Equitable Implementation of Green Roofs in The Hague

Integrating Social Cost–Benefit Analysis with Spatial Equity Assessment

David Lock

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Integrating Social Cost-Benefit Analysis with Spatial Equity Assessment

by

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TU Delft Delft University of Technology

Executive Summary

Context and Research Aim

Cities are increasingly confronted with climate change impacts such as flooding and the Urban Heat Island (UHI) effect. Municipalities turn to Nature-based Solutions (NbS) such as green roofs to improve resilience while generating environmental and social co-benefits. Yet implementation is not automatically equitable. Without explicit attention to who bears the costs and who receives the benefits, policies risk reinforcing existing socio-spatial inequalities, for instance through processes of green gentrification. Conventional Cost-Benefit Analysis (CBA) and even Social Cost-Benefit Analysis (SCBA) demonstrate that green roofs can provide positive returns in aggregate, but rarely reveal how outcomes differ across households, housing types, or neighbourhoods. This limits their usefulness for decisions that must balance both efficiency and fairness in terms of distributive justice, procedural justice, and recognitional justice. The Hague provides a timely case: the city faces flood and heat challenges, has ambitious adaptation goals, and exhibits sharp variation in Socio-Economic Status (SES) across its postcode level areas.

The central question guiding this thesis is: *How can SCBA and spatial equity analysis support policy making for equitable and effective implementation of green roofs as NbS in The Hague?*

Methods in Brief

The framework combines several steps. A literature review identified recognised costs and benefits of green roofs and highlighted persistent gaps in monetisation, especially for co-benefits such as biodiversity and mental health. A city-wide SCBA was then carried out using harmonised Geographic Information Systems (GIS)-based data from Statistics Netherlands (CBS), roof suitability assessments, climate vulnerability indicators, and socio-economic statistics. Four expansion scenarios were analysed: environmental-priority, income-based, uniform, and optimised allocation. Results were evaluated through equity analysis, using indicators such as the Gini coefficient and Lorenz curves, followed by clustering into neighbourhood typologies. Representative neighbourhoods were then decomposed into Postcode-5 (PC5) units for detailed analysis disaggregated by housing type (*koop*, *huur particulier*, *huur corporatie*). Finally, robustness was tested with Exploratory Model Analysis (EMA) techniques, including Latin Hypercube Sampling (LHS), tornado diagrams, and Partial Dependence Plot (PDP) diagnostics.

City-wide Outcomes

The current stock of green roofs in The Hague covers about 323,000 m^2 but delivers limited societal returns. All neighbourhoods record negative Net Present Values (NPVs), and no Benefit-Cost Ratio (BCR) exceeds one. Expansion scenarios substantially improve performance. The uniform, income-based, and environmental allocations enable roughly two thirds of neighbourhoods to surpass break-even, showing that scaling up can create sufficient critical mass for societal benefits to outweigh costs. The optimised allocation, in contrast, delivers very high returns in a small number of neighbourhoods while leaving most of the city unchanged, achieving efficiency at the expense of coverage.

Equity and Distributional Patterns

The distributional analysis shows that allocation design decisively shapes outcomes. The income-based strategy performs best: it reduces inequality, directs benefits to lower-income and climate-vulnerable areas, and is the only scenario that achieves positive alignment between benefits and adaptation need. Uniform and environmental allocations increase coverage and improve averages, but fail to systematically prioritise vulnerable groups. The optimised allocation generates extreme inequality by concentrating benefits in affluent, low-density areas with high Waardering Onroerende Zaken (Dutch property valuation system) (WOZ) property values, while excluding most neighbourhoods.

Neighbourhood Insights

Clustering reveals four distinct neighbourhood types: High Gain–Equity, Low Uptake–Stable, High Risk–Reward, and Low Return–Saturated. Detailed analysis of representative cases shows how socio-economic context shapes outcomes. Affluent, low-density areas such as Zorgvliet incur the largest losses despite high roof potential, as costs are spread across fewer households and collective benefits remain limited. By contrast, dense, mixed-income areas such as Oostbroek-Zuid and Moerwijk-Noord perform relatively better in per-household terms, as health and energy benefits accumulate across many dwellings. Tenure also proves decisive: homeowners capture most property-related benefits, while tenants—particularly in social housing—gain relatively little, and housing corporations bear a disproportionate share of costs.

Uncertainty and Robustness

Exploratory analysis confirms that results are sensitive to assumptions about installation Capital Expenditure (CAPEX), annual Operational Expenditure (OPEX), flood damages, energy prices, and property values. While absolute figures such as NPV, BCR, and Internal Rate of Return (IRR) shift under different assumptions, the relative ranking of scenarios remains broadly consistent. At the same time, outcome ranges overlap, meaning no allocation is universally superior. This highlights the importance of designing flexible policies and safeguards for vulnerable groups to ensure that equity goals are met under uncertainty.

Implications for Policy

The findings demonstrate that green roofs can contribute meaningfully to The Hague's climate adaptation goals, but that distributive outcomes vary strongly by allocation strategy, neighbourhood type, and tenure composition. Efficiency and fairness are not automatic by-products of expansion; they must be deliberately embedded in policy design. For policymakers, this means that targeting denser, lower-income areas can combine efficiency with equity, collaboration with housing corporations is essential to avoid overburdening social renters, and evaluations must acknowledge co-benefits that remain difficult to monetise. By combining SCBA, spatial equity analysis, and uncertainty diagnostics, this thesis shows how economic evaluation can be extended beyond aggregate efficiency to incorporate distributive justice, procedural justice, and recognitional justice. For The Hague, and similar mid-sized European cities, this provides a framework for implementing green roofs not only as effective climate measures but also as pathways towards more inclusive and just urban futures.

Preface

My interest in climate change adaptation grew during my studies, where I became particularly intrigued by NbS as a way to combine environmental and social benefits in cities. Through the courses in the EPA programme, I discovered that spatial data analysis was one of the methods I enjoyed most, as it allowed me to explore complex urban systems in a tangible way. When the opportunity arose to work on a project about green roofs, I was immediately interested because it brought together several strands of my academic interests. This thesis gave me the chance to combine the methods I had learned, from SCBA to spatial equity analysis, while also engaging with questions of justice that I find just as important as the technical and economic dimensions of adaptation.

I would like to express my gratitude to my supervisors. Nazli guided me through numerous meetings, always offering constructive feedback and new perspectives. She also arranged group sessions with fellow students, which were a great source of support and inspiration. Jan Anne provided useful supervision on the SCBA component of this thesis, and I greatly appreciated his interest in the other methodological aspects as well.

I am also thankful to my friends with whom I could study, exchange ideas, and share the ups and downs of thesis writing. Special mention goes to the "eco-boys" from EPA, and to Sander for the countless hours we spent studying together. I also want to thank my parents and family for their continuous support throughout my studies. Last but certainly not least, I want to thank my girlfriend Ylke for her patience, encouragement, and (mostly) enthusiastic attempts to understand what I was working on. Her mental support and constant motivation made all the difference.

The Hague, September 2025
David Lock

It feels fitting to finish writing these words at my parents' house, under a green roof.

Declaration on the use of Artificial Intelligence

Throughout this thesis project, artificial intelligence (AI) tools were used to support the literature review, coding and writing processes. At no point were AI tools used to generate original research findings or fabricate results. The author developed and verified all conceptual insights, modelling decisions, data analyses and interpretations. The author takes full responsibility for the content and conclusions of this work. ChatGPT was used to summarise scientific papers or extract specific information for the literature review. It was also used to clarify methodological concepts and suggest ways to structure arguments.

During the development and application of the Social Cost-Benefit Analysis (SCBA) and spatial data analysis, ChatGPT supported coding tasks such as solving Python errors, drafting functions and refining workflows. The author wrote the scripts and models, with ChatGPT serving as an assistant to explore alternative approaches or provide illustrative examples.

Deepl was used to check grammar, spelling and clarity in the writing. ChatGPT was occasionally used to rephrase short passages to improve readability. The outputs from all AI tools were never directly duplicated, but instead served as a source of inspiration or technical assistance. The author reviewed, adapted, and critically assessed all the text to ensure academic integrity.

List of Abbreviations

BCR Benefit-Cost Ratio. i, ii, x, 3, 4, 6, 7, 9, 14, 16–21, 30, 39, 40, 45, 47, 59, 64

CAPEX Capital Expenditure. ii, 6, 7
CBA Cost-Benefit Analysis. i, 2–4, 6–8, 13, 45
CBS Statistics Netherlands. i

EMA Exploratory Model Analysis. i

GHG Greenhouse Gas. 6
GIS Geographic Information Systems. i

IRR Internal Rate of Return. ii, 6, 9, 14, 16, 30, 47, 64

LHS Latin Hypercube Sampling. i, 17

MAUP Modifiable Areal Unit Problem. 48
MCA Multi-Criteria Analysis. 49

NbS Nature-based Solutions. i, iii, vii, 1–10, 45–47, 50
NPV Net Present Value. i, ii, x–xii, 3, 4, 6, 9, 12, 14–26, 30, 32–48, 58–62, 64, 66

OPEX Operational Expenditure. ii, 6, 7

PbP Payback Period. 6, 14, 16
PC4 Postcode-4. vi, 12, 16, 55
PC5 Postcode-5. i, vi, viii, x, xii, 5, 12, 15–18, 27–31, 34, 40, 41, 45–48, 55, 56, 63, 64, 66
PC6 Postcode-6. vi, 12, 55
PDP Partial Dependence Plot. i

SCBA Social Cost-Benefit Analysis. i–iii, vii, viii, x, xii, 3–10, 12–19, 22, 24, 27, 28, 30, 31, 45–50, 55, 57, 58, 64, 66
SES Socio-Economic Status. i, x, 12, 15, 25, 26, 62

UHI Urban Heat Island. i, 6, 7, 56, 60–62

WOZ Waardering Onroerende Zaken (Dutch property valuation system). i, 13, 16

List of Terms

distributive justice The principle of evaluating fairness in how costs and benefits are distributed among different groups, often used in equity-focused analyses of climate adaptation and NbS. i, ii, 48

equity Fairness in the distribution of costs, benefits, and opportunities across social groups, considering pre-existing inequalities and vulnerabilities. i, ii, vii, viii, x, 1–10, 35, 45–51

Gini A statistical measure of inequality, ranging from 0 (perfect equality) to 1 (maximum inequality). In this thesis it is used to quantify disparities in the distribution of green roof costs and benefits across households or neighbourhoods. i, x, 8, 9, 22, 40, 45, 47, 48, 61, 62

green gentrification A process whereby investments in green infrastructure (e.g. green roofs, parks) increase property values, potentially displacing vulnerable residents and reinforcing socio-spatial inequalities. i, 3, 8, 47

Lorenz A graphical representation of inequality that plots the cumulative share of the population against the cumulative share of benefits or costs. The greater the deviation from the 45° line of perfect equality, the more unequal the distribution. In this thesis it is used to visualise how green roof benefits are distributed across neighbourhoods and households. i, x, 8, 9, 23, 45, 47, 48, 61, 62

postcode level Hierarchical spatial units used in the Netherlands and defined by Statistics Netherlands (CBS). Dutch postcodes consist of four digits followed by two letters (e.g., 2611AB).

Postcode-4 (PC4) refers to the first four digits only (e.g., 2611), which typically cover a city district of several thousand households.

Postcode-5 (PC5) extends this with the first digit of the two-letter suffix (e.g., 2611A), creating finer-grained neighbourhood units of a few streets.

Postcode-6 (PC6) is the full postcode (e.g., 2611AB), usually corresponding to one street or part of a street, often tens of households.. i, 55

procedural justice The principle of fairness in decision-making processes, emphasising inclusive participation, transparency, and equal consideration of stakeholders' voices in planning and implementation of NbS. i, ii

recognitional justice The acknowledgement and respect of diverse values, identities, and needs in planning and evaluation, ensuring that NbS policies do not marginalise or overlook particular groups. i, ii

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1

Introduction

Cities are at the frontline of climate change. Rising temperatures, heavier rainfall, and urban flooding increasingly threaten human health, critical infrastructure, and economic productivity (Aboagye & Sharifi, 2024). At the same time, cities are a major driver of climate change, contributing around 70% of global greenhouse gas emissions through energy use, transport, and land-use conversion (Shukla et al., 2022; UN-Habitat, 2024). With over half of the world's population now living in urban areas, and this figure expected to rise (UN-Habitat, 2024), cities are at the heart of the climate change problem and solution.

Urbanisation and climate change are placing increasing pressure on ecosystems. Climate change is altering the structure and functioning of ecosystems across Europe, undermining biodiversity and ecosystem service provision (Kabisch et al., 2016). At the same time, expanding urban footprints are leading to soil sealing, habitat fragmentation, and the loss of agricultural and green space (Seto et al., 2011; Theodorou, 2022). These stressors reduce cities' ability to provide essential ecological services, such as temperature regulation, water retention and carbon sequestration. As cities seek to adapt, it is not only a question of responding effectively, but also of doing so in a socially just and ecologically sustainable way.

1.1 Nature-based Solutions as Urban Climate Interventions

NbS have emerged as a widely promoted strategy to address these urban climate challenges. NbS are defined by the European Union (2017) as "actions which are inspired by, supported by, or copied from nature". NbS include interventions such as green roofs, urban green spaces, tree planting, rain gardens, and restored waterways (Faivre et al., 2017; McPhearson et al., 2023). These measures aim to mimic or enhance natural processes to achieve climate adaptation and mitigation goals, while generating co-benefits for people and ecosystems.

Unlike grey infrastructure, which is often mono-functional and resource-intensive, NbS are valued for their multi-functionality. They simultaneously provide environmental services (e.g. cooling and air purification), social benefits (e.g. mental and physical health, aesthetic value), and economic advantages (e.g. increased property values, energy savings, avoided damage from extreme weather) (Kabisch et al., 2016; Kandel & Frantzeskaki, 2024). Because of these benefits, NbS are increasingly integrated into urban climate strategies.

Although NbS offer a wide range of potential benefits, there are challenges associated with their implementation. A growing body of research reveals that NbS can increase, rather than reduce, existing socio-economic inequalities. For instance, investments in green infrastructure frequently concentrate in areas that are already well served or have a higher income, while low-income communities, despite being more exposed to climate risks, receive fewer resources for adaptation (Anguelovski et al., 2022; Shokry et al., 2020; Wolch et al., 2014).

1.1.1 Policy-relevant equity aspects and distributional effects

A growing body of research shows that NbS can inadvertently reinforce socio-spatial inequalities. For example, greening efforts often increase property values and living costs, a process described as *climate gentrification*, which can displace vulnerable residents and entrench patterns of exclusion (Anguelovski et al., 2022; Jo Black & Richards, 2020). Beyond affordability pressures, issues of accessibility, safety, and tenure security can also limit the recreational and health benefits of urban green space for disadvantaged groups (Lioubimtseva et al., 2024; Weißermel & Wehrhahn, 2024). Relatedly, Garcia-Lamarca et al. (2021) show that cities with a long-standing emphasis on greenery rhetoric often experience intensified affordability pressures and exclusionary development, a phenomenon they term *green boosterism*. These findings indicate that the absence of an equity-focused approach during the implementation of NbS can lead to the reproduction of existing inequalities.

From an economic perspective, evaluations of NbS consistently demonstrate substantial aggregate benefits, such as reduced flood damage, urban cooling, and health improvements. However, the distribution of these benefits is uneven, raising questions about who gains and who bears the costs. Recent research therefore calls for approaches to a CBA that explicitly account for socio-economic diversity and spatial variation in vulnerability (Chelli et al., 2025; Raymond et al., 2017).

Despite growing recognition of these challenges, most urban adaptation strategies still fall short of systematically integrating equity into planning and investment decisions. This is partly because technical criteria such as surface permeability or temperature reduction remain easier to measure and therefore dominate decision-making, while social indicators (i.e., income, housing status, or vulnerability) are harder to operationalise and rarely included (Hölscher et al., 2024; Kabisch et al., 2016). Evaluations also tend to emphasise aggregate effectiveness, such as total avoided damages, rather than distributional outcomes, leaving questions of fairness unaddressed (Raymond et al., 2017). Moreover, institutions often lack the governance tools and monitoring frameworks to systematically identify who benefits and who is left behind. As a result, adaptation investments frequently concentrate in already advantaged neighbourhoods, reinforcing socio-spatial inequalities and sometimes driving processes of climate gentrification (Anguelovski et al., 2022; Shokry et al., 2020; Wolch et al., 2014).As a result, the transformative potential of NbS is often constrained, with institutions lacking both the tools and the monitoring frameworks to identify who benefits and who is left behind.

In this thesis, equity refers to fairness in the distribution of NbS costs and benefits. Policies that achieve this are described as equitable. Ensuring equity in urban adaptation is not only a normative concern, but also a practical challenge, as the outcomes of NbS are rarely distributed evenly across social groups or neighbourhoods.

1.1.2 Green Roofs as NbS in The Hague

Green roofs are rooftops of buildings that are partially or completely covered with vegetation and a growing layer, installed over a waterproofing system. This often includes layers for drainage, root protection and sometimes irrigation. Green roofs can be classified as either extensive (lightweight, shallow substrate, low maintenance) or intensive (deeper substrate, higher load, allowing shrubs or small trees) (Bona et al., 2022; Faivre et al., 2017).

While many cities across Europe are adopting NbSs such as street trees, urban parks, green walls, and green roofs to respond to flooding, heat, and stormwater challenges (Kabisch et al., 2016), The Hague offers a particularly relevant case for examining how green roofs are implemented in practice with respect to equity. The municipality provides a climate-adaptation subsidy that supports green roofs, rainwater harvesting, garden greening, and replacing hard surfaces with vegetation. Owners or tenants of residential properties can receive 50% cost reimbursement (or full reimbursement if holding the *Ooievaarspas*), and these measures are now available city-wide (Gemeente Den Haag, 2025) In parallel, academic research in The Hague is investigating not only the technical and ecological performance of green roofs (e.g., heat island reduction, species diversity, air quality), but also whether access to such interventions is equitably distributed across neighbourhoods (Lindhout, 2023). Yet in the Global North more broadly, urban adaptation strategies often claim to pursue equity in planning, while it remains unclear whether the actual distribution of benefits and costs reflects this ambition. If green roofs are to fulfil their potential as a climate adaptation measure, their implementation must also be socially equitable.

The Hague exemplifies a mid-sized European city where green roofs have already been implemented, are actively promoted in policy, and have substantial potential for further expansion. The municipality's climate adaptation strategy identifies green roofs as a key measure to reduce flood risk, mitigate urban heat, and enhance liveability (Bona et al., 2022; Faivre et al., 2017; Gemeente Den Haag, 2024b; "Strong and sustainable", n.d.). Existing subsidies and local regulations support their adoption, and the city maintains detailed spatial datasets on roof suitability and existing installations.

At the same time, The Hague faces pronounced socio-spatial inequalities (Kraaijvanger et al., 2023) and heightened exposure to climate risks such as urban heat and pluvial flooding (Kempen, 2019; KNMI, 2021). This combination of active policy support, existing and planned implementation, climate vulnerability, and marked social disparities makes The Hague an ideal case to investigate how and to whom green roofs deliver value. Studying The Hague can provide insights not only for local policy, but also for other mid-sized Global North cities aiming to scale up green roof adoption while ensuring that benefits are equitably distributed.

1.2 State of the Art and Knowledge Gaps

NbS are increasingly promoted as multifunctional strategies for addressing urban climate risks while delivering environmental, social, and economic co-benefits (Bona et al., 2022; Faivre et al., 2017; McPhearson et al., 2023). In cities, these measures, such as green roofs, urban green spaces, permeable surfaces, rain gardens, and tree planting, can improve stormwater retention, reduce urban heat, enhance biodiversity, and support public health (Faivre et al., 2017; Kandel & Frantzeskaki, 2024). This multifunctionality positions NbS as central to regenerative urban planning and climate resilience.

Despite these advantages, the benefits of NbS are not equally shared. Empirical studies show that interventions are often concentrated in wealthier neighbourhoods, while low-income and marginalised communities, despite facing higher climate risks, receive fewer resources for adaptation (Anguelovski et al., 2022; Shokry et al., 2020; Wolch et al., 2014). Such patterns can exacerbate social inequalities through mechanisms like climate gentrification (green gentrification), where greening efforts raise property values and trigger displacement pressures (Jo Black & Richards, 2020). Additional barriers, such as limited accessibility, safety concerns, and tenure insecurity, further reduce the ability of vulnerable groups to benefit from NbS (Lioubimtseva et al., 2024; Weißermel & Wehrhahn, 2024).

Economic evaluations of NbSs typically focus on aggregate performance indicators such as NPV and BCR, quantifying benefits like flood mitigation, energy savings, and health improvements (**chelliEconomicValuationNaturebased2025**; Raymond et al., 2017). Yet these assessments rarely consider how benefits and costs are distributed across socio-economic groups or spatial contexts. This bias is reinforced in planning frameworks, where technical and environmental criteria dominate and indicators of social vulnerability, income, or tenure are seldom integrated into decision-support tools (Hölscher et al., 2024; Kabisch et al., 2016).

Within this broader field, green roofs have emerged as one of the most widely studied and implemented NbS in urban settings. They provide multiple services: stormwater retention, urban heat mitigation, biodiversity enhancement, and property value uplift. On the other hand they also incur significant capital and maintenance costs. Although a growing number of CBAs and SCBAs evaluate green roofs, these studies usually assess performance at the city or building scale without linking results to spatial equity patterns. As a result, there is limited empirical evidence on how green roof benefits and costs vary across neighbourhoods with different socio-economic profiles, especially in medium-sized European cities.

Research has disproportionately focused on large metropolitan areas and flagship projects in North America and the UK (Cucca et al., 2023). Medium-sized European cities, often with different governance structures, spatial inequalities, and institutional capacities, remain underrepresented in the literature. Furthermore, there is a lack of integrated approaches that combine city-scale SCBA with neighbourhood-level spatial equity analysis. Addressing these gaps is essential for developing policies that are both effective in climate adaptation and equitable in their distribution of benefits and costs.

1.3 Problem Statement

1.3.1 Gap 1: Distributional outcomes of NbS remain insufficiently understood

Although NbS such as green roofs are increasingly promoted as multifunctional strategies for climate adaptation, their implementation often reproduces rather than reduces socio-spatial inequalities. Empirical studies highlight risks of climate gentrification and green boosterism, where investments in high-profile greening projects disproportionately benefit wealthier areas and contribute to affordability pressures, while vulnerable communities remain underserved (Anguelovski et al., 2022; Garcia-Lamarca et al., 2021; Shokry et al., 2020). At the same time, benefits such as cooling, recreational value, and flood protection may not reach low-income households due to barriers of accessibility, safety, or tenure insecurity (Lioubimtseva et al., 2024; Raymond et al., 2017). Despite growing recognition of these issues, there is limited systematic and spatially explicit assessment of how the benefits and costs of NbS are distributed across different neighbourhoods.

1.3.2 Gap 2: (S)CBA frameworks insufficiently capture distributive justice

Economic evaluations of NbS typically highlight substantial aggregate benefits such as avoided flood damage, improved health outcomes, and energy savings (Chelli et al., 2025). However, methodological conventions in conventional CBAs and SCBAs, including the aggregation of outcomes, reliance on average indicators, and limited treatment of socio-economic heterogeneity, mean that distributional effects are rarely examined. This neglect is problematic because NbS generate both public and private benefits, which are not shared evenly. Without explicit integration of equity considerations, (S)CBA risks reinforcing existing inequalities, favouring homeowners over renters or higher-income groups, and leaving vulnerable populations behind.

1.3.3 Gap 3: Lack of integration between city-wide and neighbourhood-level assessments

Current evaluations of green roofs and other NbS tend to focus either on the building scale, emphasising technical feasibility and payback, or on the city scale, where aggregate indicators such as NPV or BCR are reported. Both perspectives overlook how outcomes vary between neighbourhoods with different socio-economic profiles, housing stocks, and exposure to climate risks. As a result, spatial heterogeneity in benefits and costs remains hidden, and policymakers lack the evidence to design targeted subsidies, prioritise investments, or address distributional concerns. Bridging this gap requires decision-support tools that combine city-wide assessments with neighbourhood-level dynamics, ensuring that NbS contribute not only to effectiveness but also to equity.

1.4 Research Aim and Research Questions

This thesis builds on the identified research gaps by developing a framework that combines SCBA with spatial equity analysis. The framework aims to improve our understanding of who gains and who bears the costs of green roof implementation in The Hague. Addressing the lack of equity considerations in existing evaluations (Gap 2), the absence of systematic evidence on distributional outcomes (Gap 1), and the disconnect between city- and neighbourhood-scale assessments (Gap 3), the research seeks to generate policy-relevant insights. To this end, the thesis examines the recognised costs and benefits in the literature, how these vary across space, and the influence of neighbourhood context on the distribution of outcomes. It also incorporates uncertainty analysis to ensure that recommendations remain robust under varying assumptions about costs, benefits, and future conditions. Each of the following research questions is designed to respond to one or more of these gaps.

1.5 Research Aim and Research Questions

This thesis builds on the identified research gaps by developing a framework that combines SCBA with spatial equity analysis. The framework aims to improve our understanding of who gains and who bears the costs of green roof implementation in The Hague. Addressing the lack of systematic evidence on distributional outcomes (Gap 1), the methodological neglect of equity in existing evaluations (Gap 2), and the disconnect between city- and neighbourhood-level assessments (Gap 3), the research seeks to generate policy-relevant insights. To this end, the thesis examines the recognised costs and benefits in the literature, how these vary across space, and the influence of neighbourhood context on the distribution of outcomes. It also incorporates uncertainty analysis to ensure that recommendations remain robust under varying assumptions about costs, benefits, and future conditions. Each of the following research questions is designed to respond to one or more of these gaps.

Main Research Question: How can Social Cost-Benefit Analysis and spatial equity analysis support policy making for equitable and effective implementation of green roofs as NbS in The Hague?

Sub-research question 1: How are costs, benefits, and equity aspects of green roofs evaluated in (S)CBA, and what can this reveal for combining SCBA with spatial equity analysis?
This question establishes the conceptual foundation by identifying how impacts are currently defined, valued, and included or excluded in economic evaluations. Reviewing the literature clarifies both the strengths and blind spots of existing approaches, with particular attention to whether distributional outcomes are considered. In doing so, it responds to Gaps 1 and 2 by showing where knowledge on distributional outcomes remains limited and where methodological improvements are needed.

Sub-research question 2: What are the costs, benefits, and equity outcomes of alternative green roof expansion scenarios at city scale in The Hague?
This question applies a city-wide SCBA to assess the aggregate impacts of different expansion strategies, highlighting overall feasibility while also identifying broad spatial and social disparities. In doing so, it addresses Gap 2 by adapting

SCBA to explicitly integrate equity considerations, and begins to bridge the city–neighbourhood divide outlined in Gap 3.

Sub-research question 3: How do economic outcomes and equity indicators from the city-wide SCBA vary spatially across The Hague, and how can these patterns be classified?
This question explores intra-urban variation by mapping and classifying neighbourhood-level outcomes, revealing spatial patterns that aggregate results may conceal. In doing so, it directly responds to Gap 1 by uncovering distributional effects and to Gap 3 by explicitly linking city-scale analysis with neighbourhood-level dynamics.

