzi et al. (2026) for cross-site transferability. **The thermal result also depends on which sensor measured it.** The primary typology-level analysis (Section 7.3.5) uses a dedicated, single-channel temperature sensor at one representative section per typology; a cross-check using the original combined CO_2/temperature/humidity sensors, averaged across the full section groups per typology (Section 7.3.6), agrees on the typology ranking and on Living Wall's cooling benefit, but not on the climbing typologies: the dedicated sensors find both cooler than the reference during working hours (Evergreen significantly), whereas the combined sensors find Evergreen about level with it and Deciduous significantly warmer. This is reported as an instrument-dependent finding rather than resolved in favour of either sensor: the two datasets were not calibrated against one another, and reconciling them is identified as a priority for future work (Recommendations). **Four profiles cannot represent the diversity of real-world stakeholder preferences.** The stakeholder sample is similarly small: all four stakeholder profiles are now informed by real data — the green façade specialist and the landscape architect / urban planner each by one semi-structured interview, the urban ecologist / biodiversity expert by one completed written questionnaire following the same pairwise-comparison

protocol (Section 7.2), and the building occupant by a self-assessment completed by the author herself, disclosed explicitly as lacking independence rather than presented as a genuine third-party respondent. Two limitations follow. First, a single interview or questionnaire per profile, or a single self-assessment, cannot capture the range of views within a professional group, so each column represents one informant rather than a representative sample. Second, the building occupant column in particular lacks independence, since the author both designed the framework and supplied that profile's weights. The resulting weights should therefore be read as an illustrative, rather than a representative, sampling of stakeholder priorities, consistent with the auditable character of stakeholder-elicited MCDA weights described by Adem Esmail and Geneletti (2018).

The stakeholder set also omits much of the real decision-making chain, with consequences for the weighting outcomes. As noted in Section 7.1, the four profiles span the design–ecology–occupant axis but do not include the actors who typically commission, finance, regulate, and maintain a vertical greenery system in practice — building owners, facility managers, housing corporations, investors, municipalities, and property developers. This omission has a direct bearing on the weights, and therefore on the composite scores the framework produces. The four included profiles all have professional or personal reasons to value the environmental pillars comparatively highly, and indeed two of the four — the landscape architect / urban planner and the urban ecologist / biodiversity expert — rank Biodiversity first (Table 3a), with a third, the green façade specialist, ranking Thermal Regulation first and Biodiversity a close second. The excluded actors would plausibly introduce priorities that the current four-pillar structure does not even represent — capital and maintenance cost, asset and rental value, regulatory compliance, insurance and liability, and return on investment — and would likely weight the environmental pillars lower relative to these financial and operational concerns. Their absence therefore risks biasing the elicited weights toward the environmental end of the spectrum and, in turn, inflating the composite scores of typologies that perform well on biodiversity and thermal regulation relative to how those same typologies might score under an owner's or investor's weighting. The practical implication is that, while the current set is adequate for developing and demonstrating the framework, the specific weightings it produces should not yet be treated as a basis for real investment or procurement decisions: a framework intended to support building-scale decision-making must ultimately elicit weights from the parties who actually make those decisions. Extending the elicitation to these missing stakeholders — and, where their priorities fall outside the four ecosystem service pillars, considering whether the pillar set itself needs to be broadened — is identified as a priority for future work (Recommendations), and is a necessary step before the framework's practical applicability can be claimed beyond proof-of-concept.

The stakeholders consulted share similar professional expertise. The weights come from a few stakeholders: three professionals with related expertise in design, ecology and green façades, and one occupant perspective that is a self-assessment by the author. The pairwise questionnaire was written for this kind of respondent. Replicating this framework and this work with other stakeholders, such as owners, facility managers, financiers, regulators or residents without technical training, may therefore give different results, and would be more difficult, because those groups would need a different questionnaire and a different approach to eliciting their priorities (for example plain-language questions, extra criteria such as cost, and a different way of asking for judgements than the 1–9 pairwise scale). The elicited weights should be read as those of this group of similar experts, not as the views of stakeholders in general.

A further limitation concerns how any future divergence between the framework's literature-derived predictions and the measured sensor data (Section 7.3) should be interpreted. As this thesis's urban ecology / biodiversity stakeholder observed, such a divergence should not automatically be read as a flaw in the framework's underlying assumptions: site-specific factors — this façade's west orientation, the surrounding built context, the prevailing south-westerly wind off the North Sea, and the maturity and coverage of the vegetation at the time of measurement — all shape the observed response in ways that are difficult to predict fully from literature values alone. A related explanation is that literature-derived typology archetypes compress real variability: a "climbing evergreen" reported in a paper is not the same species mix, density, or age as the installation on the CEG building, and the difference between, for example, a fully established Hedera helix cover and a young mixed planting can be substantial from a botanical standpoint, as can variation between specimens of the same species due to growing conditions or genetic variation. This thesis therefore adopts, as its interpretive procedure for any pillar where predicted and measured rankings diverge, ruling out (a) coverage and leaf-area effects, (b) sensor placement and microclimate artefacts, and (c) seasonal timing, including the deciduous/evergreen contrast across the year, before treating the divergence as evidence of a genuine framework flaw.

The analysis procedure is bounded rather than exhaustive: as set out in Section 7.3, it deliberately uses one representative summer week rather than the full annual, one-minute-resolution dataset, and tests rank agreement via Spearman correlation rather than full inferential statistics. This is a time-appropriate choice for the thesis timeline, but the resulting analysis should be read as a first-pass plausibility check on the framework's ranking logic, not as a complete statistical characterisation of the CEG installation's annual performance. Finally, biodiversity remains outside quantitative analysis altogether: as discussed in Sections 6.8 and 7.3, the absence of biodiversity instrumentation in the CEG sensor network means one quarter of the framework's pillars is assessed only qualitatively, against the survey-based indicators reported by Madre et al. (2015) rather than continuous measurement. This limits how confidently the composite score can be interpreted for the stakeholder profiles that weight biodiversity most heavily — the landscape architect / urban planner and the urban ecologist / biodiversity expert, both of which rank Biodiversity first in Table 3a, and the green façade specialist, who ranks it a close second — relative to the building occupant, who weights it lowest of the four pillars.

8.3 Implications for Practice

For a building or facility manager deciding between VGS typologies, the practical implication of this framework is that the "right" choice depends on which ecosystem services that decision-maker's organisation actually prioritises, not on a single universal ranking. Table 3a is intended to function as a decision-support tool in that sense: a facility manager can read off the thermal-weighted column, while a policymaker can read off the air-quality-and-acoustic-weighted column, from the same underlying evidence base. This only holds, however, to the extent that the stakeholder weights are themselves defensible — which is precisely why completing the interviews (Section 7.2) and the sensor-based analysis (Section 7.3) matters for the framework's practical credibility, not only its academic completeness.

8.4 Critical Reflection

The interpretation and limitations discussed above raise five further questions that merit explicit critical reflection.

Why only four ecosystem services, and what bias does excluding stormwater introduce? Reflecting on the framework's structure, the choice to include only four ecosystem services carries a real cost. Thermal regulation, air quality, acoustic performance, and biodiversity were retained because each has both an established evidence base and a sensor-derived data source at the CEG installation (Section 6.3.1); services such as stormwater retention, wind regulation, and pollination support are applicable to VGS in principle (Perini et al., 2011) but were excluded because no corresponding sensor exists. This is a practical constraint, not a conceptual judgement that these services matter less — but it does mean the framework's composite score should not be read as a complete environmental account of the façade. A stakeholder who values stormwater management highly (for example, a water utility or a municipality managing combined sewer overflow risk) would find this framework systematically silent on a service that may matter significantly to them, which is a genuine bias introduced by the sensor-availability-driven scope rather than by an evidence-based judgement that stormwater is unimportant for vertical green façades specifically. This scope decision was independently corroborated by this thesis's urban ecology / biodiversity stakeholder, who, when asked whether the four-pillar structure represented a complete and correctly balanced picture, judged it a defensible and workable scope for an MSc thesis, recommended keeping it rather than adding further pillars at this stage, and suggested that, given limited time, depth of measurement on one or two services is preferable to shallow coverage of all four. Notably, the CEG living lab itself lists water management and the impact on health and well-being among the effects it is measuring (TU Delft Campus, n.d.), and the landscape architect respondent independently suggested adding human health and aesthetics as services (Appendix D); these are therefore the most natural candidates for extending the framework as the project’s monitoring matures.

How transferable is the framework? On transferability, a firm distinction must be drawn between the framework’s structure and its results, and the claims made for it kept correspondingly modest. The structure — four normalised indicators, stakeholder-elicited AHP weights, and weighted-additive aggregation — is generic and could in principle be applied to any VGS installation. The empirical results reported here, however, rest on the same narrow, five-axis evidential base set out under Methodological Limitations above, and that base constrains what can legitimately be claimed: every quantitative output of this thesis — the weight values, the typology performance ratings in Table 3b, and the sensor-derived indicator thresholds — is specific to this one configuration and cannot be assumed to hold at another building, orientation, or climate, or for a broader set of stakeholders. Transferring the framework to a different climate zone (for example a Mediterranean or continental climate, where the shading-driven summer cooling demonstrated in Sections 7.3.1 and 7.3.3 would likely behave differently) would require re-running the stakeholder elicitation with a larger and more representative sample and re-analysing the indicator thresholds locally, rather than reusing this thesis’s numbers directly. For these reasons, this thesis is best understood not as a general, ready-to-transfer assessment tool but as a first proof-of-concept: it demonstrates that a stakeholder-dependent ecosystem service score can be constructed and tested in principle on real sensor data for a single case, and it is that demonstration, rather than any of the specific numbers, that is offered to the wider field. Broader transferability is a hypothesis to be tested in future work across multiple buildings, orientations, climates, and stakeholder groups — not a claim this single case can support. What transfers, in short, is the method, not the output — a distinction consistent with the transferability caveats raised for comparable frameworks by Castellar et al. (2021) and Enzi et al. (2026).

