Towards the utilisation of green roofs with the pursuit of sustainable urban development

A full life cycle cost benefit analysis

Faculty of Civil Engineering and Geosciences
Vitali van Elk

Technische Universiteit Delft

TU Delft

Towards the utilisation of green roofs with the pursuit of sustainable urban development

A full life cycle cost benefit analysis

Master thesis

In partial fulfilment of the requirements for the degree of
Master of Science in Building Engineering
specialization 'Building physics and technology'

To be defended publicly on
Monday October 2, 2023 at 2:00 pm.

door

Vitali van Elk

Graduation Committee

Chairman graduation
Prof. dr. H.M. Jonkers, Technische Universiteit Delft

Supervisors
Msc. E. Stache, Stache Architects
Dr. D.F.J. Schraven, Technische Universiteit Delft
Dr. ir. M. Ottele, Technische Universiteit Delft

Interested party's:
G. Bakker, Intermaris
W. van Lubeck, Intermaris

Keywords: Nature based solutions, green roofs, cost benefit analysis, life cycle assessment, environmental product declaration, external costs

ISBN 000-00-0000-000-0

An electronic version of this dissertation is available at
`http://repository.tudelft.nl/`.

What is needed now is a new era of economic growth
- growth that is forceful and at the same time socially and environmentally sustainable

Brundtland, 1987

If I had six hours to chop down a tree, I'd spend the first four hours sharpening the axe

Abraham Lincoln

Preface

Before you is the master's thesis "Towards the utilisation of green roofs with the pursuit of sustainable urban development, A public and private full life cycle cost benefit analysis of a green roof". This thesis constitutes the completion of the Master of Science in Building Engineering with a specialisation in Building Technology and Physics at the Faculty of Civil Engineering and Geosciences of Delft University of Technology. This research was conducted in cooperation with TU Delft and Intermaris and has provided me with valuable knowledge and experience that can be useful in my professional career.

My interest in plants and nature has always been a personal passion. During a course within my master, led by Henk Jonkers and Marc Ottelé, I came across the ecological impact hidden behind the built environment and how these two seemingly different worlds can work together. This created my fascination for how ecology and built environment can be intertwined. This new outlook changed my perspective on the world and made me increasingly enjoy how nature finds a way into even the most urbanised environments. From this mindset, the topic as Eva Stache introduced it was an excellent opportunity for my master's thesis. Working with Intermaris offered me insight into the practical challenges and gave me the chance to apply theoretical knowledge in practice. However, I wanted to follow my own analytical approach and not be influenced by a desire to exaggerate the role of green roofs. Instead, I wanted to contribute in an honest and realistic way to the position of green in sustainable development within the urban environment. The result ultimately exceeded the academic contribution alone.

Looking back on this journey of writing my master's thesis, I realise it has been a path of learning moments, challenges and engaging discussions. Therefore, I would like to thank everyone who supported me throughout this process. First of all, I would like to thank Eva Stache for her guidance, advice and, above all, inspiring conversations about the role of green in both academia and practice. Next, my thanks go to my thesis committee for their guidance, advice and insight throughout my graduation process. Henk, Marc and Daan, thank you very much for your guidance, advice and feedback regarding the academic foundation of my research. Your critical eye and reflection helped me keep my research within a manageable scope and contributed to the quality improvement and academic value of my work. I would also like to thank Gijs Bakker and Walter van Lubeck for their cooperation, positive feedback and enthusiasm with which my research was received. In addition, I would also like to thank the other people within the TU Delft whose knowledge made a valuable contribution to this research.

In addition, many thanks to my friends, environment and fellow students for their continuous support during my studies and for the challenge, motivation and strength I can draw from them. You have made my period in Delft fantastic and will forever look back on this with pleasure. A special thanks to my family for their support during my career and the pride and appreciation I feel from them. This motivation and support means a lot to me.

For now, I hope you find joy in reading my thesis!

Vitali J. van Elk
Rotterdam, August 2023

Summary

Introduction

The urban environment is increasingly proving to be an unhealthy place to live. Given the fact that cities often face multiple significant challenges simultaneously, it is important to seek out multi-functional solutions. The flexible, multi-functional and adaptable characteristic of nature have been proven to work effectively against climate change hazards and contribute towards human prosperity and well-being. With 40-50% of the total impervious urban area being made up of roofs, green roofs could play an important role in the mitigation of some of the challenges that cities face. Previous research has shown that there is widespread outcome of the cost benefit analysis of a green roof. Local parameters influence the outcome, but additionally there is a fragmentation in the benefits that are being included in the analysis. Simultaneously there is a lot of research that focuses on the external costs of production materials. A solid bridge between these two fields of science is currently lacking. This research positively contributes towards bridging the gap between the two scientific fields, while at the same time also analyses the current state of the literature and the methodologies used to define the economic value of the benefits of green roofs. To fill the current gap in the literature and to add towards sustainable development, the following main research question was formulated:

What are the private and public costs and benefits of applying a green roof during all life cycle stages?

Methodology

To answer the research question, this study developed a research cycle consisting of four phases: design, analysis, synthesis and evaluation. The first phase involved a literature review that served as the basis for the research. The aim of this phase was to gather the necessary knowledge to bridge the gap between materials science and economic research and identify an appropriate approach to analyse the existing literature on cost-benefit analysis of green roofs. The information from this phase was used in the second phase to systematically deconstruct 20 peer-reviewed articles to gather knowledge and assess the current methodologies used to value the benefits of green roofs. The synthesis phase gave meaning to the knowledge from both design and analysis by applying it to a case study. This case study of Betsy Perk was used to evaluate the current approach and provide new insights, and also gave an indication of the potential future values. The final stage was used to provide interpretation of this result, based on which conclusions could be drawn and recommendations made for future researchers.

Results

The goal of this research was to make a positive contribution towards sustainable development. In doing so the aim was to provide a holistic and fair overview of the costs and benefits of a green roof for both the public and private party. To determine the costs of the roof a close collaboration with Intermaris provided us with values regarding the purchase and maintenance price. The external costs were determined by quantitative values from the environmental product declaration as provided by Zinco made according to the standard of a life cycle assessment. This standard distinguishes between 19 different impact categories, which can be subdivided according to their impact on human health, ecosystems or natural resource depletion. The quantitative values were monetized using the Ecocosts, which represent the marginal prevention costs of harmful emissions linked to the emissions themselves.

This study conducted a systematic analysis of 13 ecosystem services and found that similar approaches are often used to quantify these services in the literature. However, differences in interpretation were also found, especially in methodologies to quantify values. The study compared these assumptions and focused on parameters that influence value. There was considerable variation in values, with location and local climate being important factors. The analysis showed that many assumptions were made in quantification, which reduced the precision of values.

The study then examined valuation methods to monetise quantitative benefits, and searched for the causal relationship between the quantification and valuation. There was no consensus in the current literature and sources used a variety of valuation methods. A recurring problem was the distinction between avoided impact costs and avoided mitigation costs. These methods led to different stakeholders, which, because of mutual exclusivity, sometimes made choices necessary. The study highlighted the need for better guidelines and more research to inform decisions.

Following the literature review, it appears that private parties experience several benefits, including cost reduction, income generation and property value increase. However, due to methodological limitations, not all benefits can be expressed in financial terms. The literature does not sufficiently understand the full potential of water use (for toilet flushing, irrigation and drinking water) that reduces the water requirement of buildings, the reduction in energy requirement through the urban heat island effect. Similarly, the benefits of increased property value through aesthetics and recreational opportunities are not fully understood.

Based on literature knowledge, concrete economic value can be realised for private parties. This includes income from material production multiplied by the selling price, cost savings for sewerage and wastewater treatment due to incentives, reduced energy demand due to improved thermal insulation, and savings in costs for sound insulation and a conventional roof due to the sound insulation effect and life extension. In addition, improved sound insulation contributes to property value appreciation due to the direct correlation between noise level and value.

After completing the literature review, it can be concluded that due to methodological limitations or groundless assumptions, not all benefits can be expressed in financial terms for society. Volunteers in rooftop garden projects can share in the annual yield, experience pleasure and social benefits, such as satisfaction, relaxation, social contact and community building, while residents enjoy comfort and recreational value and the health benefits through noise level reduction. Governments avoid costs through efficient storm water management, flood risk reduction and biodiversity promotion.

Multiple parties share in benefits such as educational value and cost savings in health, environment, heritage and economy through reduced flood risk and urban heat island effect along with reduced energy requirements for temperature regulation. Improvement in aesthetics can increase property value and is also considered an independent value in the immediate area. Also, benefits such as food security and avoidance of external production costs can benefit society as a whole. However future research is needed to develop a method to monetise all of these.

A number of benefits can be expressed in financial terms. These benefits include avoided impact costs for transport and treatment associated with preventing impact costs for public authorities, due to the reduced runoff volume. For society as a whole, there is a good method of direct air cleaning by plants at the local level and indirectly by reducing emissions from power plants in remote locations. These benefits can be quantified by multiplying the avoided cost by the replacement cost or the avoided cost method. The beneficial effects of improved air quality directly affect people, the climate and the natural environment. They have positive effects on things like health, agriculture, floods, ecosystems and climate change.

Applied to the case study, the study shows that it is difficult to find values that are accurate and recent. Close stakeholder collaboration is needed to bridge the information gap. Finally, the financial summary shows the costs and benefits of green roofs for both public and private stakeholders. While the implementation of green roofs seems to be beneficial for society, this is not the case for the project developer. Combining both stakeholders also results in a positive value. It is important to note that these values are based on the current knowledge base and are thus just a indication of the full potential. Additional research is needed to get a full picture of economic profitability at both public and private levels.

CONCLUSION

Ultimately, this study was successful in answering the research question by providing a comprehensive overview of both the costs and benefits of a green roof. The study effectively presented the existing knowledge on the benefits of a green roof and drew conclusions on the current state of the methodologies used. It has also built a bridge with materials science by including the external costs of the green roof in the analysis. In doing so, the study has laid a solid foundation for a cost-benefit analysis of a green roof that is as consistent as possible with the principles of sustainable development, taking into account people, planet and profit.

Throughout this process, valuable insights have been generated, not only for the academic world, but also for practical applications. The current overview untangled the current information and the open approach, including potential opportunities and contradictions of ethical, moral and political perspectives, has led to the initiation of discussions. These discussions can engage scholars and experts in the field to further refine and extend this basic concept. In this way, the research has been of significant value in improving the position of the green roof as a means of addressing current urban issues.

Contents

List of Figures

List of Tables

LIST OF ABBREVIATIONS

LIST OF ABBREVIATIONS

NBS	Nature based solution
EGR	Extensive green roof
IGR	Intensive green roof
LCA	Life cycle assessment
s-LCA	Social Life Cycle Assessment
e-LCA	Environmental Life Cycle Assessment
EPD	environmental product declaration
LCI	Life Cycle Inventory
CBA	Cost Benefit Analysis
LCC	Life Cyle Costing
NPV	net present value
UHIE	Urban Heat Island effect

1

Introduction

This chapter begins with the research context, which sets the tone by exploring the historical and theoretical foundations of our study area. The problem definition brings into focus the specific challenges we intend to address. Next clear research objectives guide our efforts towards tangible results, while the central research question drives our research. Based on this the chosen research methodology outlines our systematic approach, and the thesis guide provides a roadmap for the chapters ahead, illustrating how each section contributes to clarify the overarching research objective.

1.1. Research context

1.1.1. Urbanization and stress on cities

Over the past 200 years, people have increasingly been living in urban environments. The United Nations World Urbanization Prospects has estimated that 68% of the world's population lives in an urban area in 2050, up from 54% in 2014 (Herath and Mittal, 2022). In the Netherlands, 74% of people lived in urban regions in 2014. Of these, about half lived in small urban regions (= less than 500,000 inhabitants) and the other half in large urban regions (= more than 500,000 inhabitants) (Nabielek and Hamers, 2015). On average, 523 people live per square metre in the Netherlands, ranking it at number 27 in the world (Centraal Bureau Statistiek, 2023; worldpopulationreview, 2023).

A variety of diverse activities take place in these urban centers, encompassing residential, occupational, commercial, and recreational functions. These activities coexist within the limited spatial boundaries of cities, contending for available resources and land. This urban environment is increasingly proving to be an unhealthy place to live. Despite occupying only 3% of the Earth's land surface, cities exert a disproportionately large influence on various environmental indicators. Notably, urban centers bear a considerable burden in terms of global energy consumption, ranging from 60% to 80% of the total consumption. Moreover, approximately 75% of the global carbon emissions can be attributed to urbanized regions. Additionally, cities are responsible for utilizing over 60% of the world's resources (Manso et al., 2021). Already back in 1999, Fenger found a noticeable difference in the quality of the air within and outside of cities, as a result of the pollutants that are emitted as a result of the high intensity and variety of activities that take place in urban areas.

Climate experts stress that cities are undergoing additional stress caused by the increase in extremes such as the number of heat waves, droughts and floods (Albers et al., 2015; Bai et al., 2018). The impacts become obvious when contrasting urban and rural settings, see figure 1.1. The difference between the two can be seen in more places. The urban water cycle is increasingly polluted with various emerging organic compounds (Pal et al., 2014). The Urban heat island effect (UHIE) first described by Howard (1818) is created by and affects cities. In which, cities become warmer than the rural environment around them (Rosenzweig et al., 2011), due to the higher heat absorption coefficient of materials used in cities. Rather than reflecting the heat, the surface materials will absorb it. These all directly negatively affect the people and environment in the city.