Sub-research question 4: What are the detailed economic outcomes of typology neighbourhoods, and how do they compare across these typologies?
This question deepens the analysis by conducting detailed SCBA for representative neighbourhoods from different typologies, enabling a more nuanced understanding of distributional effects in specific contexts. It therefore reinforces Gap 1 and advances Gap 3 by showing how city-wide outcomes play out at the neighbourhood level.

Sub-research question 5: Which uncertainties influence SCBA outcomes the most, and how robust are the results to uncertainty in these parameters?
This question examines the sensitivity of results to key assumptions, ensuring that policy recommendations are based on outcomes that remain robust under different plausible futures. By testing the stability of results, it contributes to Gap 3 by strengthening the reliability of an integrated city–neighbourhood assessment for equitable NbS implementation.

1.6 Thesis structure

The remainder of this thesis is organised as follows. Section 2 reviews the existing literature on green roofs, NbS, and economic evaluation, with particular attention to recognised costs and benefits, equity dimensions, and methodological challenges. Section 3 outlines the methodological framework, describing the integration of SCBA, spatial equity analysis, clustering, and uncertainty analysis. Section 4 presents the empirical findings for The Hague, structured around the five sub-research questions: city-wide outcomes of green roof expansion, equity implications of allocation strategies, neighbourhood typologies, detailed case studies at the PC5 level, and robustness under uncertainty. Section 5 synthesises these findings by drawing conclusions, situating them within the wider scientific literature, and outlining their policy implications, while also reflecting on the limitations of the study and identifying directions for future research.

2

Literature Review

2.1 Literature Methodology

The literature review addressed Sub-research Question 1: What does the literature say about costs, benefits, and equity implications of green roofs, and how are these incorporated into CBAs and SCBAs? It combined academic and grey literature to identify (i) the range of monetised and non-monetised costs and benefits of green roofs, (ii) methodological approaches to Social Cost-Benefit Analysis (SCBA) in the context of nature-based solutions, and (iii) how equity considerations are incorporated into such analyses. Academic sources were identified primarily through Scopus and Web of Science, using keyword combinations such as: *green roofs" AND Cost-Benefit Analysis"*, *green roofs" AND Social Cost-Benefit Analysis"*, *Nature-based Solutions" AND equity"*, and *urban green infrastructure" AND distribution" OR "access"*.

Results were filtered for peer-reviewed journal articles in English published between 2000 and 2025. Reference snowballing and citation network exploration were used to locate additional relevant studies; for the latter, the Research Rabbit platform (Research Rabbit, 2025) was employed to visualize and follow connections between publications. Grey literature was included where it provided applied, context-specific information, particularly for The Hague and the Netherlands. This included municipal climate adaptation strategies, subsidy regulations, and technical reports.

The LIFE@Urban Roofs 3.0 background report (Arcadis et al., 2024) was identified as the most comprehensive and locally relevant applied CBA of green roofs in the Dutch context. While its parameter values were used as the primary reference for this study's SCBA, similar ranges for key benefit categories (e.g., stormwater retention, energy savings, property value uplift) were found across multiple other references, confirming their plausibility.

2.1.1 Typical Cost and Benefit Categories for Green Roofs

Green roofs have emerged as one of the most studied and implemented NbS in urban areas. They offer a broad spectrum of environmental, social, and economic benefits, yet their implementation also incurs significant costs. CBA has been widely applied to assess their performance under different scenarios, contexts, and policy frameworks.

A systematic review by Chelli et al. (2025) confirms that most urban CBA studies of NbS focus on core economic indicators such as NPV, BCR, IRR, and Payback Period (PbP). These studies typically monetise benefits such as flood mitigation, energy savings, improved air quality, and thermal comfort, while accounting for CAPEX and OPEX. However, they vary considerably in their assumptions regarding baselines, time horizons, and scope of co-benefits included.

In the case of green roofs specifically, studies have emphasized their multifunctionality. For example, Hekrle et al. (2023) compared multiple CBA methodologies to value green roofs, including their impact on runoff reduction, energy efficiency, and property values. Wilbers et al. (2022) detailed the flood mitigation potential of green roofs, as well as co-benefits such as increased housing prices and avoided sewage treatment costs in Oslo. These benefits were contrasted with standard CAPEX and OPEX profiles and benchmarked against grey infrastructure alternatives.

Some studies provide location-specific insights. For instance, Shin and Kim (2019) evaluated five green roof coverage scenarios (0–100%) in Seoul and concluded that full coverage became economically viable (BCR > 1.17) only when including non-market benefits such as aesthetics and comfort, monetized through contingent valuation. Similar evidence is found in Johnson et al. (2021), who used urban climate modelling to quantify the monetary value of reduced heat-related mortality, energy savings, and biodiversity provided by green roofs in Austrian cities. They found that "Green City" scenarios, including green roofs, consistently achieved a BCR greater than 1.

From a methodological standpoint, CBA studies vary in the breadth of benefits included. Zhang and Ayyub (2020) integrated stormwater retention, UHI mitigation, air quality improvement, Greenhouse Gas (GHG) reductions, and even job creation into a 40-year analysis for Washington, D.C., showing a high total net benefit for green roofs.

However, they noted that green roofs had a lower BCR compared to cool roofs, highlighting the need to consider alternatives in SCBA.

Conversely, more conservative CBAs such as Wang et al. (2021) and Niu et al. (2010) have focused exclusively on flood reduction or stormwater fees, neglecting to consider other (co)-benefits. These findings demonstrate that when only direct benefits are monetised, green roofs may appear marginally viable or uncompetitive, highlighting the necessity of incorporating ecosystem services in evaluations.

Teotónio et al. (2018, 2021) have categorized the full benefit profile of green roofs into stormwater management, thermal regulation, biodiversity enhancement, air purification, property value uplift, and even farming potential. Yet, they also stress the challenges of monetizing these benefits and the need for multi-tiered valuation approaches.

Studies like Claus and Rousseau (2012) and Liberalesso et al. (2023) further illustrate the role of public subsidies. They show that green roofs often fail to be profitable for private actors without incentives, despite having high public value. This underlines the policy relevance of understanding distributional effects from green roof investments.

Cost categories in the literature.
Across the literature, costs are most frequently grouped into capital, operational, and replacement expenditures, with some studies also accounting for administrative or transaction costs. Typical categories include:

- *CAPEX*: installation costs, substrate and vegetation, waterproofing, structural reinforcement (Hekrle et al., 2023; Wilbers et al., 2022).
- *OPEX*: annual maintenance, inspection, replacement of vegetation layers (Claus & Rousseau, 2012).
- *Replacement costs*: periodic renewal of certain components (e.g., waterproofing membranes) (Niu et al., 2010).
- *Administrative costs*: design, permitting, and project management (Arcadis et al., 2024).

Benefit categories in the literature.
Monetised benefits are highly diverse, with variation in the range and valuation methods applied. Common categories include:

- *Stormwater retention*: reduced sewer overflows, avoided treatment costs, and reduced flood damage (Wilbers et al., 2022; Zhang & Ayyub, 2020).
- *Urban heat mitigation and cooling*: lower ambient temperatures and building cooling loads, with some studies explicitly linking benefits to reduced UHI exposure (Johnson et al., 2021; Zhang & Ayyub, 2020).
- *Energy savings*: reduced heating and cooling costs (Shin & Kim, 2019).
- *Air quality improvements*: reduced health costs from air pollution exposure (Zhang & Ayyub, 2020).
- *Carbon sequestration*: avoided greenhouse gas emissions costs (Teotónio et al., 2021).
- *Biodiversity enhancement*: habitat provision for pollinators and other species (Teotónio et al., 2018).
- *Property value uplift*: increased market values due to aesthetic and environmental improvements (Arcadis et al., 2024).
- *Public health benefits*: reduced mortality/morbidity from heat, improved mental health (Johnson et al., 2021).

Arcadis et al. (2024) quantify these categories for the Rotterdam context, which is climatically and institutionally comparable to The Hague. Their estimates align closely with ranges reported in studies from other high-income, temperate-climate cities (e.g., Johnson et al. (2021), Shin and Kim (2019), and Wilbers et al. (2022)).

2.1.2 SCBA Model Choices

The Dutch Bureau for Economic Analysis (CPB) provides standard modelling parameters for CBA in the Netherlands, including discount rates and time horizons, which are widely adopted in applied studies. Variations occur in baseline choice (business-as-usual vs. grey infrastructure alternatives), benefit inclusion scope, and time horizon. CBA focuses purely on efficiency, while SCBA can integrate distributional considerations through equity weighting or disaggregated analysis (Romijn & Renes, 2013).

2.2 Valuation Challenges in SCBA of NbS

Economic evaluations of NbS face several methodological challenges that influence the reliability and comparability of results across studies. These include the selection of valuation methods, the treatment of overlapping benefits, the monetisation of non-market outcomes, and the transferability of valuation parameters between contexts.

2.2.1 Property Value Uplift as a Valuation Category

The literature recognises property value uplift as a potentially significant benefit of green infrastructure, including green roofs, although estimated magnitudes vary widely by context, methodology, and market conditions. Arcadis et al. (2024) estimate an uplift in the range of $1.4–20\%$ for properties benefiting from green roofs in Rotterdam, values which are broadly consistent with those reported in international studies (Johnson et al., 2021; Shin & Kim, 2019; Wilbers et al., 2022).

Hedonic pricing analyses are the most common method, using regression models to isolate the marginal effect of green roof presence or nearby green space on transaction prices. Other approaches include contingent valuation and stated preference surveys, which can capture non-market willingness to pay in contexts where transaction data are limited. The magnitude of uplift often depends on property type, building age, and neighbourhood socio-economic characteristics. While uplift is typically considered a positive outcome, it has also been linked to "green gentrification," where rising property prices contribute to displacement pressures in lower-income areas (Anguelovski et al., 2022; Garcia-Lamarca et al., 2021).

2.2.2 Double Counting Risks

A persistent issue in CBA and SCBA is the potential for double counting when benefits are interdependent or already capitalised in other measures. For example, property value uplift may partially or fully reflect benefits such as cooling, energy savings, or aesthetic improvements, which are sometimes valued separately in the same analysis. To address this, some studies adopt a residual benefit approach. In practice, this means that researchers first estimate the total increase in property values associated with green roofs. They then identify which portion of that increase is likely to come from benefits that are already being quantified elsewhere in the analysis, such as reduced energy bills or flood protection. That portion is deducted, and only the remaining share of the property value increase is counted as an additional benefit. This ensures that the same underlying effects are not included twice under different labels (Wilbers et al., 2022).

2.2.3 Non-Market Benefit Monetisation

Many co-benefits of green roofs, such as biodiversity enhancement, aesthetic value, and mental health improvements, are difficult to monetise due to limited market analogues and the absence of standardised valuation techniques. Studies rely on methods such as contingent valuation, benefit transfer, or avoided cost proxies, but these approaches introduce uncertainty and context sensitivity. Reviews highlight that differences in monetisation methods can significantly influence SCBA outcomes, complicating cross-study comparisons (Teotónio et al., 2018, 2021).

2.2.4 Transferability of Valuation Parameters

The transfer of valuation parameters from one context to another is common in NbS CBAs due to data limitations, but it raises concerns about validity. Factors such as climate, building stock, socio-economic conditions, and governance frameworks can affect the magnitude of benefits. While studies such as Arcadis et al. (2024) provide locally calibrated values for the Dutch context, many international assessments caution that results may not be directly transferable without adjustment for local conditions.

2.3 Equity in NbS Evaluation

2.3.1 Distributional Analysis

The literature on NbS equity often distinguishes between three dimensions: *distributional equity* (fairness in the allocation of costs and benefits), *procedural equity* (fairness in decision-making processes), and *recognitional equity* (acknowledgement of diverse needs and identities). Studies examining distributional equity commonly apply statistical measures such as Gini coefficients, Lorenz curves, Theil indices, and benefit incidence analysis to quantify disparities in the receipt of NbS benefits or exposure to environmental burdens. Spatially explicit methods, including local indicators of spatial association (LISA) and Getis–Ord Gi* hot spot analysis, are increasingly used to identify clusters of advantage or disadvantage in access to green infrastructure and associated ecosystem services (Raymond et al., 2017; Vincent et al., 2017).

2.3.2 Approaches for Linking Socio-Economic Indicators with SCBA Outcomes

Empirical studies that explicitly link SCBA outcomes of NbS to socio-economic indicators remain rare. In the limited examples available, researchers have mapped monetised benefits against neighbourhood-level socio-economic status scores, housing tenure distributions, and climate vulnerability indices (Anguelovski et al., 2022; Weißermel & Wehrhahn, 2024). The existing evidence base shows that such integration can reveal significant disparities in the spatial distribution of NbS benefits, often correlated with patterns of income, tenure, or vulnerability. However, most of this work has focused on large metropolitan contexts in North America and the UK, with medium-sized European cities under-represented. Reported challenges include limited availability of disaggregated socio-economic data, governance fragmentation, and the absence of institutionalised procedures for embedding equity metrics into economic evaluations of NbS.

2.4 SCBA and Equity Approaches in the Literature

The integration of SCBA outcomes with spatial equity analysis has been approached in diverse ways in the NbS literature, though most studies focus on either economic valuation or equity mapping in isolation. A limited number of works combine the two, often by linking monetised benefits to socio-economic and spatial datasets to explore correlations or disparities (Raymond et al., 2017; Vincent et al., 2017).

Figure 1 provides a schematic overview of how SCBA and equity analyses are typically addressed in the literature. On the one hand, SCBA studies assess the efficiency of green roofs by monetising costs and benefits such as stormwater retention, cooling, energy savings, and property value uplift, producing indicators like NPV, IRR, and BCR. On the other hand, equity analyses focus on how these outcomes are distributed across social groups, using measures such as Gini coefficients, Lorenz curves, or benefit incidence analysis. The literature shows that these approaches are rarely combined, even though they address complementary dimensions of policy relevance.

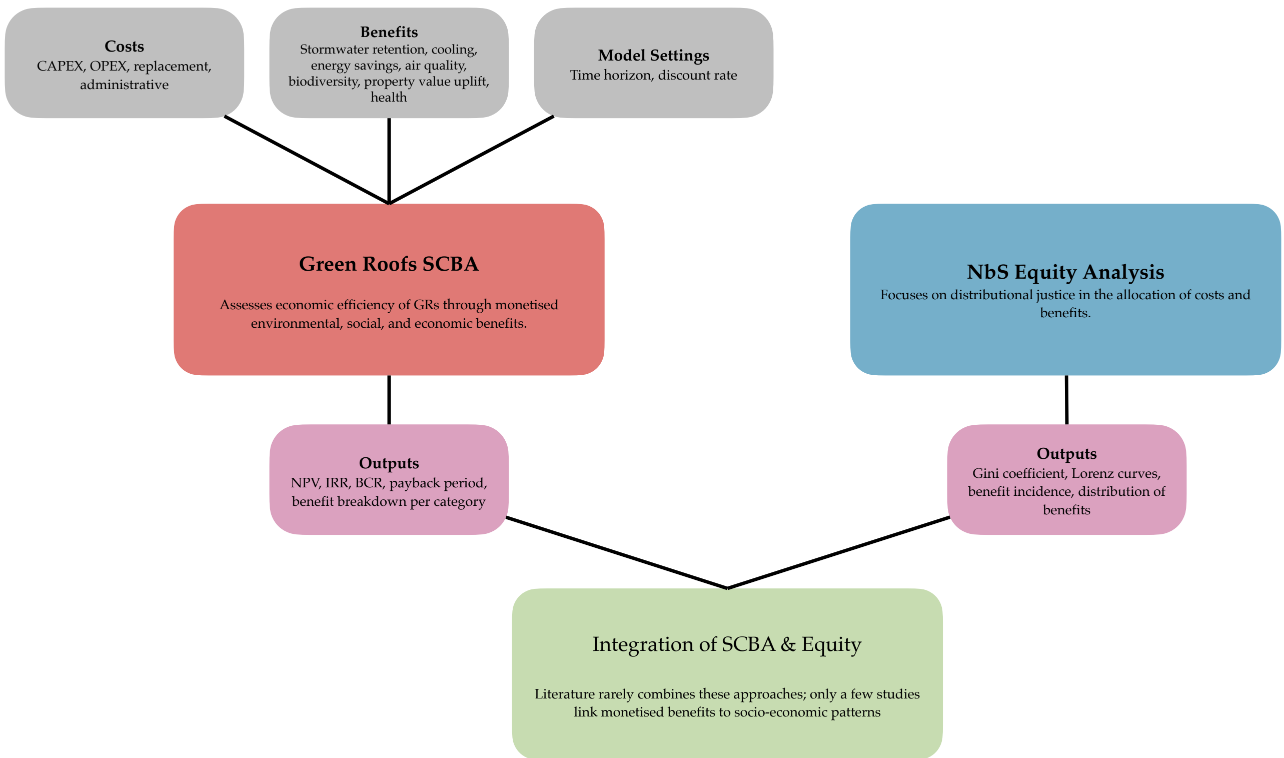


Figure 1: Schematic overview of SCBA and equity analysis in the literature.

In multi-scale applications, some research conducts city-wide economic assessments before examining selected case-study areas in greater detail, enabling both broad policy relevance and context-specific insight (Shin & Kim, 2019; Wilbers et al., 2022). However, fully integrated frameworks that couple SCBA with systematic spatial equity classification are rare, particularly in medium-sized European cities. The literature suggests that such integration could support more targeted and equitable implementation strategies for NbS, yet empirical demonstrations remain scarce. In this thesis, the schematic overview in Figure 1 is complemented by a methodological framework (Section 3) that sets out the stepwise integration of SCBA and spatial equity analysis.

3

Data and Methods

3.1 Overview of Research Design

The research design brings together different methods to answer the main question of this thesis. It follows a stepwise logic, where each stage builds on the previous one. The flowchart in Figure 2 illustrates this sequence. On the left side, the data sources are shown. The coloured blocks represent the main analytical steps, and each box also shows the key outputs. The labels (SRQ2–SRQ5) connect each step directly to the sub-research questions of the thesis. Taken together, the diagram shows how the study moves from a city-wide assessment, through equity and clustering analysis, towards detailed neighbourhood cases and finally a robustness check.

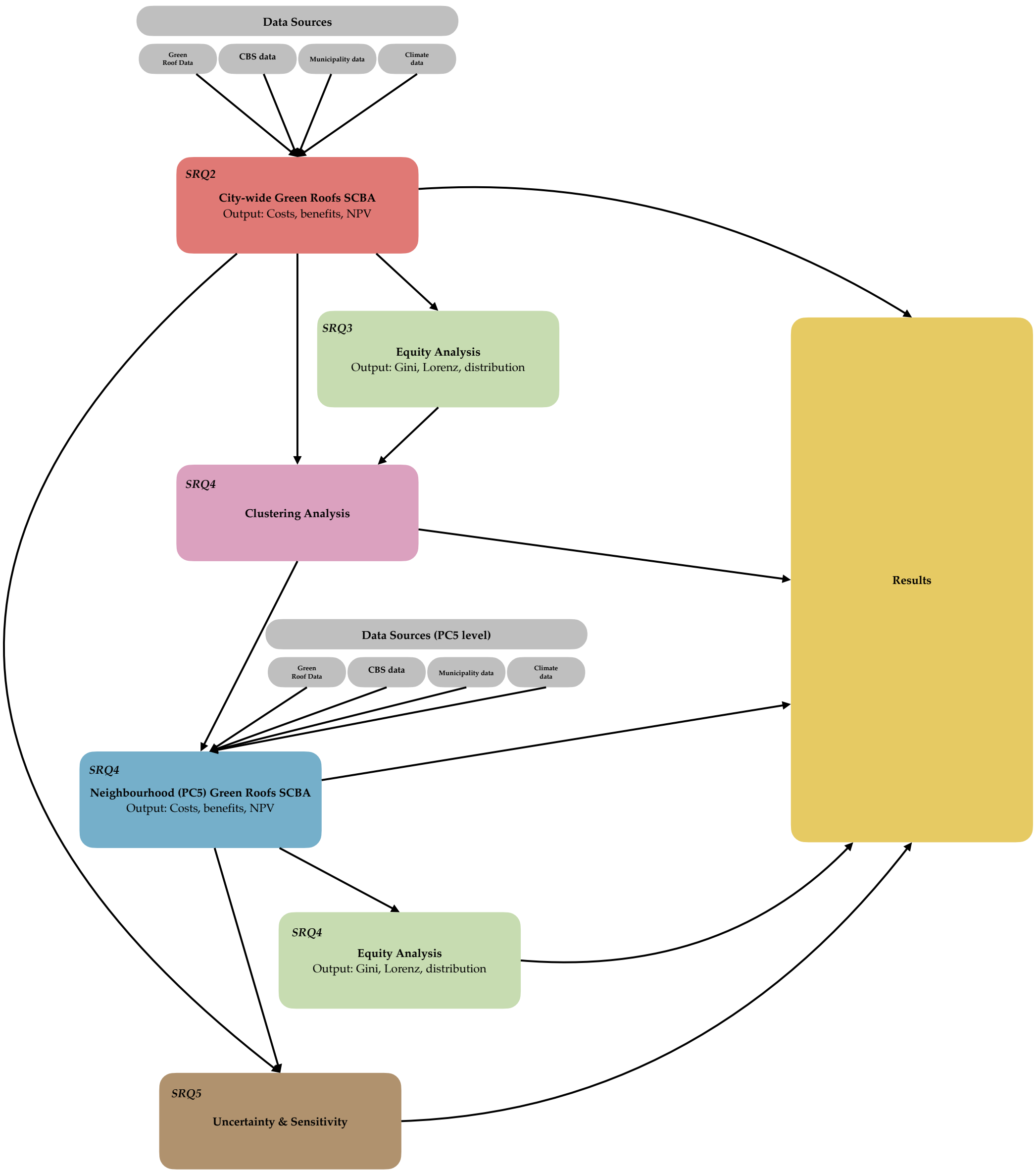


Figure 2: Flowchart of the methodological framework, linking data inputs, analytical steps, outputs, and sub-research questions (SRQs).

The design can be summarised in five stages:

1. **City-wide SCBA (SRQ2)**: Using socio-economic, roof, and climate data, the first step evaluates The Hague under a reference case without any green roofs, as well as four alternative expansion scenarios. This provides an overall picture of costs, benefits, and NPV across all neighbourhoods.
2. **Equity analysis (SRQ3)**: These city-wide results are then examined for fairness. By combining them with indicators such as income levels and climate vulnerability, inequality measures (Gini coefficients, Lorenz curves) are used to show who gains and who is left behind.
3. **Clustering (SRQ4)**: Neighbourhoods with similar profiles are grouped into typologies. This helps to detect systematic patterns and guides the selection of four representative neighbourhoods for deeper study.
4. **Detailed neighbourhood SCBA (SRQ4)**: The selected neighbourhoods are analysed at a finer PC5 scale. Here, results are also split by housing type (owner-occupied, private rental, social rental), revealing how benefits and costs play out within communities.
5. **Uncertainty and sensitivity analysis (SRQ5)**: Finally, the reliability of all results is tested by varying key assumptions, such as installation costs or flood damage values. This shows which parameters matter most and whether the main conclusions remain robust.

In short, the figure shows how the study progresses from broad city-wide outcomes to detailed neighbourhood insights, and how each step answers a specific sub-research question. This flow ensures that the results are not only economically sound but also socially relevant and robust under uncertainty.

3.2 Data Sources

The analysis integrates geospatial and statistical datasets on roof characteristics, green roof adoption, socio-economic conditions, and climate vulnerability in The Hague. An overview is provided in Table 1, while detailed metadata and preprocessing steps are documented in Appendix A (see also dataset sources listed there).

Table 1: Key datasets used in the SCBA and equity analysis

Dataset	Description	Scale	Year	Use in analysis
Dakvlakken Den Haag	Roof polygons with area, slope, use attributes	Building/roof	2024	Identify technically suitable roof stock
Zonnepanelen en Groene Daken	Locations of existing green roofs and PV panels	Roof/address	2022	Measure current green roof adoption
Den Haag in Cijfers	Municipal socio-economic and housing statistics	Neighbourhood	2019–2025	Income, SES, property values, demographics
CBS postcode data	Boundaries and statistics for PC4–PC6	Postcode	2021–2022	Energy consumption, high-resolution socio-economic data
Hittekaart Den Haag	Urban heat island raster (100 × 100 m)	Grid	2017	Local heat exposure for vulnerability analysis
Flood exposure maps	Municipal inundation depth model	Neighbourhood	2021	Share of area exposed to pluvial flooding

All datasets were harmonised to CBS neighbourhood and postcode boundaries (EPSG:28992). Roof suitability was estimated by filtering out segments steeper than 25° or located in heritage zones, while adoption was measured both as the share of suitable roof *area* greened and the share of suitable *segments* with a green roof. Socio-economic indicators (income, SES, property values, dwelling counts) were matched to neighbourhoods and postcodes, and flood and UHI rasters were aggregated to the same units. Neighbourhoods with fewer than 100 residents or 50 addresses were excluded to avoid unstable denominators.

These harmonised inputs form the basis for all subsequent analyses: modelling city-wide costs and benefits (Section 3.3), assessing equity (Sections 3.4 and 3.7), clustering neighbourhoods (Section 3.5), and conducting detailed PC5-level SCBAs (Section 3.6) and uncertainty analysis (Section 3.8). Descriptive maps of roof suitability, adoption, and vulnerability are presented in the Results (Section 4).

3.3 City-wide SCBA Methodology

The SCBA was conducted at neighbourhood level to evaluate the economic viability and distribution of green roof adoption across The Hague. This spatial resolution was chosen to capture how identical interventions generate different outcomes depending on local socio-economic and environmental conditions. The design follows the Dutch *Werkwijzer CBA* guidelines (Romijn & Renes, 2013), adapted for nature-based solutions and extended with spatial equity metrics (Chelli et al., 2025; Raymond et al., 2017). All monetary values are expressed in constant 2023 euros, with a 40-year time horizon and a real social discount rate of 2.25%. Detailed parameter values and equations are provided in Appendix B.

Reference case and intervention scenarios

The reference case is defined as a hypothetical The Hague without any green roofs. Against this counterfactual, three situations were assessed:

1. **Current stock:** the costs and benefits of all existing green roofs relative to the reference case.
2. **Expansion scenarios:** four alternative strategies allocating 50% of the technically suitable roof area to new green roofs (Section 3.3.1).
3. **Neighbourhood variation:** results reported per neighbourhood, revealing how outcomes differ across socio-economic and environmental contexts.

Cost categories

Two categories of costs were included, consistent with Dutch SCBA practice:

- **Installation costs (CAPEX).** One-off investment of €75/m^2 for new and existing green roofs, covering substrate, vegetation, waterproofing, and reinforcement (Arcadis et al., 2024).
- **Maintenance costs (OPEX).** Recurring annual costs of €1.50/m^2/year, including vegetation upkeep and inspection, applied over the 40-year horizon.

These values reflect average Dutch market estimates. They were applied uniformly, so neighbourhood variation arises from differences in roof stock rather than cost heterogeneity.

Benefit categories

Five monetised benefit categories were included, chosen for their prominence in Dutch and international SCBA studies (see Section 2). Parameter values were drawn from Arcadis (2024), CBS statistics, and related applied studies. Detailed functional forms are provided in Appendix B.