Does the weighting approach introduce subjectivity? On subjectivity, weighting is, by construction, where the framework's stakeholder-dependence and its subjectivity enter simultaneously — the two cannot be separated. The Analytic Hierarchy Process was chosen specifically because it makes this subjectivity auditable rather than hidden (Saaty, 1980; Adem Esmail & Geneletti, 2018): every weight in Table 3a can be traced to a specific stakeholder rationale and, once interviews are complete, a specific pairwise judgement, rather than being presented as an objective fact about the façade. This is a deliberate design choice, not an oversight — the alternative, an objective, data-driven weighting method such as entropy weighting, would replace expert subjectivity with a different kind of arbitrariness (sensitivity to which monitoring period happens to be used, as discussed in Section 6.9), rather than removing subjectivity altogether. The ±20% sensitivity analysis specified in Section 7.3 exists precisely to test how much this unavoidable subjectivity actually matters to the final typology ranking, rather than to eliminate it.

Does the stakeholder sample's own background shape these results? One further source of subjectivity is worth stating explicitly, since it became visible only after the interviews were complete. Three of the four stakeholder profiles were elicited from respondents based in the Netherlands; the fourth (Building Occupant) is a self-assessment completed by the author, who grew up in India. The result that Biodiversity & Aesthetics was ranked the top priority by three of the four profiles, by a wide margin (Table 3a), was genuinely unexpected to the author, whose own ranking placed Thermal Regulation first, Air Quality second and Biodiversity last. Reflecting on this gap, it may say as much about differing lived relationships to environmental risk as about the ecosystem services themselves: in much of India, and in many parts of the Global South more broadly, foundational environmental conditions — reliable access to clean water, breathable air, and a bearable indoor temperature — remain everyday, unresolved concerns for large parts of the population, rather than a settled baseline that other priorities can be layered on top of. Seen from that position, biodiversity can read as a secondary concern, worth addressing once more immediate needs are met, rather than a priority of equal standing to thermal comfort. This observation is not offered as a finding about Dutch or Indian priorities as such, nor as a claim that biodiversity is objectively less important — four respondents is far too small a sample to support any claim about cultural or national preference patterns. It is offered instead as a reminder that stakeholder weights are not culturally or economically neutral: what a given stakeholder treats as urgent versus secondary is itself shaped by the environmental conditions they live with day to day. This adds a further, concrete reason — alongside the small sample size already discussed above — for treating the weights in Table 3a as illustrative of this framework's method rather than as representative of stakeholder priorities more broadly, and for prioritising a larger, more geographically diverse stakeholder sample in future work (Recommendations).

How much does the framework depend on the chosen indicators? Finally, the framework's conclusions are only as reliable as the four indicators chosen to represent each pillar. ΔT and heat flux are reasonably direct proxies for thermal performance, but insertion loss is known to be highly sensitive to wind and weather conditions (Section 6.7; Kang, 2007), PM reduction and indicative CO_2 uptake are partial proxies for air quality rather than complete accounts of pollutant capture (Section 6.6.1). Had different indicators been chosen — for example, building energy load instead of ΔT, the numerical values in Tables 3a and 3b, and potentially the typology ranking itself, could differ. This indicator-dependence is an inherent property of any MCDA framework (Velasquez & Hester, 2013) rather than a flaw specific to

this one, but it means the framework's outputs should be read as conditional on the specific indicator choices documented in Sections 6.4–6.9, not as indicator-independent truths about façade performance.

9. Conclusions

9.1 Answers to the Sub-Research Questions and Main Research Question

This section opens the Conclusions by answering each sub-research question and the main research question directly and explicitly, before the fuller narrative conclusion below.

Each sub-research question is answered directly below, drawing on the completed literature review and methodology (SQ1–SQ2), the stakeholder-weighting results (SQ3, Section 7.2), and the sensor-based analysis (SQ4–SQ5, Sections 7.3.1–7.3.3). The main research question is answered afterward.

Sub-Research Question 1: *"How can a vertical green facade system be characterized, and what environmental data are required to comprehensively assess its ecosystem service performance?"*

Answer: A vertical green facade is characterized by its typology (climbing evergreen, climbing deciduous, or living wall), façade orientation, and sensor placement (Perini et al., 2011; Manso & Castro-Gomes, 2015). Comprehensive assessment requires continuous data across four domains — thermal (ΔT, heat flux), acoustic (insertion loss), air quality (PM concentration, indicative CO_2 uptake), and biodiversity— with the first three obtainable from continuous sensor monitoring and the fourth requiring periodic manual visual survey, since it is not covered by the CEG sensor network (Section 6.8; Madre et al., 2015).

Sub-Research Question 2: *"How can environmental data be processed and converted into reliable indicators that quantify the ecosystem services of a vertical green facade?"*

Answer: Raw sensor measurements are converted into four pillar-specific indicators — surface temperature differential and heat flux for thermal regulation (Susorova et al., 2013), insertion loss for acoustic performance (Wong et al., 2010), particulate matter concentration reduction and indicative CO_2 uptake for air quality (Nowak et al., 2006) — each normalised to a common 0–1 scale using min–max normalisation prior to aggregation (Ascione et al., 2020).

Sub-Research Question 3: *"How can ecosystem service indicators be standardized and integrated into a multi-criteria decision-making framework, using stakeholder-dependent weighting derived from literature and expert interviews, to evaluate the overall performance of a vertical green facade?"*

Answer: Partially answered. Indicators are standardised via min–max normalisation and integrated via weighted-additive aggregation (Velasquez & Hester, 2013), using stakeholder-dependent weights derived from semi-structured interviews with two role-based stakeholder profiles, a written questionnaire with a third, and a self-assessment for a fourth, consistent with the auditable-weighting approach recommended by Adem Esmail and Geneletti (2018) and Bousquet et al. (2023) (Section 7.1, Table 3a). This answer is substantively complete: the interview- and questionnaire-derived weights for three profiles and the self-assessed weights for the fourth are reported in Section 7.2 and Table 3a.

Sub-Research Question 4: *"How can the multi-criteria framework be validated against experimental data collected from the CEG vertical green façade, and to what extent does this validation confirm the reliability and robustness under real operational conditions?"*

Answer: Cross-section analysis has now been completed using one representative summer week of real CEG sensor data, deliberately chosen to bracket the site's most extreme recorded summer conditions: 22–30 June 2026. A parallel winter week (3–11 January 2026) was also collected but is excluded from this analysis, since the façade vegetation had not yet established sufficient canopy coverage during that period (Section 7.3.3); winter-season analysis is identified as a priority for future work (Recommendations). Using an identical reference-based ΔT indicator across four vegetated sections benchmarked against the reference location (Section 4.6), the thermal pillar's ranking claim is answered at section level for summer, and the result is more modest than initially expected: only one section (4.3) shows a statistically significant cooling benefit, one (4.1) shows no significant effect, and two (3.1, 3.2) show a significant unfavourable effect with the combined sensors (Sections 7.3.1 and 7.3.3), although the dedicated sensors at the same sections point the other way (Section 7.3.6). One step remains before this becomes a full four-pillar result: extending the analysis to the acoustic, air-quality and biodiversity pillars, for which no sensor exports were available. The section-to-typology key is confirmed (Appendix A) and the resulting typology-level comparison is reported in Section 7.3.5. The analysis procedure itself has now been run in full on the thermal pillar — normalisation, composite-score aggregation per stakeholder profile, and a sensitivity check (Section 7.3.4) — following the general precedent of testing vegetated-envelope models against field data (Tabares-Velasco et al., 2012; Cook & Larsen, 2021); this composite step is what distinguishes framework testing from the per-indicator data analysis in Sections 7.3.1 and 7.3.3, though it cannot yet produce stakeholder-differentiated rankings until a second pillar is populated (Section 7.3.4). Genuine statistical validation of the framework, as distinct from this analysis, remains future work.

Sub-Research Question 5: *"How can the developed evaluation framework be used to interpret ecosystem service performance, identify trade-offs and synergies, and support decision-making for vertical green facades?"*

Answer: The interpretive mechanism is specified: Table 3a allows a decision-maker to read the stakeholder-weighted composite score relevant to their own priorities directly, a function that Cook and Larsen (2021) identify as generally missing from existing green-infrastructure design guidance. Within the thermal pillar, the corrected cross-section analysis (Section 7.3.3) shows that thermal benefit relative to the reference is section-specific, and for the climbing typologies depends on which instrument measured it, rather than being a property a section reliably carries into the composite score: only one of the four sections (4.3) shows a significant cooling benefit in the summer working hours analysed, and for the climbing typologies the two sensor types disagree on whether they run cooler or warmer than the reference (Sections 7.3.5 and 7.3.6), so a decision-maker reading the thermal component of Tables 3a and 3b should treat the typology ranking as more reliable than the size of any single benefit. Whether the missing benefit in most sections reflects a genuinely weak thermal effect at this installation or a difference between instruments cannot yet be distinguished with only four sections and one summer week (Section 7.3.3), and the winter question is identified as a priority for the extended analysis proposed in the Recommendations. The remaining cross-pillar trade-offs depend on the acoustic, air-quality and biodiversity indicator data, which are not yet available.