Therefore, the United Nations has set "Sustainable cities and communities" as one of its sustainable development goals (United Nations, 2022). The goal is to improve the living environment in cities for the ever-increasing number of residents. The issue is that these solutions often only address one problem at a time,

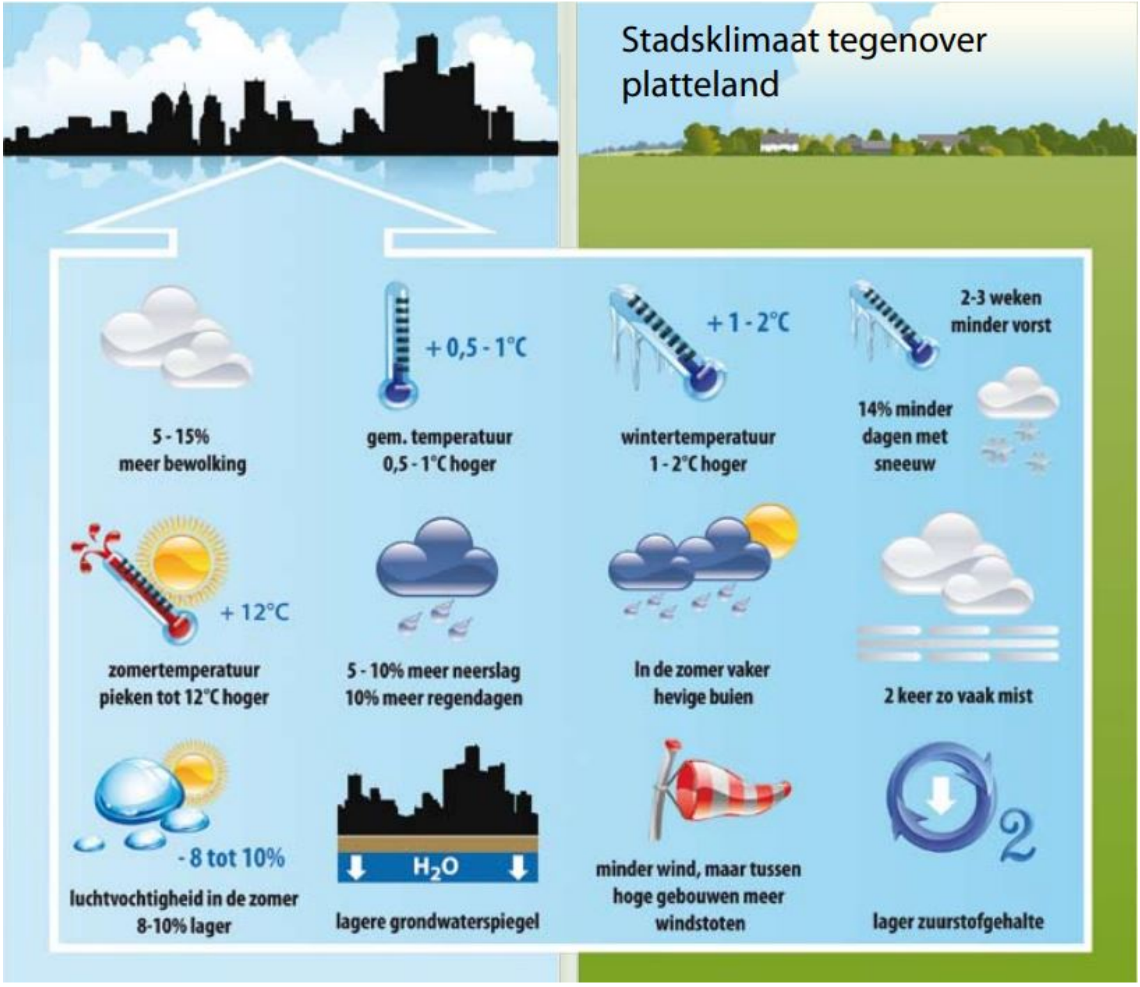

Figure 1.1: City vs Urban climate (Hop and van Wetten, 2010)

and may even exacerbate issues in other areas. Given that cities often face multiple significant challenges simultaneously, it is important to seek out multi-functional solutions. One that benefits the city's inhabitants, the environment and the economy (people, planet and profit) (Hop and van Wetten, 2010).

1.1.2. NATURE BASED SOLUTIONS

Around the 2000 the concept of a city as an ecosystem emerged (Grimm et al., 2000). While cities in the past strive to promote the market economy and achieve increased human well-being, these new insights provide the motivation to reconnect nature with the city and its ecosystem goods and services (Elmqvist et al., 2013). The main benefit of adding nature into the cities, is its wide variety of ecosystem service. The use of nature against social-environmental problems is referred to as nature based strategies (NBS). These NBS, have been proven to work more effectively against climate change hazards than traditional approaches. This is mainly due to the flexible, multi-functional and adaptable characteristic of nature on an ever-changing climate issue (Hobbie and Grimm, 2020). These initiates also reduce the threat on the remaining vegetation and preserve it (Standish et al., 2013). A previous classification of these ecosystem services and their contribution towards human prosperity and well-being is made by Gómez-Baggethun et al. (2013), figure 1.2.

Making adjustments within the urban environment to provide space for these NBS is proven to be difficult once the layout is of a city is fixed (Wang and He, 2015). The total amount of public land still available is used in providing new buildings, space for infrastructure but also well-known conventional urban green infrastructures such as urban park systems and urban forestry, including street trees. These are all competing for the available land which increases its price in cities. This calls for solutions from outside the public domain. About 40-50% of the total impervious urban area is made up of roofs. The roof area therefore offers plenty of

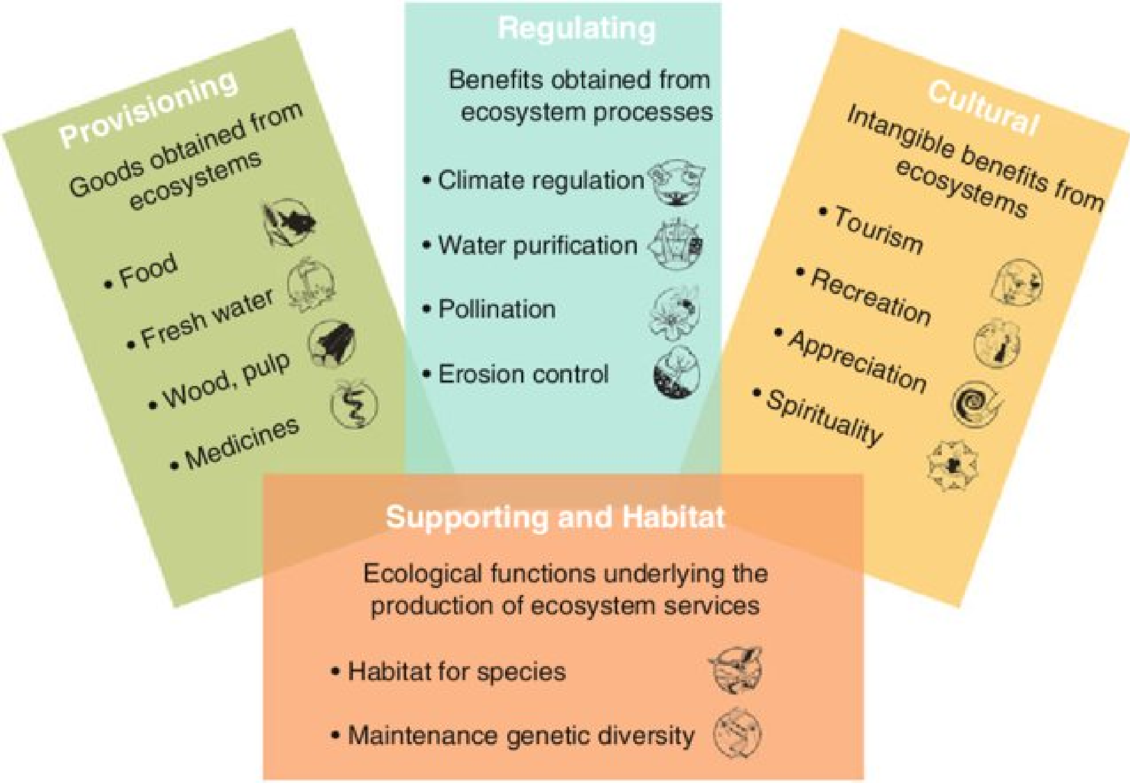

Figure 1.2: Classification of ecosystem services (Gómez-Baggethun et al., 2013).

room for opportunities to achieve a more sustainable and better living environment (Shafique et al., 2020).

Using green roofs for their qualities on the environment is relatively new but increasingly proven effective (Gaffin et al., 2012). Around the 20th century, this technique was used to protect buildings from the physical effects of solar radiation, but then also to combat fire hazards (Oberndorfer et al., 2007). However, more research shows that green roofs have many more additional benefits such as absorbing air pollution (Currie and Bass, 2008; Yang et al., 2008), absorbing noise pollution (Van Renterghem and Botteldooren, 2009, 2011; Van Renterghem et al., 2013), rainwater retention (Mentens et al., 2006; Vijayaraghavan and Raja, 2014) temperature regulation (Rosenzweig et al., 2006b; Smith and Roebber, 2011; Feitosa and Wilkinson, 2018), contributing to a healthier living environment (Bertram and Rehdanz, 2015) and the provision and preservation of habitat for flora and fauna (Mayrand and Clergeau, 2018; Teotónio et al., 2021). The big advantage is that existing buildings can be used to achieve habitat improvement. This saves on the cost of a piece of green space, especially since maintenance requires additional costs such as the economic and natural resources to keep the green space alive (Salmond et al., 2016).

1.2. PROBLEM DEFINITION

In this chapter, a closer look is given at the current literature in order to find a possible barrier to the widespread adoption of green roofs. Where first, the problem is defined based on literature review, to then identify the gap in the literature.

1.2.1. PROBLEM STATEMENT

The current environmental impacts on our cities call for a viable approach that can preserve, protect and improve our cities. Green roofs are being put forward as a resilient, natural and effective tool as part of the solution. In recent years, green roofs have become increasingly common because of the many benefits involved at the building scale. Nevertheless, when examining the broader scope, the significance of these benefits becomes overshadowed. While a large-scale implementation can have a reinforcing effect. To fully realize the advantages on a larger scale, encompassing neighborhoods, districts, and entire cities, it becomes crucial to implement this approach extensively and with strategic spatial distribution (Versini et al., 2020). However, implementation is limited by a number of barriers identified by Zhang and He (2021). Lack of government policy, unreliable technology level, unreliable economic assessment or lack of individual cooperation provide barriers that limit the adoption of green roofs.

The barrier at the economic level is characterised by the outcome of different studies on the return on investment (Mahdiyar et al., 2021). For instance, the payback period varies from 7 years in America (Carter and Keeler, 2008) to never at all in Southern Europe (Ascione et al., 2013). Studies in China show a 10-year payback period (Chan and Chow, 2013) and in Singapore with a 15-year payback period lie between those values (Wong et al., 2003b). The big difference between these studies can originate from local parameters such as climate, cost, price of maintenance and price of electricity. Often, these are assumptions made based on common local values. Therefore, the results of these studies cannot be used globally but are location-specific (Mahdiyar et al., 2021).

However, for an incentive in the use of green roofs, it is important for investors to understand the financial picture more concretely. This sector looks at the financial return and risks of different alternatives. Green roofs are often more expensive than conventional roofs and also require additional maintenance during their lifetime (Bianchini and Hewage, 2012a). The cost of green roofs is not only more expensive, there is also an imbalance between the part that is paid back economically and socially. Consequently, not all the proceeds of the green roof end up with the investor (Mahdiyar et al., 2021). This requires an integrated approach with close cooperation between public and private parties. When the public sector is included in the solution framework, their interests should be carefully taken into account. This therefore requires analyses to include a presentation that correctly and fully reflects the associated financial flows of a green roof.

Additionally, a change in how the building process is viewed is taking place in recent years, which reveals the costs for society. A growing awareness of the environmental impact through the design, construction, operation, and demolition of a building has caused the construction industry to look for ways to reduce the amount of environmental impact and energy consumption. In the Netherlands, the coalition agreement has expressed firm ambitions. For instance, its climate target is to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990. To achieve these goals, the government must not only encourage by means of subsidy schemes, but also take a framework-driven approach. Whereby targeted regulations must lead to the achievement of strict goals (Planbureau voor de Leefomgeving, 2021). Cities are being responsible for about 70% of global carbon emissions and about 60% of resources used (United Nations, 2022). That also means a hefty task for the construction industry. The 2018 transition agenda circular construction economy states the goal of halving CO_2 emissions in construction by 2030 (transitieteam circulaire bouweconomie, 2018). The elaboration, advisory route to a circular economy in construction 2022, even talks about reducing CO_2 50-60% (transitieteam circulaire bouweconomie, 2022). However, CO_2 is not the only measure to be considered, there are several environmental impact categories that deserve all attention in achieving the sustainable ambitions. In general it all comes perfectly as cited by Andrews: "When considering products and services in a sustainable development perspective, a life cycle perspective brings powerful insight. It aims to provide increased knowledge on the 3P's – the three pillar approach of sustainable development: People, Planet and Profit/Prosperity"– along the whole supply chain, from extraction of raw materials to end of life. This is all meant to inform more comprehensive decision making" (Andrews (2009) p.16) Therefore, an integrated approach should be sought that takes into account the environmental as well as cost-related aspects, so that a sustainable design can emerge (Shafique et al., 2020).