- **Flood damage avoided.** Green roofs retain stormwater and reduce sewer overflow. A retention capacity of 0.03 m^3/m^2 and avoided damages of €500/m^3 were assumed, consistent with Dutch valuation studies (Arcadis et al., 2024; Wilbers et al., 2022).
- **Energy savings.** By improving insulation, green roofs reduce household gas demand in winter (−2%) and electricity demand in summer (−1%). Values of €1.00/m^3 (gas) and €0.25/kWh (electricity) were applied, based on CBS consumption averages and valuation reviews (Teotónio et al., 2021).
- **Health benefits.** Cooling reduces heat-related morbidity and productivity losses. Following Arcadis (2024), each 1% increase in roof coverage avoids 0.167 patients per 1,000 residents. Avoided cases were valued at €917 (treatment) and €6,679 (productivity), reflecting established links between urban greening and health (Raymond et al., 2017).
- **Property value uplift.** By enhancing amenity and liveability, green roofs increase housing values. Benefits were modelled as proportional to roof coverage, multiplied by neighbourhood WOZ values. The Arcadis (2024) tiered schedule was applied, with a linear slope for the first 500 m^2 to capture smaller roofs. Benefits were capped at installation costs to avoid overlap with other categories. The full tier structure is provided in Appendix B.
- **Roof lifespan extension.** By shielding membranes, green roofs extend roof life. A deferred benefit of €45/m^2 was included in year 25, representing avoided replacement costs (Teotónio et al., 2021).

Together, these categories cover the most significant monetised impacts of green roofs in the Dutch policy context, while avoiding double counting. They align with the benefit categories consistently highlighted in systematic reviews of SCBA for NBS (Chelli et al., 2025; Teotónio et al., 2021).

Indicators
Neighbourhood-level outcomes were reported using standard efficiency indicators: NPV), BCR, IRR, and PbP. To assess distributional outcomes, NPV was also expressed per-capita and per-address. Equity was evaluated using Gini coefficients, Lorenz curves, and a need-adjusted NPV that weights benefits by flood and heat vulnerability (see Section 3.4).

Local variation
Although parameters were applied uniformly, outcomes vary substantially between neighbourhoods due to differences in roof suitability, income levels, property values, and climate exposure. This variation allows the analysis to identify where green roofs are most economically viable and where they deliver the greatest equity gains.

3.3.1 Expansion Scenarios

Four expansion scenarios were designed to compare normative strategies with an efficiency-driven optimisation (Table 2). Each assumed that 50% of the technically suitable roof area was converted to green roofs, but allocated the new area differently:

- **Environmental priority:** proportional to composite climate vulnerability (flood + UHI).
- **Income-based:** inversely proportional to neighbourhood income, favouring lower-income areas.
- **Uniform:** proportional to the size of the suitable roof stock.
- **Optimised:** allocation determined by linear programming to maximise marginal NPV.

Table 2: Expansion scenarios for city-wide green roof allocation

Scenario	Principle	Allocation rule (summary)
Environmental priority	Target adaptation need	Proportional to composite flood and UHI exposure.
Income-based	Promote social equity	Inversely proportional to neighbourhood income.
Uniform	Proportionality	Proportional to suitable roof stock.
Optimised	Efficiency	Maximise total marginal NPV (linear programming).

The first three strategies represent different normative priorities (need, equity, proportionality). The optimised scenario reflects a purely efficiency-based approach. Formal allocation rules and optimisation functions are reported in Appendix C.

3.4 City-wide Equity Analysis

To complement the efficiency indicators of the city-wide SCBA, distributional outcomes were evaluated across all neighbourhoods in The Hague. The aim was to assess whether the costs and benefits of green roofs are shared fairly between different parts of the city and whether they accrue in areas with greater adaptation need. This equity assessment is not a separate model, but a reinterpretation of the neighbourhood-level SCBA outcomes through distributive lenses.

Equity indicators
Three complementary indicators were applied (formal definitions in Appendix D):

- **Per-capita and per-address NPV.** Aggregate neighbourhood benefits were normalised by population and dwelling counts, enabling comparison across differently sized neighbourhoods. This captures how much each resident or household effectively benefits from green roof expansion.
- **Inequality metrics.** The Gini coefficient and Lorenz curve were calculated on per-capita NPV to quantify the degree of inequality between neighbourhoods. These measures are widely used in environmental justice and distributive assessments of NBS (Raymond et al., 2017; Vincent et al., 2017).
- **Need-adjusted NPV.** Each neighbourhood's per-capita NPV was weighted by a composite index of flood and UHI exposure, providing an indicator of how far benefits align with areas of highest climate vulnerability.

Interpretation

Together, these indicators provide a multidimensional view of equity: they show the scale of benefits per resident, the degree of inequality between neighbourhoods, and the extent to which benefits flow to vulnerable areas. This approach follows recent recommendations to integrate SCBA outcomes with spatial equity metrics (Chelli et al., 2025). Formal definitions and functional forms are provided in Appendix D. These indicators were applied consistently across all four expansion scenarios, allowing a comparative assessment of how different allocation strategies perform on both efficiency and equity.

3.5 Clustering Analysis

Clustering was applied to the city-wide SCBA *results* in order to identify systematic patterns and select representative neighbourhoods for detailed PC5-level analysis. This step bridges the aggregate assessment with the neighbourhood case studies, ensuring that local analyses capture the diversity of contexts across The Hague.

Purpose

The clustering had two objectives:

1. To classify neighbourhoods into typologies that reflect different combinations of economic efficiency, social conditions, and climate vulnerability.
2. To select four representative neighbourhoods (one from each cluster) for detailed SCBA at PC5 scale.

Feature selection

Four standardised indicators were chosen to reflect both efficiency and equity considerations:

- **Per-capita NPV (income-based scenario):** captures economic efficiency while incorporating socio-economic weighting.
- **Average SES score:** represents socio-economic context and equity concerns.
- **Composite climate vulnerability (flood + UHI):** measures adaptation need.
- **Green roof adoption rate:** indicates the baseline level of uptake and saturation.

The income-based allocation scenario was selected as the SCBA input because it explicitly accounts for socio-economic differences and performed best on equity indicators (see Section 3.4).

Clustering procedure

K-means clustering was applied using `scikit-learn` (**macqueenSomeMethodsClassification1967**). The number of clusters was determined by comparing three diagnostics (Elbow curve, mean silhouette score, silhouette profiles). All indicated that $k = 4$ provided a parsimonious solution, balancing interpretability with separation between groups. Detailed diagnostic plots are included in Appendix **??**.

Cluster interpretation and case selection

Inspection of cluster centroids yielded four distinct typologies:

1. **High Gain–Equity**: above-average per-capita NPV, relatively equitable distribution, and moderate vulnerability.
2. **Low Uptake–Stable**: low adoption but stable socio-economic conditions and moderate-to-low vulnerability.
3. **High Risk–Reward**: high climate vulnerability and socio-economic disadvantage combined with relatively high potential NPV.
4. **Low Return–Saturated**: high existing adoption and limited additional potential, leading to lower marginal returns.

These categories provide an analytical typology rather than normative labels. From each cluster, the neighbourhood closest to its centroid was selected as the representative case for detailed PC5-level SCBA (Section 3.6). This ensured that the case studies reflect the diversity of contexts across The Hague while keeping the scope manageable.

3.6 Neighbourhood SCBA (PC5-level)

To capture intra-neighbourhood variation and distributional mechanisms, detailed SCBAs were conducted for four representative neighbourhoods identified through clustering (Section 3.5). These neighbourhoods were decomposed into PC5 units, which provide a finer spatial resolution than CBS neighbourhoods while still aligning with available socio-economic and housing data. This level of detail makes it possible to assess who benefits most within a neighbourhood, across different tenure groups.

Reference case and intervention

As in the city-wide analysis, the reference case was defined as The Hague without any green roofs. Two situations were then evaluated for each representative neighbourhood:

1. **Current stock:** the costs and benefits of all existing green roofs at PC5 scale, compared to the reference case.
2. **Expansion scenario:** a uniform addition of 50% of the remaining technically suitable roof area in each PC5, capped at technical capacity. New green roof area was distributed across housing types in proportion to their current roof stock.

Disaggregation by housing type

To reveal intra-neighbourhood distributional effects, all costs and benefits were split across three housing tenure groups:

- Owner-occupied dwellings (*koop*),
- Private rental dwellings (*huur particulier*),
- Social rental dwellings (*huur corporatie*).

This allows assessment of whether public investment in green roofs disproportionately benefits certain tenure groups.

Cost categories

The same two cost categories as in the city-wide SCBA were applied, but disaggregated by tenure:

- **Installation costs (CAPEX):** €75/m^2 for all newly greened roof area, differentiated by PC5 unit and housing type.
- **Maintenance costs (OPEX):** €1.50/m^2/year for ongoing upkeep, discounted over the 40-year horizon.

Benefit categories

The same five monetised benefits as in the city-wide SCBA were included, but with finer-grained indicators and tenure disaggregation:

- **Flood damage avoided:** retention of 0.03 m^3/m^2 multiplied by avoided damages of €500/m^3, applied to new roof area at PC5 level.
- **Energy savings:** based on interpolated household gas and electricity consumption from PC4 to PC5, adjusted for dwelling counts and allocated by housing type.
- **Health benefits:** refined relative to the city-wide model by incorporating local UHI exposure and population structure. Medical benefits were linked to the elderly population, and productivity benefits to the working-age population and household income levels.
- **Property value uplift:** applied using local WOZ values per dwelling, with the Arcadis (2024) tiered schedule. A linear slope was used for the first 500 m^2 to capture variation in smaller roofs. Benefits were capped at installation costs and split by housing type.
- **Roof lifespan extension:** deferred benefit of €45/m^2 in year 25, disaggregated by housing type.

Indicators

Outputs were expressed using the same efficiency indicators as in the city-wide analysis (NPV, BCR, IRR, and PbP), but calculated separately for each tenure group and aggregated to neighbourhood level. This dual reporting provides both a neighbourhood-level economic assessment and a disaggregated view of who gains within each neighbourhood.

Local variation
The PC5-level analysis allows differentiation not only between neighbourhoods but also within them. By combining spatial variation in UHI exposure, property values, and socio-economic composition with tenure-specific disaggregation, the model captures whether certain housing groups systematically benefit more or less from green roof investments.

3.7 Neighbourhood Equity Analysis

Equity analysis was also conducted for the detailed neighbourhood SCBAs at PC5 scale. Whereas the city-wide analysis compared outcomes *between* neighbourhoods, the local equity analysis focused on disparities *within* neighbourhoods, across housing types. The aim was to assess how benefits and costs are distributed among owners, private renters, and social renters under the same intervention.

Equity indicators
Three complementary indicators were applied at the PC5 level:

- **NPV by housing type.** Costs and benefits were disaggregated for owner-occupied, private rental, and social rental dwellings, providing a direct measure of which groups gain or lose economically.
- **Within-neighbourhood inequality.** Gini coefficients of per-capita NPV across housing types were calculated to capture how evenly outcomes are distributed locally.
- **Benefit shares.** The proportion of total benefits accruing to each housing type was tracked, highlighting which groups are favoured under the intervention.

Interpretation
This disaggregated equity assessment enables comparison of efficiency and fairness at a finer spatial scale, complementing the city-wide results. It reflects recent work emphasising that social housing and tenure structure are central to distributive justice in NBS implementation (Anguelovski et al., 2022; Weißermel & Wehrhahn, 2024). Formal indicator definitions are provided in Appendix D.

3.8 Uncertainty and Sensitivity Analysis

To test the robustness of results, the SCBA models were embedded in an exploratory modelling framework and systematically re-run under parameter uncertainty. This step ensures that conclusions about efficiency and equity are not artefacts of specific parameter choices, but hold across plausible ranges.

Approach
The analysis used the `EMA Workbench` Python package (Bankes, 1993; Kwakkel, 2017, 2023), which combines Monte Carlo–style sampling with global sensitivity analysis. The procedure involved three steps:

1. Define uncertain parameters and their ranges, based on literature values and $\pm 10\%$ bands around baseline assumptions.
2. Generate random draws using LHS, ensuring efficient coverage of the multidimensional uncertainty space.
3. Recompute the full SCBA for each draw, storing both efficiency indicators (e.g. mean NPV, BCR) and equity indicators (e.g. Gini coefficient of per-capita NPV).

Uncertain parameters
Uncertain inputs included:

- **Costs:** installation and maintenance costs,
- **Physical performance:** stormwater retention, avoided flood damages, energy savings,
- **Socio-economic parameters:** health coefficients, productivity effects, property value uplifts,
- **Discounting and timing:** discount rate, lifespan benefit year.

These ranges reflect both empirical variation reported in the literature and the inherent uncertainty of future socio-economic and climate conditions.

City-wide experiments
At neighbourhood level, the four allocation scenarios (Environmental, Income-based, Uniform, Optimised; Section 3.3.1) were each re-evaluated under $N = 500$ random draws. This sample size was chosen as a balance between robustness of results and computational feasibility. Outputs included distributions of mean NPV, BCR, Gini coefficients, and neighbourhood-level NPVs. Sensitivity analysis was conducted using rank correlations, ANOVA F-statistics (tornado plots), and Partial Dependence Plots (PDPs), highlighting which parameters most strongly influence results.

Neighbourhood-specific experiments
At PC5 level, uncertainty analysis was applied to the four representative neighbourhoods. Instead of allocation strategies, four policy scenarios were tested (10%, 25%, 50%, and 75% of suitable roof area greened). For each scenario, $N = 500$ random parameter draws were performed. As in the city-wide analysis, this sample size was selected to ensure robust coverage of parameter space while remaining computationally feasible. Outputs were disaggregated by housing type (owner-occupied, private rental, social rental), allowing evaluation of intra-neighbourhood equity under uncertainty. Results were summarised using comparative boxplots, tornado plots, and uncertainty maps of mean and standard deviation of per-capita NPV.

Purpose
By combining uncertainty quantification with global sensitivity analysis, this step identifies which assumptions are most critical for outcomes and which policy strategies remain robust under uncertainty. The results strengthen the validity of the SCBA and support prioritisation of parameters for future data collection.

4

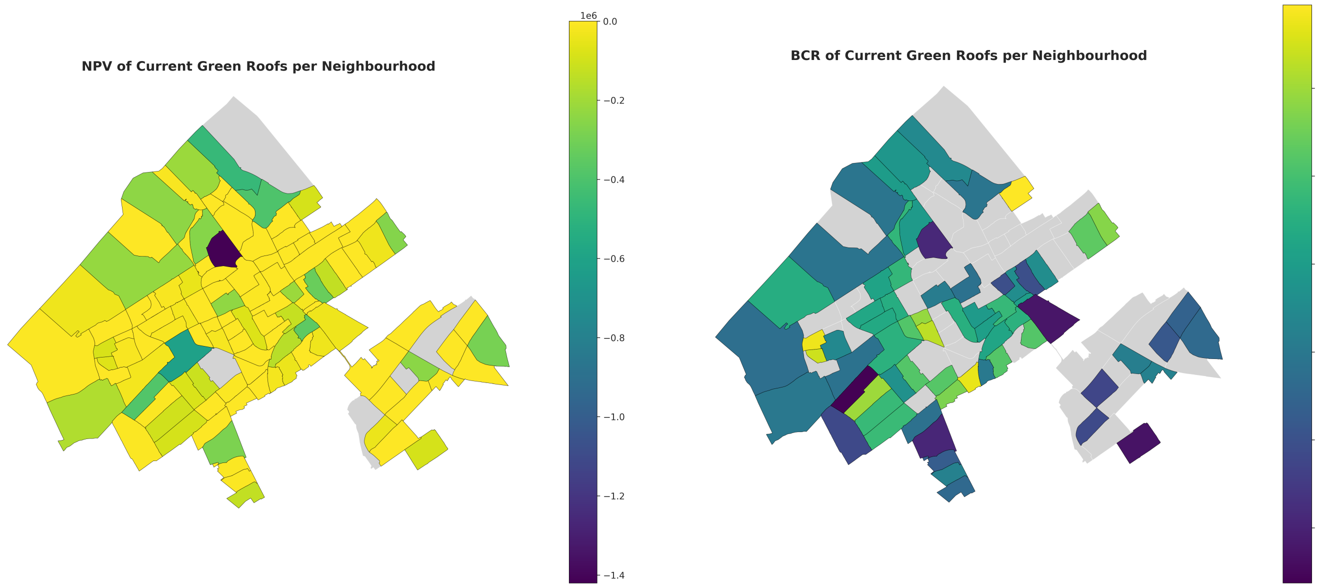
Results

4.1 City-wide SCBA Results

4.1.1 Current Green Roofs

Across The Hague, the current stock of green roofs covers approximately 323,000 m^2. From a societal perspective, this current situation is not economically viable: no neighbourhood achieves a benefit–cost ratio above 1, and most record slightly negative net present values (NPVs). This outcome reflects the combination of high upfront installation costs and limited aggregate benefits, given the still modest scale of adoption.

Figure 3 shows the spatial distribution of outcomes. Negative NPVs are particularly evident in affluent, low-density neighbourhoods, where fewer households share the costs of installation and collective benefits are limited. In contrast, denser, mixed-income districts approach break-even more closely because the benefits are spread across more dwellings (panel a). Benefit–cost ratios cluster well below unity (panel b), though some central and peripheral areas come relatively closer to break-even. Detailed statistics and excluded neighbourhoods are reported in Appendix A.



(a) NPV map

(b) BCR map

Figure 3: Spatial distribution: (a) neighbourhood-level NPV, (b) neighbourhood-level BCR. Negative NPVs are widespread, and no neighbourhood achieves a BCR above 1.

Overall, the current situation confirms that existing green roofs do not yet deliver positive societal returns. This underscores the importance of evaluating expansion strategies: the question is not whether green roofs are viable at current scale, but under which allocation strategies they could become both economically viable and socially equitable.

4.1.2 Expansion Scenarios

Table 3 summarises aggregate outcomes for the four expansion strategies. All three broad allocation strategies (*Uniform*, *Income-based*, and *Environmental*) assume the same additional area (1.94 million m^2), while the *Optimised* strategy selects a smaller subset (0.80 million m^2) to maximise returns.

Across the broad allocations, mean neighbourhood NPVs increase from €−0.08 million to between €0.18 and €0.26 million, and around two thirds of neighbourhoods surpass the break-even threshold. This pattern underlines that socio-economic structure matters: compact, lower-income districts concentrate more people beneath the same roof area, so every square metre of green roof delivers relatively more cooling, health, and energy benefits per euro invested. In contrast, wealthier, low-density areas with larger dwellings benefit less from collective non-market effects, making green roofs less financially attractive despite high roof potential. By contrast, the Optimised strategy yields very high benefit–cost ratios in a small set of neighbourhoods, but leaves most others unchanged, with only 18% above break-even. A striking result is that the Optimised allocation achieves this despite using less than half the green roof area of the other strategies. It therefore delivers "more with less" in efficiency terms, but only for a few locations, making it highly exclusionary.

Table 3: Summary statistics for the current situation and four expansion scenarios. NPVs in millions of 2023 euros.

Scenario	Total area (m^2)	Mean NPV	Median NPV	% BCR $>$ 1	NPV range
Current	323,333	−0.078	−0.007	0	−1.42−0.00
Uniform	1,937,193	0.182	0.158	67	−5.61−1.35
Income-based	1,937,193	0.260	0.185	66	−1.29−0.96
Environmental	1,937,193	0.192	0.192	66	−5.56−1.62
Optimised	797,624	0.125	0.000	18	0.00−1.73

Figures 4, 5, and 6 show the spatial imprint of the four strategies. The broad allocations lift outcomes across most neighbourhoods, though with different emphases: the Income-based allocation favours southern and western districts, the Environmental allocation aligns more with vulnerable areas, and the Uniform approach spreads benefits widely. The Optimised scenario leaves most neighbourhoods untouched but delivers very high returns in the few areas where investments are concentrated.

Figure 4: Neighbourhood-level NPV under the four expansion scenarios.

This makes clear that Optimised allocation can produce exceptional local returns, while Income-based and Environmental strategies perform best when city-wide equity and broader coverage are desired.

Overall, the expansion analysis highlights a fundamental trade-off: *broad allocations* (Uniform, Income-based, Environmental) generate widespread though moderate improvements, while the *Optimised* allocation maximises efficiency locally but sacrifices coverage and equity. This trade-off becomes even clearer when examining inequality

Figure 5: Neighbourhood-level BCR under the four expansion scenarios.

Figure 6: Incremental ΔNPV relative to the Current situation under the four expansion scenarios.

and need alignment in the next section.

4.1.3 City-wide Equity Results

To complement the efficiency outcomes of the city-wide SCBA, this section evaluates how benefits and costs are distributed across neighbourhoods and whether they align with adaptation need. Three sets of indicators are presented: inequality (Gini coefficients), cumulative distribution (Lorenz curves), and need alignment.

Inequality (Gini)

Figure 7 presents the Gini coefficients of $NPV^{\text{per capita}}$ across neighbourhoods. Values range between 0.53 and 0.94, highlighting strong variation in the evenness of outcomes. The *Income-based* allocation yields the lowest inequality ($G \approx 0.53$), followed by *Uniform* ($G \approx 0.62$) and *Environmental* ($G \approx 0.65$). In practice, this means that investments in denser, lower-income southern districts spread returns across many households, while Optimisation concentrates spending in high-value, low-density areas where property uplift is large but the number of beneficiaries is small. This leads to very unequal per-capita outcomes. By contrast, the *Optimized* allocation shows very high inequality ($G \approx 0.94$), as benefits concentrate in a few neighbourhoods while most remain unchanged.

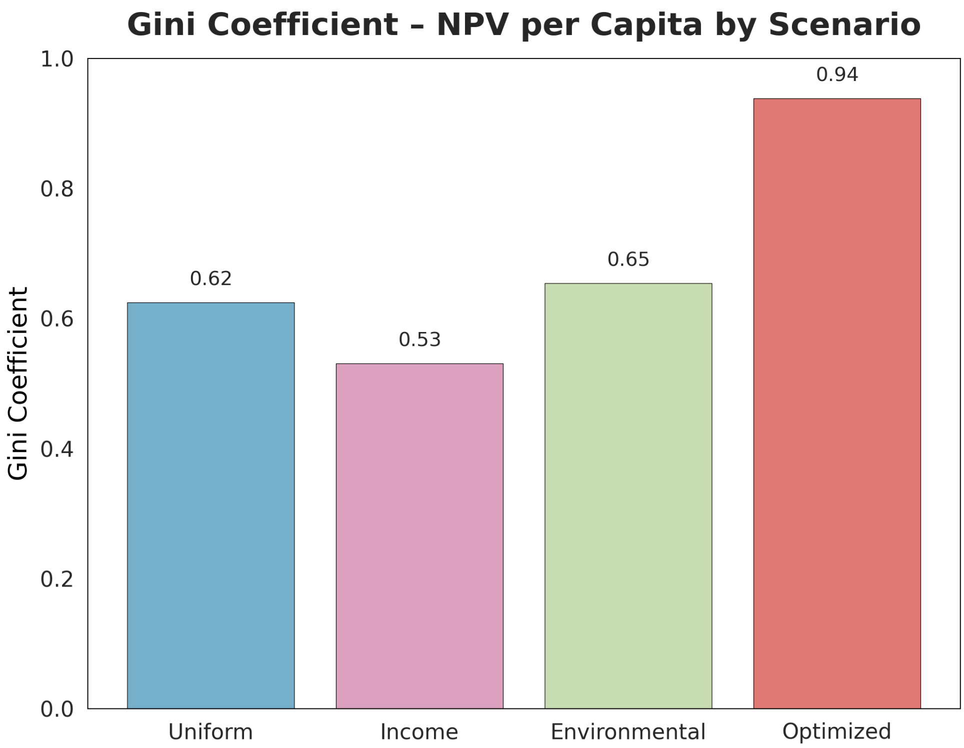


Figure 7: Gini coefficient of $NPV^{\text{per capita}}$ by scenario. Lower values indicate a more even distribution of per-capita benefits across neighbourhoods.

This confirms that inequality is lowest when investments are directed by income, while efficiency-driven optimisation amplifies disparities to extreme levels.

Cumulative distribution (Lorenz)

Lorenz curves in Figure 8 illustrate how per-capita benefits accumulate across the city. The *Income-based* strategy lies closest to the equality line, confirming its more balanced distribution of outcomes. *Uniform* and *Environmental* strategies follow similar but more unequal paths, while the *Optimized* scenario deviates furthest, indicating highly concentrated benefits.

The gap between the Income-based curve and the Optimised curve underlines the core trade-off: balancing broad fairness versus concentrating benefits in a few areas.

Need alignment

Table 4 and Figure 9 present results weighted by neighbourhood climate vulnerability (flood and UHI exposure). Only the *Income-based* and *Optimized* allocations achieve positive need-weighted outcomes (€45 and €61 per capita).

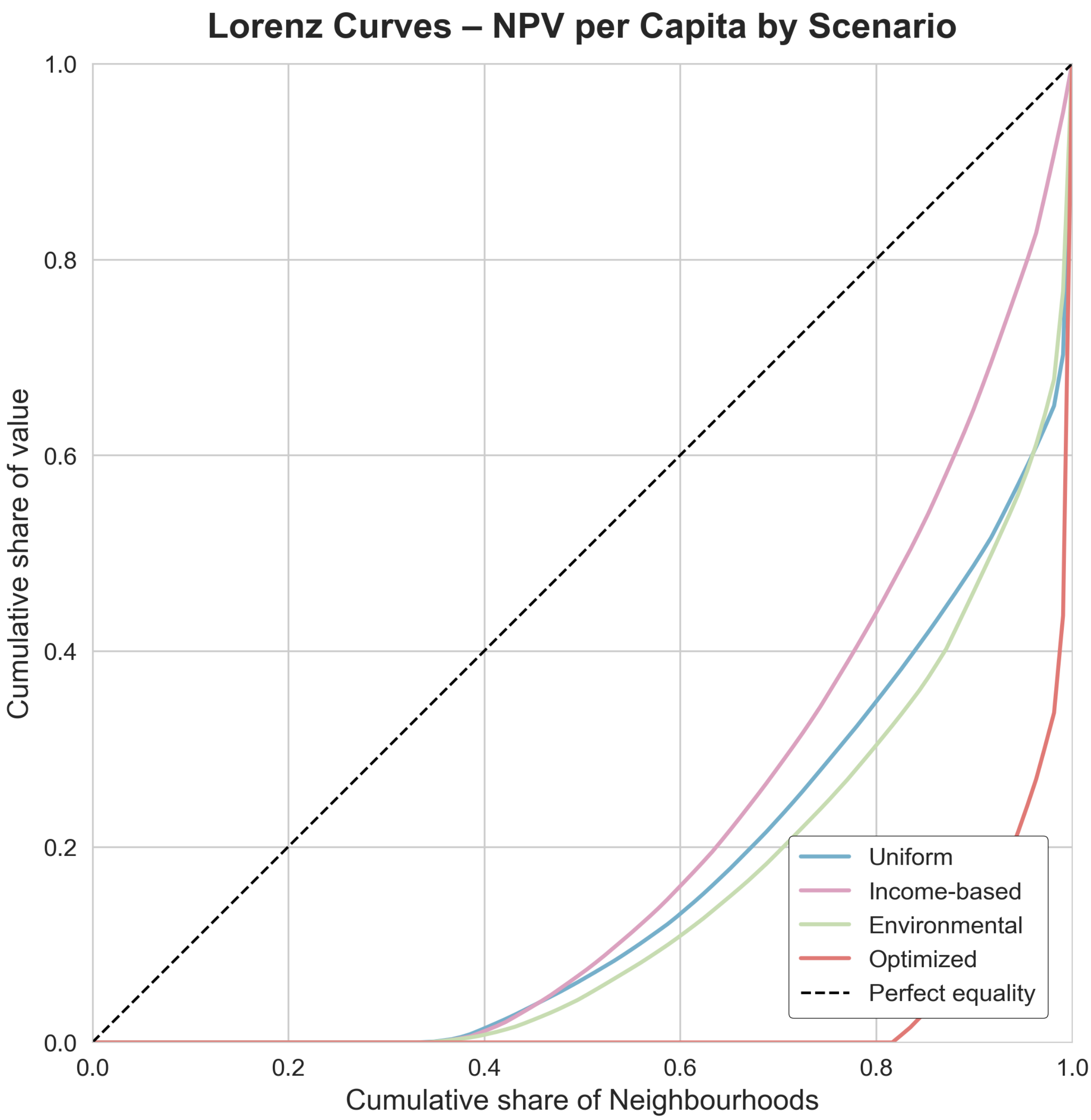


Figure 8: Lorenz curves of $NPV^{\text{per capita}}$ by scenario. The 45° line indicates perfect equality. Greater bowing of the curve represents higher inequality in the distribution of benefits.