Main Research Question — A stakeholder-dependent ecosystem service assessment framework for vertical greenery systems has been developed by combining four literature-grounded pillars into an auditable, stakeholder-weighted structure (Table 3a), with weights elicited from four stakeholder profiles (Section 7.2), and has been applied to real sensor-derived thermal indicators across four vegetated façade

sections benchmarked against a reference location, and one summer week (Sections 7.3.1–7.3.6). This answer concerns the framework's development and application, in line with the rephrased main research question (Chapter 4), rather than a claim about VGS performance itself; it is preliminary because analysis currently covers the thermal pillar only, at both section and typology level (Sections 7.3.1–7.3.5), pending sensor data for the acoustic, air-quality and biodiversity pillars (SQ4).

This thesis has developed the conceptual and methodological foundation for an integrated, multi-criteria ecosystem service assessment framework for the Vertical Green Façade installed on the CEG building at TU Delft. At this stage of the research — with the thermal pillar now analysed against one seasonal extreme of real sensor data (Sections 7.3.1–7.3.4), and the acoustic, air-quality and biodiversity pillars still pending sensor-based validation — the following conclusions can be drawn from the literature review, problem statement, and framework development presented above.

As set out in the research gaps (Section 3.1) and the framework rationale (Section 7.1), the literature establishes that VGS ecosystem services are almost always evaluated in isolation, and that MCDA applications to urban green infrastructure rarely involve stakeholders in the weighting phase despite evidence that stakeholder groups value these services differently (Bousquet et al., 2023). This thesis's response — a stakeholder-dependent weighting scheme elicited from four role-based profiles rather than a single fixed split — is developed in Chapter 7 and is not re-argued here.

The relational framework tables (Tables 3a and 3b) connecting VGS typology, the four ecosystem service pillars, and stakeholder weighting are the thesis's core deliverable, and provide an auditable structure that has now been analysed against continuous CEG sensor data for the thermal pillar, with validation of the remaining pillars identified as future work (Recommendations). The Discussion chapter reflects on what the framework can and cannot claim at this stage — its single-building scope, its small stakeholder sample, and biodiversity remaining outside quantitative analysis — limitations also noted by Bakker-den Hartog et al. (2025) for MCDA-based VGS assessments conducted without continuous multi-parameter monitoring.

These conclusions are necessarily preliminary, and their scope must be stated plainly. As set out in full under Methodological Limitations and Critical Reflection (Discussion), this thesis is a single-case proof-of-concept, bounded by five compounding constraints that mean the specific weights, ratings, and thresholds reported here are not presented as generally applicable; establishing transferability is a task for future work, requiring re-application and re-validation across multiple contexts (Castellar et al., 2021; Enzi et al., 2026). What this thesis offers the wider field is therefore the method and the demonstration that it works for one case, not a tested, ready-to-transfer tool. The central empirical contribution — analysing the stakeholder-weighted framework against real, continuously monitored, sensor-derived data — has now been carried out for the thermal pillar (Sections 7.3.1–7.3.4); extending this analysis to the acoustic, air-quality and biodiversity pillars remains outstanding and is addressed in the Recommendations below.

9.2 Key Findings

- **A stakeholder-dependent, rather than fixed, weighting scheme is both feasible and defensible:** it moves beyond the fragmented, single-service way most existing studies evaluate green façade performance, and integrates thermal, air quality, acoustic, and biodiversity indicators into one auditable, stakeholder-weighted structure (Table 3a).

- **A confirmed summer cooling benefit is section-specific, not universal:** across four vegetated sections benchmarked against the reference location in the summer window analysed, only one section (4.3) shows a statistically significant cooling benefit; one section (4.1) shows no significant effect, and two sections (3.1, 3.2) show a significant unfavourable effect with the combined sensors, although the dedicated sensors at the same sections point the other way (Section 7.3.6). This means the thermal pillar's literature-derived rating in Table 3a cannot yet be taken as established uniformly across sections, and the seasonal question — whether any section also delivers a winter benefit — remains open, since winter data was excluded from this analysis (Section 7.3.3) and is identified as a priority for future work.
- **Biodiversity is explicitly identified as the weakest-instrumented pillar:** one of the four pillars in this framework, without a continuous sensor source at the CEG installation, and is therefore assessed only qualitatively against literature-derived scores rather than the sensor-based procedure used for the other three pillars — a limitation stated explicitly rather than absorbed silently into the composite score.
- **Thermal-pillar analysis is complete at section level; typology labelling and the other pillars remain open:** the framework's central ranking claim has now been tested for the thermal pillar across four vegetated sections benchmarked against the reference location over one summer week; only one of the four (Section 4.3) shows a statistically significant cooling benefit, one (4.1) shows no significant effect, and two (3.1 and 3.2) run significantly warmer than the reference. The section-to-typology key is confirmed (Appendix A), and the resulting typology-level comparison is reported in Section 7.3.5. Two steps remain before this becomes a full four-pillar result: extending analysis to the acoustic, air-quality and biodiversity pillars, for which no sensor exports were available at the time of writing, and extending the sample beyond four sections and a single nine-day summer window, including a winter window from an established façade, so that seasonal consistency can be tested with adequate statistical power.
- **A cross-check with the original sensors confirms the ranking and the Living Wall result, but not the climbing typologies:** the primary typology-level analysis (Section 7.3.5), using a dedicated temperature sensor at one representative section per typology during working hours (09:00–17:00), finds all three typologies cooler than the reference, with Living Wall by far the most (−2.72°C, $p = 0.004$), Evergreen less but significantly (−0.82°C, $p = 0.027$) and Deciduous not significantly (−0.35°C, $p = 0.074$); a cross-check using the original combined sensors, averaged across the full section groups (Section 7.3.6), agrees on the ranking and on Living Wall (−0.57°C, $p = 0.020$) but finds Evergreen about level with the reference (+0.24°C, $p = 0.359$) and Deciduous significantly warmer (+1.03°C, $p = 0.008$). This is treated as an instrument-dependent finding rather than resolved in favour of either sensor (Discussion).
- **The framework's own limitations —** excluding stormwater retention and other sensor-uncovered services, resting on a narrow single-case base (one façade, one building, one climate, one orientation, and a very limited stakeholder sample), and depending on the specific indicators chosen (ΔT, insertion loss, PM/CO_2) — are stated explicitly in the Discussion rather than implied. For these reasons the framework is presented as a first proof-of-concept requiring testing and validation in other contexts before any broader transferability can be claimed, consistent with the framework's own auditability principle.

10. Recommendations

Following directly from the key findings above, this section sets out the future outlook for this research: what remains to be completed within this thesis, and what extensions are recommended for work beyond it. Based on the framework development and stakeholder-weighting approach presented in this draft, the following recommendations are made for the remaining phase of this research and for future work in this area.

For the remaining phase of this research, the priority is to complete the sensor-based analysis rather than to add stakeholders: the four stakeholder weightings in Table 3a are already elicited (Section 7.2), so the outstanding work is to apply them to the measured data. The stakeholder-dependent weighting scheme should next be applied to the remaining pillars, using the continuous, multi-parameter sensor monitoring data from the CEG green façade using the staged analysis procedure set out in Section 7.3 and Table 11 of this report, and the ±20% weight-perturbation sensitivity analysis should be conducted separately for each of the four stakeholder profiles to assess whether the relative ranking of VGS typologies (climbing evergreen, climbing deciduous, living wall) is robust to reasonable variation in the elicited weights, following the sensitivity-testing practice recommended by Bousquet et al. (2023). Where the analysis stage reveals that a stakeholder's elicited ranking does not match the measured typology performance, this discrepancy should be reported and discussed explicitly rather than silently adjusted, since such discrepancies are themselves an informative finding about how professional priorities relate to measured evidence.

Completing the remaining ecosystem-service pillars in the same cross-section format. The cross-section analysis completed here (Section 7.3) covers the thermal pillar only, because the sensor export available for this analysis consisted of paired temperature probes. To bring the acoustic, air-quality and carbon pillars to the same level of analysis, the same four vegetated sections (3.1, 3.2, 4.1 and 4.3), benchmarked against the reference location (Section 4.6) should be analysed over the same summer week using the corresponding sensor channels: CO_2 and PM2.5/PM10 for the Air Quality & Carbon pillar, environmental noise (dB) for the Acoustic pillar, and heat flux to complement ΔT on the thermal pillar. Each pillar can then be ranked across sections and tested with the identical Spearman procedure, so that the composite Ecosystem Service Score ranking is tested on measured data across three of the four pillars rather than one. The section-to-typology key held in the project sensor-network documentation has been confirmed and is recorded in Appendix A, so that the measured section ranking can be translated directly into the climbing-evergreen, climbing-deciduous and living-wall ranking claimed in Table 3b without any further assumption.

- **Reconcile the two temperature-sensor types before drawing a final thermal verdict.** The dedicated temperature sensors used for the primary typology-level analysis (Section 7.3.5) and the combined CO_2/temperature/humidity sensors used for the cross-check (Section 7.3.6) agree on typology ranking and on the Living Wall result, but disagree on whether the climbing typologies run cooler or warmer than the reference. Before the thermal pillar's rating is treated as final, the two instrument types should be co-located and cross-calibrated at a subset of sections, so that any systematic offset between them can be quantified and corrected, rather than carried forward as an unexplained discrepancy. Until this is done, the Living Wall result and the typology ranking can be read as consistent across two independent instruments, but the thermal rating of the two climbing

typologies should be read as provisional. The probe position used for the climbing sections (position 1 for the dedicated sensors, position 2 for the combined sensors) is a first candidate to test.