1.2.2. LITERATURE GAP

Something has to change to improve the living conditions in cities and to reduce the effects of climate change in the urban environment. However, this must be done within the new approach and goals of the construction industry, while remaining insightful to investors to encourage them to opt for a sustainable and green choices. Green roofs are being put forward as a nature-based solution to help tackle this, but the implementation is still limited by certain barriers. To overcome this, it is important for the study to be comprehensive and insightful. Based on existing literature, a picture of the various aspects belonging to the current knowledge gaps can be obtained.

Literature review revealed that reports show a wide range of return on investment for different situations. The cause of this can be traced to site-specific parameters or differences in the structure of the reports. The answers that can explain this difference are sought outside the site-specific parameters. The difference in outcomes can be explained if we start looking at the parameters included in the analysis. When comparing studies of Carter and Keeler (2008), Bianchini and Hewage (2012b), Chan and Chow (2013), Ascione et al.

(2013), Peng and Jim (2015) and (Teotónio et al., 2018) it becomes clear that the same financial effects are not always included in setting up the cost-benefit picture. This makes it difficult to compare the different studies, as also mentioned by Teotónio et al. (2021). Many studies lack a clear rationale as to why influences of a green roof are not included. Secondly not all life cycle stages are included in all of the literature. As a result, the design of some studies seems arbitrarily chosen. There may also be an asymmetry in how the results were arrived at. For instance, almost every study includes the effect of a green roof on a building's energy demand. However, how this calculation is addressed and calculated varies from one study to another. All of this means that the current studies do not provide a complete unilateral representation of the cost-benefit of a green roof over all life phases.

Additionally, the assessment of green spaces usually considers local biodiversity (in situ) that relates to the site on which the building is constructed. Biodiversity affected outside the construction site (ex situ), which relates to materials extraction, transport and waste, is rarely included in the project assessment (Brachet et al., 2019). Much of the literature does focus either on the in situ part or ex situ effects. The studies by Ziogou et al. (2017, 2018); Teotónio et al. (2018) and Alves et al. (2019) make an attempt to assess the societal/environmental impact of using green roofs throughout their life cycle by looking at local benefits. However, they do give a distorted picture by including the absorption of pollutants but not the emissions generated during the life-cycle phase on the cost side, creating a potentially too positive picture. Bianchini and Hewage (2012b) makes an attempt to include emissions during the production phase, but only includes CO_2 and NO_x in this calculation. Other studies as summarized by Shafique et al. (2020) look only at the release of emissions, and lack the benefits gained during the use stage. The studies by Yao et al. (2020), Wang et al. (2020) and Rasul and Arutla (2020) are a step in the right direction when it comes to create a bridge between the two approaches. The outcomes give an overview of the emissions released during the various life phases of a green roof. However, the quantification of these numbers are hard to interpret by investors, because they lack the translation into monetary terms.

Combining all these aspects, paying special attention to both environmental and cost assessment, is essential for decision making (Shafique et al., 2020). The current disadvantage is that fragmentation creates a risk that the outcomes could be used in the wrong framework. These numbers can be used for a phenomenon called green washing. This gives the impression of making green sustainable choices when this is not necessarily the case. It is therefore important to work towards a situation where all separate components are included in one study so that a complete and therefore fair statement can be made.

After reviewing the existing literature, the following specific aspects can be summarised:

- There is great variety in benefit assessment, both in its effects and in its calculation
- There is a need for a study that uses an integrated approach to present an accurate representation of the use of green roofs and their environmental impact and benefits during all life cycle phases
- The environmental impact should be determined based on a standardized approach in order to able to rightfully check and compare outcomes. The EPD calculation should also allow for monetizing so that the environmental impact can correctfully interpreted by stakeholders

1.3. RESEARCH OBJECTIVE

The aim of this study is to present a comprehensive cost-benefit analysis of the use of green roofs in a Dutch case study, within the context of sustainable development. This means that the study should consider social, ecological and economic aspects. In doing so, it is important to move away from the fragmented approach currently prevalent in the literature and towards a holistic approach. In doing so, this research strives to encompass knowledge from the existing literature in order to arrive at new academic insights. On this basis, an overview of both the impact and benefits of green roofs for all stakeholders can be created. In doing so, the study tries to take a step forward from existing literature and creates a more balanced picture in cost-benefit analyses by implicitly including environmental impacts. This contributes to a more realistic picture of green roofs and minimises the risk of "green washing". Ultimately, the structured organisation of financial aspects should results in a clear financial picture that is clear, complete and fair to both project developers and society.

The higher goal of this study is to enable, through a financial overview of green roofs, a fully informed, fair and transparent choice of this alternative in renovation or new construction. This will help reduce the negative impacts of human activity, especially in urban areas, and promote a more favourable climate within cities. Green roofs can serve as versatile solutions within the natural urban ecosystem, contributing to various functions. This study contributes to a deeper understanding of this contribution and the current pool of information within the literature. As a result, cities can ultimately become more attractive and liveable for all inhabitants, with a focus on sustainable development as a guiding principle.

The research should therefore be both insightful and comprehensive so that it can add value to the academic field and provide a valuable and insightful contribution to both project developers and public parties. This requires a well structured set-up and the presentation of clear results accordingly.

In doing so, the novelty of this research is that it captures and combines the previously fragmented literature. By building on the number of studies within the literature that come close to the attempted outcome, the qualities of different cost-benefit studies will be compared and combined leading to new insights about the current state of literature. Next this new insight on one hand and product environmental impact studies on the other have to be combined. This will bridge the current gap in the literature by making the value transparent and including the environmental impact during the usage phase as well as the production and demolition phase. Distinguishing between the costs and benefits for the project developer and the costs and benefits for society gives a rightful overview. This way the outcome of this study can be a stepping stone to a larger-scale application of green roofs which is honest to people, planet and profit. Through the results, it should allow the social and environmental interest versus private to be determined and taken into account when decisions are made.

1.4. RESEARCH QUESTION

In order to fulfil the research objective, a main research question is formulated. This main question is as follows:

- What are the private and public costs and benefits of applying a green roof during all life cycle stages?

The formulation of relevant sub-questions clarifies and structures the main research question. The sub-questions serve as tools to reduce the complexity of the main question and find targeted answers. As a result, the research is conducted in an effective and efficient manner and creates more depth and understanding of the topic. The sub-questions are designed to provide a systematic approach and in-depth knowledge of the topic. By answering the sub-questions, different aspects of the topic are highlighted and a clear overview of the findings emerges. To guide the research in a structured way, the main research question is divided into three sub questions:

- What is the environmental impact of the production of a green roof, and how can these be expressed in monetary terms?
- What are the private benefits of the ecosystem service of a green roof, and how can these benefits be expressed as an economic value?
- What are the public benefits during the use stage of the ecosystem services of a green roof, and how can these benefits be expressed as an economic value?

1.5. RESEARCH FRAMEWORK

Within the framework of the subject, there are plenty of directions and parameters that can be included in the research. The parameters chosen determine the final quality of the result of the research. For this research, it has been chosen through delineations that certain issues are not included in the analysis. This is based on the angle from which the subject is highlighted. The limits of the study are given and indicates the precise study boundaries. From this basis, the reliability and validity of the research is formulated on the basis of which the results can only be referred back in this framework.

SCOPE

There are many benefits and economic values associated with the application of green roofs, both for individuals and society. Because of the wide extend in which the current literature has tried to make cost benefit analysis (CBA) for green roof, the focus of this review is to condense, summarise and make conclusions based on this information. The aim of this study is not to come up with new calculation methods to determine the value of the ecosystem services, nor is it to fill in all the gaps from existing methods. The focus is to highlight all the practises currently used in the literature so that follow up research can reflect on these and add to the existing knowledge pool in the literature. This study will review the literature and existing calculation methods will be identified and assessed into a usable whole that will form the basis for the calculations on the case study.

This will be complemented by the environmental impact of the materials to provide a more holistic analysis of the roof. Literature will again be used for this, however the goal is not to determine the environmental impact from scratch within this study. Instead examples or sought to act as a proof of concept. The focus will be on providing information to bridge the gap.

CASE STUDY

The author was alerted to the case study by Eva Stache, whose involvement is in the renovation of the Betsy Perk project. Thanks to her involvement, a meeting was arranged with Gijs Bakker, Senior Project Leader Property Management at Intermaris, and Walter van Lubeck, Programme Director Kersenboogerd at Intermaris. Both gentlemen showed considerable interest in the study, and their participation in the project is of eminent importance in arriving at case-specific findings.

Betsy Perk in Hoorn. Betsy Perk is a complex where elderly people live independently. As most residents of the complex are over 70 years old, living with care is combined. The district in which the complex is located is going through a renovation with the aim to improve public spaces and increase safety so that a sense of social cohesion is restored. In addition, homes will be made more sustainable (Intermaris and Gemeente Hoorn, 2022). The renovation of Betsy Perk is going to increase the thermal insulation, which in combination with the connection of the complex to a city heat grid will reduce the energy demand of the building. In addition, the complex will be integrated with nature. A green roof and green facade will offer all its benefits to both the building and the residents. The area surrounding the building will be addressed as well and will receive a new layout, again with the aim to integrate nature.

This case study does not only provide the means to bridge the gap between theoretical literature and a real life example, it is important both for the scientific value of the research and for its social relevance. On the one hand, the case study provides the concrete data, figures and results that help to bridge the gap between theoretical literature and practical examples. This allows the methods found to be tested and real figures to provide deeper interpretations of the research findings.

On the other hand, the case study is in an environment that is open to learning from the research findings. Intermaris not only values the research's contribution to their own interests as a private party, but also looks more broadly at the social contribution of green roofs. They are willing to invest in applications that offer both economic and social value. This approach to sustainable development, as explored in the study, aligns with Intermaris' vision. As a result, the impact of the research goes beyond simply contributing towards scientific knowledge, the research interacts directly with involved stakeholders who want to use the results. This allows the study's findings to be shared directly with parties interested in working with green roofs and in need of relevant insights.

CONSTRUCTION TYPE

The building sector consists of several building usages. Due to the difference in use, ecosystem services will also be used differently. This study focuses on residential buildings. Residential buildings were chosen because of their relation to the case study. It is expected that due to the different needs of the users, ecosystem services will be estimated differently. Because users of residential buildings experience a building in a different way compared to buildings for commercial purposes. This distinction may be of value later when looking for key features in the literature. The main choice regarding the scale of the study was made using the scale of the building. Therefore, the parameters excluded from this study are those that are mainly influenced by a neighbourhood/urban approach.

BUILDING ELEMENT

The goal of this research is to assess a life cycle analysis of a green roof in order to show its potential. Most literature makes a distinction between intensive green roofs (IGR) and extensive green roofs (EGR). Both have different effects on the building. The main parameter in determining whether or not they are being included in the analysis is whether they require structural adjustments to the building. This will have to be determined based on literature and case specific parameters. This research is aimed to eliminate any big structural adjustments required to carry the load of the roof.

LIFE CYCLE PHASE

This study aims to conduct a comprehensive analysis of the full life cycle of green roofs. This includes the evaluation of costs, impacts and benefits during all phases of the life cycle. In this way, a comprehensive understanding is obtained. That also means that the aim is to include the information from all life cycle stages as best as possible.

LEVEL OF DETAIL

The goal of this research is to provide insight on the effect of implementing a green roof. This study aims to ensure that different impacts can be easily and insightful juxtaposed. For more in-depth analyses on the specific behaviour of a green roof, separate studies have already been done or are still needed. Hendriks et al. (2016) links the services of a green roof to the layers of the green roof package. It is beyond the scope of this study to verify this at a detailed level. The main issue is how much effect adding additional detailed information has on the value of the final result. Because the outcome of this research should mainly serve as the starting point for follow-up research, topics that require in-depth attention are only addressed superficially. This is done because ever so much can be addressed within this research and statements should not be made based an incomplete view of the literature.

1.6. RESEARCH METHODOLOGY

The study has been approached from the perspective of adding value to the literature but additionally should be presentable and of value at the decision-making table. It has been reasoned in such a way that the results that emerge from the study can help with this. This will help bridge the gap between the theoretical scientific side and the world of practice in which choices are ultimately made. In this chapter, the design of the study will be explained step by step.