Uniform and *Environmental* allocations remain negative (−€916 and −€881), meaning that they do not systematically prioritise vulnerable areas.

Table 4: Need-aligned performance using climate vulnerability as weights (values in euro per capita). $\Delta NPV^{\text{per capita}}$ indicates the change relative to the current situation.

Scenario	**Weighted mean (€ per capita)**	
	$NPV^{\text{per capita}}$	$\Delta NPV^{\text{per capita}}$ (vs. current situation)
Uniform	−€916	−€824
Income-based	€45	€137
Environmental	−€881	−€789
Optimized	€61	€153

Interestingly, both the Income-based and the Optimised allocations improve alignment with vulnerability, but through very different mechanisms: the former by targeting disadvantaged areas, the latter by chance overlap between efficiency "hotspots" and vulnerable neighbourhoods.

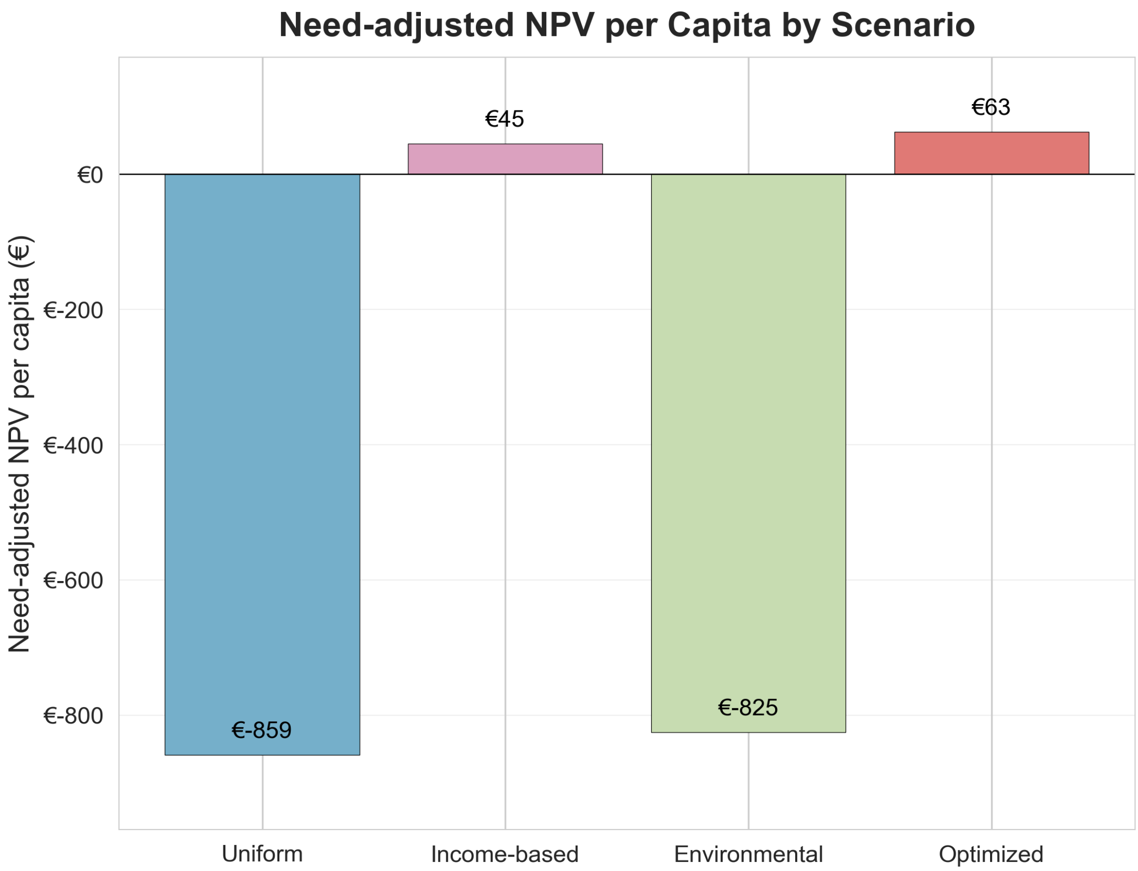


Figure 9: Climate-vulnerability–weighted $NPV^{\text{per capita}}$ by scenario. Bars show weighted means; labels report values in euros per capita.

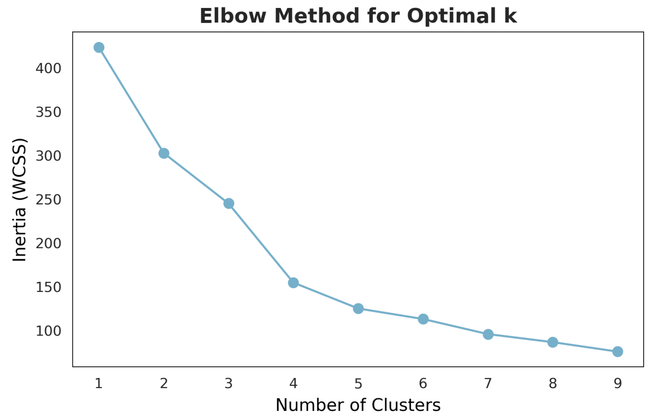
Interpretation
Taken together, these results show a clear efficiency–equity trade-off. The *Income-based* allocation stands out as the only strategy that combines lower inequality with positive alignment to vulnerability, suggesting that targeting denser, lower-income areas can improve both fairness and efficiency. By contrast, the *Optimized* allocation achieves the highest need-weighted performance but does so by concentrating benefits in just a few neighbourhoods, producing extreme inequality elsewhere. Strikingly, the *Uniform* and *Environmental* allocations not only fail to prioritise vulnerable areas but also perform worse than the current situation once outcomes are adjusted for climate risk. These findings highlight the central tension between maximising aggregate returns and ensuring that benefits flow to those most in need. To explore how such trade-offs manifest in different local contexts, the next section introduces clustering of neighbourhood outcomes.

4.2 Clustering Results

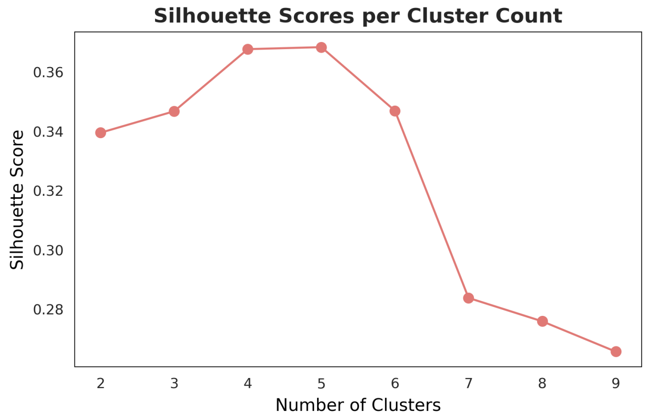
Clustering was applied to the city-wide SCBA outcomes to identify systematic neighbourhood typologies and to select representative cases for detailed PC5-level analysis. This step connects the aggregate city-wide perspective with the neighbourhood-specific results, ensuring that local analyses reflect the diversity of contexts across The Hague.

4.2.1 Cluster diagnostics

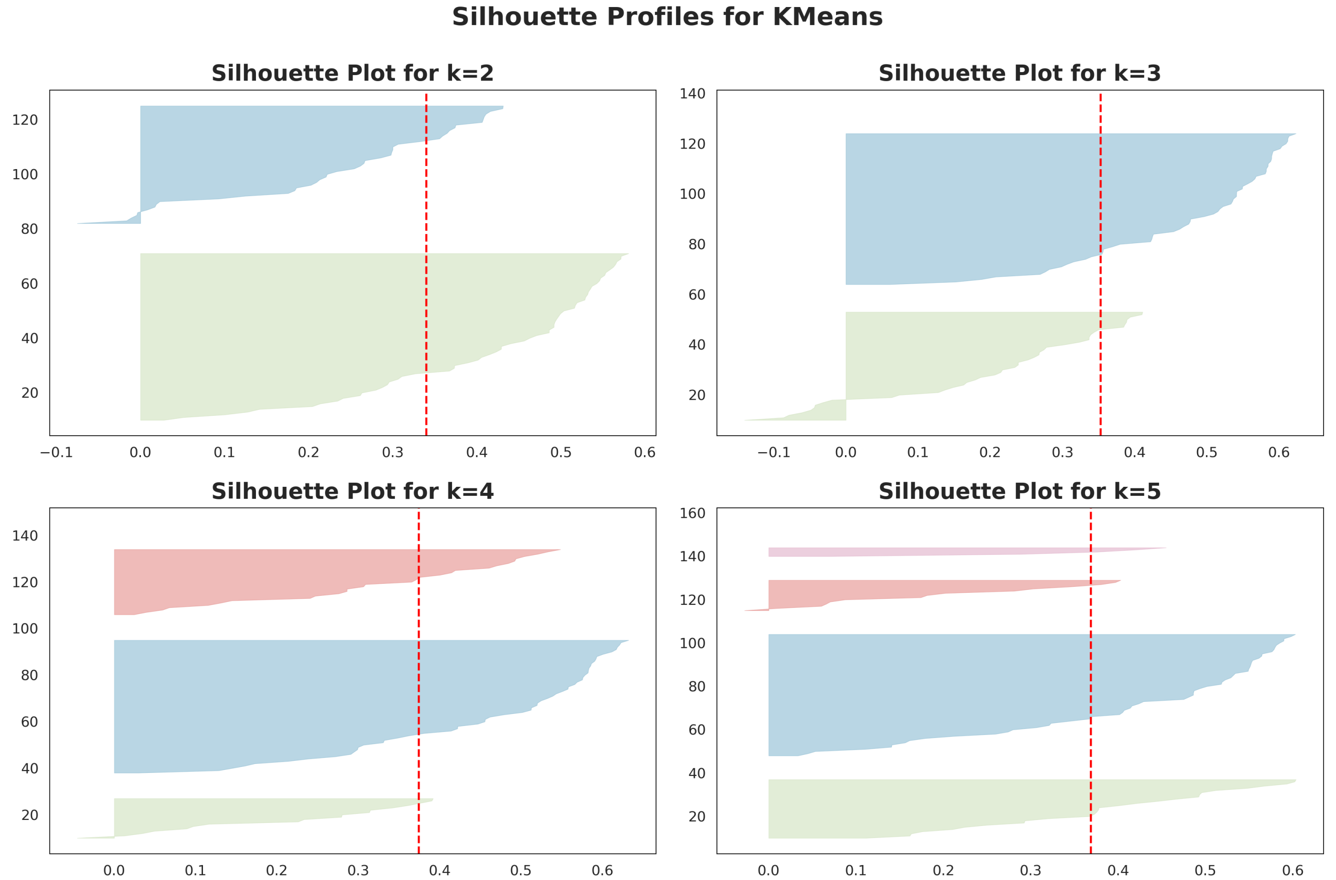
The optimal number of clusters was determined by comparing three diagnostics: the Elbow criterion, mean silhouette scores, and silhouette profile plots. All indicated that $k = 4$ provided the most parsimonious solution, balancing interpretability with separation between groups. The diagnostic outputs are shown in Figure 10.



(a) Elbow: diminishing returns after $k = 4$.



(b) Mean silhouette: near-maximum at $k = 4$–5.



(c) Silhouette profiles: $k = 4$ yields compact, well-separated clusters; $k = 5$ introduces a small low-quality group.

Figure 10: Clustering diagnostics supporting $k = 4$ as the most parsimonious solution.

4.2.2 Cluster typologies

Inspection of centroid profiles yielded four distinct cluster types:

1. **High Gain–Equity**: above-average per-capita NPV, relatively equitable outcomes, and moderate vulnerability.
2. **Low Uptake–Stable**: low adoption but stable socio-economic conditions and moderate-to-low vulnerability.
3. **High Risk–Reward**: high climate vulnerability and socio-economic disadvantage combined with relatively high potential NPV.
4. **Low Return–Saturated**: high existing adoption and limited additional potential, resulting in lower marginal returns despite favourable socio-economic conditions.

To contextualise the clustering, Figure 11 shows the spatial distribution of the four variables used as inputs: per-capita NPV, SES score, climate vulnerability, and adoption rate.

Figure 11: Spatial distribution of the four clustering variables: (i) per-capita NPV, (ii) SES score, (iii) climate vulnerability (flood + UHI), and (iv) share of roof area already greened. These variables defined the cluster centroids and underpin the typology interpretation.

4.2.3 Spatial distribution and case selection

The spatial distribution of clusters across The Hague is shown in Figure 12. High Gain–Equity neighbourhoods are mainly located in central mixed-income areas, Low Uptake–Stable areas in peripheral districts, High Risk–Reward in the vulnerable south, and Low Return–Saturated in affluent zones with already high adoption.

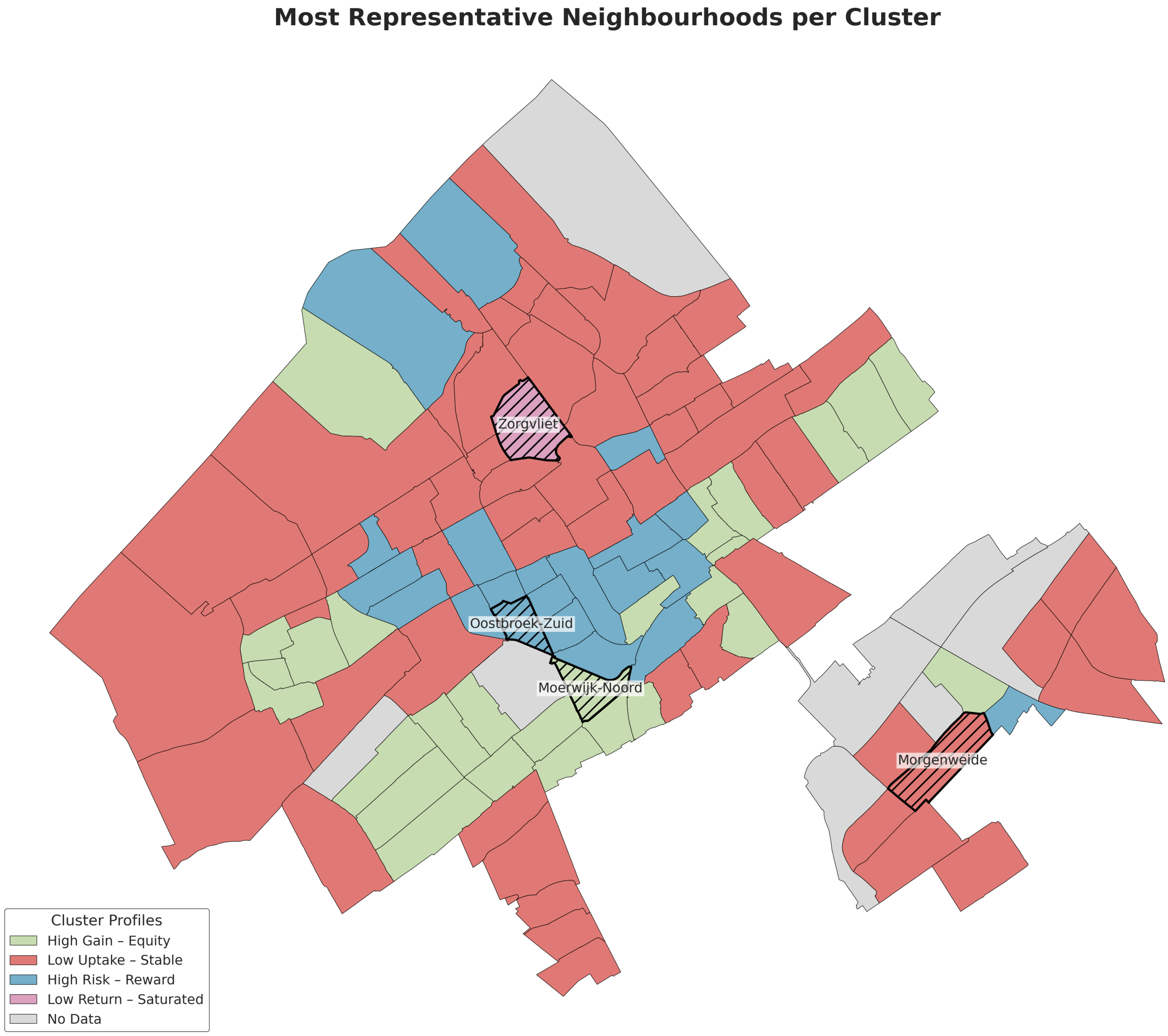


Figure 12: Cluster membership across The Hague. Hatched polygons mark the four representative neighbourhoods selected for detailed PC5-scale SCBA.

From each cluster, the neighbourhood closest to its centroid was selected as the representative case: *Zorgvliet* (Low Return–Saturated), *Oostbroek-Zuid* (High Gain–Equity), *Moerwijk-Noord* (High Risk–Reward), and *Morgenweide* (Low Uptake–Stable). These serve as the focus for the neighbourhood-specific SCBA in Section 3.6.

4.3 Neighbourhood SCBA Results (PC5-level)

To complement the city-wide results, detailed SCBAs were conducted for four representative neighbourhoods identified through clustering: *Zorgvliet*, *Oostbroek-Zuid*, *Moerwijk-Noord*, and *Morgenweide*. These cases capture diverse socio-spatial contexts in The Hague, enabling a closer look at how local characteristics shape economic outcomes.

A key finding is that dense, mixed-income areas such as *Oostbroek-Zuid* and *Moerwijk-Noord* consistently perform better in per-household terms, while affluent or peripheral areas (*Zorgvliet*, *Morgenweide*) face the largest losses despite their high roof potential.

4.3.1 Neighbourhood Decomposition into PC5 Units

To enable the detailed SCBA at a finer spatial scale, neighbourhoods were decomposed into CBS PC5 units. Because PC5 geometries do not align perfectly with administrative neighbourhood boundaries, a refinement procedure was applied. First, PC5 polygons were intersected with neighbourhood boundaries to ensure consistent spatial units.

Second, polygons were excluded if they lay largely outside the target boundary or contained very few households. This ensured that only representative PC5 units were retained while avoiding spurious or marginal cases.

Figure 13 illustrates the procedure for the four representative neighbourhoods. Green areas indicate PC5 units retained for analysis, while striped areas show excluded polygons. The figure highlights how refinement removes peripheral or low-population units, ensuring robust alignment with administrative boundaries.

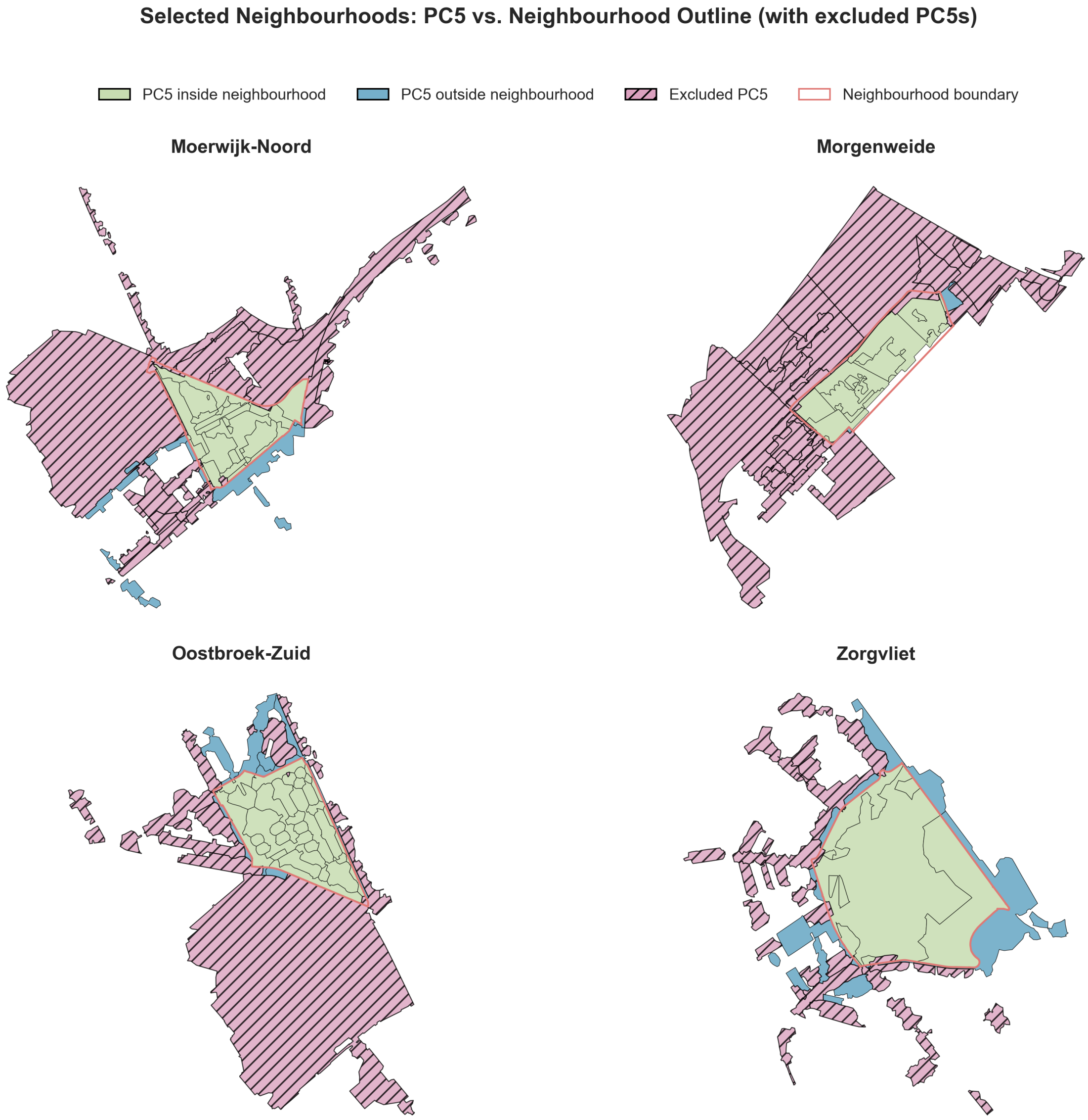


Figure 13: Neighbourhood decomposition into PC5 units. Green polygons show included PC5 units inside the neighbourhood boundary, blue polygons PC5 units outside the boundary, and hatched areas excluded PC5s. The refinement procedure ensures consistent and representative units for the detailed SCBA.

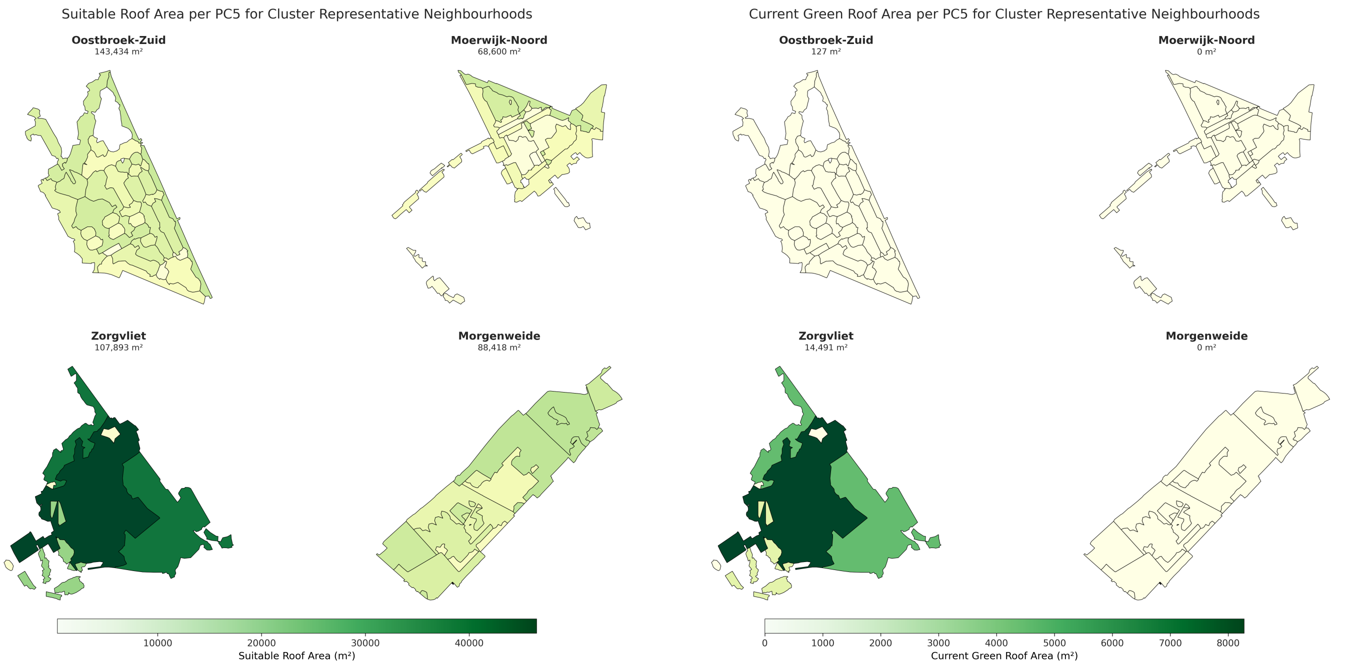
4.3.2 Profiles and Potentials

Table 5 summarises housing and roof characteristics. *Zorgvliet* is affluent and low-density, with the largest roof potential per household. *Oostbroek-Zuid* and *Moerwijk-Noord* are denser, mixed-income areas, offering large collective potential but smaller roofs per dwelling. *Morgenweide*, at the urban fringe, has intermediate density and moderate per-household potential.

Figure 14 compares technically suitable roof area with current adoption. Despite high potentials, realised adoption is negligible in three of the four cases; only *Zorgvliet* has a modest stock of existing green roofs. This mismatch between capacity and uptake illustrates the untapped scope of expansion.