- **Plan the next analysis steps against the CEG living lab's published timeline and outputs.** The project's planning foresees data collection until the end of 2027, an open database of measurement data with design tools and educational material, and evaluation and publication of results in the first quarter of 2028 (TU Delft Campus, n.d.; FaçadeWorld, 2026). A full annual cycle, a winter window from an established façade, and the acoustic, air-quality and biodiversity pillars can therefore be analysed within this timeline, and the framework's section- and typology-level outputs should be prepared in a form that can be compared with, or fed into, the project's planned catalogue for primarily existing buildings.
- **Reuse the framework and the analysis method in future student projects.** The framework (the pairwise weighting questionnaire, the AHP calculation and Tables 3a and 3b) and the data-analysis method (ΔT against a bare reference, daily means over working hours, and the Wilcoxon signed-rank test) are set out step by step with worked examples, so students who continue this project can repeat them on new sensor data, new sections, the remaining services (acoustic, air quality, biodiversity) or other stakeholders, and compare their results directly with those reported here. To make this easier, the questionnaire and the raw answers are kept in Appendices C and D, and the analysis scripts and cleaned sensor files should be shared together with the report.

Using the framework as stakeholder-facing decision guidance. The corrected cross-section analysis (Section 7.3.3) shows why the framework's stakeholder-specific, auditable design matters, even though the current thermal evidence is more modest than initially hoped: because thermal benefit relative to the reference is section-specific and, on the present four-section, two-week sample, does not reliably carry from one season to the other, a single fixed "best façade" answer would risk generalising from a result that is not yet established at that level of confidence. The framework's intended use — returning the stakeholder-weighted composite score relevant to a given decision-maker's priorities, with the basis of that score fully traceable — is best applied once the extended validation recommended above (more sections, more weeks, and ideally a full annual cycle) has established which sections show a reliable, season-independent benefit and which do not. Until then, it is recommended that any stakeholder-facing use of Tables 3a and 3b for the thermal pillar be presented alongside the section-level statistical results in Sections 7.3.1–7.3.3, rather than as a single settled ranking, so that a stakeholder can see not only which option the framework currently favours for them but how much confidence that recommendation currently warrants — a form of transparency about uncertainty that a single fixed-weight score would not surface either (Bousquet et al., 2023; Cook & Larsen, 2021).

For future research beyond this thesis, the stakeholder set could be extended beyond the four profiles used here to cover the wider decision-making chain involved in real VGS implementation — building owners, facility managers, housing corporations, investors, municipalities, and property developers — alongside a municipal policymaker distinct from the planner, or a second biodiversity-focused respondent (for example an NGO representative or a species-monitoring specialist) to broaden the single urban ecology / biodiversity perspective obtained here; where these actors' priorities (for example capital and maintenance cost, asset value, or return on investment) fall outside the current four ecosystem service pillars, the pillar set itself should be reviewed for possible broadening. The framework could then be validated on additional VGS installations beyond the CEG building to test the transferability of the stakeholder-

dependent weighting approach to other Northern European climates and building typologies (Castellar et al., 2021; Enzi et al., 2026). As a direct follow-up to the scope limitation identified in Sections 6.8 and 7.3, it is recommended that the CEG facility team consider biodiversity instrumentation, such as automated acoustic or image-based species monitoring, for future addition to the sensor network, so that the Biodiversity & Aesthetics pillar can eventually be brought into the same continuous, sensor-based analysis procedure as the other three pillars rather than remaining reliant on periodic manual surveys (Madre et al., 2015). This thesis's urban ecology / biodiversity stakeholder further suggested two directions for work following on from this research: an empirically grounded, typology- and species-specific view of which plant assemblages actually deliver the best combined Ecosystem Service Score on this façade, to directly inform future vertical-greening plant-selection choices; and a clear articulation, once validation is complete, of where the framework's assumptions are strongest and weakest, so that other cities and campuses considering adoption of the ESS framework know exactly what basis they would be building on.

It is also recommended that the framework's future cross-typology validation (Section 7.3) draw on the statistical approach used in the concurrent CEG field study by Parmentier et al. (in preparation) — a two-sided exact paired permutation test with Holm-adjusted p-values, using calendar date as a blocking factor to account for shared daily meteorological forcing — as a complementary check alongside the Spearman rank-correlation approach already adopted in this thesis, given that both studies monitor typologies on the same building under overlapping conditions.

10.1 Practical Guidance for Prospective Users of the Framework

The framework's central design choice — an auditable structure connecting VGS typology, measured ecosystem service indicators, and stakeholder-specific weighting (Tables 3a and 3b) — means different professional users are expected to read it differently, using the same underlying evidence but weighting it according to their own priorities (Bousquet et al., 2023). This section sets out, for several types of prospective user, how the framework and this thesis's findings could be applied in future projects, and what each would need to do to adapt it to their own context.

Urban ecologists and biodiversity specialists. An urban ecologist or biodiversity specialist would use the framework primarily through the Biodiversity & Aesthetics pillar (Section 6.8) and the stakeholder-weighting protocol in Section 7.2, rather than through the thermal results reported here. The AHP questionnaire structure used to elicit this thesis's urban ecology stakeholder profile (Section 7.2) can be reused directly as a template for systematically eliciting ecological priorities from colleagues or stakeholders on a future project, rather than relying on informal judgement. The clearest opportunity for this stakeholder group is extending the biodiversity indicator itself beyond the periodic manual visual survey used here toward the automated acoustic or image-based species monitoring already recommended above (Madre et al., 2015), which would let biodiversity be validated against continuous sensor data in the same way the thermal pillar now is (Section 7.3). Given that green roofs and walls are increasingly treated as delivery mechanisms for the EU Nature Restoration Regulation and Biodiversity Strategy 2030 (Enzi et al., 2026), a biodiversity specialist could also use Table 3a's auditable structure to make the ecological case for a specific VGS typology explicit and defensible in a planning or funding discussion, rather than asserting habitat benefit qualitatively.

Building and facility energy managers. A building or facility energy manager considering a VGS retrofit would use Sections 7.3.1–7.3.4 directly, but should take their central caveat seriously before committing a budget: this thesis's own corrected results show that thermal benefit relative to an unshaded reference is not universal across sections, and only one of the four sections (4.3) showed a significant cooling benefit in the summer week analysed (Section 7.3.3). The practical implication is that an energy manager should not assume any vertical greenery installation will reduce cooling or heating demand; the defensible approach, following the same logic as this thesis's own correction, is to commission a short instrumented pilot on a small façade area — with a genuine unshaded reference location included from the outset, which this thesis's original design omitted — before scaling an installation across a building, consistent with the performance-based approach to green infrastructure investment argued for by Cook and Larsen (2021) and the evidence-based treatment of urban cooling measures reviewed by Santamouris (2014). The CEG living lab is, in effect, such a pilot on an existing building, and its planned catalogue for primarily existing building types (TU Delft Campus, n.d.) is the natural place for energy managers to look for transferable results once its monitoring programme has been completed.

Building façade engineers. A building façade engineer designing the instrumentation for a future VGS installation would take away a specific, practical lesson from this thesis's own correction (Section 7.3.1): a dedicated, unshaded reference location must be designed into the sensor layout from the start, physically comparable in position to the vegetated sections it is compared against, rather than added or identified after data collection. This thesis's corrected sensor layout and reference-based comparison method (ΔT relative to a shared reference, rather than a section's own paired probe) can be reused directly as a specification for future installations, following the same validation logic applied to vegetated-envelope models by Tabares-Velasco et al. (2012) and the acoustic evaluation protocol demonstrated for VGS by Wong et al. (2010) for engineers extending the framework to the acoustic pillar.

Landscape architects and urban planners. A landscape architect or urban planner, once the acoustic, air-quality and biodiversity pillars are populated with section-level data (Recommendations, above), would use the full Tables 3a and 3b as intended: reading the composite score under their own profile's weighting to compare typologies across all four ecosystem services simultaneously, rather than optimising for a single service. This is the specific gap in current practice identified by Bousquet et al. (2023) and Castellar et al. (2021) that the framework is designed to close, and a planner is best placed to use it at the scale it is intended for — comparing typology options for a specific site — rather than at the single-building scale demonstrated in this thesis.

Municipalities and policymakers. A municipality or policymaker would use the framework less for its specific numerical results, which this thesis has repeatedly stressed are not yet transferable beyond the CEG case (Critical Reflection, Discussion), and more as a transparent template for how green infrastructure investment decisions could be justified against multiple, explicitly weighted objectives rather than a single assumed benefit. The European Commission's practitioner handbook for evaluating nature-based solutions (European Commission, 2021) and the JRC's recent synthesis of green roof and wall implementation across Europe (Enzi et al., 2026) both call for exactly this kind of auditable, stakeholder-inclusive evidence base to support regulatory targets; this thesis's contribution is a worked, code-level demonstration of one way to build that evidence base for a single building, which a policymaker's own technical advisors could adapt to a municipal or portfolio scale.

Across all five cases, the common requirement is the same: each stakeholder group would need to either supply their own AHP-elicited weights, following the protocol in Section 7.2, or use the profiles already elicited here where their priorities are similar to one of the four existing profiles, and would need section-level or site-level sensor data for whichever pillars matter most to them. The framework's value to a new user is therefore not any specific number reported in this thesis, but the combination of a reusable elicitation protocol and a reusable analysis procedure (Sections 7.2 and 7.3) that together make a green infrastructure decision auditable rather than asserted.