DESIGN

The literature review begins by establishing the outline and framework for this research. The analytical framework for this research begins by using the cascade framework. This framework first focuses on looking at stakeholders and highlighting the potential of collaboration between these different stakeholders in a dynamic environment. Based on this, the framework initially focuses on a usual cost-benefit analysis without external costs. Thereby, this must first be worked out as a solid basis before external costs can be linked to it. Different project evaluation methods and various economic tools for monetary expression are first examined. Then, a categorisation of ecosystem services that can serve as a starting point for the analysis of ecosystem services to monetary values is sought. Information on ecosystem services, available economic instruments and stakeholders involved is used to systematically cover all ecosystem services according to established inclusion and exclusion criteria. Existing peer-reviewed articles investigating the costs and benefits of green roofs will be systematically filtered into a list that will be covered. A structured approach has been adopted for each step to create a reproducible study while allowing for open reflection.

Next, the possibilities of including the impact of material production in the analysis will be investigated. This integrates so far separate impacts of material production into the analysis. However, this requires research into different available methods to quantify this impact and how this impact can be converted into a monetary value. Here, clear insight into the use of this tool is crucial so that results can be interpreted. The choice of standardised methods facilitates verification and comparison of results.

ANALYSIS

To build an effective foundation of the current state of green roof studies for future research, it is essential to understand what benefits the studies contain and how they are quantified. This process partly determines the calibre of the outcomes, as it involves translating abstract concepts into monetary terms. To accurately assess the various case study benefits, it is necessary to first be familiar with existing practices. This can provide both theoretical and practical insights into how these benefits have been treated in previous literature. Any benefits described in the identified literature will be evaluated and gaps may be identified for future research. The readers for whom this section is mainly intended are researchers in the scientific community.

SYNTHESIS

Once the exact method for calculating green roofs has been established based on the literature review, a search for relevant data can begin. The reader for whom this section is intended is more focused on Intermaris itself and other stakeholders from the field. To make the results of the research specific to the Betsy Perk case, the cooperation of Intermaris is essential. As property manager, Intermaris has detailed information about the complex, which serves as a basis for making the results specific. Moreover, Intermaris can help in establishing contacts with involved parties, such as suppliers. In addition, existing databases and literature will be used, but contact will also be made with the manufacturers of the Betsy Perk components.

Literature will mainly be consulted for key figures when a specific approach is not possible. This can be the case both for the effects of green roofs and for calculating future cash flows. For the latter, it is important to make predictions about the future. Values are back-calculated using a discount rate, for example to account for inflation or social value.

When requesting data, the author should always weigh up the added value of these data for the study. This consideration can be made in consultation with Intermaris, Zinco or other parties involved. The data obtained will only be used within the framework of the research. On 31 October 2022, the author presented the privacy criteria to Intermaris during a meeting. From this, both parties concluded that there were indeed areas within the study that could potentially contain privacy-sensitive information. Based on this, the author decided not to include possible privacy-related information.

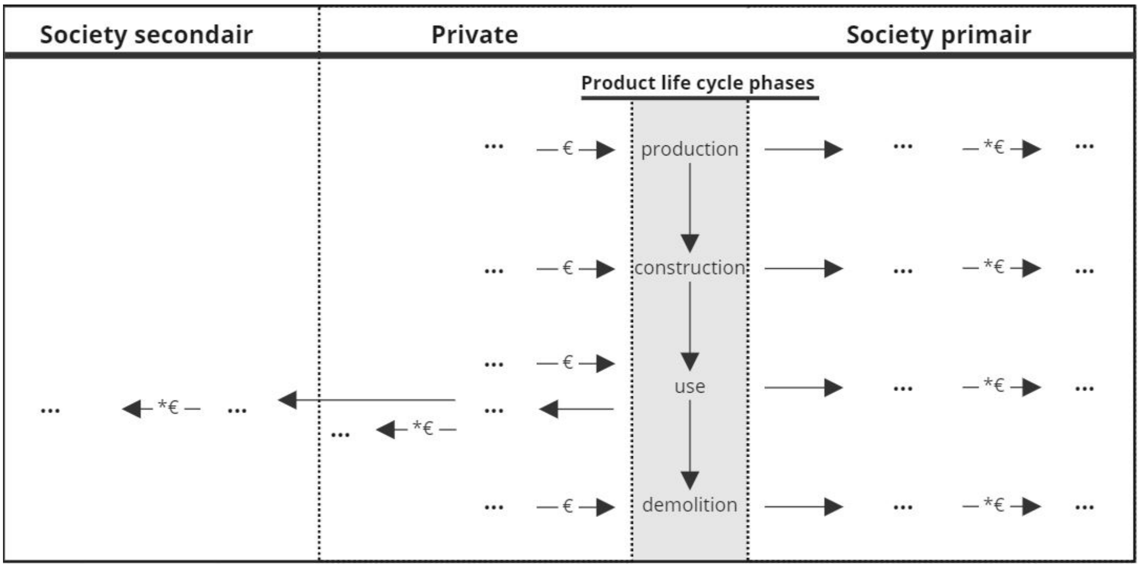

Figure 1.3: Research layout: overview of flows to determine monetary values

When all data and calculation methods are known, all values can be calculated. In concrete terms, this means that the cash flows can be put directly into a model, for example the purchase value, benefits, costs etc. Then we have the direct effects of a green roof. For the investor and for society. For society, there are also indirect advantages/disadvantages. The effects for the investor can be translated into social costs. Less energy used by the building results in a cost saving for the investor but for society it means that less emissions are released, this can be passed on to a value, figure 1.3.

Once all data has been converted to a value expressed in money, all values can be back-calculated using the discount rates. This is done using software such as excel. The idea is to create a clear calculation model so that it can be used for other purposes with minimal modifications. It also subjects the individual values to sensitivity analysis. The aim is to provide a clear financial and economic overview of a green roof. For each stakeholder, its costs and benefits will be outlined. This way, the overview can be used directly by the stakeholder concerned in its decision-making. An integral overview will also be made that includes the virtual money flows of all stakeholders.

EVALUATION

This report moves towards a desired future image in which social costs and benefits are taken into account at all decision moments. That is why in the last phase, the evaluation phase, the theoretical findings are discussed, the shortcomings of the current state of the literature is mentioned, the implications it has for the conducted case study and a conclusion is presented. In the end, recommendations are given for further improvement and implementation of this research.

1

The results can be used by both researchers, stakeholders and decision makers. They can also be used by investors who want to bridge a gap in the budget of an investment. Or, viewed from the other side, by government agencies that want to encourage the use of green roofs through subsidies because the social costs are amply repaid over the lifetime. The structure of the study and the breakdown by stakeholder should make this possible.

1.7. THESIS GUIDE

This section contains the outline of this research project. It consists of 7 chapters in four phases, see figure 1.4

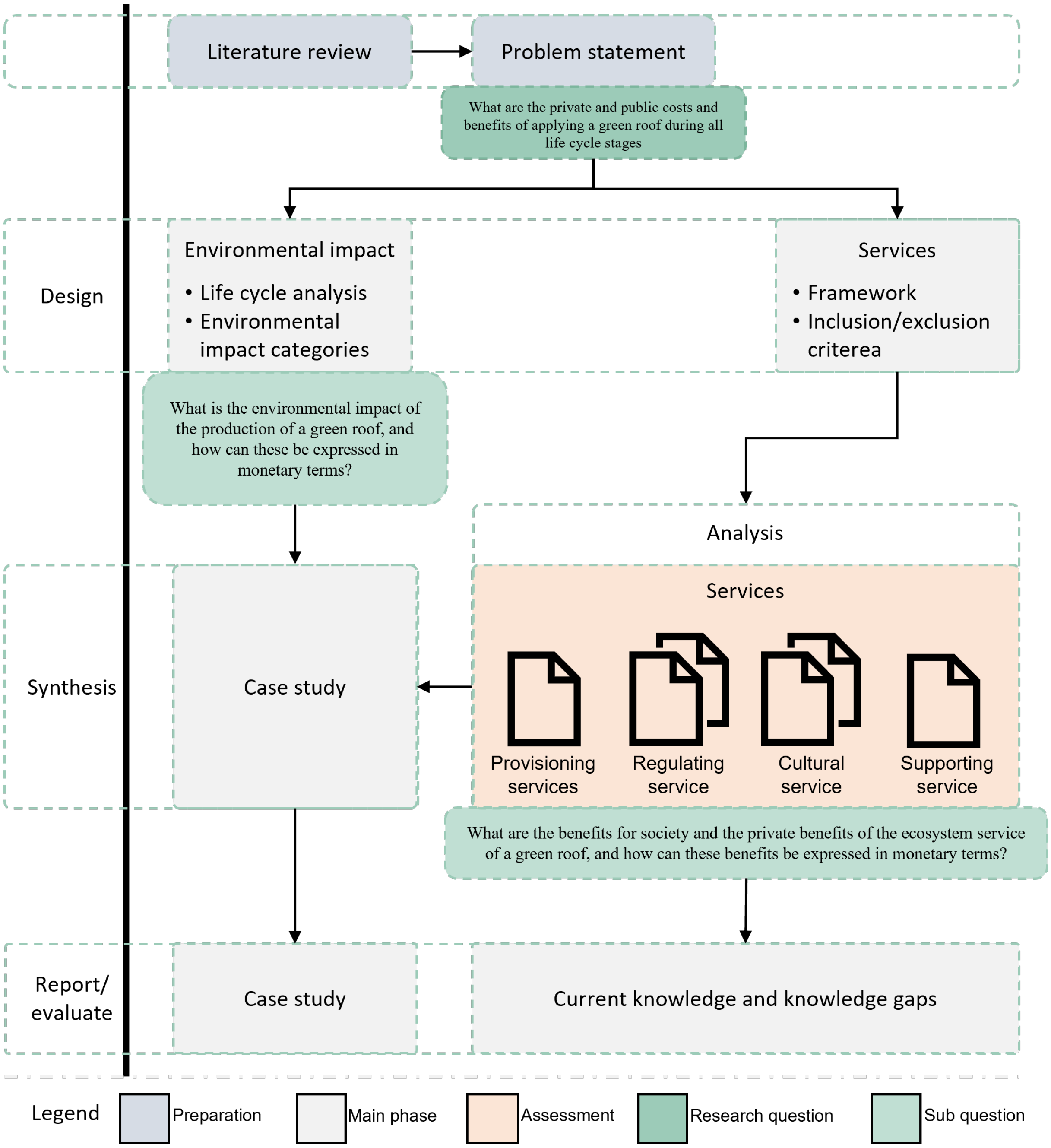

Figure 1.4: Flowchart report

Part A | Design phase

The next part in this study is the design phase. This phase includes a literature review that broadens the knowledge on the topic and focuses on the analytical framework for investigating the costs and benefits of green roofs. It includes the use of the cascading framework, analysis of ecosystem services and impacts of material production.

2

Theoretical framework

2.1. Introduction

To make a statement on the case study in this research, weighing the initial investment against the benefits during the use phase, it is essential to analyse both aspects thoroughly. As part of a growing focus on sustainability, the initial investment is no longer seen only as a financial cost, but the aim is to look beyond it by including environmental costs throughout the life cycle. To supplement the existing literature and thus take a step forward, this chapter explores the context of the subjects in the literature. It draws on existing academic knowledge in the literature and attempts to form a basic understanding of how to shape this approach based on that knowledge. It also uses this context to develop an approach to systematically review existing cost-benefit analyses in the ecosystem services literature. The literary knowledge from this chapter forms the basis for the research and provides the academic foundation, stability and structure for the rest of the research.

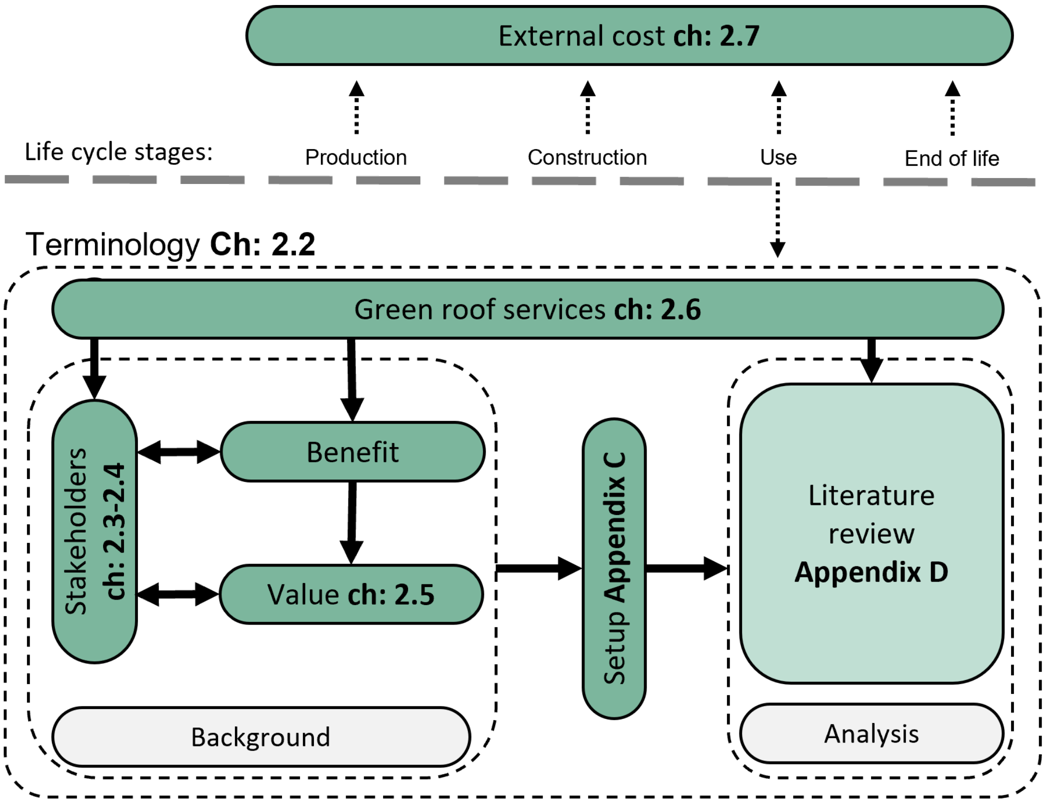

Figure 2.1: Overview of the research methodology and the relation to the literature review in part B based on the cascade framework

The methodology used to examine the papers was based on the cascade framework. Within this framework, a categorisation and flow of information was logically created to link ecology with the social domain. Section 2.2 presents the framework and its terminology. Section 2.3 highlights the importance of a select number of stakeholders and introduces the way different values can be categorised. Section 2.4 adds the sustainable development goals and highlights the opportunities they present. Section 2.5 looks at how value is represented and how it is created. Section 2.6 provides a systematic definition of ecosystem services as a starting point for further research. Finally, section 2.7 examines the addition of external costs to the current methodology.