Table 5: Neighbourhood statistics at PC5 level

Neighbourhood	Households	Current GR (m²)	Suitable roof (m²)	50% expansion (m²)
Zorgvliet	1,210	14,491	107,893	46,702
Oostbroek-Zuid	3,540	127	143,434	71,653
Moerwijk-Noord	2,870	0	68,600	34,300
Morgenweide	2,050	0	88,418	44,209



(a) Suitable roof area

(b) Current green roof area

Figure 14: Comparison of (14a) technically suitable roof area and (14b) current green roof adoption at PC5 level.

4.3.3 Economic Outcomes

Under the uniform 50% expansion scenario, each neighbourhood would convert half of its technically suitable roof stock into green roofs (Figure 15). Expansion ranges from 34,000 m² in *Moerwijk-Noord* to over 70,000 m² in *Oostbroek-Zuid*.

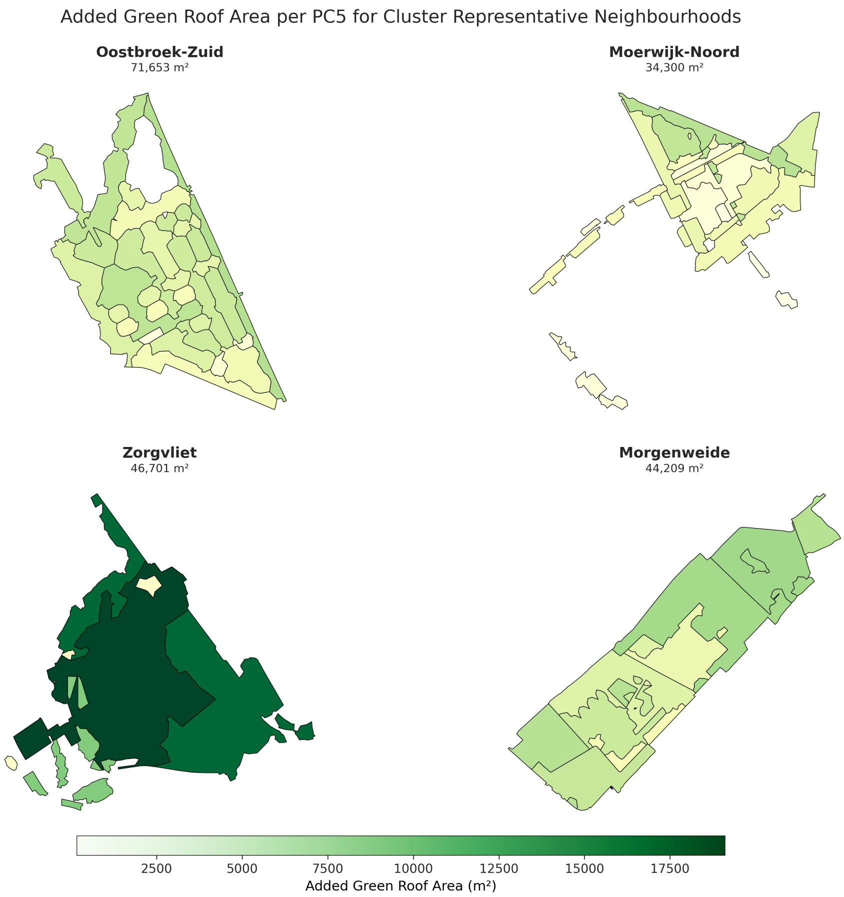


Figure 15: Allocated green roof area under the uniform 50% expansion scenario at PC5 level.

SCBA results (Table 6) show that all four neighbourhoods record negative NPVs, confirming that expansion is not societally profitable under current assumptions. Yet differences are notable: *Zorgvliet* suffers the largest aggregate losses (−€2.9m), while *Morgenweide* bears the heaviest per-household burden (−€935/HH). By contrast, denser *Oostbroek-Zuid* and *Moerwijk-Noord* show smaller per-household deficits (−€350 to −€515), because costs are spread across more households.

Table 6: SCBA results under the uniform 50% expansion scenario

Neighbourhood	Total NPV (€)	NPV/HH (€)	BCR	IRR (%)
Zorgvliet	−2,890,000	−2,390	0.41	−4.3
Oostbroek-Zuid	−1,250,000	−350	0.56	−3.2
Moerwijk-Noord	−1,480,000	−515	0.52	−3.7
Morgenweide	−1,920,000	−935	0.47	−3.9

Interpretation

These contrasts underscore the importance of density and roof stock. Affluent, low-density areas accumulate high property-related benefits but still record large net losses. Denser, mixed-income areas distribute costs more evenly, mitigating per-household losses. Peripheral areas like *Morgenweide* face the worst relative outcomes, as limited property values and moderate densities constrain benefits. This difference reflects socio-economic contrasts: in *Zorgvliet*, large detached homes with high property values capture uplift benefits, but the small population base means that health and energy co-benefits are limited. Conversely, in *Moerwijk-Noord* and *Oostbroek-Zuid*, dense rental blocks and mixed-income populations spread costs thinly, so per-household losses are smaller even if aggregate NPVs remain negative.

4.3.4 Benefit Composition

Figure 16 shows the breakdown of monetised benefits. Patterns mirror socio-economic profiles: *Zorgvliet* is dominated by property value uplift; *Oostbroek-Zuid* and *Moerwijk-Noord* rely more on energy and health benefits; *Morgenweide* exhibits a balanced but low-level mix.

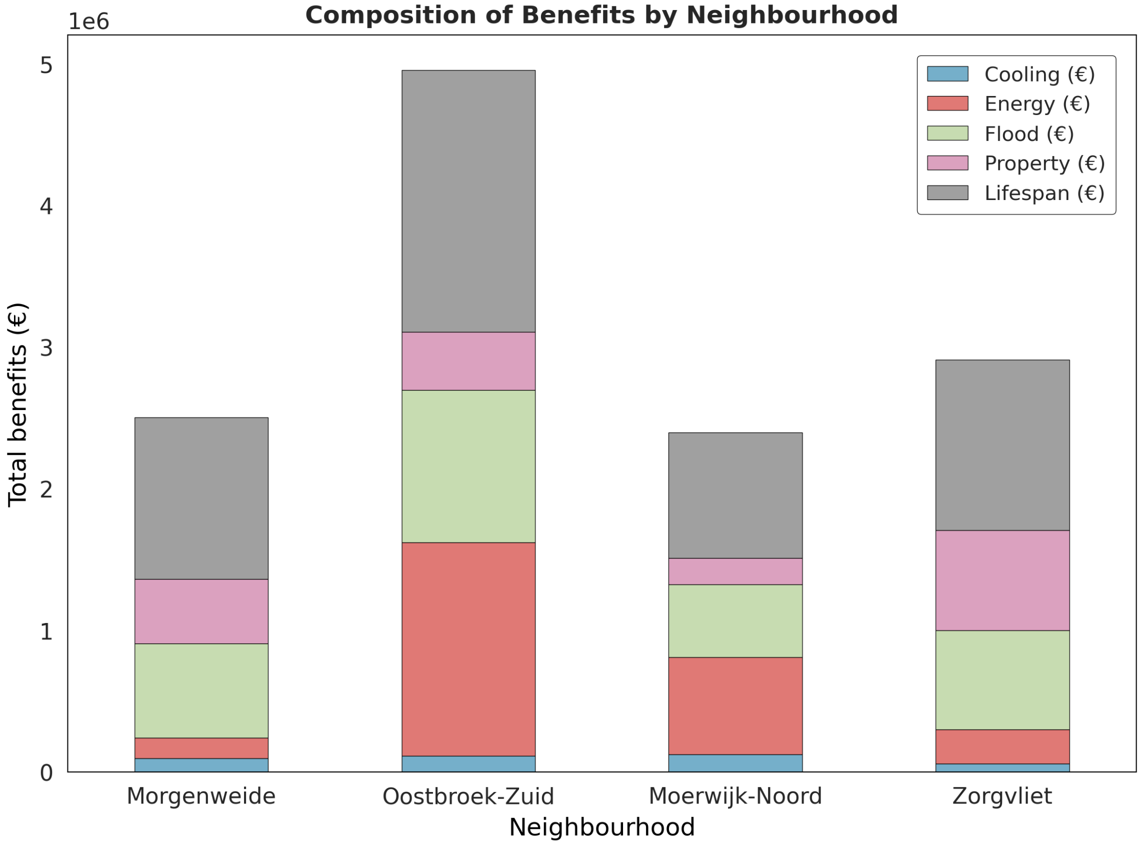


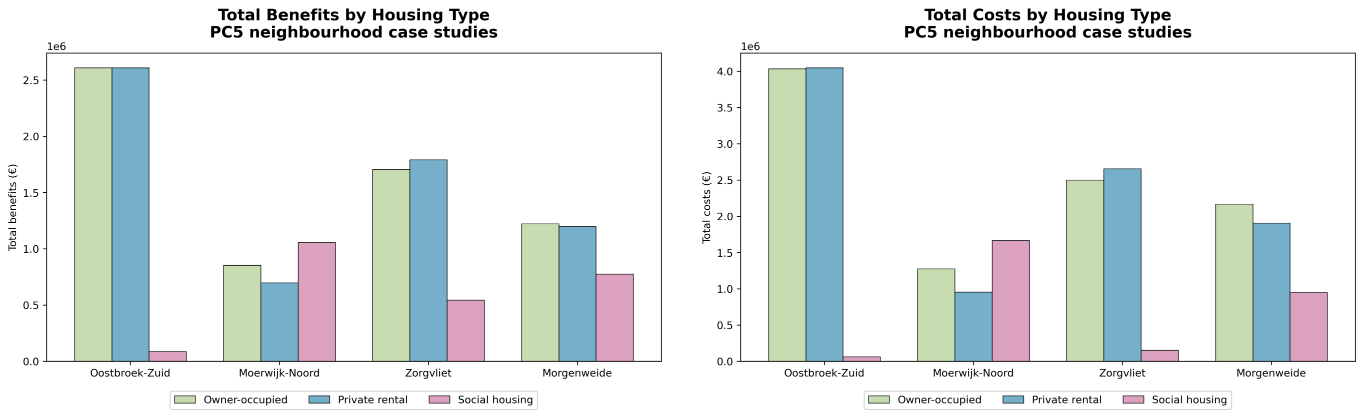
Figure 16: Composition of benefits (flood, energy, health, property, lifespan) for the four case study neighbourhoods under the uniform 50% expansion scenario.

Interpretation
Benefit structures explain cost–benefit variation: high-value areas gain from property markets, while denser areas derive more from collective non-market benefits (health, energy). Yet in all cases, benefits remain too small to outweigh costs.

4.3.5 Neighbourhood Equity Results

Beyond aggregate outcomes, the neighbourhood SCBA at PC5 level allows assessment of who benefits and who bears the costs. This section evaluates equity across tenure groups (owner-occupied, private rental, social rental) and within-neighbourhood inequality.

Distribution by housing type
Figures 17 and 18 show how benefits and costs are distributed across tenure groups. In most neighbourhoods, costs outweigh benefits, but patterns differ: in *Zorgvliet*, losses concentrate in the owner-occupied and private rental stock, with little effect on social housing; in *Oostbroek-Zuid*, high costs dominate across all tenures; in *Moerwijk-Noord*, social housing bears a disproportionate share of losses; and in *Morgenweide*, all tenures record net losses of similar magnitude.



(a) Total benefits

(b) Total costs

Figure 17: Distribution of (a) benefits and (b) costs by housing type across the four case study neighbourhoods under the uniform 50% expansion scenario.

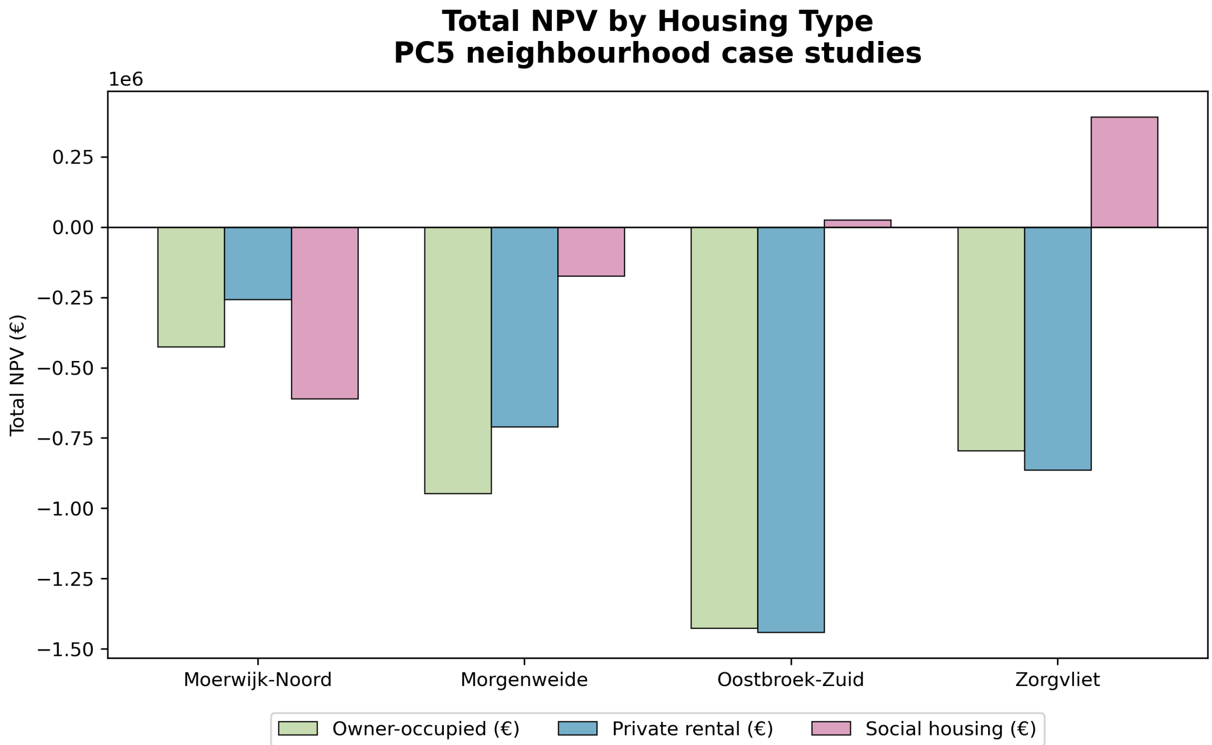


Figure 18: NPV by housing type in the four case study neighbourhoods under the uniform 50% expansion scenario.

Robustness to property value assumptions

Figure 19 compares the results of the current situation with an alternative specification where property value uplift is only attributed to homeowners. The shift shows that much of the apparent benefit to tenants arises from treating property value effects as societal benefits. When these are excluded, renter outcomes become more negative, highlighting how modelling assumptions influence distributional results.

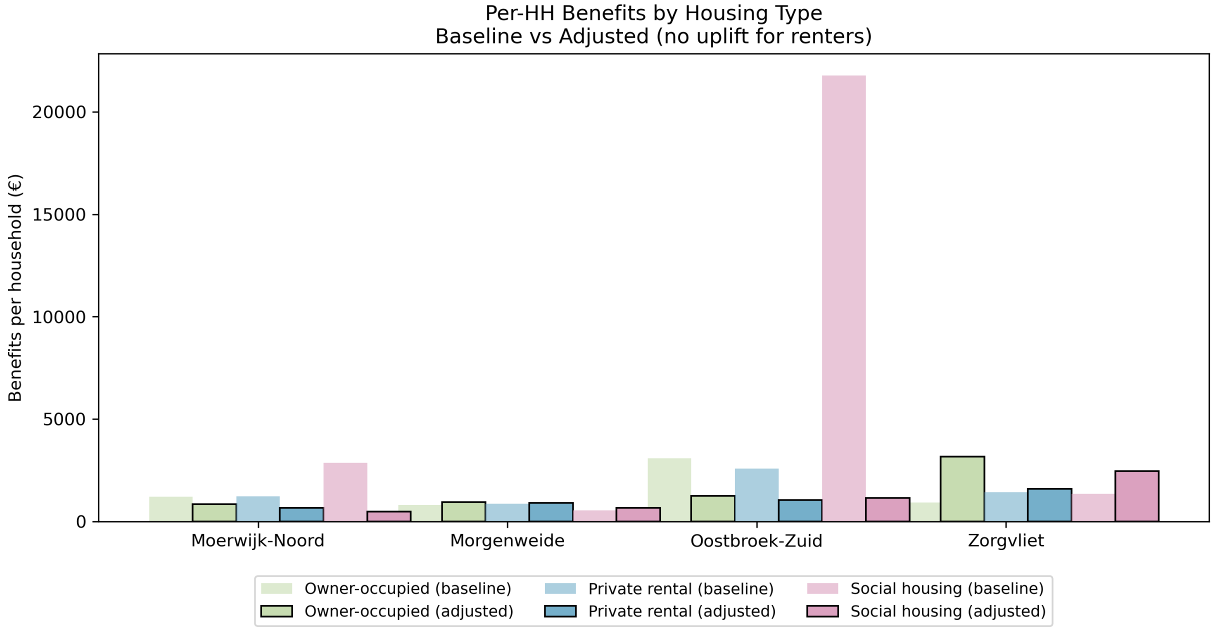


Figure 19: Comparison of current situation vs. adjusted specification where property value uplift is excluded for renters. Results per household of each tenure type.

Inequality within neighbourhoods

Table 7 and Figure 20 report inequality in per-household NPVs within each neighbourhood. *Oostbroek-Zuid* and *Morgenweide* show relatively low inequality, while *Zorgvliet* displays the highest concentration of outcomes, and *Moerwijk-Noord* records moderate inequality.

Table 7: Inequality in $NPV^{\text{per household}}$ within the four case study neighbourhoods (Gini coefficients).

Neighbourhood	Gini coefficient
Oostbroek-Zuid	0.20
Moerwijk-Noord	0.31
Zorgvliet	0.41
Morgenweide	0.22

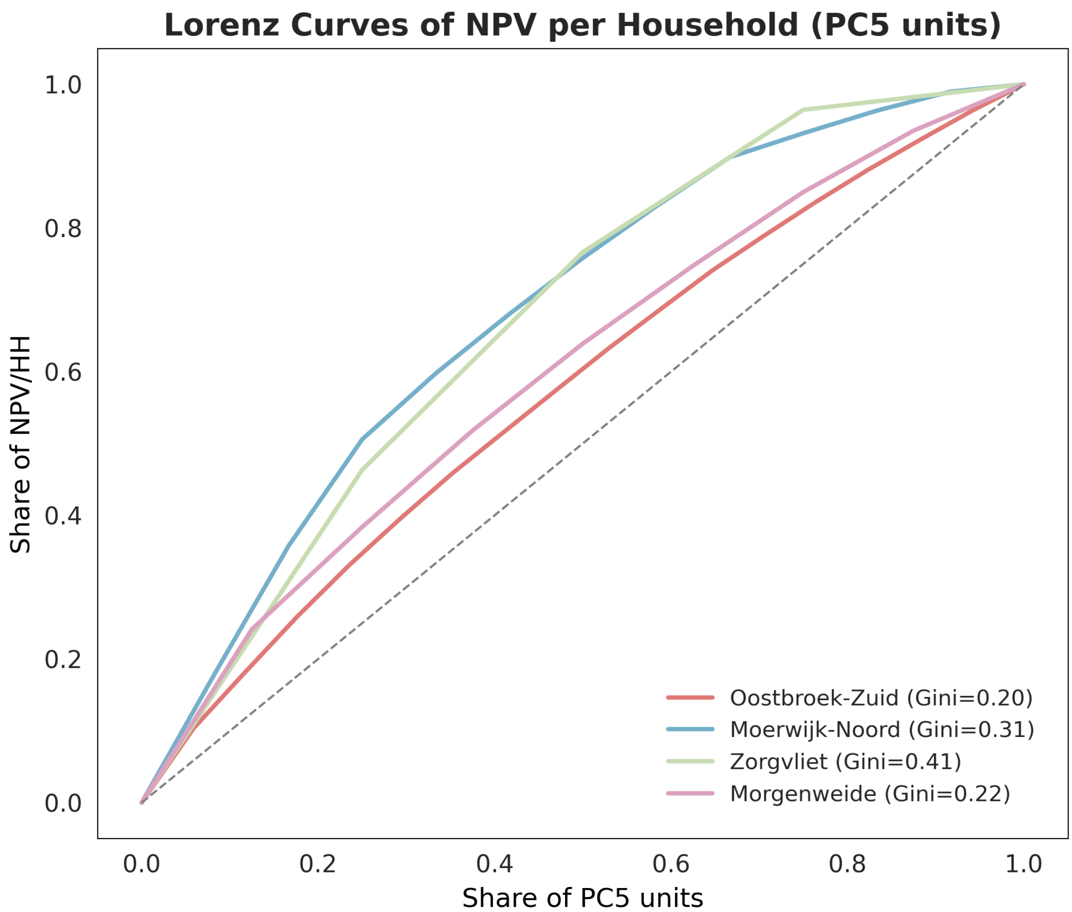


Figure 20: Lorenz curves of $NPV^{\text{per household}}$ across PC5 units within the four case study neighbourhoods. Greater deviation from the 45° line indicates higher inequality.

Need alignment

Finally, Figure 21 shows NPVs weighted by climate vulnerability. *Moerwijk-Noord*, with high exposure to flood and heat risk, improves relative to its unweighted outcome, while *Morgenweide* performs worst overall due to low vulnerability and weak benefits. All neighbourhoods remain negative in absolute terms.

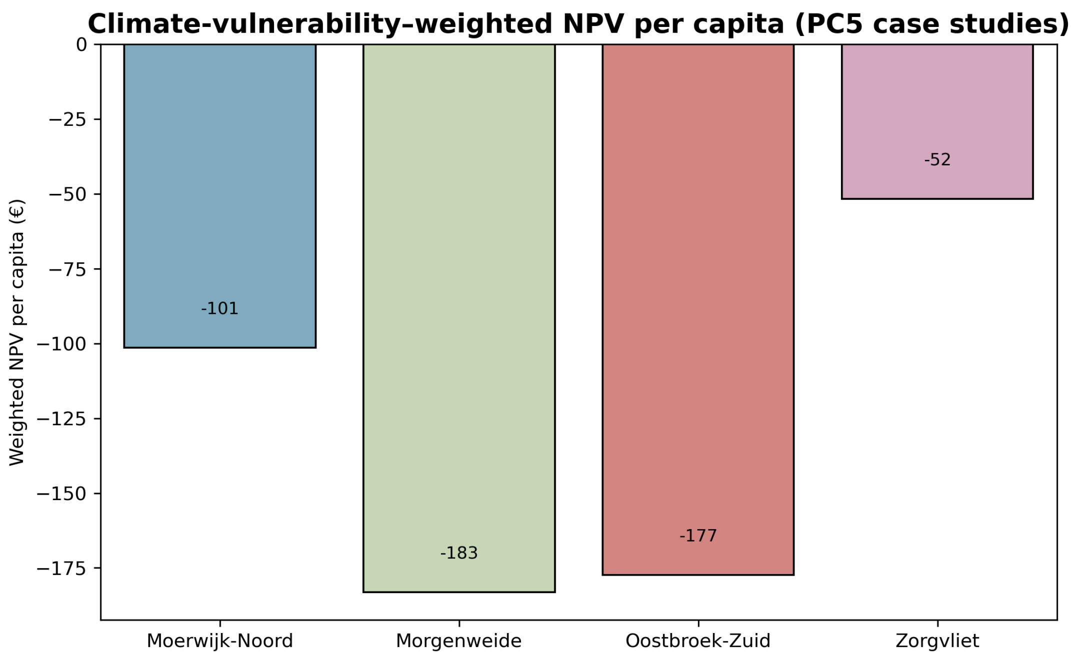


Figure 21: Climate-vulnerability–weighted $NPV^{\text{per capita}}$ for the four PC5 case study neighbourhoods. Values are weighted by local flood risk and UHI exposure.

Interpretation
The neighbourhood equity analysis reveals that: (i) social housing can bear disproportionate costs, especially in *Moerwijk-Noord*; (ii) affluent neighbourhoods like *Zorgvliet* show concentrated losses among homeowners; and (iii) vulnerability-weighted results slightly favour poorer areas but remain negative overall. These results confirm that distributional outcomes depend not only on density and roof stock, but also on tenure composition and modelling choices. Taken together, the case studies underline a critical insight: targeting expansion toward denser, lower-income neighbourhoods offers the best balance between economic efficiency and equity, while investments in affluent or peripheral areas risk high societal losses with limited social return.

4.4 Uncertainty and Sensitivity Results

4.4.1 City-wide experiments

To test robustness, each of the four allocation strategies (Environmental, Income-based, Uniform, Optimised) was re-evaluated under 500 parameter draws. Results confirm that outcomes are highly sensitive to input assumptions.

Distribution of outcomes
Figure 22 shows the distribution of mean NPVs per scenario. Central tendencies remain broadly consistent with deterministic results (Section 4.1.2), but spreads are wide, highlighting that scenario differences are not absolute.

The key insight is that, although central tendencies mirror the deterministic outcomes, uncertainty is large enough that scenario rankings overlap, meaning no allocation is universally dominant.

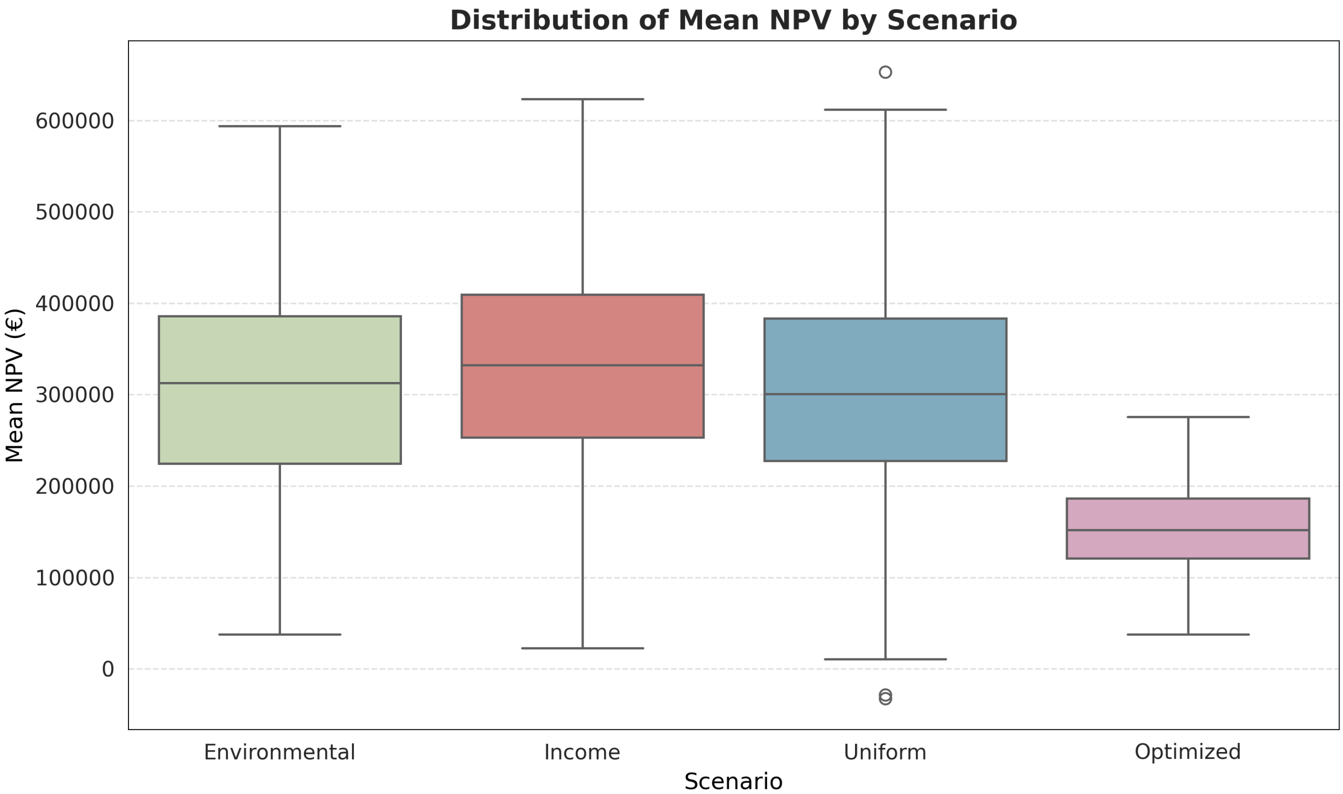


Figure 22: Distribution of mean NPV across 500 experiments for each allocation scenario. Boxes indicate interquartile ranges, whiskers the full range, and horizontal lines the medians.