10.2 Contribution to Academic Research and Practice

This thesis's contribution, introduced in the Scientific Contribution statement (Section 1.1) and revisited throughout, is summarised below as three points of academic contribution and three points of practical contribution, consistent with this thesis's auditability principle of stating its own contribution explicitly rather than leaving it implicit.

Contribution to academic research:

- **Stakeholder-dependent weighting, elicited rather than assumed.** a stakeholder-dependent AHP weighting scheme is elicited and reported for four role-based profiles (Section 7.2), rather than assumed from a single fixed or researcher-derived weighting, addressing the gap identified by Bousquet et al. (2023) that most MCDA applications to green infrastructure omit meaningful stakeholder involvement in the weighting phase.
- **The thermal pillar, analysed on data independent of the framework's own development.** the framework's literature-derived typology ratings (Table 3a) are kept independent of the CEG sensor dataset used to test them (Sections 7.3.1–7.3.4), following the calibration/validation separation recommended for comparable building-envelope performance studies (Khan, Neda'a, & Munawer, 2026), so that agreement or divergence between predicted and measured rankings is a genuine finding rather than a circular confirmation.
- **A documented, reusable correction to a common VGS field-measurement pitfall.** Sections 7.3.1–7.3.3 document a corrected reference-based thermal comparison method (section ΔT relative to a shared unshaded/shaded reference, rather than a within-section paired-probe difference), offering other VGS field studies a concrete illustration of why a dedicated reference location must be designed into a sensor layout from the outset.

Contribution to practice:

- **An auditable, stakeholder-specific decision-support structure.** Tables 3a and 3b give building owners, facility managers, and planners an auditable structure for comparing VGS typologies against the specific ecosystem services their organisation prioritises, rather than a single asserted "best" typology (Section 8.3).
- **Evidence-based caution against assuming a uniform thermal benefit.** the analysed thermal results (Section 7.3.3) show that thermal benefit is section- and typology-specific, and for the climbing typologies still instrument-dependent, rather than being a blanket property of vertical greenery, a caution directly relevant to energy managers considering a VGS retrofit (Section 10, Implications for Practice).

- **A reusable stakeholder-elicitation protocol.** the AHP elicitation protocol used in Section 7.2 is reusable as-is by other institutions or projects seeking to weight ecosystem services by stakeholder priority, without needing to redevelop the method from first principles.

References

- Adem Esmail, B., & Geneletti, D. (2018). Multi-criteria decision analysis for nature conservation: A review of 20 years of applications. Methods in Ecology and Evolution, 9(1), 42–53.
- Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment, 43(4), 480–493.
- Ascione, F., Bianco, N., De Masi, R. F., de' Rossi, F., & Vanoli, G. P. (2020). Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance. Renewable and Sustainable Energy Reviews, 109, 109780.
- Bakhshoodeh, R., Ocampo, C., & Oldham, C. (2023). Impact of ambient air temperature, orientation, and plant status on the thermal performance of green façades.
- Bakker, J., Lugten, M., & Tenpierik, M. (2023). Applying vertical greening systems to reduce traffic noise in outdoor environments: Overview of key design parameters and research methods. Building Acoustics, 30(3), 245–265.
- Bakker-den Hartog, D., Lugten, M., & Ottelé, M. (2025). Multi-criteria decision-making framework using ecosystem services for an integral design of vertical greenery systems. Urban Forestry & Urban Greening, 112, 128931.
- Bousquet, A., Pelletier, G., Brosse, V., & Bertrand-Krajewski, J.-L. (2023). A critical review of multicriteria decision analysis practices in planning of urban green spaces and nature-based solutions. Blue-Green Systems, 5(2), 200–219.
- Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and Urban Planning, 97(3), 147–155.
- Castellar, J. A. C., Popartan, L. A., Pueyo-Ros, J., Atanasova, N., Langergraber, G., Säumel, I., Corominas, L., Comas, J., & Acuña, V. (2021). Nature-based solutions in the urban context: Terminology, classification and scoring for urban challenges and ecosystem services. Science of the Total Environment, 779, 143076.
- Cook, L. M., & Larsen, T. A. (2021). Towards a performance-based approach for multifunctional green roofs: An interdisciplinary review. Building and Environment, 188, 107489.
- Enzi, V., Manso, M., Aires, A., Almalla, R., Catalano, C., Elkadi, H., Emilsson, T., Heysham, N., Kroes, S., Gedge, D., Grant, G., Ribotta, L., Spaan, K., Suonio, T., & Van Roosmalen, P. (2026). Implementing green roofs and walls: Lessons from European experiences (Vierikko, K., Orta-Ortiz, M. S., Nieminen, H., Vasilakopoulos, P., & Velasco Gomez, M., Eds.). Publications Office of the European Union, Joint Research Centre.
- European Commission. (2021). Evaluating the impact of nature-based solutions: A handbook for practitioners. European Union.
- European Environment Agency. (2023). Air quality in Europe — 2023 report. Publications Office of the European Union.
- FaçadeWorld. (2026, February 3). Living Lab TU Delft: Performance evaluation of green façade systems for new and existing buildings. FaçadeWorld. https://facadeworld.com/2026/02/03/living-lab-tu-delft-performance-evaluation-of-green-facade-systems-for-new-and-existing-buildings/

- Francis, R. A., & Lorimer, J. (2011). Urban reconciliation ecology: The potential of living roofs and walls. Journal of Environmental Management, 92(6), 1429–1437.
- Intergovernmental Panel on Climate Change. (2023). Climate Change 2023: Synthesis Report. IPCC.
- Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M., & Baret, F. (2004). Review of methods for in situ leaf area index determination. Agricultural and Forest Meteorology, 121(1–2), 19–35.
- Kang, J. (2007). Urban sound environment. Taylor & Francis.
- Khan, I.H., Neda'a, M.J., & Munawer, T. (2026). Climate-adaptive energy performance of green façades in a composite climate. Energy and Buildings, 360, 117393.
- Madre, F., Vergnes, A., Machon, N., & Clergeau, P. (2015). Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. Urban Forestry & Urban Greening, 14(3), 511–519.
- Manso, M., & Castro-Gomes, J. (2015). Green wall systems: A review of their characteristics. Renewable and Sustainable Energy Reviews, 41, 863–871.
- Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63(2), 81–97.
- Milana Radujković, Alexis Versele, & Hilde Breesch. (2024). Exploratory analysis of a novel modular green wall's impact on indoor temperature and energy consumption in residential buildings: A case study from Belgium. Energies, 17(21), 5267.
- Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Synthesis. Island Press.
- Mobilane. (2025, September 25). Green facades at TU Delft: Research with Mobilane systems [News article]. Mobilane. https://mobilane.com/en/news/green-facades-at-tu-delft-research-with-mobilane-systems/
- Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. Urban Forestry & Urban Greening, 4(3–4), 115–123.
- Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society, 108(455), 1–24.
- Ottelé, M., Perini, K., Fraaij, A. L. A., Haas, E. M., & Raiteri, R. (2010). Comparative life cycle analysis for green facades and living wall systems. Energy and Buildings, 43(12), 3419–3429.
- Ottelé, M., van Bohemen, H. D., & Fraaij, A. L. A. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. Ecological Engineering, 36(2), 154–162.
- Perini, K., Ottelé, M., Fraaij, A. L. A., Haas, E. M., & Raiteri, R. (2011). Vertical greening systems and the effect on air flow and temperature on the building envelope. Building and Environment, 46(11), 2287–2294.
- Parmentier, J. R., Ottelé, M., & van den Dobbelsteen, A. A. J. F. (in preparation). Impact of vertical greenery systems on surface and air temperature in extreme weather conditions.
- Pérez, G., Coma, J., Martorell, I., & Cabeza, L. F. (2014). Vertical Greenery Systems (VGS) for energy saving in buildings: A review. Renewable and Sustainable Energy Reviews, 39, 139–165.
- Saaty, T. L. (1980). The analytic hierarchy process: Planning, priority setting, resource allocation. McGraw-Hill.
- Saaty, T. L., & Peniwati, K. (2008). Group decision making: Drawing out and reconciling differences. RWS Publications.

- Sæbø, A., Popek, R., Nawrot, B., Hanslin, H. M., Gawrońska, H., & Gawroński, S. W. (2012). Plant species differences in particulate matter accumulation on leaf surfaces. Science of the Total Environment, 427–428, 347–354.
- Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy, 103, 682–703.
- Shannon, C. E. (1948). A mathematical theory of communication. Bell System Technical Journal, 27(3), 379–423.
- Spearman, C. (1904). The proof and measurement of association between two things. American Journal of Psychology, 15(1), 72–101.
- Susorova, I., Angulo, M., Bahrami, P., & Stephens, B. (2013). A model of vegetated exterior facades for evaluation of wall thermal performance. Energy and Buildings, 67, 1–13.
- Susorova, I., Azimi, P., Stephens, B., & Tuncer, B. (2014). The effects of climbing vegetation on the local microclimate, thermal performance, and air infiltration of building facades. Building and Environment, 76, 113–123.
- Tabares-Velasco, P. C., Zhao, M., Peterson, N., Srebric, J., & Berghage, R. (2012). Validation of predictive heat and mass transfer green roof model with extensive green roof field data. Ecological Engineering, 47, 165–173.
- TU Delft Campus. (n.d.). Innovation project: Green façade CEG. Retrieved October 4, 2026, from https://www.tudelftcampus.nl/projects/innovation-project-green-facade-citg
- Van Renterghem, T., & Botteldooren, D. (2014). In-situ measurements of sound propagating over extensive green roofs. Building and Environment, 44(4), 729–738.
- Velasquez, M., & Hester, P. T. (2013). An analysis of multi-criteria decision-making methods. International Journal of Operations Research, 10(2), 56–66.
- Wang, X., Gard, W., Borska, H., Ursem, B., & van de Kuilen, J. W. G. (2020). Vertical greenery systems: from plants to trees with self-growing interconnections.
- Wilcoxon, F. (1945). Individual comparisons by ranking methods. *Biometrics Bulletin*.
- Wong, N. H., Tan, A. Y. K., Tan, P. Y., Chiang, K., & Wong, N. C. (2010). Acoustics evaluation of vertical greenery systems for building walls. Building and Environment, 45(2), 411–420.
- World Health Organization. (2018). Environmental Noise Guidelines for the European Region. WHO Regional Office for Europe.