2.2. TERMINOLOGY

The complexity of ecosystems' contribution to supporting human activities through goods and services cannot be underestimated. It includes a wide range of processes and interactions between living and non-living elements, taking place at different scales and levels with feedback, time lag and nested phenomena (Fisher et al., 2009). This complexity makes it difficult to establish unambiguous terminology and definition for ecosystems and their contribution to human activities (La Notte et al., 2017; Kadykalo et al., 2019). The lack of a consolidated categorization has has led to much discussion and debate regarding the interpretation of ecosystems' function in promoting human welfare and existence. Considerable efforts have been made to overcome these barriers in terminology (Kadykalo et al., 2019). Every categorization methodology presents certain restrictions and limitations of comprehensively encompassing ecosystems' complete impact on human activities. Thus, acknowledging that any classification is simply a single perspective to understanding the complexity of ecosystems (De Groot et al., 2010b).

Despite these challenges, it remains crucial to establish an appropriate ecosystem classification that effectively communicates their significance and worth to human undertakings. A well-defined and unambiguous classification aids in recognizing the most significant ecosystems with regard to enhancing human welfare and the ones that are most susceptible to deterioration. This allows targeted actions to be taken to ensure the protection and sustainable use of these ecosystems (De Groot et al., 2010b).

In view of the expected results from this study, it was decided to exercise caution. It is highly likely that a lot of data is still missing from the results of this study. As a result of the various disciplines involved in the findings of this study, it may serve as the foundation for future research that may involve scientists from various fields. Integrating various knowledge systems, such as natural and social sciences, engineering, local and indigenous knowledge, as well as involving various stakeholders such as indigenous communities, businesses, farmers, local and rural communities, is considered necessary for developing a holistic understanding of the full range of information and knowledge about human-nature relations (Kadykalo et al., 2019). For this reason, it is important to define the terminology used in advance so that subsequent research can build on it. This requires clear rules on the classification of these studies, as communication on this may be impossible at a later date. The aim is to be effective in creating a framework for future studies, where the results of this study can serve as a basis. Furthermore, the classification of these studies should be based on objective criteria and standardized procedures to ensure consistency and comparability across different studies. This will facilitate the synthesis and integration of findings from different studies, leading to a better understanding of the research topic.

2.2.1. CASCADE FRAMEWORK

This report uses De Groot et al. (2010b) classification as a frame of reference, see figure 2.2. This classification contributes to the clarity of the key concepts used through comprehensive terminology and sophisticated language. The cascade method is a way of understanding the relationship between ecology and the benefits to human well-being and the contribution to support human life (La Notte et al., 2017; Zhang et al., 2022a). It is crucial to the evaluation and mapping of ecosystem services as well as decision-making research. The three main aspects in this are the mapping of ecosystems, the service assessment of the ecosystem and value accounting. Ecosystem services are linked to human activities and needs in the cascade framework, so depending on the context, the service may or may not exist. In this way, an overview must be extracted from the complexity for each situation instead of an overview sufficient for the whole world (Haines-Young et al., 2010). The standardized and consistent approach would enable ecosystem assessments to be conducted uniformly and reliably and serves as a universal reference for a variety of studies. The framework offers such flexibility that it can be developed and elaborated in a manner relevant to location-based studies (Potschin-Young et al., 2018), both on a national and global scale (La Notte et al., 2017).

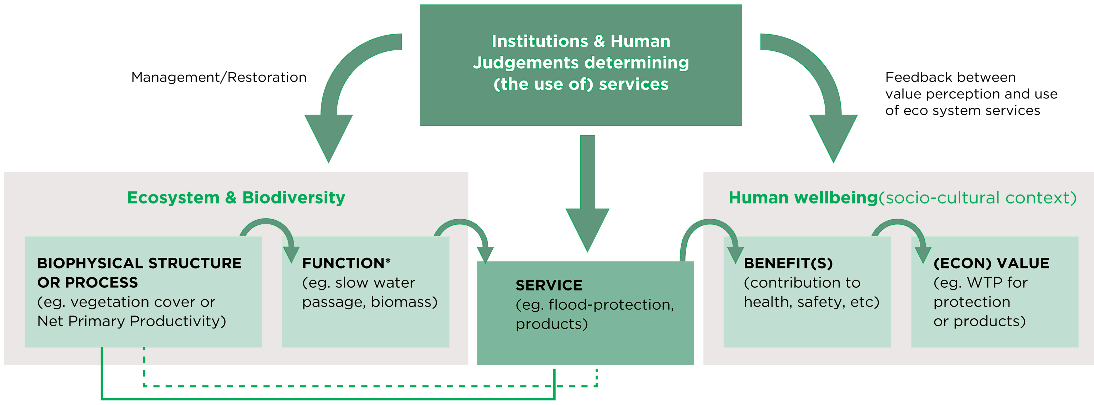

Figure 2.2: The pathway from ecosystem structure and processes to human well-being. From Jones et al. (2019)

By utilizing this particular framework, there would be a noteworthy enhancement in the comparability of the methodology. The adoption of this framework provides that more accurate and reliable results can be produced, which would not only facilitate better cooperation and communication among various stakeholders but also permit the identification of trends and patterns in a more comprehensive and comparable manner. Furthermore, implementing this framework would encourage policy decisions based on sound and consistent scientific evidence, thereby contributing to a more sustainable and adaptable future for our ecosystems.

However, it is important to note that this systematisation and associated terminology is not indisputable and is subject to possible discussion and criticism from other experts in the field. Especially given the complex relationships when linking social with ecological systems. It is therefore important to keep a critical eye on the chosen classification and terminology and evaluate them in the light of possible alternatives and new developments in this field (De Groot et al., 2010b).

This becomes evident in the different definitions used in the literature for the different elements within the cascade framework. Within this framework, different definitions are associated with the terminology of: biophysical structure, process, function, service and benefit (La Notte et al., 2017). Costanza et al. (2017) continues by saying that the cascade approach fails to adequately describe the complexity of relationships through straightforward linearity. Additionally, it appears to lean to the traditional economic school of thought, which limits the definition of value to components that offer an indirect benefit. However, it is noted that not all attention should be paid to the precise definition of the terminology, but the results of the analyses should be holistic and watertight. Attention should be paid to achieving consistent valuation without duplicating data (La Notte et al., 2017).

2.2.2. THE ECONOMICS OF ECOSYSTEMS AND BIODIVERSITY TYPOLOGY

To conduct this study, the classification as compiled in The Economics of Ecosystems and Biodiversity (TEEB) is used as a starting point. The main objective is to establish the interpretation of the literature of the translation of ecosystem services into human benefits and their economic value. For this reason, this study chose to focus on elaborating the definitions of these elements. More specifically, it will focus on the specific features and characteristics of the translation of ecosystem services into human benefits, and how this translation affects the economic value of these benefits. The used definition of the typology is:

- **Function**
  "The potential that ecosystems have to deliver a service which in turn depends on ecological structure and processes." (De Groot et al. (2010b), p. 11)
- **Service**
  "Ecosystem services are actually conceptualizations (labels) of the “useful things” ecosystems “do” for people, directly [1] and indirectly [2] whereby it should be realized that properties of ecological systems

[1]Direct-use values are the benefits derived from the services provided by an ecosystem that are used directly by an economic agent. These include consumptive uses (e.g. harvesting goods) and nonconsumptive uses (e.g. enjoyment of scenic beauty). (The Economics of Ecosystems and Biodiversity (TEEB) (2010) p. 35)

[2]Non-use value: benefits which do not arise from direct or indirect use. (The Economics of Ecosystems and Biodiversity (TEEB) (2010) p. 35)

that people regard as “useful” may change over time even if the ecological system itself remains in a relatively constant state." (De Groot et al. (2010b), p. 12)

- **Benefit**
  "Welfare gains generated by ecosystem services" (De Groot et al. (2010b), p. 12)

- **(Economic) value**
  "The contribution of an action or object to user specified goals, objectives, or conditions" "the common metric in economics is monetary valuation" (De Groot et al. (2010b), p. 13)

2.3. THE INTERPLAY BETWEEN STAKEHOLDERS AND GREEN ROOFS

The installation of green roofs affects society, the environment and the economy. In this, the benefits during the user phase as well as the resources used (such as materials and man-hours) have an impact on and a relationship with various stakeholders. Luckily, there is an increasing recognition of the central role of stakeholders among managers, policy makers and researchers. Stakeholder perspective studies in urban redevelopment projects are an essential part of sustainability management, with sustainability being one of the hottest topics in stakeholder perspective studies in construction projects (Xue et al., 2020).

Given that the delivery of ecosystem services depends on the capacity or ability to carry out activities that are potentially beneficial for human purposes (Haines-Young et al., 2010), it is crucial to engage the right stakeholders in this process. Stakeholder identification is an important ethical and moral issue for companies. A responsible organisation is aware of its relationship with internal and external stakeholders. It should then provide the means to achieve a dialogue on decision-making plans, even if the influence of the stakeholder is limited. This deontological duty care is part of acting responsibly taking into account existing stakeholder relationships and the consequences of intended actions (Simmons and Lovegrove, 2005). Involving these stakeholders in the decision making process can empower them, increasing the complexity and difficulty (Reed et al., 2009). The additional conflicting interests need consideration within this process. However, the only way to involve the appropriate stakeholder, is by means of a clear understanding of all the stakes involved, the underlying initiative, the nature of claims and the inter-relationship.

An important ethical aspect of green roofs is that the impact and benefit can be delivered over a wide range of scales, both in time and location. First of all, the location it occurs is not always the same as the location where the roof is located. There are several links between the location of the roof and the location of impact, including in situ, directional and omni-directional, see figure 2.3 (De Groot et al., 2010a). In addition, impact of the benefits can apply to a wide variety of different scales. Ranging from the small size of a single plant all the way up to the global scale. The functioning of the different scales are linked together and have an influence on each other. The larger ecological scale sets out the constraint of the smaller ecological scales, but is driven by the shared impact of all the smaller scale ecosystems. The smaller scale ecological level generally operates at a smaller time scale, while the larger scale systems are bound by a more long term temporal scale (Hein et al., 2006).

These effects can add up in time, both positively and negatively. The cumulative nature should be taken into account as well when looking at the assessment. Some of the impacts will remain even if the green roof is removed. Another part of the benefits is only present together with the green roof. This mostly determines how stakeholders are affected and how long that effect lasts. This framework may be completely mapped out to determine how stakeholders view the roofing (Proost and Rousseau, 2007).

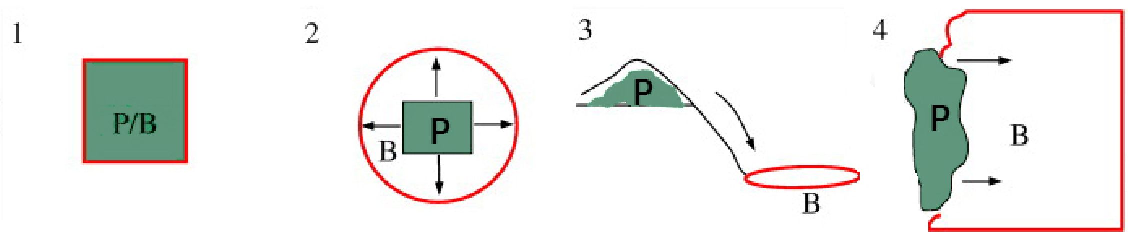

Figure 2.3: Spatial relationships between service production areas (P) and service benefit areas (B). Panel 1: in situ, panel 2: omni-directionally, panels 3 and 4 directional benefits. From De Groot et al. (2010a)

The scale, the cumulative nature and the direction of the impacts can determine which stakeholder might benefit. A green roof in this case can supply both an impact and ecosystem services to a range of different stakeholders. For both, the relationship with the relevant stakeholder is important; that way, a direct link can be established with who the impact affects. Especially when looking at social and environmental benefits, since these can affect a wide variety of stakeholders.