Spatial variation
Uncertainty also manifests spatially. Figure 23 shows the mean and standard deviation of NPVs across neighbourhoods. Some consistently perform better, while others fluctuate widely, underscoring that equity outcomes depend not only on allocation but also on local sensitivity to parameter uncertainty.

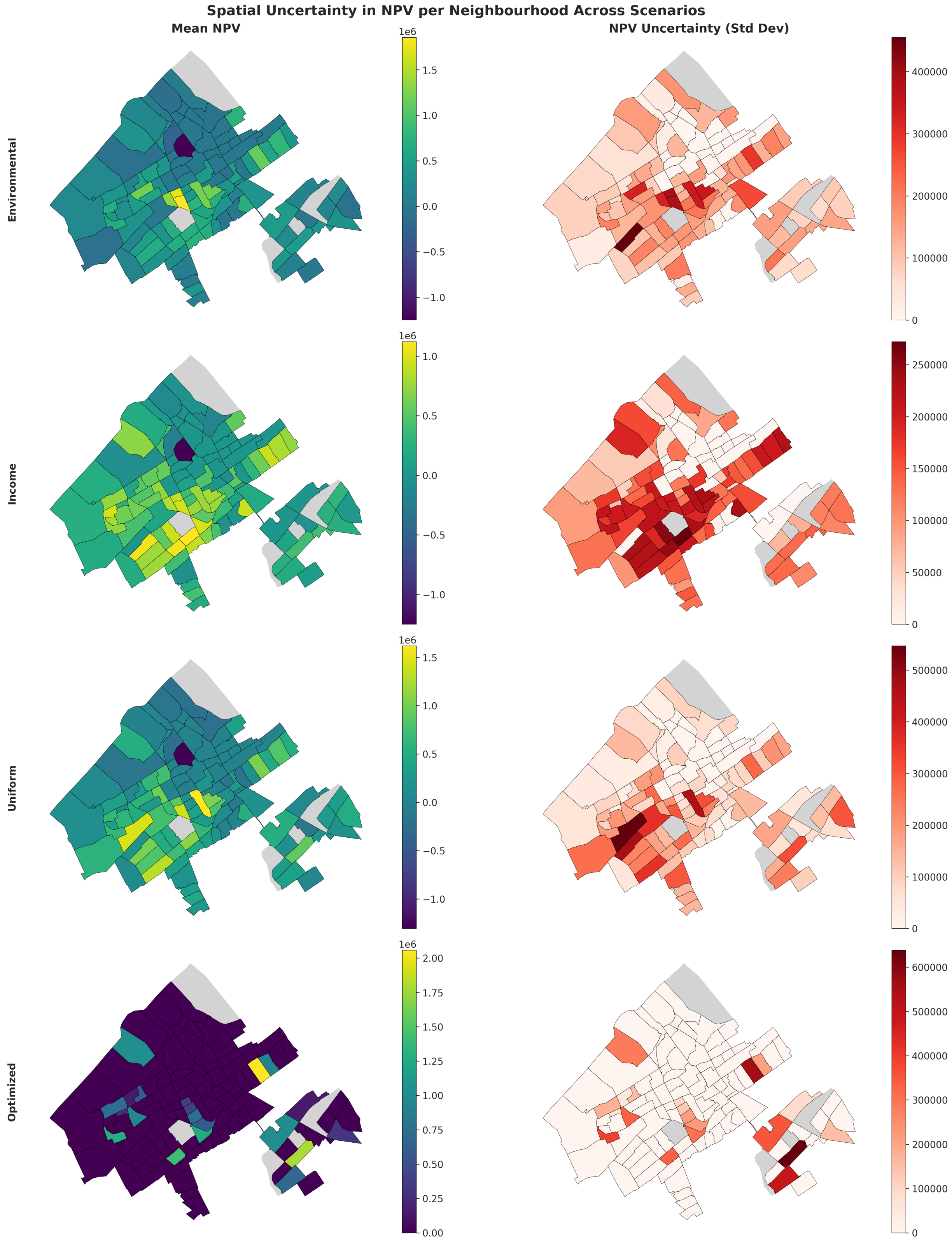


Figure 23: Spatial distribution of mean (left) and standard deviation (right) of NPV across 500 runs per neighbourhood.

Key parameters

Sensitivity analysis (Figure 24 and 25) identifies installation costs and flood-related benefits as the dominant drivers of outcomes. Health and energy parameters are less influential but still non-negligible. The Optimised scenario shows particular vulnerability to installation costs, while broader allocations are more balanced.

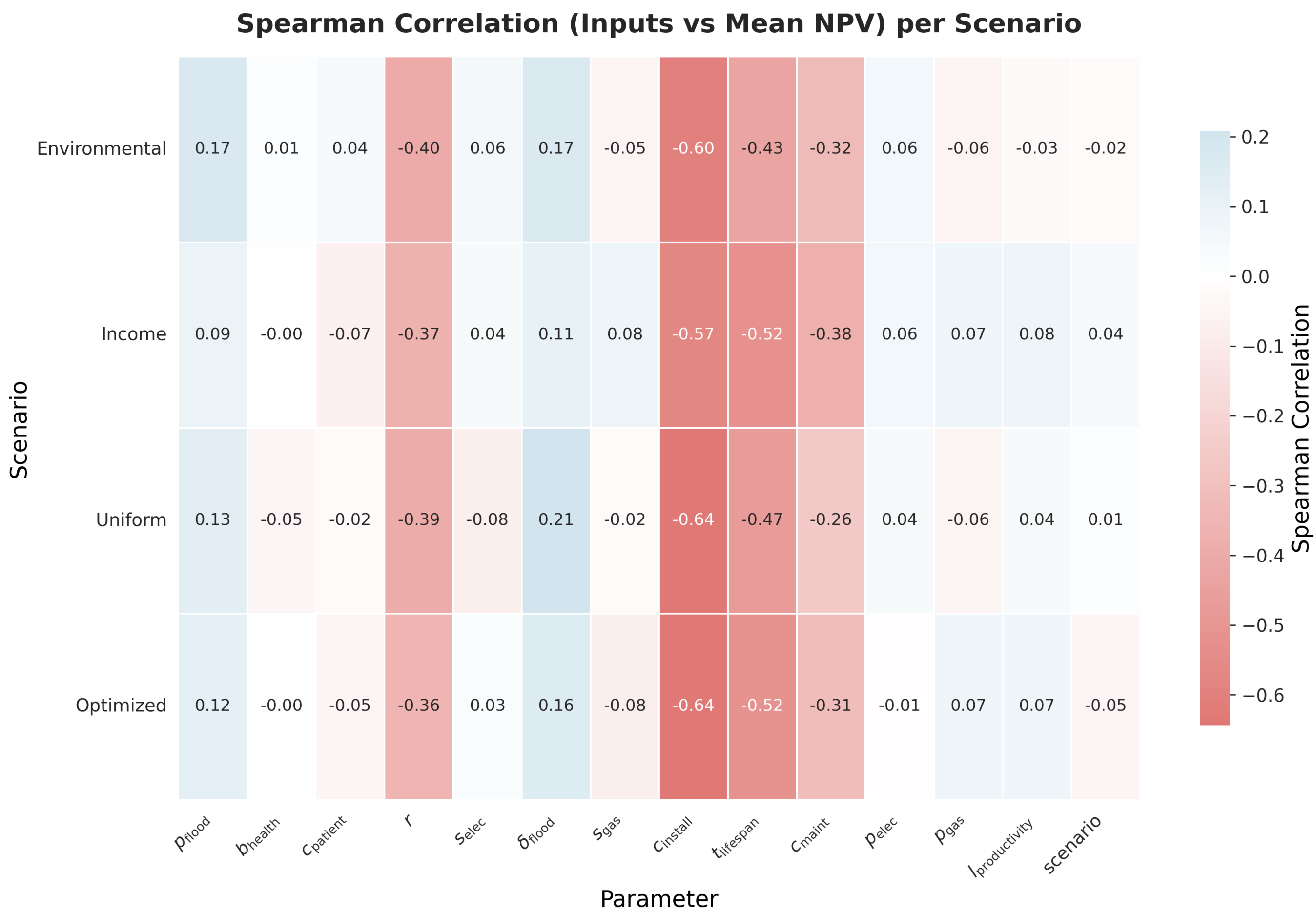


Figure 24: Spearman correlations between uncertain parameters and mean NPV across scenarios.

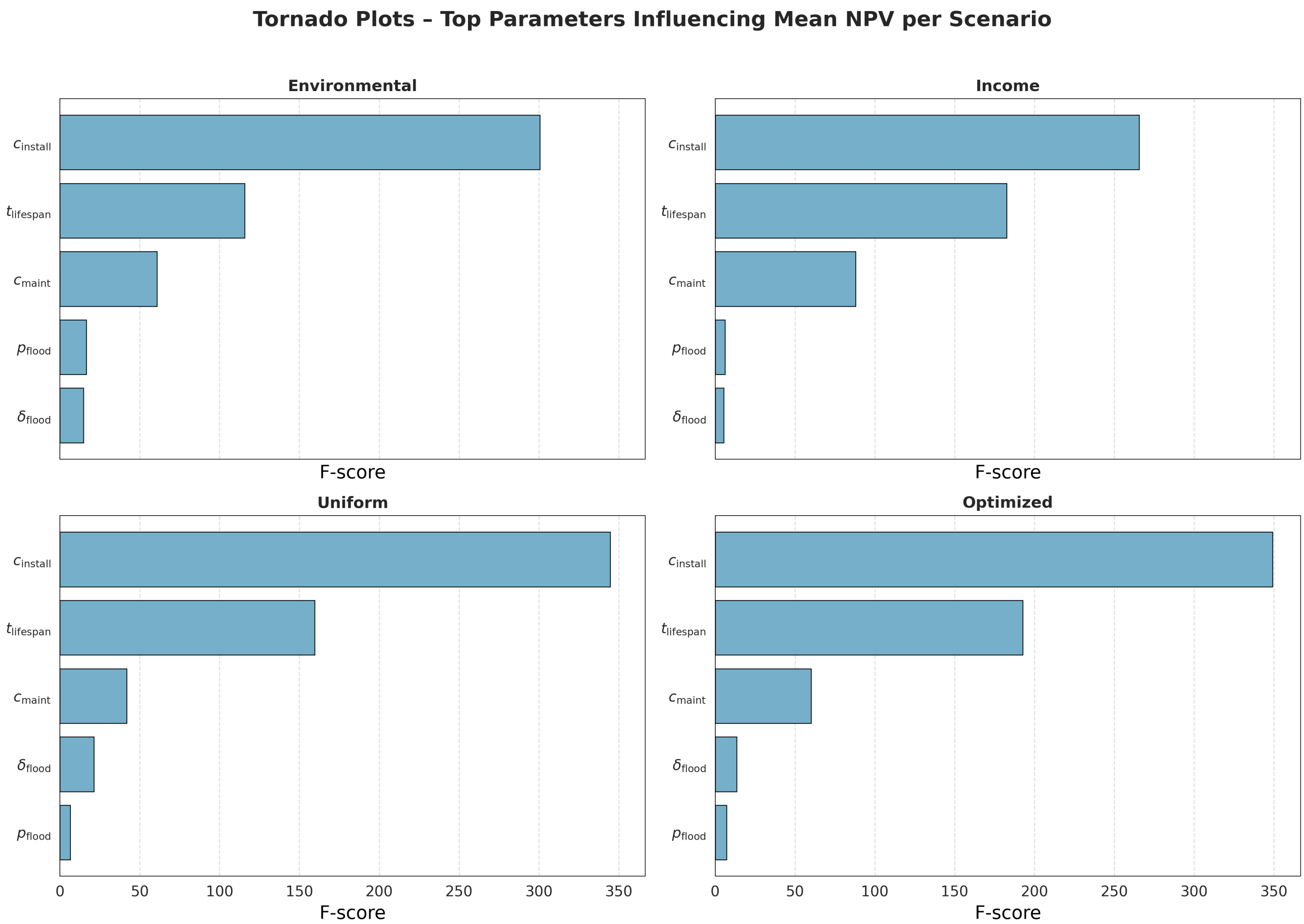


Figure 25: Tornado diagrams of the five most influential parameters for mean NPV in each allocation scenario.

Non-linear effects

Partial dependence plots (Figure 26) confirm near-linear responses for cost and discount parameters, while flood benefits show diminishing returns once thresholds are reached.

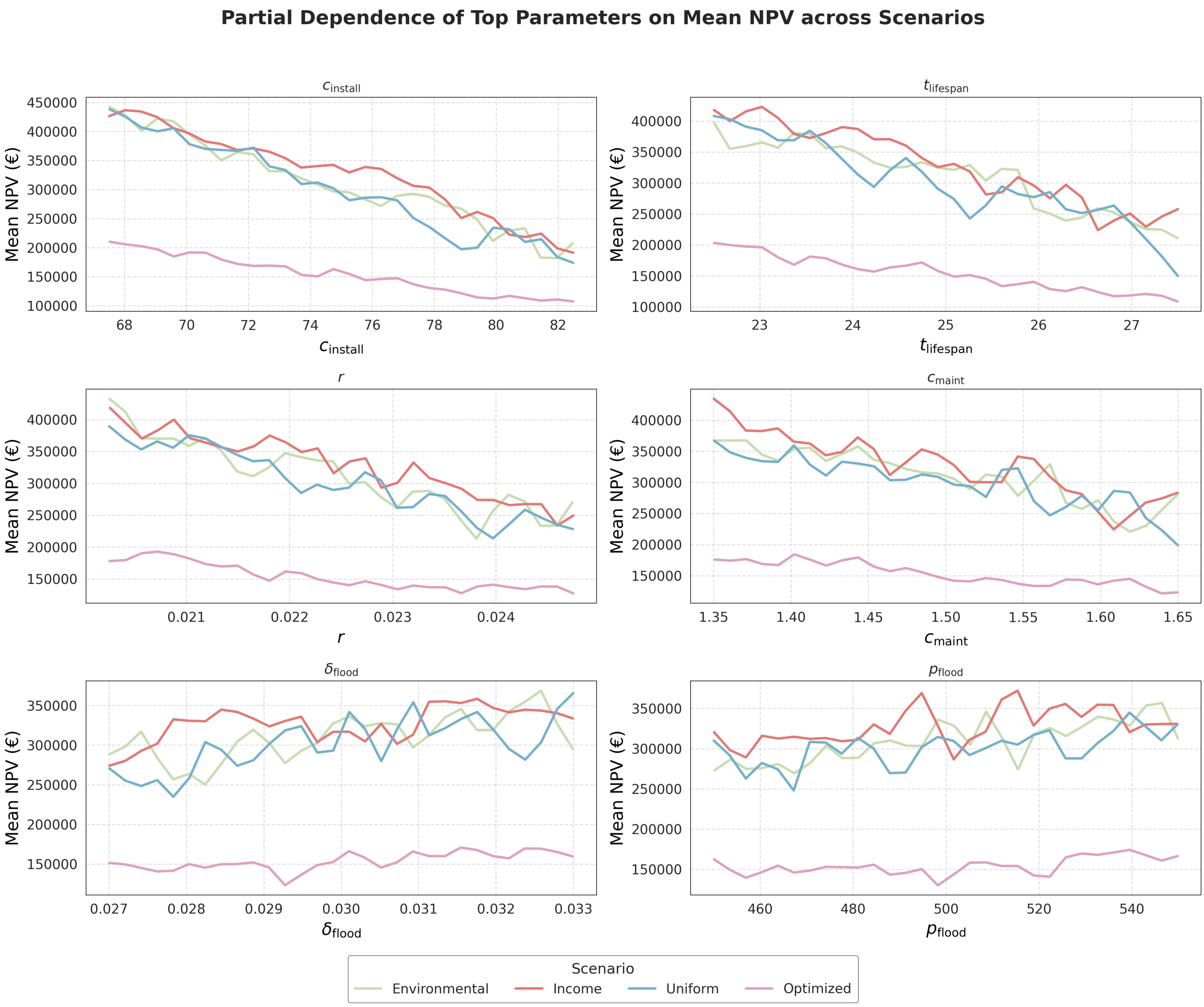


Figure 26: Partial dependence of mean NPV on the six most influential parameters. Coloured lines represent different allocation scenarios.

Equity–efficiency trade-off

Figure 27 plots mean BCR against the Gini coefficient. Broad allocations (Income-based, Uniform, Environmental) generally combine higher returns with lower inequality, whereas the Optimised strategy achieves high efficiency only in a few areas at the cost of extreme inequality.

This highlights the key trade-off: broad strategies (income-based, uniform and environmental) are found in the moderate efficiency and lower inequality quadrant, while optimised allocation is found in the higher efficiency and very high inequality area.

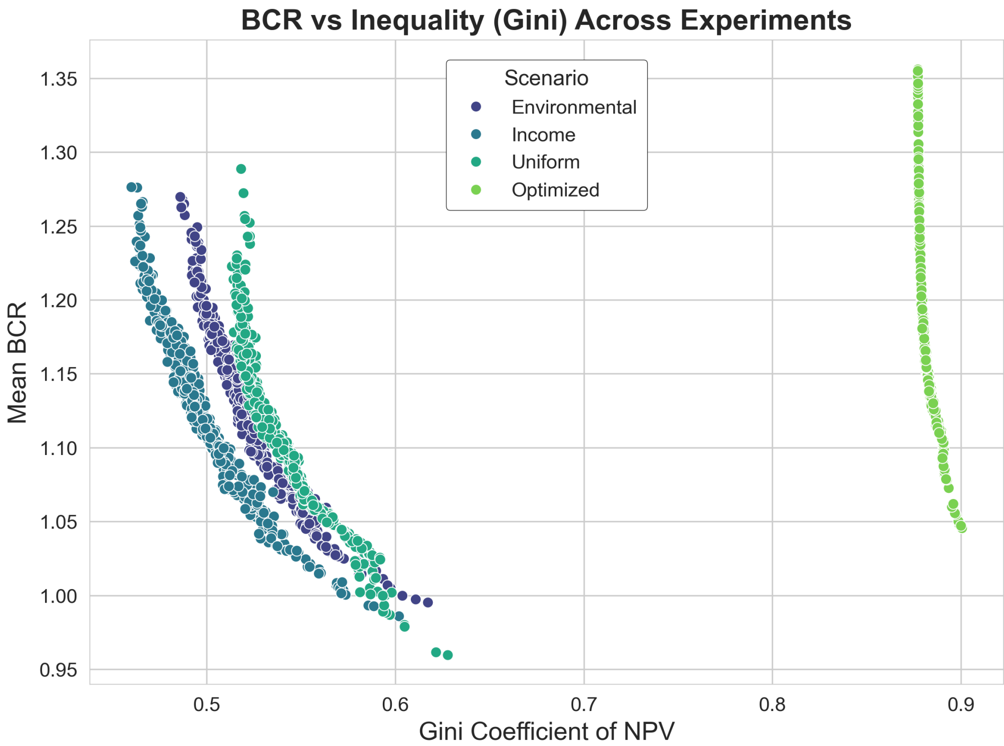


Figure 27: Trade-off between mean BCR and inequality (Gini) across 500 runs. Colours denote allocation strategies.

4.4.2 Neighbourhood-specific experiments

For the four representative case studies, EMA was applied at PC5 scale with four expansion settings (10%, 25%, 50%, 75% of suitable roof area greened). Each was tested under 500 random parameter draws.

Distribution of outcomes

Figure 28 shows the spread of NPVs per policy. Some neighbourhoods (e.g. *Zorgvliet*) remain negative under most draws, while others (*Moerwijk-Noord*) can reach positive values under favourable assumptions. Spread widths indicate different sensitivities.

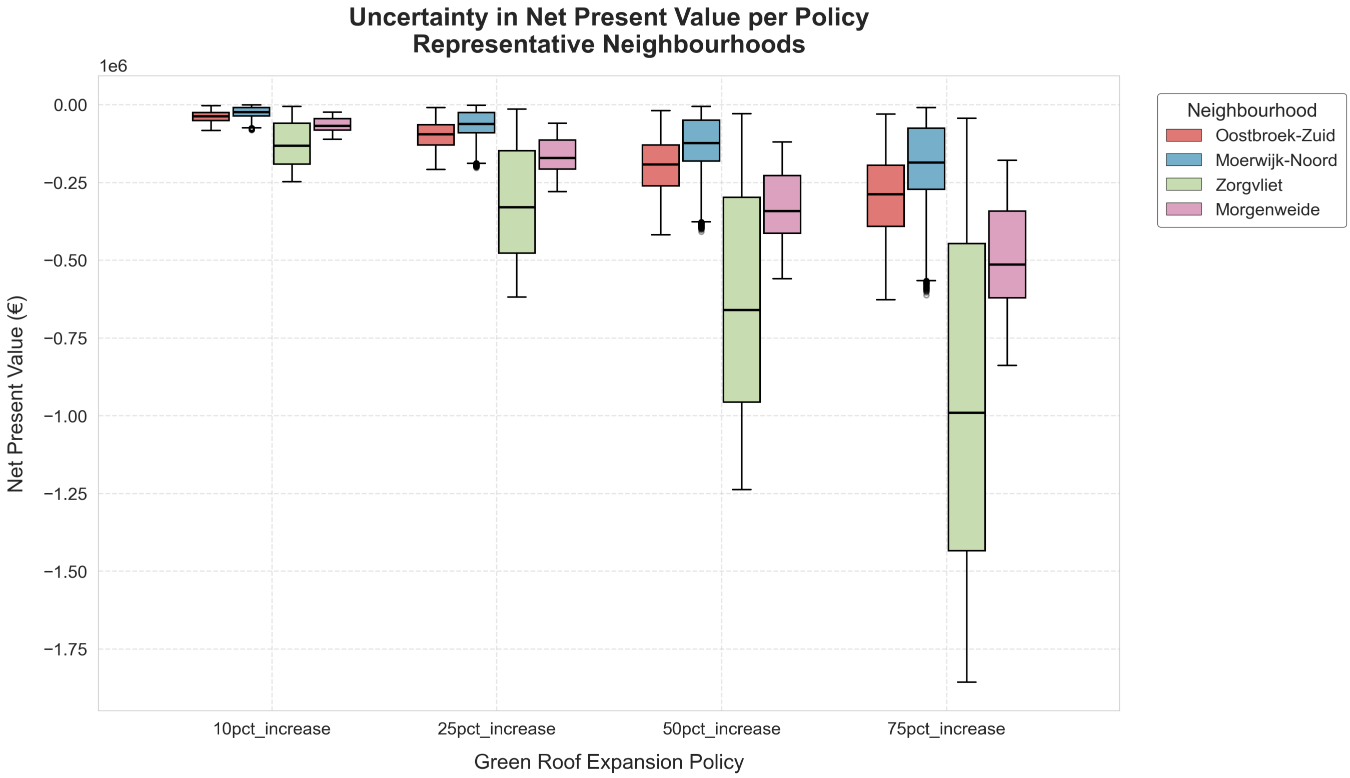


Figure 28: Distribution of NPV outcomes across 500 experiments for four representative neighbourhoods under varying expansion policies.

Spatial variation

Figure 29 illustrates mean and standard deviation of NPVs across PC5 units. *Oostbroek-Zuid* and *Moerwijk-Noord* exhibit heterogeneous results, while *Zorgvliet* shows uniformly negative outcomes with low variance.

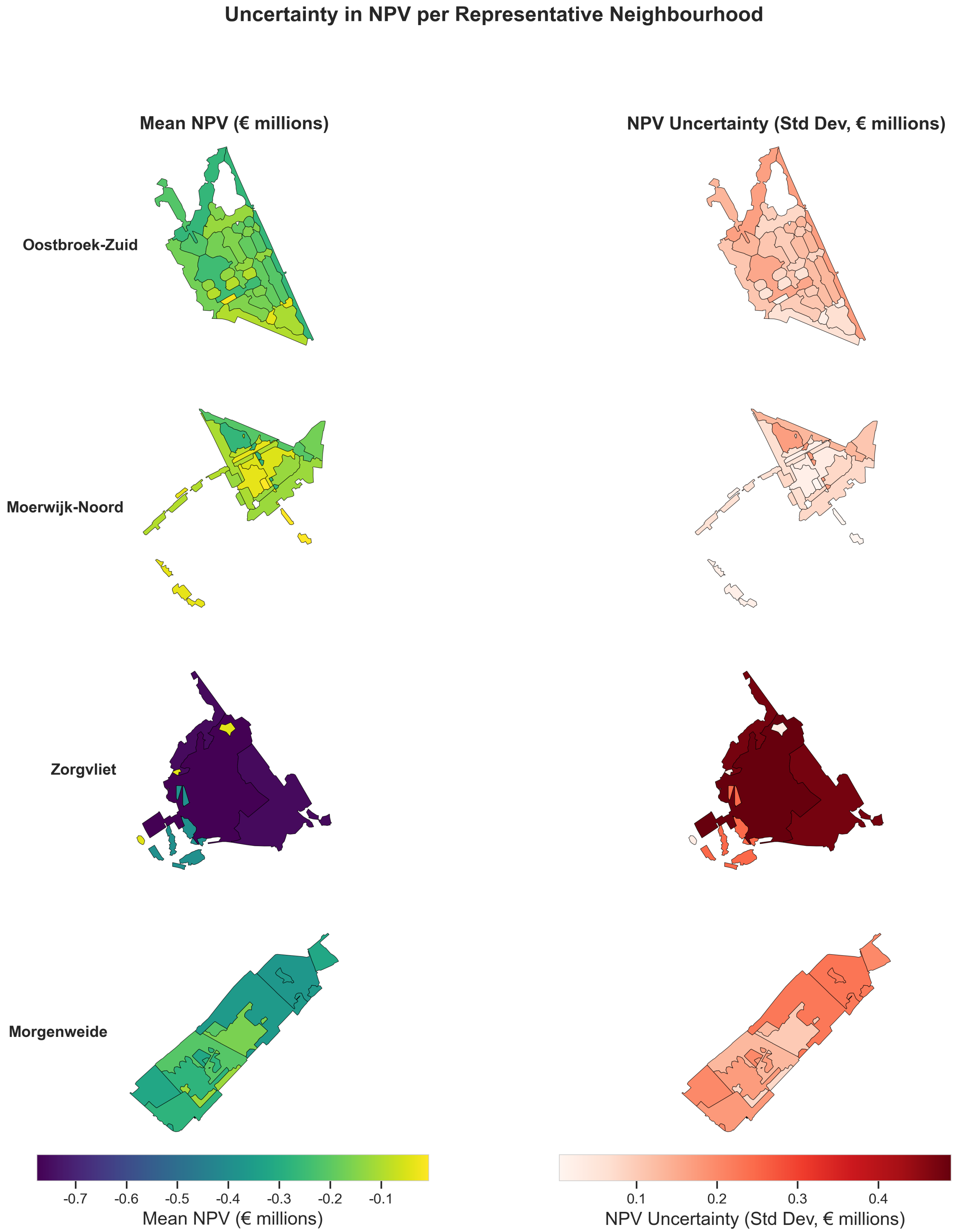


Figure 29: Mean (left) and standard deviation (right) of NPV across 500 runs for the four representative neighbourhoods.