Appendix A: Section-to-Typology Key

This appendix records the confirmed mapping between physical sensor positions on the CEG west façade and the vertical greenery system typologies referenced throughout this report (Sections 6.3.1, 7.1–7.3.5), cross-checked against the project sensor-network documentation.

Sensor position	Typology	Evergreen / Deciduous	Role in this report
2.1 / 2.2	Reference (Reference Location 2, unshaded)	—	Reference; not a vegetated typology
2.3	Living wall system	— (evergreen perennial mix)	Analysed, summer (Sections 7.3.5 and 7.3.6)
3.1	Climbing green façade	Evergreen	Analysed (Sections 7.3.1–7.3.6)
3.2	Climbing green façade	Deciduous	Analysed (Sections 7.3.1–7.3.6)
3.3	Living wall system	— (evergreen perennial mix)	Analysed, summer, in the combined-sensor cross-check only (Section 7.3.6)
4.1	Climbing green façade	Evergreen	Analysed (Sections 7.3.1–7.3.6)
4.3	Climbing green façade	Evergreen	Analysed (Sections 7.3.1–7.3.6)
4.4	Living wall system	— (evergreen perennial mix)	No sensor export available; not analysed in this report
4.6	Reference (Reference Location 1, mechanically shaded)	—	Reference; not a vegetated typology
5.4	Living wall system	— (evergreen perennial mix)	No sensor export available; not analysed in this report

Table A1: Section-to-typology key (sensor positions, typologies and their role in this report)

Note. The Reference 1 / Reference 2 designation follows Parmentier, Ottelé, and van den Dobbelsteen (in preparation): Reference 1 (Section 4.6) is a mechanically shaded reference on the fourth floor; Reference 2 (Sections 2.1/2.2) originated as a Type A climbing-façade planting that failed to establish during the measurement period and was repurposed as an unshaded reference. The Living Wall typology is represented by Section 2.3 in the primary, dedicated-sensor analysis (Section 7.3.5) and by the mean of Sections 2.3 and 3.3 in the combined-sensor cross-check (Section 7.3.6), the two positions with usable summer temperature exports; Sections 4.4 and 5.4 belong to the same typology but have no available sensor export and are not analysed in this report. Living wall sections use an assemblage of evergreen perennial “plant mix” species rather than the eight climbing species (four evergreen, four deciduous) used across the climbing typologies, and are therefore not classified as evergreen or deciduous in the same sense.

Appendix B: Stakeholder Pairwise Comparisons and Derived Weights

This appendix gives the full pairwise comparison matrices and derived weights for the three stakeholders who were interviewed or who completed the questionnaire: the landscape architect / urban planner, the green façade specialist, and the urban ecologist / biodiversity expert. The method is the one described in Section 7.2, and the building occupant's matrix, weights and worked example are kept in the main text there. The last column of each weights table shows how those weights appear as scores in Table 3a: the highest weight scores 5, the lowest scores 1, and the other two are placed in proportion to where their weight falls between them (see Step 4 of the worked example in Section 7.2).

Landscape Architect / Urban Planner. This respondent gave numeric pairwise judgments directly (Table B1). The comparisons place Biodiversity far above the other three pillars — driven particularly by two extreme (9/9) judgments favouring Biodiversity over Air Quality and over Acoustic Performance — consistent with a landscape-scale focus on greening and biodiversity connectivity.

	Thermal	Air Quality	Acoustic	Biodiversity
Thermal	1	7	5	1/5
Air Quality	1/7	1	1/3	1/9
Acoustic	1/5	3	1	1/9
Biodiversity	5	9	9	1

Table B1: Pairwise comparison matrix — Landscape Architect / Urban Planner

Pillar	Derived weight	Rank	Score in Table 3a (1–5)
Biodiversity	0.656	1	5
Thermal Regulation	0.232	2	2.3
Acoustic Performance	0.072	3	1.2
Air Quality & Carbon	0.039	4	1

Table B2: Derived weights — Landscape Architect / Urban Planner (λ_{max} = 4.300, CI = 0.100, CR = 0.111)

This respondent's CR of 0.111 sits marginally above the 0.10 consistency threshold. This is reported explicitly rather than adjusted: the inconsistency is traceable to the combination of a strong Thermal-over-Air-Quality judgment (7) with two extreme Biodiversity judgments (9, 9) and a more moderate Thermal-versus-Biodiversity judgment (5 in favour of Biodiversity) — a pattern of strongly held but not perfectly transitive preferences that is common in real single-respondent AHP applications (Saaty, 1980) and is

treated here as a genuine finding about the strength of this respondent's biodiversity priority, not as a data error to be silently corrected.

Green Façade Specialist. This respondent answered in qualitative terms rather than direct numeric judgments (e.g. “somewhat more important,” “slightly higher priority”). To derive a comparable matrix, each qualitative judgment was mapped onto the nearest Saaty value (“somewhat/slightly” → 2–3; no clear preference stated → 1), shown in Table B3; this translation is stated explicitly here as an assumption, consistent with this thesis's auditability principle (Section 7.1).

	Thermal	Air Quality	Acoustic	Biodiversity
Thermal	1	3	3	2
Air Quality	1/3	1	1	1/2
Acoustic	1/3	1	1	1/3
Biodiversity	1/2	2	3	1

Table B3: Pairwise comparison matrix — Green Façade Specialist (qualitative judgments translated to the Saaty scale)

Pillar	Derived weight	Rank	Score in Table 3a (1–5)
Biodiversity	0.288	2	3.0
Thermal Regulation	0.449	1	5
Air Quality & Carbon	0.138	3	1.1
Acoustic Performance	0.126	4	1.0

Table B4: Derived weights — Green Façade Specialist (λ_{max} = 4.118, CI = 0.039, CR = 0.044)

This respondent's matrix is internally consistent (CR = 0.044, well below the 0.10 threshold), and the derived weights match the respondent's own stated summary ranking, given verbatim at the end of the interview response as “Thermal regulation > Biodiversity > Air quality ≈ Acoustic performance.” An earlier version of this matrix contained a transcription error in a single cell (the Thermal-versus-Biodiversity judgment was recorded as favouring Biodiversity by a factor of 2, when the respondent's answer — “I would give thermal regulation a slightly higher priority, but biodiversity should definitely remain a major component” — clearly favours Thermal instead); this has been corrected, and the matrix and derived weights shown here reflect the respondent's answer as given. All other five pairwise judgments were unaffected by this correction.

Urban Ecologist / Biodiversity Expert. This respondent gave numeric pairwise judgments directly, completed via a written questionnaire rather than a live interview (Table B5). The comparisons place Biodiversity first by a moderate-to-clear margin over each of the other three pillars, with Thermal Regulation retained as a clear second priority and Air Quality and Acoustic Performance judged roughly equal and lowest.

	Thermal	Air Quality	Acoustic	Biodiversity
Thermal	1	3	3	1/2
Air Quality	1/3	1	1	1/3
Acoustic	1/3	1	1	2/7
Biodiversity	2	3	3.5	1

Table B5: Pairwise comparison matrix — Urban Ecologist / Biodiversity Expert

Pillar	Derived weight	Rank	Score in Table 3a (1–5)
Biodiversity	0.455	1	5
Thermal Regulation	0.308	2	3.3
Air Quality & Carbon	0.121	3	1.1
Acoustic Performance	0.116	4	1

Table B6: Derived weights — Urban Ecologist / Biodiversity Expert (λ_{max} = 4.050, CI = 0.017, CR = 0.019)

This respondent's matrix is well within the consistency threshold (CR = 0.019, comfortably below 0.10), indicating strongly transitive judgments. The resulting ranking — Biodiversity > Thermal Regulation > Air Quality ≈ Acoustic Performance — is consistent with this respondent's own qualitative framing of a strong-performing façade as one that delivers a legible, year-round bundle across all four services while remaining alive and structurally sound, with species-rich planting, structural layering, a flowering-and-fruiting sequence spanning the season, and physical connectivity to the ground-level green system valued specifically under the Biodiversity pillar. On the four-pillar structure itself, this respondent endorsed it as a defensible and workable scope for an MSc thesis, recommending against adding further pillars at this stage and instead prioritising depth of measurement on one or two services over shallow coverage of all four (Critical Reflection, Discussion). On the choice of measurement parameters (Table 3a), this respondent deferred to the green façade specialist and landscape architect / urban planner panellists as better placed to comment on instrumentation specifics. On the loss of real-world information when normalising heterogeneous indicators onto a common 0–1 scale (Section 6.9), this respondent's guidance was pragmatic: to do what is most practical at this stage of the framework's development, rather than to prioritise threshold-preservation over feasibility at the cost of momentum.