A significant level of social acceptance is essential for the effective implementation (Zihlmann Sánchez, 2023). Various stakeholders were examined in more detail to determine their views. In this, it is important to determine whether stakeholders can influence decision-making and policy measures related to the specific issue, or conversely, can they be influenced by these decisions and policy measures. Identifying potential stakeholders can be useful to identify possible coalitions for support (Bah et al., 2021). Moreover, information on the position of stakeholders can be useful in developing scenarios and strategies, and in assessing the risks involved. In addition, it can help build trust between scientists and the wider community.

This chapter explains the role of natural value in relation to a number of stakeholder groups to provide a general sense of their relevance and relationship to the green roof. This can provide insight into the position of this stakeholder within the process. When identifying stakeholders during the green roof benefits study, this information can help to correctly represent the parties.

2.3.1. THE ROLE OF NATURAL VALUE IN THE WORLD

The human species, as well as plants and animals, are completely dependent on nature for their survival. In 2011, the total annual value of ecosystem services worldwide was estimated at US$125 trillion per year (Costanza et al., 2014), including tangible material benefits such as provisioning services and intangible benefits such as regulatory and cultural services. But also the supporting services which are necessary for the well functioning of all other ecosystem services (Millennium Ecosystem Assessment, 2005; Haines-Young et al., 2010; Felipe-Lucia et al., 2015).

Due to changes in land use, the value of these ecosystem services declined globally between 1997 and 2011 by an estimated $20 trillion annually (Costanza et al., 2014). Therefore, nature itself should be considered a capital asset. Unfortunately, these systems are still poorly understood, resulting in poor control and often deteriorating or depleting rapidly. Therefore, it is very important to handle the flow of both material and immaterial goods from nature in the right way. This is because nature provides a flow of vital services such as the production of goods, life-supporting processes and life-affirming conditions (Daily et al., 2000), providing multiple benefits, both social, environmental and economical (Shafique et al., 2018). But most of these vital services have been proven to be finite when the natural balance is distorted (Fisher et al., 2009).

Nowadays, more and more research is recognising the importance of these ecosystem services. The importance is evidenced by the publication of the Millennium Ecosystem Assessment (MA), involving more than 1,300 scientists. One of the main and most important findings was that 15 of the 24 ecosystem services studied worldwide are in decline. The consequences of this are most likely negative for human well-being, both now and in the future (Fisher et al., 2009; Haines-Young et al., 2010). This acknowledges that human well-being cannot be sustained without also ensuring the health of the rest of nature (Costanza et al., 2014).

Ecological restoration measures can act as solutions to reduce physical, chemical and biotic stresses in urban areas while providing ecosystem services. Moreover, green infrastructure, including green roofs, can help address issues such as climate change, ecological and environmental degradation, energy consumption, and improving equitable and practical access to natural space (Liu et al., 2021a). The composition of these future urban habitats is likely to differ from historical local vegetation due to changing biotic and abiotic conditions, partly influenced by human activities. Nevertheless, these new ecosystems can also add value to urban areas (Handel et al., 2013).

2.3.2. THE ROLE OF ECOSYSTEMS WITHIN SOCIETY

Throughout history, there has always been a natural balance between human species, plants and animals. About 10,000 years ago, the human species began to undergo a turnaround. People began to see that, through direct influence, nature could be used for their own benefits. This led to targeted animal husbandry and agriculture that allowed for increased productivity of previously randomly available resources (Fisher et al., 2009). Through more efficient production, an understanding of the importance of ecosystem services began to emerge within the human species. However, the desire to extract more and more services from nature caused some civilisations to also discover its negative consequences. Throughout history, many societies have ignored the importance of a well functioning ecosystem, resulting in habitat loss, soil loss, loss of biomass production and disrupted water regulation. The lack of these services caused entire societies to collapse (Fisher et al., 2009). The significance of our natural resources, including individuals, society, the built economy and ecosystems as essential elements of prosperity, well-being, and sustainability is highlighted by a deeper understanding of the role of ecosystem services. All of our resources must be balanced if humanity is to have a sustainable and desirable future (Costanza et al., 2014).

The social-ecological sphere of play is full of complex interactions (Shafique et al., 2018). Given the intrinsic and but mainly the relative nature of ecosystem services within the social context, in which these services play a vital role in modern society, it is crucial to create an accurate overview of the benefits these services provide to humans (Costanza, 2020). These services can occur at different scales and in various forms, ranging from households to national and even international communities (Teotónio et al., 2020). This natural capital provides benefits only to human well being through the presence of people, their communities and the built environment (Costanza et al., 2014). By understanding and valuing the impact of these services at different levels, we can effectively evaluate their economic value and ensure their long-term potential. This requires a thorough structure, as there are often multiple stakeholders involved in this process (De Groot et al., 2010a).

This complex social-ecological playing field that is crucial to understand for all of society. By categorising and mapping the different elements of a system, patterns and relationships can be discovered that would otherwise remain hidden. As a result, controlling these systems can be simplified and optimised. Consequently, there are many different ways of categorizing ecosystem services, like the categorisation by Millennium Ecosystem Assessment (2005) used in chapter 2.6. A method of identifying how individuals interact with various ecosystem services is by examining two characteristics as distinguished between by economics: rivalry and exclusivity (Fisher et al., 2009; Haines-Young et al., 2010; Costanza, 2020). Rivalry refers to the extent to which a good is scarce or finite, while exclusivity refers to the ability to use a good exclusively. Ecosystem services come in different forms within this spectrum and can even move within the spectrum depending on the degree of use. As a result of their rivalry, not all ecosystem services have a finite presence (Fisher et al., 2009). Combined with their exclusively this creates asymmetry in the distribution of benefits within society, with, in practice, often the poorest sections of the population having the shortest end (Turner et al., 2003). Spatial features are determinants in the uneven distribution of ecosystem service provision.

Ecosystems provide a wide range of services that are vital for the well-being, health, livelihood and survival of humanity (Costanza et al., 2014), but the majority of these advantages only become apparent over time (van den Bos, 2021). A major problem exists where the stakeholder responsible for managing nature-based solutions gains limited benefits, while the rest of the benefits are for society (Costanza et al., 2014). In general, the services are non-excludable and therefore benefit everyone in the geographical area concerned. Therefore, the tragedy of ecosystem services is that they are often under provided because there are no well-developed institutions and policies to ensure their continuous delivery (Lant et al., 2008). In addition, interactions between ecosystem features and ecosystem services also play a role. Sometimes the use of one benefit can mean that another benefit is reduced or disappears, while other times the benefits reinforce each other. On the other hand, interactions between stakeholders, some of which arise from power relations, can affect access to and management of ecosystem services (Felipe-Lucia et al., 2015).

In the context of social developments, but also ethically, identifying these benefits is a step in the right direction so that their distribution can be made more equitable (Haines-Young et al., 2010). In this way, awareness can be gained about the importance of these systems. This is especially true in situations where complex services are provided that are offered at different scales, times and locations (Costanza et al., 2017). As a result, numerous stakeholders are involved in the process and it is vital to be able to manage in a timely manner. The lack of oversight allows a small select few to profit from the services provided on the backs of others. Identifying ecosystem services can help improve the distribution of these services within society. For society, this means a power-full communication tool to inform and drive fair decision-making. To adequately carry out this control and steering requires knowledge and training. This knowledge can be used as a tool to promote the use of conservation-oriented solutions to contribute to sustainable development.

2.3.3. THE ROLE AND INTEREST OF THE GOVERNMENT

In general, it can be said that the successful implementation of green roof initiatives depends on public policy. Because the majority of ecosystem services are either common pool resources that are rival but not excludable or public goods that are non-rival and non-excludable (Costanza et al., 2014). This implies that, at best, traditional markets and privatization are only occasionally successful. Through mandatory or voluntary regulations, incentives and guidance, and the provision of guidelines and training, the government can play a crucial role in promoting sustainable urban development (Zhang and He, 2021). In doing so, they aid in the transition to sustainability and help contribute to an environment in which "green" solutions have a fair chance to compete with existing goods and services and create healthy living conditions for its citizens (Vogtlander, 2023). In this regard, governments and other public agencies have a crucial role in protecting society so that the consequences of complexity, non-excludability and rivalry of ecosystem services do not fall on the most vulnerable groups in society (Costanza, 2020).

The most effective method for putting urban sustainability efforts into practice is government policy (van den Bos, 2021) . This policy has the power to impose required and optional restrictions on stakeholder behavior. Specifications, restrictions, and standards make up the harshest type of policy. But for such a strategy, the government must have the information and expertise necessary to make well informed decisions. Given the complexity of green roofs, which have interfaces with many disciplines, this should also be included in government policy. When putting it into practice, it must take into account economic and technological factors in the context of the complex environment. The energizing and leading of government organizations is also essential. The government could, for instance, impose fines for non-compliance or provide incentives for the creation, construction, and maintenance of green roof systems. For this, the government must establish regulations that can act as a means of control. Developing guidelines that can provide information to a wide range of stakeholders is also a sensible step. Such guidelines can contribute to increasing people's knowledge and awareness. In addition, there must be a government policy for training specialists. Policy should support the transition from scientists to practitioner (Zhang and He, 2021). The mechanism to act according to governments has led to the greatest environmental progress for companies to act environmentally friendly over the past 20 years (Vogtlander, 2023).

In striving for a greener world, it is vital for governments to play their part in moving forward. In doing so, government decisions are guided by three fundamental principles (Daily et al., 2000):

- Public policy decisions focus on incremental improvements to the current situation rather than revolutionary changes.
- In a democratic society, the values used in social decision-making should be derived from the values of individual citizens and not imposed by the state.
- If possible, people's values should be derived from concrete decisions made rather than imposed values.

This means that public bodies cannot take the lead directly. In this, they are limited in their spending by the fact that public money is involved. This requires accountability to citizens, but also that the risks must be limited. However, contrary to what the article says, the author believes that understanding the benefits can make a helpful difference even for governments. Namely, when we look at the three fundamental steps for decision-making; 1. Identification of alternatives, 2. Identification and measurement of the effects of the alternatives, 3. Valuation in comparable units (Daily et al., 2000). Then we see that this understanding of the benefits of green roofs can contribute in all three steps. A broad understanding gives both the ability to identify new alternatives, identify and measure their impacts and then value them in a comparable unit. But even without subsequent valuation, according to Costanza et al. (2017), simply listing all ecosystem-related services can help ensure their inclusion in public policy. By having an in-depth understanding of the possibilities and consequences of ecological initiatives, it is possible to appreciate and compare them with the current situation, which can lead to deviation from the status quo.

Public authorities should assume their central role in addressing pressures on ecosystem services. By taking into account the different scales at which ecosystems are at play, it is important that a central party takes the lead. Governments can still get things done in this place within their own capabilities, with the ultimate goal of improving conditions for society. Government policy stability plays an important role here (Vogtlander, 2023). This can be achieved by applying policies, regulations and legislation, which can implement adaptation policies and measures, in order to reduce society's vulnerability to climate change (Nesshöver et al., 2017). Additionally they can enforce property rights to prevent over use (Costanza, 2020). Knowledge and understanding of the benefits and services of ecosystems should help in this regard. It can also ensure that, despite, limited resources, incentives can be found to achieve certain societal goals.

2.3.4. THE ROLE OF PROJECT DEVELOPERS

For project developers trade-offs are made when making investment decisions, and this implies valuation of alternatives. This also holds true for investments in ecosystem services, as most environmental decisions weigh the costs and a wide range of benefits associated with a proposed course of action. Most of the time, especially in the long run, these benefits and costs are poorly understood and quantified (Costanza, 2020). Both the benefits and drawbacks must be taken into account to encourage private parties to invest in nature. Because using nature involves spending money, labor hours, etc., it's critical to understand the value of nature from the opposite perspective.

Due to the division in thinking between returns for society and returns for the investor, private investors favor the extra space for recreation and improved thermal comfort (Teotónio et al., 2020). The existence of external values for ecosystem services used to be of no additional value to project developers. Free riders who profit from these services without making investments in their long-term availability were encouraged by the external returns. Due to this, there is a problem with developing to provide tradeable goods and services even at the expense of ecosystem services, whose value to society outweighs the benefits to the landowner economically (Lant et al., 2008). However, by means of identifying these values, new opportunities arise. By fully mapping the benefits, a full financial overview can be made. This insight offers opportunities to involve parties to come to a realisation in a situation where, for the project developer, the benefit of the installation does not outweigh the capital he has to contribute.

These businesses are typically reluctant to take on these projects without enough government supervision and backing, claims Zhang and He (2021). In order to persuade potential private investors to build green roofs, subsidies for green roofs are necessary and socially desirable (Claus and Rousseau, 2012). For the project developer, this can entail that a party fills the gap by contributing financially or in another way. De Groot et al. (2010a) discusses the crucial ideas in this regard. The establishment of a clear metrics for measuring service delivery and economical payment system with low transaction costs are needed. A subsidy program, for instance, could be implemented in this fashion. Transferring social equity to private investors eases the burden of the life cycle. This means accepting financial considerations as the sole basis for decision-making, despite the fact that stakeholders may take into account a variety of other factors when making such an investment. In addition, the knowledge can also be used to score points during tender procedures or other decision moments. In this way, the knowledge is applied to promote the positive contribution of the project to the outside world. However, nature-based solutions deliver different technical performance and political strategies and incentives must take this into account when deciding which solutions to focus on first. In addition, technical behaviour also affects economic returns (Teotónio et al., 2021).