Key parameters

Tornado diagrams (Figure 30) reveal different sensitivity profiles: *Oostbroek-Zuid* responds mainly to installation and health parameters, *Moerwijk-Noord* to property uplift and heat assumptions, *Zorgvliet* to flood-related parameters and discount rate, and *Morgenweide* to mixed drivers including productivity and flood.

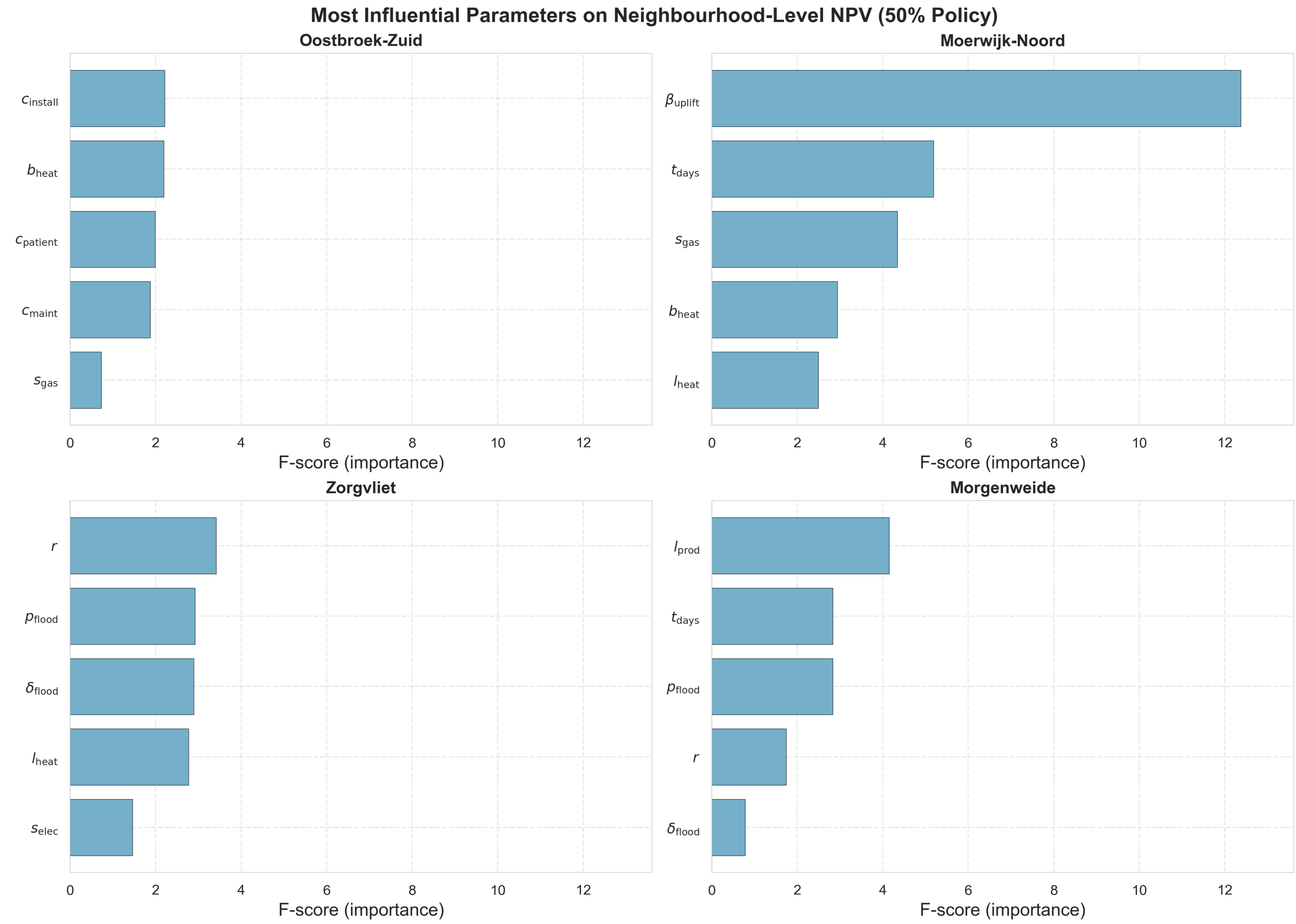


Figure 30: Top five influential parameters for mean NPV in each representative neighbourhood (50% expansion scenario). Bars show F-scores.

Interpretation

Neighbourhood EMA confirms that cost assumptions and flood-related benefits dominate overall, but sensitivity varies with socio-spatial context. Dense, mixed-income areas are more influenced by health and productivity assumptions, while affluent or peripheral neighbourhoods respond mainly to costs and flood benefits. This reinforces that robust policy design must consider both parameter uncertainty and local context.

4.5 Summary of Results

Taken together, the results show that large-scale green roof expansion in The Hague substantially improves outcomes compared to the current situation, but the magnitude and distribution of benefits vary strongly by allocation strategy and local context. At city-wide scale, the three broad allocation strategies (Uniform, Income-based, Environmental) enable around two thirds of neighbourhoods to surpass break-even, while the Optimised strategy achieves very high returns in a few locations despite using less than half the green roof area. This highlights a central trade-off: broad allocations provide widespread but moderate improvements, whereas optimisation maximises efficiency locally but sacrifices coverage and equity.

Equity analysis reveals that allocation design decisively shapes distributive outcomes. The Income-based strategy stands out as the only one that reduces inequality while aligning benefits with climate vulnerability, showing that efficiency and fairness can be combined when social criteria are embedded in allocation rules. By contrast, optimisation delivers "more with less" in efficiency terms but at the cost of extreme inequality. Uniform and Environmental strategies broaden coverage but fail to systematically prioritise vulnerable groups. These findings emphasise that distributive justice cannot be assumed as a side-effect of expansion, but must be deliberately built into policy design.

Neighbourhood-level analysis adds further nuance. Affluent or peripheral areas such as *Zorgvliet* and *Morgenweide* record the largest absolute and per-household losses, despite their high technical potential. Dense, mixed-income neighbourhoods such as *Oostbroek-Zuid* and *Moerwijk-Noord* perform relatively better in per-household terms, but still yield negative NPVs. Tenure structures prove decisive: homeowners capture most property-related benefits, while tenants, especially in social housing, gain relatively few direct advantages, and housing corporations often bear a disproportionate share of costs. Vulnerability-weighted results improve slightly for poorer, exposed areas, yet remain negative overall.

Finally, exploratory uncertainty analysis demonstrates that results are highly sensitive to parameter assumptions. Installation costs and flood benefits dominate overall, but sensitivity profiles differ by context: dense areas are more influenced by health and productivity assumptions, while affluent or peripheral areas depend more on cost and flood parameters. Importantly, scenario rankings overlap across uncertainty ranges, meaning that no allocation is universally superior. Robust policy design therefore requires flexibility, safeguards, and explicit attention to both parameter uncertainty and socio-spatial context.

5

Conclusion, Discussion and Policy Implications

5.1 Conclusion

This research evaluated how SCBA, combined with spatial equity analysis, can inform the equitable and effective implementation of green roofs in The Hague. By addressing five sub-research questions, the study uncovered how costs and benefits vary across scales, allocation strategies, and socio-spatial contexts, and how uncertainty affects robustness.

5.1.1 SRQ1: Literature on costs, benefits, and equity implications

The literature confirms that green roofs deliver multiple benefits beyond direct financial returns: stormwater retention, energy savings, improved health through cooling, extended roof lifespan, and property value uplift (Arcadis et al., 2024; Castleton et al., 2010; Van Oorschot et al., 2021). Yet conventional CBA has focused narrowly on energy, under-valued non-market benefits, and rarely addressed distributional outcomes. This creates a gap in understanding not just whether green roofs are efficient overall, but also who benefits and who bears costs. Recent contributions stress the need to integrate distributive equity and uncertainty into SCBA (Chelli et al., 2025; Raymond et al., 2017). This thesis responds by embedding Gini coefficients, Lorenz curves, and climate-vulnerability weighting into an SCBA framework, explicitly addressing distributive outcomes.

5.1.2 SRQ2: City-wide outcomes of expansion scenarios

At the city-wide (neighbourhood) scale, the existing stock of green roofs yields uniformly negative NPVs, with no neighbourhood achieving a BCR above one. This aligns with Dutch and European evidence showing limited financial viability without subsidies or mandates (Arcadis et al., 2024; Van Oorschot et al., 2021). Expansion scenarios transform this picture: Uniform, Income-based, and Environmental allocations enable roughly two thirds of neighbourhoods to surpass break-even, while the Optimised allocation concentrates very high BCRs in a few locations but leaves most areas unchanged. Scale and allocation strategy are thus decisive: expansion can generate societal viability, but only with strategic distribution. Optimisation maximises efficiency locally, but sacrifices inclusiveness.

5.1.3 SRQ3: Equity implications of allocation strategies

The equity analysis highlights striking contrasts. The Income-based allocation performs best: it produces the lowest inequality (Gini ≈ 0.53) and uniquely achieves positive alignment with climate vulnerability, directing benefits to lower-income and climate-exposed neighbourhoods. By contrast, the Optimised allocation generates extreme inequality (Gini ≈ 0.94), concentrating resources in already favourable areas while excluding most of the city. Uniform and Environmental allocations fall in between: they broaden coverage but fail to prioritise vulnerable areas, as benefits remain modest where socio-economic and building conditions limit monetised returns. These results confirm that distributive fairness cannot be assumed as a side-effect of NbS investment, it must be designed explicitly.

5.1.4 SRQ4: Neighbourhood typologies and detailed outcomes

Detailed PC5-scale analysis of four representative neighbourhoods reveals how socio-spatial context and housing tenure shape distributive outcomes. In affluent, low-density *Zorgvliet*, losses are largest in absolute terms (almost €2.9 million), with property uplift dominating the benefit profile but insufficient to offset costs. In suburban *Morgenweide*, per-household losses are highest (–€935/HH), showing that technical potential alone does not guarantee viability. By contrast, dense mixed-income neighbourhoods such as *Oostbroek-Zuid* and *Moerwijk-Noord* record smaller losses per household (−€350 to −€515/HH), with health and energy benefits contributing more. Still, even here NPVs remain negative overall. Tenure structures decisively condition outcomes: homeowners capture most property-related benefits, while tenants (especially in social housing) see few direct gains.

5.1.5 SRQ5: Uncertainty and robustness

Uncertainty analysis confirms that outcomes are highly sensitive to parameter assumptions. Installation costs and flood-related benefits dominate across scenarios, while health and energy parameters exert smaller effects. Sensitivity profiles vary by context: dense neighbourhoods are most affected by health and productivity assumptions, while affluent or peripheral areas hinge on costs and flood parameters. This shows that robustness is context-specific. Without accounting for uncertainty, deterministic SCBA results risk overstating certainty and misguiding policy.

5.1.6 Synthesis of findings

Three overarching lessons emerge. First, efficiency and equity are tightly linked: strategies that target low-income, vulnerable areas (e.g. Income-based) deliver both higher aggregate returns and fairer distributions, while optimisation maximises efficiency locally but creates extreme inequality. Second, socio-spatial context and tenure structure decisively shape outcomes: wealthy areas accrue property-related benefits but underperform societally, while tenants often benefit least and housing corporations carry substantial costs. Third, robustness under uncertainty is not uniform: cost and flood parameters dominate overall, but local sensitivity differs, making deterministic results unreliable.

Taken together, this thesis shows the added value of combining SCBA with spatial equity analysis. Doing so reveals not only whether green roofs are viable in aggregate, but also how distributive outcomes shift with allocation strategy, neighbourhood type, and parameter assumptions. This provides a richer evidence base for policy, demonstrating that equity-sensitive allocation can simultaneously enhance fairness and efficiency, while context-aware and uncertainty-tested approaches are essential for robust and just urban adaptation.

5.2 Discussion

5.2.1 Interpreting the Findings

Three core insights stand out from the results. First, equity and efficiency are not necessarily in conflict: the Income-based allocation shows that targeting vulnerable, low-income areas can simultaneously enhance aggregate returns and reduce inequality. Second, socio-spatial context and tenure structures decisively shape outcomes: homeowners capture most property-related benefits, while tenants gain relatively little, and housing corporations face most costs. Third, robustness is strongly context-dependent: dense neighbourhoods are sensitive to health-related assumptions, while affluent or peripheral areas hinge on costs and flood parameters. These findings together demonstrate that distributive justice must be designed explicitly into NbS, and that deterministic results risk misleading policy if uncertainty and tenure structures are overlooked.

The neighbourhood typology analysis reinforces these points. The poor performance of affluent areas such as *Zorgvliet*, despite high property values, reveals the limits of hedonic uplift as a driver of societal benefits. Property-related gains tend to reward owners in high-value markets but offer little to renters, raising equity concerns when such metrics dominate. By contrast, dense mixed-income areas like *Oostbroek-Zuid* and *Moerwijk-Noord* achieve stronger health and energy benefits, but still fall short of positive NPVs, showing that technical suitability alone does not guarantee viability. Tenure therefore emerges as a key equity dimension: owners capture value, while tenants in rental housing remain excluded unless safeguards are applied.

Another important implication is methodological. City-wide results applied a simplified coefficient for avoided health impacts, which inflates benefits in aggregate. At the PC5 scale, health effects were modelled more precisely with local temperature exposure, age structure, and income, yielding smaller but more credible results. This explains why aggregate NPVs are systematically lower at the PC5 level. Methodologically, the PC5 specification is preferable for distributive analysis, while the city-wide calculation provides a useful upper bound for strategic planning. Together, they bracket a plausible range of outcomes.

Finally, the results show that institutional incentives matter. When costs fall on housing corporations or landlords but benefits accrue mainly to owners, tenants risk being doubly disadvantaged: excluded from most direct gains while still exposed to climate risks. Without safeguards, NbS can unintentionally deepen inequalities. Addressing this requires instruments that go beyond household subsidies, focusing on partnerships with corporations, regulation for landlords, and collective investment models that align institutional incentives with societal benefits.

5.2.2 Positioning in Literature

These findings confirm, extend, and nuance existing debates on NbS, equity, and economic evaluation.

Nature-based solutions and multifunctionality.
The results align with research emphasising the multifunctional potential of NbS in urban contexts. Studies such as Faivre et al. (2017), Kabisch et al. (2016), and McPhearson et al. (2023) highlight the diverse co-benefits of green infrastructure. The baseline results here confirm earlier findings that energy savings alone are insufficient in temperate climates (Arcadis et al., 2024; Van Oorschot et al., 2021). By including a broader benefit set, this thesis operationalises multifunctionality in an SCBA framework, showing both its potential and the limitations of monetisation.

Equity and risks of green gentrification.
Critical research warns that urban greening can exacerbate inequalities through green or climate gentrification (Anguelovski et al., 2022; Cucca et al., 2023; Shokry et al., 2020; Wolch et al., 2014). The city-wide analysis echoes these concerns: optimisation strategies concentrated benefits in affluent areas, while vulnerable neighbourhoods remained excluded. At the same time, the income-based allocation demonstrated that equitable targeting can improve both fairness and efficiency, offering an alternative to the "just green enough" paradox (Wolch et al., 2014). The neighbourhood analysis reinforces insights from Dutch practice that social housing is a critical locus for equitable adaptation (Snep et al., 2023). The adjusted per-household analysis further shows that tenants benefit least, while landlords and corporations bear costs, underlining that landlord–tenant dynamics are central to distributive justice in NbS.

Methodological advances in SCBA for NbS.
This thesis contributes methodologically by extending SCBA beyond aggregate efficiency. Standard Dutch guidance (Romijn & Renes, 2013) focuses on indicators such as NPV, BCR, and IRR, but typically omits distributional aspects. International reviews note similar gaps (Chelli et al., 2025). More applied green roof studies (Arcadis et al., 2024; Hekrle et al., 2023; Teotónio et al., 2021) vary methodologically but rarely integrate equity. By embedding distributive metrics (Gini, Lorenz, vulnerability weighting) and incorporating uncertainty analysis, this thesis demonstrates a justice-oriented, robustness-informed approach. It bridges economic appraisal with the equity concerns increasingly stressed in the NbS literature (Raymond et al., 2017).

Synthesis.
Taken together, the findings position this thesis at the intersection of three debates: (i) demonstrating multifunctionality of green roofs as NbS, (ii) critically engaging with risks of inequitable outcomes and gentrification, and (iii) advancing methodological approaches to SCBA. By combining these, it responds to calls for integrated, equity-aware, and context-sensitive evaluations of urban NbS.

5.3 Limitations

While this thesis successfully combines SCBA with spatial equity analysis to evaluate green roof expansion, several limitations arise from methodological choices, data availability, and the operationalisation of equity. While these limitations do not invalidate the findings, they should be taken into account when interpreting the results and their implications for policy.

Spatial representation and boundary misalignment
One key limitation is the spatial definition of neighbourhoods. PC5 units often span multiple neighbourhoods,

necessitating clipping and areal interpolation in order to align with administrative boundaries. This introduces uncertainty, as the approach assumes a uniform distribution of attributes within polygons. Although sensitivity checks suggest that overall patterns are robust, fine-grained differences, particularly in areas with significant misalignment, such as *Zorgvliet*, may be overstated or understated. This reflects a broader issue in spatial analysis: the modifiable areal unit problem (Modifiable Areal Unit Problem (MAUP)), where results depend on the scale and zoning system chosen (Dark & Bram, 2007; Fotheringham & Wong, 1991). Multi-scale analysis (neighbourhood–PC5) partly mitigates this, but absolute comparability across levels remains imperfect.

Temporal mismatch and harmonisation

The datasets used span different years: socio-economic indicators cover 2019–2025, property values are from 2022, energy use data from 2021, and UHI exposure from 2017. Combining these assumes stability in relative spatial patterns over time, which may not fully hold given changes in energy consumption, climate exposure, or demographic composition. As a result, outcomes may reflect historical conditions as much as present realities.

Benefit valuation and scope

This thesis included property value uplift as a benefit, consistent with the hedonic pricing method applied in the research by Arcadis et al. (2024). However, doing so is unconventional in SCBA. Dutch guidance (Romijn & Renes, 2013) generally advises against treating capitalised housing market premiums as societal benefits, since they reflect transfers between buyers and sellers rather than a net welfare gain. Similar concerns are raised in the wider SCBA literature, where property value changes are seen as prone to double counting if the underlying environmental or health benefits are already included (Louali et al., 2022).

Nevertheless, from an equity perspective, including property value effects provides valuable insight into distribution. Gains from this category accrue primarily to homeowners and landlords, meaning that affluent groups are more likely to capture such benefits. Tenants, by contrast, see far fewer direct advantages, since rental contracts rarely translate capitalised housing premiums into household-level welfare gains. As Louali et al. (2022) emphasise, SCBA can help reveal not only aggregate welfare impacts but also how benefits are distributed across stakeholder groups, thereby enriching the analysis of distributive justice.

The Arcadis report (Arcadis et al., 2024) does account for potential double counting by isolating the hedonic value of green roofs in housing prices, ensuring that uplift estimates are not simply the sum of energy, health, and other benefits already monetised. Nonetheless, the inclusion of this component remains a source of uncertainty, both in terms of its normative justification and its sensitivity to local housing market conditions. Similarly, the calculation of health benefits differs between scales: city-wide results apply a simplified coefficient to total populations, whereas the PC5 analysis uses finer demographic and income data alongside local temperature exposure. This methodological refinement reduces inflation from aggregation but also yields smaller benefits, contributing to discrepancies in NPVs across scales.

Scenario assumptions and allocation mechanics

The expansion scenarios assume a stylised 50% increase of suitable roof area. This figure is not a forecast but was chosen to reflect the scale of ambition articulated in municipal climate adaptation plans for The Hague (Gemeente Den Haag, 2024b; Gemeente Den haag, 2025). Nevertheless, it is not directly grounded in binding policy targets or detailed financial feasibility assessments. The Optimised strategy distributes area to maximise marginal NPVs, yet in practice uptake would be constrained by behavioural, institutional, and regulatory factors that are not modelled here. Similarly, the proportional allocation of new roof area across housing types assumes an even distribution, whereas ownership structures (e.g. homeowners' associations versus housing corporations or private landlords) strongly shape feasibility in reality. These simplifications mean that scenario outcomes should be interpreted as indicative explorations of possible futures rather than precise forecasts of adoption trajectories.

Equity operationalisation

The analysis operationalised distributive equity using per-capita NPVs, Gini coefficients, Lorenz curves, and a composite climate vulnerability weighting. The vulnerability index combined three components: flood exposure, heat exposure and socio-economic sensitivity. Each component was normalised to a 0–1 scale and given equal weight. Although this approach provides a systematic way to adjust outcomes according to relative need, it also oversimplifies complex realities. In practice, flood risk, heat stress and socio-economic disadvantage may contribute unevenly to overall vulnerability, so assigning them equal weighting may understate or overstate their true importance. Furthermore, the normalisation procedure yields relative rather than absolute measures of need, meaning the results emphasise comparative patterns between neighbourhoods rather than policy-relevant intervention thresholds. Finally, distributive outcomes are assessed for place-based units without taking into account social ties, governance capacities or household-level heterogeneity. Consequently, the results should be interpreted as indicative of broad equity patterns rather than precise allocations of costs and benefits.

Equity scope
The focus on distributive outcomes means that other dimensions of justice (i.e. procedural and recognition) are outside the scope of this thesis. The analysis did not cover decision-making power, cultural values associated with green roofs or the capacity of local institutions to implement measures. This restricts our ability to understand how green roof policies may empower or marginalise particular groups beyond the distribution of costs and benefits.

Suitability constraints and alternative measures
A further limitation concerns the technical suitability of the roof stock. While this thesis applied filters based on slope and heritage status to identify feasible roof segments, these criteria are conservative. Some buildings with a protected municipal or national status (*gemeentelijk* or *rijksmonument*) may in practice still accommodate green roofs if installations are not visible from the street or are otherwise compatible with preservation requirements. As a result, the analysis may underestimate the total feasible roof area. Conversely, roof suitability inherently constrains the scope for green roof adoption, meaning that a significant share of the building stock will remain unavailable. This raises an equity concern: households located in older or heritage districts may systematically miss out on the benefits of green roofs if no alternative adaptation options are offered. To address this, complementary measures that reduce flooding or urban heat (e.g. façade greening, pocket parks, or blue–green infrastructure) merit further assessment through SCBA and equity analysis. This would help ensure that adaptation opportunities extend also to households and neighbourhoods excluded from green roof provision due to technical limitations.

Uncertainty treatment
Finally, while this thesis moves beyond deterministic approaches by incorporating sensitivity and uncertainty analyses, the scope of the investigation is limited. Only quantifiable parameters (e.g. installation costs, flood benefits and health coefficients) could be varied; structural uncertainties, such as long-term climate trajectories, institutional capacity and shifting social preferences, were not considered. This means that robustness was assessed within a defined parameter space and not across deeper uncertainties. Consequently, the results highlight sensitivity profiles rather than complete uncertainty envelopes and should not be interpreted as definitive forecasts.

Summary
Overall, these limitations suggest that the results are best viewed as indicative of broad patterns and trade-offs rather than as precise predictions. The framework provides new insights into efficiency, equity, and robustness, but future applications should aim to integrate richer benefit categories, improve spatial and temporal alignment, refine vulnerability metrics, incorporate behavioural and institutional constraints, and expand the scope of uncertainty explored. These limitations do not detract from the broader insights of this thesis, but they do highlight opportunities for refinement in both future research and policymaking, which are discussed in the following section.

5.4 Future Research

This thesis contributes methodologically and substantively to the evaluation of green roofs, but also reveals several gaps where further research is needed.

Firstly, the valuation of benefits requires refinement. While this study included property value uplift, energy savings, health improvements and flood mitigation, important categories such as biodiversity, cultural value and social cohesion were omitted due to data and monetisation challenges. Future research should aim to address the persistent under-valuation of non-market benefits. Combining SCBA with approaches such as Multi-Criteria Analysis (MCA) can help to capture values that resist monetisation but remain central for urban residents' well-being (Teotónio et al., 2023). This would enable a more comprehensive representation of the co-benefits of green roofs, particularly those that are difficult to monetise yet highly relevant to urban residents.

Secondly, vulnerability weighting could be expanded. In this study, the weight assigned to flood, heat, and socio-economic sensitivity was equal, yet in practice these drivers of disadvantage may have unequal effects. Future work could calibrate weights based on empirical health, economic or climate risk data, or use participatory approaches to align weighting with community priorities. This would improve the precision of need-adjusted indicators and their usefulness for policy targeting.

Thirdly, the longitudinal dynamics of adoption remain under-explored. The expansion scenarios assumed an immediate 50% increase in suitable roof area, whereas in practice adoption is path-dependent and shaped by behavioural, institutional and financial barriers. Future research could integrate adoption models from diffusion-of-innovation theory or agent-based simulation to capture more realistic uptake trajectories and policy responsiveness.

Fourthly, structural uncertainties need to be addressed. The sensitivity analysis in this thesis varied key parameters within plausible ranges, but did not capture deeper uncertainties, such as climate change trajectories, future energy prices or governance capacity. Linking SCBA with scenario analysis or exploratory modelling frameworks (Bankes, 1993) would provide richer insights into how robust different strategies are under uncertain futures.

In addition, future research could extend the SCBA–equity framework to alternative adaptation measures beyond green roofs. For buildings that are technically unsuitable (e.g. due to slope or heritage restrictions), complementary strategies such as façade greening, pocket parks, or blue–green infrastructure could provide comparable benefits for flood mitigation and heat reduction. Evaluating such measures within the same methodological framework would not only broaden the scope of adaptation options, but also address potential equity risks by ensuring that households in older or heritage districts are not systematically excluded from climate resilience benefits.

Finally, equity analysis should move beyond distributive outcomes. While this study quantified how costs and benefits are shared across neighbourhoods and housing types, other dimensions of justice, such as procedural and recognition justice, remain unexamined. Future research could combine quantitative SCBA with qualitative approaches that explore governance processes, participation and community perceptions, thereby developing a fuller picture of equity in NbS.