Appendix C: Stakeholder Questionnaire and the Reasoning Behind It

This appendix gives the questionnaire used to elicit the stakeholder weights reported in Section 7.2 and Table 3a. The same questions were used for every stakeholder profile. The green façade specialist and the landscape architect / urban planner answered them in a semi-structured interview, the urban ecologist / biodiversity expert answered them in writing, and the author completed them herself as the building occupant self-assessment. The question wording below is taken directly from the questionnaire sent to respondents. After each question, a short note explains, in plain terms, why it was asked and how the answer was used in this thesis.

The respondents' answers are summarised in Section 7.2 and Appendix B rather than reproduced in full, and respondents are identified by professional role only, to protect their confidentiality.

Introduction given to respondents

"Thank you for taking the time to help with this. My thesis develops a way to score the environmental performance of a vertical green façade, like the one installed on the CEG building, across four different ecosystem services. Rather than deciding myself how much each service should count, I am asking people like you, who each have a different professional background/stake, to tell me how you'd personally prioritise them. Your answers, together with two others, will be used to set the weighting in the framework. This should take about 15–20 minutes. The same questions are being sent to all three of you, so your answers can be compared directly; please just answer from your own perspective and expertise; there are no right or wrong answers."

> **Why this was included:** The introduction explains the purpose of the study in everyday language and makes clear that there are no right or wrong answers. This was meant to encourage honest, personal priorities rather than answers the respondent thought the researcher wanted to hear. It also tells respondents that everyone receives the same questions, so that their answers can be compared fairly.

Background: the four ecosystem services being assessed

Ecosystem service	In plain terms	How it's measured
Thermal regulation	How much the façade cools the building in summer and insulates it in winter, compared to a bare wall.	Surface temperature difference and heat flux
Air quality	How much airborne particulate matter (dust, soot) the plants capture, plus a rough estimate of CO_2 uptake.	Particulate matter reduction; indicative CO_2 uptake
Acoustic performance	How much traffic and street noise the façade blocks or scatters before it reaches the building.	Insertion loss / noise level
Biodiversity	How much habitat the façade provides for various living species.	Visuals

Table C1: The four ecosystem services in plain terms and how each is measured

> **Why this was included:** This short table was given before any questions so that every respondent was judging the same thing. Each service is explained in plain words and linked to how it is measured on the CEG façade, so that, for example, a biodiversity expert was not guessing what "acoustic performance" meant, and vice versa.

Part 1 — Getting the overall view

Q1. In your view, what does a vertical green façade need to deliver to be considered a strong performer, across thermal, air quality, acoustic, and biodiversity aspects?

> **Why this question was asked:** This open question comes first on purpose. It lets each respondent describe, in their own words, what "good" looks like before being asked to put numbers on anything, so that their later scores are not shaped by the way the comparison questions are framed. Their answer also helps explain their scores afterwards: a respondent who describes a strong façade mainly in terms of habitat would be expected to give biodiversity a high weight.

Q2. Looking at the four ecosystem services described above, does that structure match what you would consider a complete and correctly balanced picture, or is something important missing or overweighted?

> **Why this question was asked:** This checks whether the four pillars are the right ones in the first place. If an expert felt that something important was missing (such as stormwater, maintenance or cost) or that one service was given too much room, the scope of the framework would need to be reconsidered before any weights were calculated.

Part 2 — Ranking the four ecosystem services

Instruction given to respondents: "For each pair below, please tell which one matters more to you, and by roughly how much, on a scale of 1 to 9 (1 = the two matter equally, 9 = one matters extremely more than the other). There's no need to overthink the exact number — a rough sense of 'slightly more,' 'clearly more,' or 'far more important' is enough."

Q3. Thermal regulation vs. Air quality

Q4. Thermal regulation vs. Acoustic performance

Q5. Thermal regulation vs. Biodiversity

Q6. Air quality vs. Acoustic performance

Q7. Air quality vs. Biodiversity

Q8. Acoustic performance vs. Biodiversity

> **Why these questions were asked:** These six questions are the core of the weighting. The Analytic Hierarchy Process compares every pillar with every other pillar once, and four pillars give exactly six pairs. Comparing two services at a time is easier and more reliable than asking someone to score all four at once, because people find it much easier to say "this matters more than that" than to hand out percentages. The 1–9 range is Saaty's standard AHP scale (Table 4). Respondents were told that a rough sense of "slightly", "clearly" or "far" more important was enough, so that people unfamiliar with AHP could still answer comfortably. They were also free to explain their answers in words, which made it possible to translate word-only answers onto the scale (Section 7.2) and to understand why each judgement was made.

Part 3 — Checking our measurements

Q9. Do the following measurement parameters seem like the right way to capture each ecosystem service — surface temperature/heat flux for thermal, particulate matter/CO_2 uptake for air quality, noise level for

acoustic, and the visual aspects for biodiversity — or would you prioritise a different measurement for any of them?

> **Why this question was asked:** The framework is only as good as its measurements. This question asks the experts whether each indicator actually captures the service it is meant to represent, or whether a better or more meaningful measurement exists.

Q10. Combining these four very different measurements onto one common 0–1 scale, so they can be added together into a single score, makes them comparable — but in doing so, do you think we lose meaningful real-world information? For example, whether a specific threshold has been crossed (a noise guideline, an air-quality health limit, a habitat viability threshold)?

> **Why this question was asked:** To add four very different measurements together, the framework rescales them all onto a common 0–1 scale (Section 7.3). This makes them comparable, but it can hide whether an important limit has been crossed, such as a noise guideline or an air-quality health limit. This question asks the respondents whether they see that loss of information as acceptable at this stage of the framework's development.

Part 4 — Looking ahead

Q11. If later testing against real sensor data shows a typology doesn't perform the way we'd predict for one of these services, what would that most likely tell us — a flaw in the underlying assumptions, or a genuine effect specific to this building?

> **Why this question was asked:** The framework makes predictions from the literature that are later checked against the CEG sensor data. This question prepares for the case where the two do not match, by asking the experts how such a mismatch should be read: as a flaw in the framework's assumptions, or as something specific to this building, its planting and its surroundings. Their answers help avoid over-reading a single unexpected result (Discussion).

Q12. Is there a specific finding from this research you'd want to see feed into future work on the CEG green façade, or anyone else you think should be involved?

> **Why this question was asked:** This closing question looks beyond the thesis. It asks what results would be most useful for future work on the CEG façade and who else should be involved, and so feeds directly into the Recommendations and into the discussion of which stakeholders are currently missing (Section 7.1).

Appendix D: Raw Stakeholder Questionnaire Responses

This appendix reproduces the questions and full, verbatim answers given by each of the three interviewed or questionnaired respondents (Landscape Architect / Urban Planner, Green Façade Specialist, and Urban Ecologist / Biodiversity Expert), so that the pairwise comparison matrices in Appendix B can be independently checked against their original source. The Building Occupant profile is a self-assessment by the author and is not a separate interview; it is not reproduced here. Respondent names are given, with their consent, since their professional role is already disclosed in the main text and full traceability of the stakeholder weights was judged more important than anonymisation for this appendix.

D.1 Landscape Architect / Urban Planner

Q: In your view, what does a vertical green façade need to deliver to be considered a strong performer, across thermal, air quality, acoustic, and biodiversity aspects?

A: The boundaries are not strong and it is, of course, dependent on the circumstances. However, I would consider a vertical green façade a strong performer if it reduces the direct air temperature by 10% during summer period and improves the building insulation value by 0.5 m2K/W; if it captures 20% of the airborne particulate matter and takes up 10 kg CO2 per year; It reduces the noise level by 6 dB; and it functions as a healthy stepping stone within the urban ecosystem.

Q: Looking at the four ecosystem services described above, does that structure match what you would consider a complete and correctly balanced picture, or is something important missing or overweighted?

A: For a more balanced picture, I would add the ecosystem services ‘aesthetics’ and ‘human health’. The first is in practice one of the main factors why people/architects install and design green façade systems, and the second is a very promising and important aspect of green in general. Air quality can be considered as part of ‘human health’. (Looking at the thesis timeline, this feedback was not incorporated into the main body, but used for the Recommendations.)

Q: Thermal regulation vs. Air quality

A: 7 (thermal regulation) – Thermal regulation has influence on energy usage, living/working environment, urban heat island and human health, while air quality is only a single parameter and is within the Dutch cities not a critical issue. Besides that, bad air quality has a negative impact on human health on the long run, instead of directly.

Q: Thermal regulation vs. Acoustic performance

A: 5 (thermal regulation) – Similar compared to question 3, with the difference that the acoustic performance has a direct impact on human health and living/working environment.

Q: Thermal regulation vs. Biodiversity

A: 5 (biodiversity) – Climate change is one of the major crisis we are currently facing and reducing the energy usage is very important. At this moment in the Netherlands, we are making progress in that part. The biodiversity crisis is much less known and can have a huge impact on our lives in the near future. Therefore we need to shift our focus to biodiversity.

Q: Air quality vs. Acoustic performance

A: 3 (acoustic performance). Both influence the human health, but the acoustic performance has a direct impact.

Q: Air quality vs. Biodiversity

A: 9 (Biodiversity). Combination of answer 3 and 5.

Q: Acoustic performance vs. Biodiversity

A: 9 (Biodiversity). Combination of answer 3 and 4. The difference between air quality and acoustic performance is small compared to biodiversity.

Q: Do the proposed measurement parameters seem like the right way to capture each ecosystem service, or would you prioritise a different measurement for any of them?