The knowledge and insights into how green systems work and how they relate to social and economic planes can provide a financial incentive for application from the developer's perspective. This incentive can come from cooperation between private and public parties. In this way, private investors can be involved as part of the solution field of social problems. This allows a multidisciplinary approach to be taken to achieve an integrated approach. For the project developer, this means new opportunities to carry out projects that were not possible with private economic results alone. But it can also be used by companies that are willing to accept a financial burden in order to contribute socially. However even without any subsequent valuation, the very process of listing all the services derived from an ecosystem can help ensure their recognition in public policy.

2.4. AN EVOLVING PLAYING FIELD FOR STAKEHOLDERS TOWARDS SUSTAINABLE DEVELOPMENT

With the rise of capitalism as the primary modality for organizing value generation and exchange, it has become evident that focusing exclusively on its economic consequences engenders an incomplete and deleterious perspective (Freeman et al., 2010). Hence, an emphasis has developed towards exploring the interplay between capitalism and other societal establishments. The intensification of globalization and the advent of information technology have facilitated demands for greater accountability, transparency, and ethical comportment. Which have amplified interest in comprehending how capitalism, ethics, sustainability, and social responsibility can be integrated into new paradigms of business philosophy. In pursuing this, a company looks beyond the main idea of achieving financial profits for stockholders or the law and recognises the moral criteria to which its operations are subject (Goodpaster, 1991; Vogtlander, 2023). These moral criteria therefore go beyond mere compliance with the law, which falls short of this.

Figure 2.4: Sustainability challenges and solution directions for businesses. Adjusted from de Bruyn (2017)

2.4.1. SUSTAINABLE DEVELOPMENT GOALS

In September 2015, the United Nations General Assembly adopted the 2030 Agenda, which sets 17 Sustainable Development Goals (SDGs) as a plan of action to transform the world in terms of people, planet and prosperity. The Sustainable Development Goals (SDGs)' main objective is to advance a new way of thinking and offer a plan for eradicating poverty without seriously compromising the planet's life support systems (Assembly, 2015). The 17 SDGs and the 169 targets that go along with them are linked to the economic, social, and environmental pillars of sustainable development in an effort to spur action in the years to come to change the world in the direction of a sustainable future (Omer and Noguchi, 2020).

These sustainable development goals represent a comprehensive international vision of sustainability, applicable to both public and private actors at local and global levels (Assembly, 2015). The concept of the Triple Bottom Line, also known as the 3P's - People, Planet, and Profit - forms the fundamental principles of sustainable development and contributes to the achievement of the SDGs. These P's represent the different dimensions on which sustainability should be pursued: social justice, environmental protection, and economic growth. The concept of the three P's provides a framework for achieving a balance among these dimensions, thereby promoting sustainable development. It is important to note that the three P's do not represent conflicting objectives or a compromise. It is possible to have a positive impact on both people and the planet while simultaneously achieving profitable growth (Goh et al., 2020).

In this regard, apart from the government's role, there exists a crucial responsibility for all other stakeholders to actively contribute to facilitating an industry-wide implementation (Goh et al., 2020). This dynamic reshapes the playing field for individual stakeholders, fostering the exploration of more sustainable solutions that align with the interests of diverse stakeholders. Companies are forced to understand how to collaboratively combine positive forces to create a better world by holistically addressing economic, social, and environmental challenges (Fisk, 2010). With a balanced application of this integrated dimension, the financial returns from completed construction projects will not be limited to the completion phase, but will be generating benefits for society as a whole and those who utilize and derive value from them. As a result, it is crucial to take into account the benefits for social stakeholders rather than just the initial direct and indirect costs (Goh et al., 2020).

2.4.2. SUSTAINABILITY AS AN OPPORTUNITY FOR DEVELOPMENT

Sustainability is increasingly playing an important precondition and opportunity for businesses. By contributing to the achievement of the Sustainable Development Goals, companies are placing social and environmental concerns at the core of their operations (Fisk, 2010). Of the 169 goals of the SDGs, 56 have been identified in which the building and construction sector can have a direct role in achieving (Omer and Noguchi, 2020). With the growing awareness of the impact materials and services have on nature, there is a demand for a good method that can map the impact. For companies, there are several sustainability challenges and solution directions, see figure 2.4. Green roofs can be used as a strategy to reduce these issues in order to achieve the SDG (Manso et al., 2021).

Sustainable development for companies should not be seen as a threat, but rather as an new opportunity for business (Vogtlander, 2023), whereas non-sustainability should be seen as the real threat. The consequences of non-sustainability can be seen in various consequences of human actions, such as climate change, the extinction of various animal species and the systematic disappearance of pieces of nature (Roorda, 2017). Some of these processes are irreversible, but fortunately many of them can be reversed using sustainable methods.

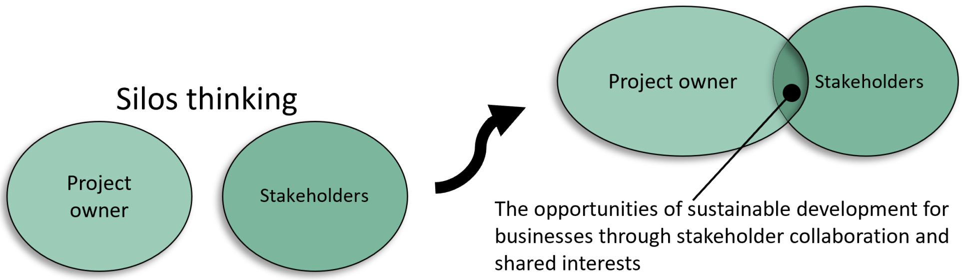

Figure 2.5: The opportunities of sustainable development for businesses from silo thinking to stakeholder collaboration and shared interests. Own work

Sustainability adds to the fact that stakeholders should no longer be seen as disconnected islands but they should rather be looked at in the search for common ground in the interests of different parties in order to promote development. This way, a move is made from fragmented stakeholder thinking to a holistic common approach in which the goals of different parties are aligned, see figure 2.5. Opportunities to realize projects through (financial) collaborative partnerships are created with the identification and utilization of these interfaces with other stakeholders. Green roof projects that would have otherwise faced obstacles can now be successfully implemented thanks to these partnerships (Liberalesso et al., 2020).

2.5. PROJECT EVALUATION

Providing insight into the economic effects of the application of a green roof is the main aim of this study's evaluation. The right data is required to substantiate the claim of green roof implementation as sustainable development. This is not only important for project developers but, because of the described benefits of a green roof during the use phase, this can also make a positive contribution towards the environment and society.

In order to evaluate an investment as positive, the anticipated future benefits must sufficiently outweigh the resources required to complete and manage the investment. These future benefits be in the form of profits, cost reductions, or societal and environmental advantages. However, achieving these benefits requires various resources such as finances, labor, and raw materials. In which implementation of green roofs requires additional resources compared to conventional roofs (Kosareo and Ries, 2007; Zuo et al., 2017). The utilization of these extra resources has financial implications as well as environmental consequences that are not typically accounted for in conventional analyses. In terms of production, it involves the use of potentially scarce goods, and at the end of the green roof's lifespan, these materials are either recycled, incinerated, or disposed of (Scolaro and Ghisi, 2022). According to Giama et al. (2021), the environmental impact of green roofs is higher than that of conventional roofs, primarily due to the negative impact of construction materials. However, the paper of Giama only looks at the negative impact of construction materials. In order to strike a balance, it is essential to calculate the full performance to know whether such roofing systems are better than conventional ones. Based on this justification, a decision can then be made by the previously defined stakeholders.

For a comprehensive approach, it is crucial to consider the full life cycle costs. The cost of a green roof partly translates into financial costs, however, more is required to achieve and maintain a roof package. These additional resources can generate external costs due to their impact on the environment and society (Lin et al., 2020). Ultimately, the goal of integrating the impact of these resources into existing analyses is to create a more equitable and holistic representation of green roof implementation (Vogtlander, 2023), as depicted in figure 2.6. Within this framework, the research questions at hand can be addressed. The resulting insights contribute to aligning with the Sustainable Development Goals, thereby advancing social justice, environmental protection, and economic growth (Ashby, 2022).

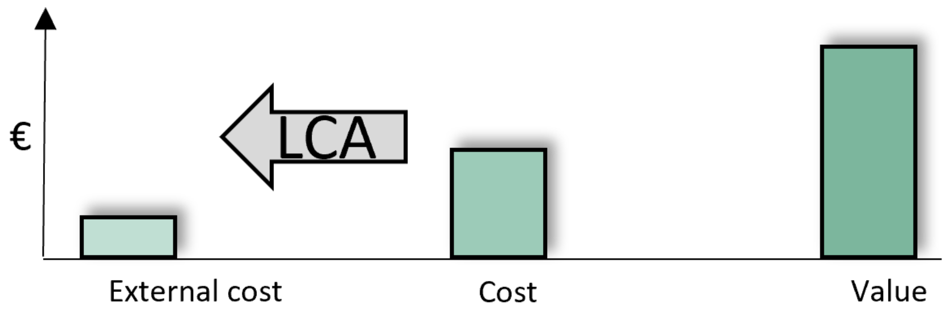

Figure 2.6: The 3 dimensions of a product: the costs, the value, and the eco-costs. Adjusted from Vogtlander (2023)

The inclusion of external costs is meant as a step forward compared to the conventional method, which only looks at internal costs. By including external costs in the method, it also looks at the damage to people and nature during the production process, this is referred to as the "polluter-pays-principle" by Jonkers (2021), see figure 2.7. This is important because there is a trend in today's society where people no longer accept companies polluting the world without consequences. Vogtländer (2023) does not expected that these external costs will be directly internalised in the cost price, but that cooperation will be enforced by adding various regulations or obligations with regard to the maximum emissions.

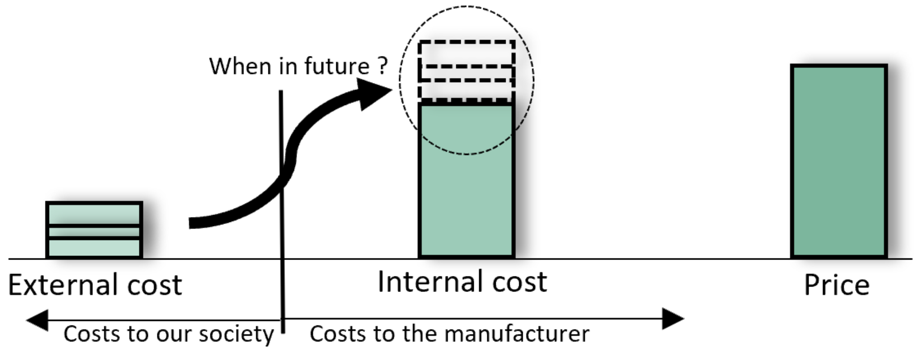

Figure 2.7: Internalisation of environmental cost. Adjusted from Vogtlander (2023)

2.5.1. PROJECT EVALUATION CATEGORIZATION

There is a need for a project evaluation method that can elaborate on the research questions as a result. Within democratic decision-making processes, transparency is essential, which is why research into explicit valuations of ecosystem services and their benefits has received considerable attention (Costanza et al., 2017).

There is a significant difference between financial and economic project evaluation to guide and inform decision-makers. While financial project evaluation is a widely used tool for the private sector, it falls short of providing a complete picture of the cost-benefit. A number of factors determine the distinction between economic and financial evaluation. For example, some in or outputs may not have an explicit market price attached to them or there are market prices other than marginal social value (Boadway, 2020). For this study, the economic project evaluation has received special attention, namely for the social and environmental benefits, since the construction of green roof presents multiple environmental and social benefits (Williams et al., 2010; Bianchini and Hewage, 2012b; Peng and Jim, 2015). The socioeconomic perspective is also used in the "Guide to Cost-Benefit Analysis of Investment Projects" by European Commission (2014), which provides practical guidance on the assessment of major projects. In particular, the results of the analysis should demonstrate the social, ecological and economic desirability of the project. A positive economic return shows that society is better off with the project.

Special attention is paid to this aspect so that additional insight can be gained into the side effects on society and nature that an intervention entails. This is done because in this way, for example, the external costs of a product can be brought to light in a targeted way. In addition, some of the benefits of green roofs are difficult to express financially through traditional means. The setup therefore attempts to include these benefits through a larger playing field. For the purpose of this study, all categories were taken into account in the project evaluation:

- **Finance**
  Includes the costs and benefits that can be directly monetised and are the responsibility of the project owner. This study assumes that the project owner takes charge of the development and owns the property throughout the study. This is in contrast to, say, a property developer who has different financial requirements for such a project due to a shorter-term vision.

- **Economy**
  This includes all the costs and benefits of the project including the once that are difficult or impossible to monetise, including social and environmental costs and benefits. There is often a lack of sufficient research that can map this relationship and even if a relationship is found, the question is to what extent it is scalable to reality where we are dealing with different behaviour and different parameters. By developing a project that also has a positive impact at this scale level, a fair and socially/environmentally responsible project is achieved.