5.5 Policy Implications

The findings of this thesis have several implications for policymakers seeking to expand green roof adoption in ways that are both effective and equitable. While the analysis is specific to The Hague, the lessons extend to other European cities facing similar challenges of urban adaptation, socio-spatial inequality, and uncertain future conditions.

Targeted support for vulnerable neighbourhoods
Income-based allocation strategies not only improve distributive equity but also enhance aggregate efficiency. Subsidies or mandates should therefore prioritise lower-income and climate-vulnerable neighbourhoods, where collective benefits such as health improvements and energy savings are greatest. Without targeted support, vulnerable areas risk being sidelined by efficiency-driven strategies, perpetuating adaptation gaps.

Safeguards for social housing and tenants
The neighbourhood analysis revealed that tenants, especially in social housing, often gain fewer direct benefits from green roofs, since property-related value increases accrue mainly to owners. At the same time, housing corporations and private landlords face most of the costs of expansion. To avoid regressive outcomes, policy should focus on institutional arrangements rather than household-level subsidies. Co-financing schemes with housing corporations, maintenance support for corporately-owned roofs, and regulatory obligations for private landlords can ensure that vulnerable tenants benefit even when they do not own the buildings they live in. This aligns institutional incentives with societal benefits and prevents vulnerable groups from being excluded.

Integrating equity into allocation mechanisms
The results indicate that equity cannot be assumed as a by-product of green roof expansion. Equity criteria should be explicitly embedded in allocation mechanisms. For example, technical potential could be combined with socio-economic and vulnerability indicators when setting subsidy eligibility or investment priorities. This can transform the efficiency–equity trade-off into a potential synergy.

Adaptive and flexible governance
Uncertainty analysis showed that economic outcomes are highly sensitive to parameters such as installation costs and flood benefits, with robustness varying across neighbourhood types. Policymakers should therefore avoid relying too heavily on deterministic forecasts. Adaptive strategies such as pilot programmes, flexible subsidy levels, and iterative monitoring can help ensure that investments remain viable as conditions change.

Ensuring inclusion of heritage and unsuitable buildings
Technical constraints mean that some roofs, particularly in older or protected districts, are unsuitable for greening. Without alternatives, households in these areas risk being systematically excluded from the benefits of green roof programmes, reinforcing spatial inequalities in climate resilience. Complementary measures such as subsidies for façade greening, pocket parks, or other blue–green infrastructure are therefore essential to ensure adaptation benefits also reach heritage neighbourhoods.

Embedding green roofs in broader policy agendas
Green roofs should not be treated as a standalone adaptation measure. They deliver benefits that cut across multiple urban agendas, including climate resilience, energy efficiency, and affordable housing. Integrating green roofs into wider municipal programmes (e.g. sustainable building standards, housing renovation policies, or district-level adaptation plans) can create synergies and ensure distributional outcomes are considered alongside other policy objectives.

Summary
In summary, equitable allocation strategies can deliver efficiency and fairness, but only if they are deliberately designed with safeguards for vulnerable groups. The Hague can expand green roof adoption in ways that enhance resilience while reducing inequality by adopting adaptive governance approaches and embedding equity criteria into municipal strategies. Complementary measures are needed to ensure that households in heritage or otherwise unsuitable buildings are not systematically excluded from adaptation benefits. These lessons extend beyond The Hague, offering guidance to other European cities seeking just and robust pathways for nature-based urban adaptation.

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Appendices

A

Data Sources and Preprocessing

This appendix provides the technical details underlying the workflow described in Section 3.2. It summarises the datasets used in both the city-wide and neighbourhood-specific SCBA, and documents the preprocessing steps (filtering, harmonisation, and inclusion criteria).

Datasets

Tables A.1 and A.2 list the datasets by source, scale, year, and purpose. These cover the spatial framework, roof geometries and adoption, socio-economic and housing data, and climate indicators.

Table A.1: Datasets used in the city-wide SCBA

Dataset	**Description**	**Scale**	**Year**	**Usage**
Buurten Den Haag (Gemeente Den Haag, 2018)	Neighbourhood boundaries for The Hague	Neighbourhood	2018	Base geometries
Dakvlakken Den Haag (Gemeente Den Haag, 2024a)	Roof polygons with area, slope, and use attributes	Building/roof	2024	Identify suitable roofs
Zonnepanelen en Groene Daken 2022 (Gemeente Den Haag, 2021)	Locations of green roofs and PV panels	Roof/address	2022	Current adoption
Den Haag in Cijfers (Gemeente Den Haag, 2019)	Socio-economic, housing, demographic indicators	Neighbourhood	2019–2025	Equity analysis
BAG adressen en postcode levels (Gemeente Den Haag, 2024c)	Building geometries with addresses and postal codes	Address	2022	Address counts

Table A.2: Additional datasets used in the neighbourhood-specific SCBA

Dataset	**Description**	**Scale**	**Year**	**Usage**
PC4 & PC5 Data 2022 (Centraal Bureau voor de Statistiek, 2022)	National postcode boundaries and statistics	PC4, PC5, PC6	2022	Base geometries, energy data (PC4)
PC5 Data 2021 (Centraal Bureau voor de Statistiek, 2022)	Energy consumption data	PC5	2021	Household gas/electricity
Hittekaart Den Haag (Gemeente Den Haag, 2017)	Urban heat island raster	100×100 m	2017	Heat exposure

Preprocessing Notes

Roof suitability filtering

Roofs filtered for slope $\leq 25°$; heritage zones excluded. Remaining polygons aggregated to neighbourhood and PC5.

Adoption metrics

Green roofs assigned to neighbourhoods via polygon centroids. Indicators: (i) % of suitable roof area greened, (ii) % of segments greened.

Socio-economic and building data

Socio-economic indicators harmonised to CBS conventions; missing values imputed by city mean. Address counts derived from BAG.

Climate vulnerability indicators

Flood exposure = share of area inundated > 10 cm. UHI exposure aggregated from raster data to polygons.

Boundary harmonisation

PC5 polygons intersected with neighbourhood boundaries. Extensive variables apportioned by overlap; counts by address shares.

Inclusion filter

Neighbourhoods with fewer than 100 residents or 50 addresses excluded.

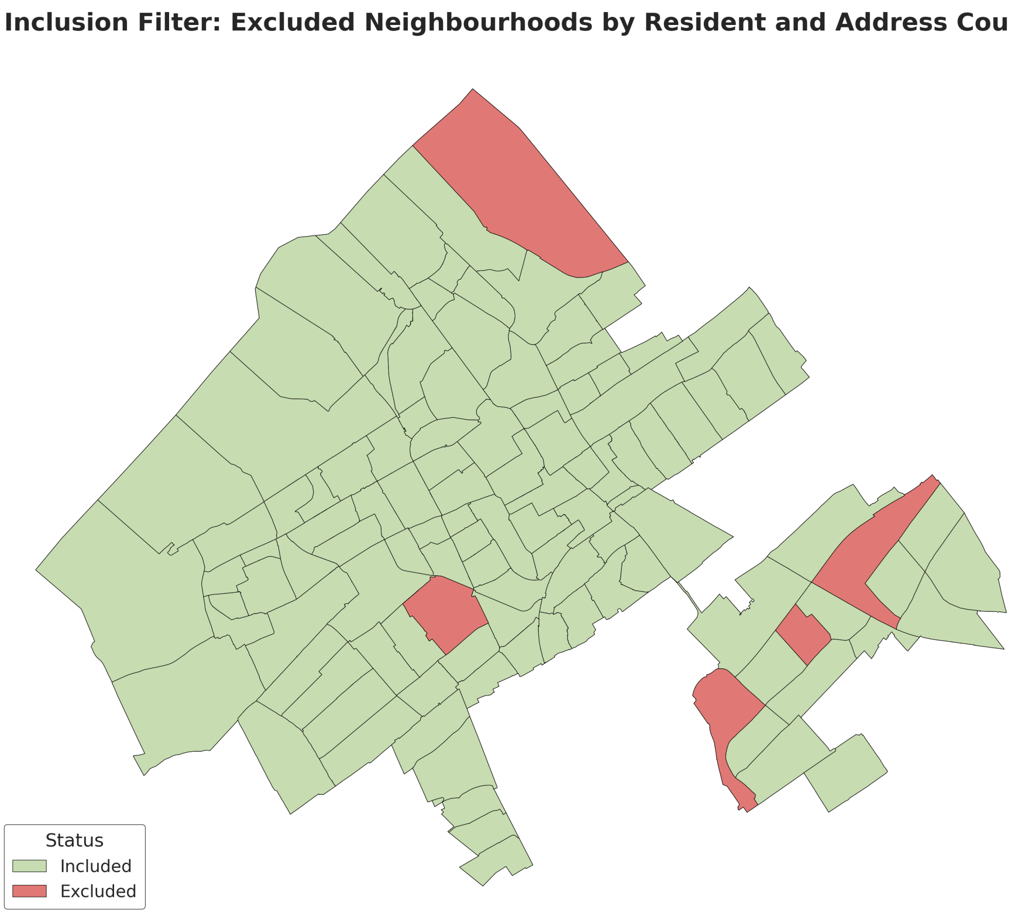

Figure A.1: Neighbourhoods excluded due to low population or address counts.

B

SCBA Parameters and Model Structure

This appendix complements Section 3.3 by providing the technical details of the city-wide SCBA model. It contains (i) parameter values, (ii) the model structure, and (iii) formal equations. All monetary values are expressed in constant 2023 euros.

Key Parameters

Table B.1 summarises the main modelling parameters, covering cost assumptions, physical performance, socio-economic effect sizes, and valuation coefficients. These parameters were applied uniformly across all neighbourhoods, with local variation in outcomes arising from differences in roof suitability, socio-economic conditions, property values, and climate exposure.

Table B.1: Key SCBA parameters and their sources

Symbol	Description	Value	Unit	Source
T	Time horizon	40	years	Romijn and Renes (2013)
r	Social discount rate	0.0225	–	Romijn and Renes (2013)
c_{install}	Installation cost per m^2	€75	€/m^2	Arcadis et al. (2024)
c_{maint}	Annual maintenance cost	€1.50	€/m^2/year	Arcadis et al. (2024)
δ_{flood}	Retention volume per m^2	0.03	m^3/m^2	Arcadis et al. (2024)
p_{flood}	Avoided flood cost	€500	€/m^3	Arcadis et al. (2024)
s_{gas}	Gas saving percentage	0.02	–	Castleton et al. (2010) and Van Oorschot et al. (2021)
s_{elec}	Electricity saving percentage	0.01	–	Castleton et al. (2010) and Van Oorschot et al. (2021)
p_{gas}	Gas price	€1.00	€/m^3	Statistics Netherlands (CBS) (2023), assumed constant
p_{elec}	Electricity price	€0.25	€/kWh	Statistics Netherlands (CBS) (2023), assumed constant
b_{health}	Patients avoided per 1% green per 1,000 residents	0.167	persons	Arcadis et al. (2024)
c_{patient}	Healthcare cost per patient	€917	€/person	Arcadis et al. (2024)
$l_{\text{productivity}}$	Productivity loss per patient	€6679	€/person	Arcadis et al. (2024)
b_{lifespan}	Lifespan extension benefit	€45	€/m^2	Arcadis et al. (2024)
t_{lifespan}	Lifespan benefit year	25	year	Arcadis et al. (2024) and Sproul et al. (2014)
u_{tiered}	Tiered property value uplift schedule (future scenarios only)	0–500 m^2: slope up to 1.4%; $\geq$500 m^2: fixed tiers up to 10.5%	–	Arcadis et al. (2024)

See Table B.2 for the full tier structure. The slope refinement for 0–500 m^2 captures variation among small roofs.

Property Value Uplift Schedule

Table B.2 provides the tiered hedonic uplift schedule applied in the expansion scenarios. For small additions (< 500 m^2 per dwelling), a linear slope of 0.2 percentage points per m^2 was applied up to the 1.4% maximum. For larger additions, fixed percentage tiers were used. This uplift aims to capture the broader amenity effects of green roofs on property values, including aesthetic appreciation, noise reduction, productivity, and comfort, as reported in the Arcadis *LIFE@Urban Roofs* background study (Arcadis et al., 2024).

Table B.2: Tiered uplift percentages by additional green roof area per dwelling

Min. area (m^2)	**Max. area (m^2)**	**Uplift (%)**
0	500	1.4
500	1000	2.5
1000	2000	5.0
2000	3000	7.5
3000	4000	10.0
4000	5000	12.5
5000	6000	15.0
6000	7000	17.5
7000	8000	20.0
8000+	–	21.0

City-Wide SCBA Model Structure

For each neighbourhood i, costs and benefits were modelled as follows.

Costs

$$C_{i,0} = A_i^{\text{new}} \cdot c_{\text{install}} \tag{1}$$
$$C_{i,t>0} = (A_i^{\text{existing}} + A_i^{\text{new}}) \cdot c_{\text{maint}} \tag{2}$$

Benefits

$$B_{i,0}^{\text{flood}} = A_i^{\text{new}} \cdot \delta_{\text{flood}} \cdot p_{\text{flood}} \tag{3}$$
$$B_{i,t}^{\text{energy}} = A_i^{\text{total}} \cdot \left[\frac{n_{i,\text{hh}} \cdot (s_{\text{gas}} p_{\text{gas}} g_i + s_{\text{elec}} p_{\text{elec}} e_i)}{A_i^{\text{roof,total}}} \right] \tag{4}$$
$$B_{i,t}^{\text{health}} = \min\left(\frac{A_i^{\text{total}}}{A_i^{\text{neighbourhood}}}, 1 \right) \cdot b_{\text{health}} \cdot \frac{\text{pop}_i}{1000} \cdot (c_{\text{patient}} + l_{\text{productivity}}) \tag{5}$$
$$B_{i,0}^{\text{property}} = n_{i,\text{affected}} \cdot v_{i,\text{house}} \cdot u_i \tag{6}$$
$$B_{i,t_{\text{lifespan}}}^{\text{lifespan}} = A_i^{\text{new}} \cdot b_{\text{lifespan}} \tag{7}$$

where g_i and e_i are the average household gas and electricity consumption in neighbourhood i, and u_i is the uplift percentage from the tiered schedule (Table B.2). The health benefits formula applies a uniform coefficient to the total population, without differentiation by age or income.

Indicators

From these flows, neighbourhood-level indicators were computed:

$$NPV_i = \sum_{t=0}^{T} \frac{B_{i,t} - C_{i,t}}{(1+r)^t} \tag{8}$$

$$BCR_i = \frac{\sum_{t=0}^{T} \frac{B_{i,t}}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_{i,t}}{(1+r)^t}} \tag{9}$$

In addition to NPV and BCR, the model also tracked IRR and payback period based on discounted cash flows.

Scenarios link

The allocation mechanisms used to distribute additional green roof area across neighbourhoods (Environmental, Income-based, Uniform, and Optimised) are described separately in Appendix C.

C

Scenario Definitions

This appendix provides the formal definitions of the four expansion scenarios described in Section 3.3.1. All scenarios allocate additional green roof area (A_i^{new}) across eligible neighbourhoods i, defined as those with non-zero suitable roof area and meeting minimum thresholds for residents and addresses (Section **??**). In three scenarios (Environmental, Income-based, Uniform), the total target expansion was fixed at 50% of the sum of all suitable roof area:

$$A^{\text{target}} = \left(\sum_{i \in \text{eligible}} A_i^{\text{suitable}} \right) \cdot 0.5 \tag{10}$$

The Optimised scenario instead uses linear programming to maximise total marginal NPV under capacity constraints.

Table C.1: Expansion scenario definitions and allocation rules

Scenario	Definition / Allocation rule
Environmental	Allocation proportional to composite climate vulnerability: $w_i^{\text{env}} = \frac{1}{2}(\hat{f}_i + \hat{h}_i)$, where $\hat{f}_i$ is normalised flood exposure and $\hat{h}_i$ is normalised UHI extent.
Income-based	Allocation weighted inversely by mean disposable household income: $w_i^{\text{income}} = 1/y_i$, where y_i is average income in neighbourhood i.
Uniform	Allocation proportional to the share of suitable roof area: $w_i^{\text{uniform}} = A_i^{\text{suitable}} / \sum_j A_j^{\text{suitable}}$.
Optimised	Allocation determined by linear programming to maximise total marginal NPV: $$\max_{x_i} \sum_{i \in \text{eligible}} NPV_i^{\text{per m}^2} \cdot x_i \quad \text{s.t.} \quad 0 \leq x_i \leq A_i^{\text{suitable}}$$ where x_i is the additional green roof area allocated to neighbourhood i.

In all scenarios, allocation proceeds iteratively using a capacity-aware redistribution algorithm: if a neighbourhood reaches its maximum suitable roof capacity ($A_i^{\text{new}} \leq A_i^{\text{suitable}}$), its unallocated share is redistributed proportionally to other neighbourhoods still below capacity.

D

Equity Indicators

This appendix provides the technical definitions of the equity indicators introduced in Section 3.3. It covers (i) Gini coefficients, (ii) Lorenz curves, and (iii) need-adjusted (vulnerability-weighted) NPV.

Gini coefficient

The Gini coefficient measures inequality in the distribution of per-capita NPV across neighbourhoods. It is defined as:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n^2\mu}$$

where x_i is the per-capita NPV for neighbourhood i, n is the number of neighbourhoods, and μ is the mean of x. A value of $G = 0$ indicates perfect equality, while $G = 1$ indicates maximal inequality.

Lorenz curve

Lorenz curves plot the cumulative share of population (x-axis) against the cumulative share of NPV (y-axis), after ranking neighbourhoods by per-capita NPV. The 45° line represents perfect equality, and deviations below this line indicate the degree of inequality.

Need-adjusted NPV

To capture the alignment of benefits with areas of greatest adaptation need, per-capita NPV was weighted by a composite vulnerability index:

$$NPV_i^{\text{adj}} = NPV_i^{\text{per capita}} \cdot v_i$$

where v_i is the normalised average of flood exposure and UHI extent in neighbourhood i. The index was scaled such that $\sum_i v_i = 1$, ensuring comparability across scenarios.

E

Equity and Clustering Methods

This appendix complements Sections 4.1.3 and 4.2 by detailing the equity indicators and clustering procedures used in this thesis.

Equity Indicators

Three indicators were used to assess equity in the distribution of costs and benefits: the Gini coefficient, Lorenz curves, and need-adjusted (vulnerability-weighted) NPV.

Gini coefficient

The Gini coefficient measures inequality in the distribution of per-capita NPV across neighbourhoods:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n^2\mu}$$

where x_i is the per-capita NPV for neighbourhood i, n is the number of neighbourhoods, and μ is the mean of x. $G = 0$ indicates perfect equality, $G = 1$ maximum inequality.

Lorenz curves

Lorenz curves plot the cumulative share of population (x-axis) against the cumulative share of NPV (y-axis), after ranking neighbourhoods by per-capita NPV. The 45° line represents perfect equality; the further the curve bows away, the higher the inequality.

Need-adjusted NPV

To capture alignment with climate adaptation needs, per-capita NPV was weighted by a composite vulnerability index:

$$NPV_i^{\text{adj}} = NPV_i^{\text{per capita}} \cdot v_i$$

where v_i is the normalised mean of flood and UHI exposure in neighbourhood i. The index was scaled such that $\sum_i v_i = 1$, allowing comparability across scenarios.

Clustering Parameters and Refinement

Neighbourhood clustering was used to identify systematic patterns in SCBA outcomes and to select representative case studies.

Feature preparation

Four features were standardised to z-scores before clustering: (i) per-capita NPV under the income-based allocation, (ii) mean SES score, (iii) composite climate vulnerability (flood + UHI), (iv) adoption rate of green roofs.

Clustering procedure

K-means clustering was applied using `scikit-learn` with: `n_clusters=4`, `init='k-means++'`, `n_init=10`, `max_iter=300`, `random_state=42`.

Diagnostics included the Elbow criterion, silhouette scores, and silhouette profiles. All pointed to $k = 4$ as a parsimonious solution, balancing interpretability with cluster separation.

Cluster interpretation
Inspection of centroid profiles yielded four typologies:

1. **High Gain–Equity**: above-average per-capita NPV, equitable distribution, moderate vulnerability.
2. **Low Uptake–Stable**: low adoption, stable socio-economic context, moderate-to-low vulnerability.
3. **High Risk–Reward**: high vulnerability and disadvantage, but relatively high potential NPV.
4. **Low Return–Saturated**: affluent, high-adoption areas with low marginal returns.

Refinement to PC5 units
For the neighbourhood case studies, PC5 geometries were intersected with administrative neighbourhood boundaries. Extensive variables (roof area, adoption, energy use) were apportioned by relative overlap, while dwelling and household counts were allocated using BAG addresses. Peripheral sliver units were excluded if $> 90\%$ of their area lay outside the neighbourhood or if they had fewer than 50 households.

This refinement ensured that only consistent PC5 units were retained, aligning the detailed local analysis with the city-wide SCBA.

F

Neighbourhood-Specific SCBA

This appendix complements Section 4.3 by providing the detailed PC5-scale SCBA model specifications and supplementary results.

Model Specification

At PC5 level, costs and benefits were disaggregated by housing type $h \in \{$*koop*, *huur_particulier*, *huur_corporatie*$\}$. This allowed analysis of distributional outcomes within neighbourhoods.

Costs

$$C_{i,h,0} = A_{i,h}^{\text{new}} \cdot c_{\text{install}} \tag{11}$$

$$C_{i,h,t>0} = \left(A_{i,h}^{\text{existing}} + A_{i,h}^{\text{new}}\right) \cdot c_{\text{maint}} \tag{12}$$

$$C_{i,h}^{\text{total}} = \sum_{t=0}^{T} \frac{C_{i,h,t}}{(1+r)^t} \tag{13}$$

Benefits

$$B_{i,h,0}^{\text{flood}} = A_{i,h}^{\text{new}} \cdot \delta_{\text{flood}} \cdot p_{\text{flood}} \tag{14}$$

$$B_{i,h,t}^{\text{energy}} = A_{i,h}^{\text{new}} \cdot \left(\frac{n_{i,\text{hh}} \cdot (s_{\text{gas}} p_{\text{gas}} g_i + s_{\text{elec}} p_{\text{elec}} e_i)}{A_i^{\text{roof,total}}} \right) \tag{15}$$

$$B_{i,h,t}^{\text{health}} = \Delta T_i \cdot \left(\frac{\text{Elderly}_i}{1000} \cdot b_{\text{health}} \cdot (c_{\text{patient}} + l_{\text{productivity}}) \right) \tag{16}$$

$$B_{i,h,0}^{\text{property}} = n_{i,h,\text{affected}} \cdot v_{i,\text{house}} \cdot u_{i,h} \tag{17}$$

$$B_{i,h,t_{\text{lifespan}}}^{\text{lifespan}} = A_{i,h}^{\text{new}} \cdot b_{\text{lifespan}} \tag{18}$$

Indicators

$$NPV_{i,h} = \sum_{t=0}^{T} \frac{B_{i,h,t} - C_{i,h,t}}{(1+r)^t} \tag{19}$$

$$NPV_i = \sum_h NPV_{i,h} \tag{20}$$

Outputs also included BCR, IRR, payback period, and within-neighbourhood equity metrics.

Supplementary Neighbourhood Results

Several additional outputs were produced at PC5 scale but summarised only briefly in the main text.

Benefit composition

Figure 16 in the main text shows benefit structures. Additional disaggregated tables are provided in the digital repository.

Within-neighbourhood inequality
Table 7 and Figure 20 report Gini coefficients and Lorenz curves of per-household NPV. These complement city-wide inequality indicators.

G

Explaining the Divergence Between Citywide and PC5 SCBA

This appendix explains the divergence between citywide and PC5 SCBA outcomes by focusing on the treatment of health benefits. The decomposition in Figure G.1 shows the contribution of health and other benefits under three approaches: (1) Citywide SCBA, (2) PC5 SCBA with cooling-based health, and (3) PC5 SCBA with the citywide health formula applied.

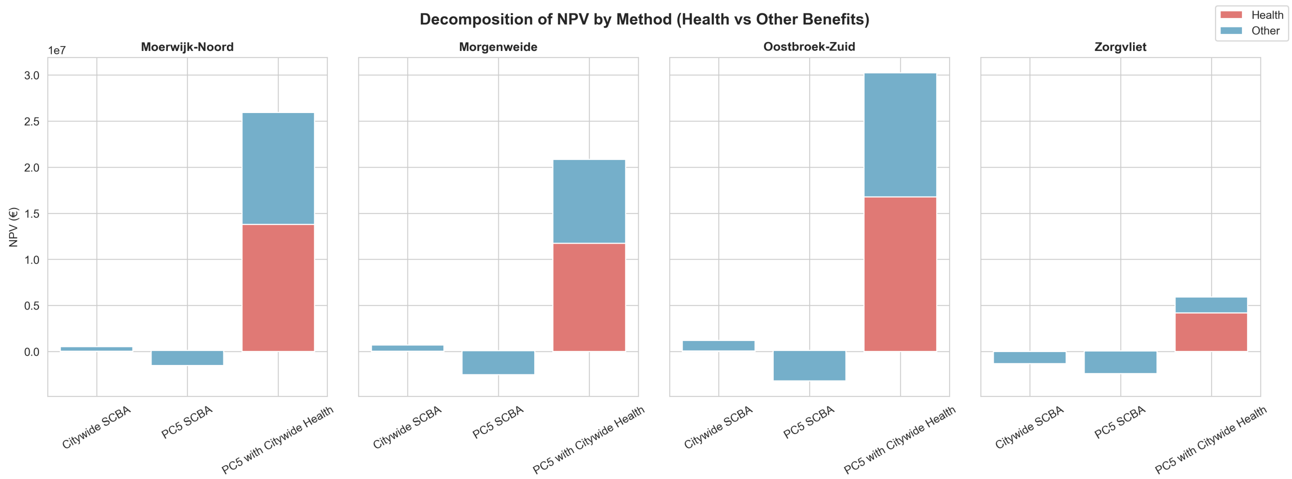

Figure G.1: Decomposition of NPV into health and other benefits across methods.

Table G.1 reports the aggregated values across the four representative neighbourhoods. It clearly illustrates that the NPV gap is explained by health benefits alone: while the cooling-based method produces relatively modest values, the citywide formula applied to the same data results in benefits that are one to two orders of magnitude larger.

Table G.1: Comparison of health benefit estimates under different methods (Uniform scenario).

Neighbourhood	**Citywide Health (€)**	**PC5 Cooling (€)**	**PC5 with Citywide Health (€)**	**ΔNPV (PC5–City)**	**ΔNPV if Citywide Health**
Oostbroek-Zuid	75,789	114,065	16,775,300	$-4,409,560$	$+12,251,670$
Moerwijk-Noord	22,543	123,502	13,781,030	$-2,044,390$	$+11,613,140$
Zorgvliet	2,249	60,795	4,192,474	$-1,072,055$	$+3,059,624$
Morgenweide	26,917	98,029	11,729,240	$-3,230,044$	$+8,401,171$
Total	127,498	396,392	46,478,045	$-10,756,049$	$+35,325,605$

The comparison between the citywide and PC5 SCBA shows that the large divergence in NPV outcomes is almost entirely driven by the health benefit calculation. While the citywide method assigns substantial health benefits based on avoided patients and productivity gains, the PC5 cooling-based method yields much smaller values. As shown in Appendix **??**, applying the citywide health formula to PC5 data nearly eliminates the gap.