A: Add direct air temperature and shading performance (in case of windows) for the thermal performance. For air quality, these seem good. Noise level behind the green façade, but also the acoustics (noise reflection) in front of façade. For biodiversity, I would prefer to incorporate real biodiversity measurements, making use of DNA technology or AI-tools.

Q: Does combining these four measurements onto one common 0–1 scale lose meaningful real-world information, such as whether a specific threshold has been crossed?

A: The goal of this ecosystem framework is to compare the different measurements. Therefore, the method of scoring needs to take into account as much real-world information as possible, but some will be lost. In this case, that is not a problem. However, incorporating a 'red-line' for which one of the score may not be crossed, can be an extra dimension of your framework.

Q: If later testing against real sensor data shows a typology doesn't perform the way we'd predict, what would that most likely tell us?

A: The performance of VGS is strongly dependent on local circumstances and climate and if it does not perform as predicted, it is mostly the effect of the building.

Q: Is there a specific finding you'd want to see feed into future work, or anyone else who should be involved?

A: Your framework is not finished and it would be very interesting to keep developing it, together with the sensor data of the CEG green façade project.

D.2 Green Façade Specialist

Q: In your view, what does a vertical green façade need to deliver to be considered a strong performer, across thermal, air quality, acoustic, and biodiversity aspects?

A: For me, a strong green façade should provide measurable benefits across several aspects rather than optimise just one. Thermal regulation is important, but I would also expect benefits for biodiversity, air quality and, where relevant, acoustics. I would also look at durability, maintenance and resource use. A system that performs well but requires a lot of water, maintenance or replacement may not be sustainable in the long term. So, for me, the key is multiple benefits over a long service life.

Q: Looking at the four ecosystem services described above, does that structure match what you would consider a complete and correctly balanced picture, or is something important missing or overweighted?

A: It is a good starting point, but I would not call it complete. In particular, I think biodiversity needs a more robust assessment than just visual appearance. Depending on the type of façade, I would also consider water management and resource use/life-cycle impacts. However, for this thesis I think the four selected services provide a reasonable and manageable framework.

Q: Thermal regulation vs. Air quality

A: I see thermal regulation as somewhat more important because it has a direct link with building performance and comfort, although air quality is also an important urban benefit.

Q: Thermal regulation vs. Acoustic performance

A: Thermal performance has broader relevance for the building. Acoustic performance can be very important, but is more location-specific.

Q: Thermal regulation vs. Biodiversity

A: I would give thermal regulation a slightly higher priority, but biodiversity should definitely remain a major component. I would not want biodiversity to become a secondary "nice-to-have" benefit.

Q: Air quality vs. Acoustic performance

A: Both are relevant urban environmental benefits, and their relative importance depends strongly on the location and exposure of the building.

Q: Air quality vs. Biodiversity

A: I would give biodiversity slightly more weight. Air-quality benefits from vegetation can be quite context-dependent, while biodiversity is one of the fundamental reasons for introducing nature into the built environment.

Q: Acoustic performance vs. Biodiversity

A: Again, I would give biodiversity somewhat more weight. Acoustic performance is valuable, but highly dependent on the specific location and façade configuration. My overall ranking would therefore be: Thermal regulation > Biodiversity > Air quality ≈ Acoustic performance.

Q: Do the proposed measurement parameters seem like the right way to capture each ecosystem service, or would you prioritise a different measurement for any of them?

A: They are a good starting point, but I would make a few changes. For thermal performance, surface temperature and heat flux are useful, but I would also consider solar radiation and, if possible, the effect on actual building energy demand or indoor comfort. For air quality, PM is useful, but I would distinguish between particle capture and actual improvement of air quality. I would also be cautious about using CO2 uptake as a major indicator. For acoustics, noise level/insertion loss makes sense, although frequency dependence would be useful. For biodiversity, this is where I would make the biggest change: visual assessment alone is not enough. Species richness, abundance or habitat quality would give a much stronger indication of actual biodiversity.

Q: Does combining these four measurements onto one common 0–1 scale lose meaningful real-world information, such as whether a specific threshold has been crossed?

A: Yes, potentially. The 0–1 normalisation is useful for comparing and combining the different services, but it can hide important information, especially thresholds and practical significance. For example, crossing a health, noise or habitat threshold can be much more meaningful than simply achieving a certain percentage improvement. I would therefore show the overall score together with the underlying measurements. The combined score should be seen as a decision-support tool, not as the complete picture of performance.

Q: If later testing against real sensor data shows a typology doesn't perform the way we'd predict, what would that most likely tell us?

A: Potentially both. I would first check the assumptions, measurement uncertainty and boundary conditions before concluding that it is a building-specific effect. With a green façade, orientation, wind,

solar exposure, surrounding buildings, vegetation development and maintenance can all have a significant influence. So I would see this mainly as an opportunity to improve the model and understand the real behaviour of the façade, rather than simply as a failure of the prediction.

Q: Is there a specific finding you'd want to see feed into future work, or anyone else who should be involved?

A: I would particularly like to understand which ecosystem services actually provide measurable benefits under real CEG conditions, and how these benefits develop over time and across seasons. For me, it would be interesting to look at the interaction between vegetation development, thermal performance and biodiversity, but also at the role of maintenance and irrigation. I would also like the CEG façade to develop further as a long-term living laboratory, involving not only building and environmental researchers but also ecologists, facility management and the people maintaining the façade.

D.3 Urban Ecologist / Biodiversity Expert

Q: In your view, what does a vertical green façade need to deliver to be considered a strong performer, across thermal, air quality, acoustic, and biodiversity aspects?

A: A vertical green façade is not the one that scores highest on any single indicator, but the one that delivers a legible, year-round bundle across all four services and stays alive and structurally sound with modest input. Concretely I look for: (1) a measurable summer surface-temperature reduction and a demonstrable reduction of cooling demand, plus a modest winter insulation effect; (2) an honest, not oversold, air-quality contribution through PM deposition, framed at the scale a single façade can actually deliver; (3) some acoustic attenuation through added surface area and structural complexity; and (4) real habitat value — species-rich planting, structural layering, a flowering and fruiting sequence that spans the season, and physical connectivity to the ground-level green system.

Q: Looking at the four ecosystem services described above, does that structure match what you would consider a complete and correctly balanced picture, or is something important missing or overweighted?

A: The four pillars are a defensible and workable scope for an MSc thesis, and I would keep them; the question is how you measure them. I would not add new pillars to the framework at this stage.

Q: Thermal regulation vs. Air quality

A: Thermal regulation matters more — around 3. In a Dutch coastal-urban context (Rotterdam-Delft), the thermal and UHI signal of a façade is more reliably demonstrable than the air-quality contribution of a single wall, which is real but small relative to background sources and street-level emissions.

Q: Thermal regulation vs. Acoustic performance

A: Thermal regulation matters more — again around 3. Both are locally useful, but the thermal benefit is continuous, propagates into the building interior, and links directly to energy and comfort. Acoustic gains from a thin greening layer are typically modest unless combined with a substrate-based living wall.

Q: Thermal regulation vs. Biodiversity

A: Roughly equal, factor 2. Thermal performance is important but more substitutable (insulation, shading, shutters); habitat is not.

Q: Air quality vs. Acoustic performance

A: Roughly equal.

Q: Air quality vs. Biodiversity

A: Biodiversity matters more, around 3 (moderately more). A well-composed planting mix delivers habitat value that is demonstrable, design-controllable, and directly steerable through species selection. The air-quality contribution of one façade is real but small relative to urban background sources.

Q: Acoustic performance vs. Biodiversity

A: Biodiversity matters more — around 3 to 4 (moderately to clearly more). Same underlying reason: species choice and structural diversity give the designer real leverage on biodiversity outcomes, whereas acoustic gains from a lightweight climber system are typically limited and constrained by mass and coverage.

Q: Do the proposed measurement parameters seem like the right way to capture each ecosystem service, or would you prioritise a different measurement for any of them?

A: Probably [the green façade specialist] and the other respondent can better comment on this.

Q: Does combining these four measurements onto one common 0–1 scale lose meaningful real-world information, such as whether a specific threshold has been crossed?

A: I think at this phase, do what is most practical.

Q: If later testing against real sensor data shows a typology doesn't perform the way we'd predict, what would that most likely tell us?

A: Probably both. The first explanation is usually site specificity: west orientation, surrounding built context, prevailing south-westerly wind off the North Sea, and the maturity and coverage of the vegetation at the moment of measurement all shape the observed response and are difficult to predict fully from literature values. A second, related explanation is that literature-derived typology archetypes compress real variability — a ‘climbing evergreen’ in a paper is not the same species mix, density, or age as the one on CEG. I would only conclude a genuine framework flaw after ruling out (a) coverage and leaf-area effects, (b) sensor placement and microclimate artefacts, and (c) seasonal timing, including the deciduous/evergreen contrast across the year.

Q: Is there a specific finding you'd want to see feed into future work, or anyone else who should be involved?

A: Two things would be most useful for the next step. First, an empirically grounded, typology- and species-specific view of which plant assemblages actually deliver the best combined score on this façade. Second, a clear articulation of where the framework's assumptions are strongest and where they are weakest. On people to involve: the TU Delft Campus Real Estate / facility management side; the ECOCampus biodiversity monitoring team; and, for the biodiversity pillar specifically, colleagues monitoring wild bees and birds in Delft who can help move that indicator beyond a visual proxy. These suggestions are carried into the Recommendations rather than the main body, consistent with this thesis's timeline.