2.5.2. TOTAL ECONOMIC VALUE

When making choices, it is necessary to go through a process that involves valuation (Costanza et al., 2017). This valuation often shows measurable functionality, as numerous decisions require trade-offs between various aspects that exert different influences on the well-being of individuals. As such, valuation becomes an inevitable and crucial aspect within the broader framework of the decision-making process. Valuation involves assessing these trade-offs to achieve a specific goal (Costanza et al., 2014). The value of ecosystem services can be expressed in a variety of metrics, such as money, time, labour, or in relative terms using various indicators (Costanza et al., 2014, 2017; Costanza, 2020). The choice of the most appropriate unit of measurement often appears to depend on contextual nuances and the target group within the decision-making context.

Transparency and explicit valuation play a crucial role in democratic decision-making processes (Costanza et al., 2017). Because of the complexity that makes it challenging for the general public to understand the underlying linkages, it is crucial to adopt a methodology that is accessible to everyone (Costanza et al., 2014). The emphasis is once again on the benefits that ecosystems can offer people, but only when those people are present (i.e., when there is human capital, social capital, and built capital present). In an economic context, built capital is expressed in monetary terms. According to Costanza (2020) all ecosystem services can be expressed in monetary terms if at least one of the components being traded can be. Additionally, expressing the value in monetary terms has the important benefit of being a unit of measurement that the majority of people are familiar with.

Thus in this analysis money is used as a measure to indicate a certain utility. In this, it is important to note that this is only a medium intended to provide insight into the effects of green roof implementation. Expressing all these effects in monetary terms allows for comparison and provides an overview that can serve as the basis for weighing the advantages and disadvantages of the measure (Romijn and Renes, 2013). This approach is necessary because the core of this research has connections to social, ecological, and economic desirability, which is also increasingly embedded in decision-making (Costanza et al., 2017). These are three pillars that may give rise to conflicting interests and are not directly comparable. Better decisions making is facilitated by increased transparency regarding the valuation of ecosystem services (Costanza et al., 2014). Therefore, the decision was made to examine how all costs and benefits can be expressed in the same unit measure, money. However it should be noted that even without any subsequent valuation, the very process of listing all the services derived from an ecosystem can help ensure their recognition in public policy.

Ecosystem services, derived from natural capital, are invaluable for human well-being and have contributed undeniably to our civilisation. Nevertheless, these services are rarely traded in markets, which has led to undervaluation and underestimation of the extensive benefits they provide (Lant et al., 2008). To determine the total value of a green roof, all relevant values should be taken into account, including those that are difficult to express in monetary terms. A well-structured framework for this is provided by the total economic value. The framework enables the consideration of all the values provided by an ecosystem to individuals, society, and the economy by categorizing them into two broad categories (Ten Brink, 2012). A common distinction in this context concerns both use value and non-use value. Use value consists of direct, indirect and option use values, while non-use value is further divided into three types, namely existence value, altruistic value and bequest value, all from Hein et al. (2006), see also figure 2.8.

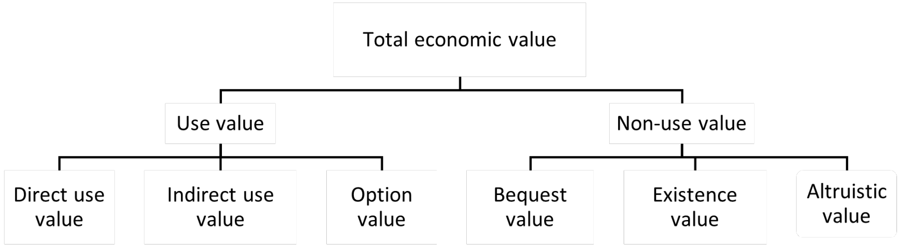

Figure 2.8: Total economic value use and non-use values. Classification from Hein et al. (2006)

- **Direct use values**
  The ecosystem services or goods that can be consumptive or non-consumptive. These are concrete and measurable values that provide direct benefits to people, but also cultural services such as recreation.
- **Indirect use values**
  The ecosystem services from the green roof that can indirectly be used, such as regulatory services that improve air, water and soil quality. These valued services or goods are less tangible and harder to measure, but still have a major impact on human welfare and health.
- **Optional values**
  The ecosystem services from which people are uncertain about their future use. These are values that people attach to having the option to use a particular service in the future. These values are based on the principle of risk aversion.
- **Non-use values**
  The ecosystem services that are derived from the inherent properties of the ecosystem itself. These values are not directly related to the use of an ecosystem, but are based on moral, aesthetic and cultural considerations of the stakeholder. There may be different motives for attaching these values to an ecosystem, depending on stakeholders' cultural and moral perspectives. There are three types of non-use values, which are often both conceptually and empirically difficult to separate.
  - The existence value relies on the value that people attach to knowing that a particular something exists.
  - The bequest value is derived from the value that people assign to the wish to pass it down to posterity.
  - The altruist value is valued based on the fact that others in the current generation can use or benefit from it.

Assigning values to ecosystem services is a process that depends heavily on the stakeholders who benefit from these services (Hein et al., 2006; Costanza et al., 2017). Different stakeholders have different views and needs regarding ecosystem services, resulting in a dynamic and reciprocal relationship between stakeholders and ecosystem services. It is the nature of the services provided that determines who the relevant stakeholders are, and these stakeholders in turn determine which ecosystem services are relevant. The various spatial and temporal scales at which the services are supplied have a strong connection with the value attached by different stakeholders (Hein et al., 2006; Costanza et al., 2014; Costanza, 2020). Therefore measuring of biodiversity is not an absolute, but rather an relative practise (Vermeulen and Koziell, 2002; Costanza et al., 2017).

2.5.3. AVAILABLE METHODOLOGIES TO VALUE ECOSYSTEMS

Various methodologies exist for the valuation of use and non-use benefits, because not all values in the total economic value framework can directly be derived from market transactions. In the absence of direct market valuation a indirect market price may be derived from transactions associated with ecosystem service. If both of these valuation methods are useless due to a lack of market information, a hypothetical market can be setup. All of the methods have certain advantages and disadvantages in terms of available information, complexity and suitability (European Commission, 2016).

The main difference between the methods are the underlying data that provide information to make an estimation about the costs and values. In the case of the direct market methods this data comes from actual markets. This makes it relatively easy to obtain and also provides accurate estimation, given the fact that the data directly show the preferences. The revealed preference methods use data from observing the behaviour in existing markets and the stated preference methods use data from surveys and questionnaires (Pascual et al., 2010). The most widely used are listed here in accordance with European Commission (2016):

Direct market valuation approaches

- **Market price-based approaches**
  Values taken directly from markets.
- **Cost-based approaches**
  The avoided (damage) cost method looks at the costs that incur from the loss of the ecosystem services. The replacement cost method looks at the costs that occur from the replacement of current ecosystem services. The substitute cost method is applied to the effected services by looking at the substitute cost of providing a substitute for an ecosystem or its services. [3]
- **Production function-based approaches**
  Estimates the contribution value of an ecosystem service to the provision of goods and services.

Revealed preference approaches

- **Travel cost method**
  Estimates the time and travel cost that people incur to visit a site.
- **Hedonic pricing method**
  Estimates the direct impact to the prices of other goods in the market by looking at data with characteristics and properties. Doing so, it values the price that people allocate to specific ecosystem services.

Stated preference approaches

- **Contingent valuation method**
  Is used to describe a method in which individuals are asked to estimate their willingness to pay for the provision, maintenance or improvement of an environmental service in a specific hypothetical scenario, based on a description of the service. This is usually done through a direct survey asking individuals how much they are willing to pay for the environmental service. In some cases, they may also be asked about the amount of compensation they would be willing to accept to give up specific environmental services.
- **Choice modelling or choice experiments**
  In this method, the respondent is shown two or more alternatives that share the same characteristics but offer different levels of these characteristics. The respondent is then asked to indicate a preference at a specific price or cost to the individual. Besides offering a value, this method can also generate a ranking between different options.

LIMITATIONS OF DIFFERENT METHODOLOGIES TO VALUE ECOSYSTEM SERVICES

However the use of the different valuation methods are not without any limitations. The primarily restrictions by the presumptions and data that are needed for each methodology according to Pascual et al. (2010) and Legesse et al. (2022) are represented:

For the direct market valuation method, establishing data on the demand for ecosystem services is considerably more complex than the cost and production data on which this method primarily based. Markets for these ecosystem services often do not yet exist (Costanza, 2020), and if they do, they are often heavily influenced by subsidy schemes. This creates challenges for fair market competition, resulting in data that does not accurately reflect reality. As a result, the resulting estimates of value will be biased and will not provide reliable information.

In addition, partly as a result of existing uncertainties, certain market-based methods face specific problems. Moreover, the production function approach also faces the challenge of lacking knowledge about the cause-effect relationship. The quantification of the service or its influence, as well as the interconnection and interdependence, are poorly approximated with current knowledge. This carries the risk of double-counting certain aspects in the valuation process.

[3] The substitute cost method was added according to (King and Mazzotta, 2023)

The revealed preferences method has its limitations in the need for high-quality transaction data. This requires large data sets and complex statistical analyses that are not only time-consuming but also costly. In addition, these methods are unable to capture the non-use value from actual behaviour. This is a clear shortcoming, as the non-use value is an important contributor to the total value of ecosystem services. These methods also rely on accurate estimation of the technical relationship between the ecosystem service and the market good. This can be problematic because it is not always easy to determine this relationship and it can lead to biased estimates of the value of ecosystem services.

The most important question when applying the stated preferences method is to what extent the answers match their behaviour when actually facing the costs. What is important here is that the questionnaire design or interview technique is correct, but strategic behaviour can occur from the respondents, in addition to possible psychological effects such as 'loss aversion' and the 'endowment effect'. This has resulted in several studies experiencing lower willingness-to-pay than willingness-to-accept, which should be equal from a theoretical perspective. Another major problem in that in measuring values of public goods, survey respondents do not distinguish between different scales.

The use of the stated preference method to measure values of complex and unfamiliar public goods is also questioned because respondents may not be able to give accurate answers. Regarding the connections between ecosystem services and their well-being or the well-being of society, particularly over the long term, they lack adequate information or processing capacity (Costanza, 2020). It has been suggested that giving more information to respondents to increase their engagement and reduce cognitive constraints. This can be done, for example, through deliberative monetary valuation methods and valuation workshops (Pascual et al., 2010).

2.6. ECOSYSTEM SERVICES TYPES AND CATEGORISATION

Understanding and distinguishing the benefits of green roofs is crucial. It is essential to maximise these benefits and serve the stakeholders in the right way. The decisions we make as individuals or institutions affect ecosystem processes. These processes, in turn, determine the quality and quantity of ecosystem services that affect our well-being (Collins et al., 2011). To understand the social-ecological plane, this paper should research and analyse the various services and benefits. A closer alignment between the services and benefits to the specific requirements of stakeholders can be made by understanding these. Through effectively aligning these services and benefits with the specific needs of stakeholders, we can optimize the utilization of green roofs and create a beneficial impact on the social-ecological domain. Various papers have already tried to make a statement about this. The goal of this paper is to holistically combine this information, so that profound statements can be made and literature gaps can be highlighted for follow up studies.

Ultimately, the research findings enable us to answer the following sub-research questions:

- What are the private benefits of the ecosystem service of a green roof, and how can these benefits be expressed in monetary terms?
- What are the benefits for society during the use stage of the ecosystem services of a green roof, and how can these benefits be expressed in monetary terms?

The outcome of the literature study serve two purposes. It forms an answer to the above described research question and should allow future researchers to use it as a starting point to improve the current pool of knowledge. The structure of the research was setup in a way that allows both. To ensure a reproducible study, it was decided to take a structured approach to identifying the ecosystem services to be investigated. An important part of our structured approach is the systematic categorisation of different ecosystem services. Making this categorisation not only provides an overview of the services to be investigated, but also allows easy reference.

The classifications of these services were adapted to the specific characteristics of a green roof, because different environments provide varying types of ecosystem services (Gómez-Baggethun and Barton, 2013). For this reason, literature was first analysed for an existing general classification of ecosystem services so that the information could be placed within the appropriate service category during our research. The literature was then searched for a categorisation specifically applicable to green roofs.

The structure allows the opportunity for feedback and facilitates discussions about the quality of the choices made, the information available can be enhanced to continuously improve decision-making processes. This iterative approach allows for an ongoing refinement and ensures robust and reliable used information. By adopting a systematic methodology to assess the ecosystem services provided by green roofs, the comprehension of the advantages offered by this technological innovation can be enhanced. Making a valuable contribution towards the promotion of urban sustainability.

2.6.1. RESEARCH METHOD

ANALYSED INFORMATION SOURCES

The study "Economics of green roofs and green walls: A literature review" by Teotónio et al. (2021) was utilized as the foundation for identifying the most suitable and valuable literature pertaining to cost-benefit analysis of green roofs. This research was selected as the basis for the present study due to its broad scope of green infrastructure. The wide scope of the study is sufficient enough to not exclude potential significant studies in advance and also provides sufficient space for specialization. As a result, the study of Teotónio is more comprehensive while still showing similarities with the research conducted here. Utilizing existing literature has the advantage of utilizing the preliminary work that has already been conducted, thereby allowing for a deeper examination of the various papers.

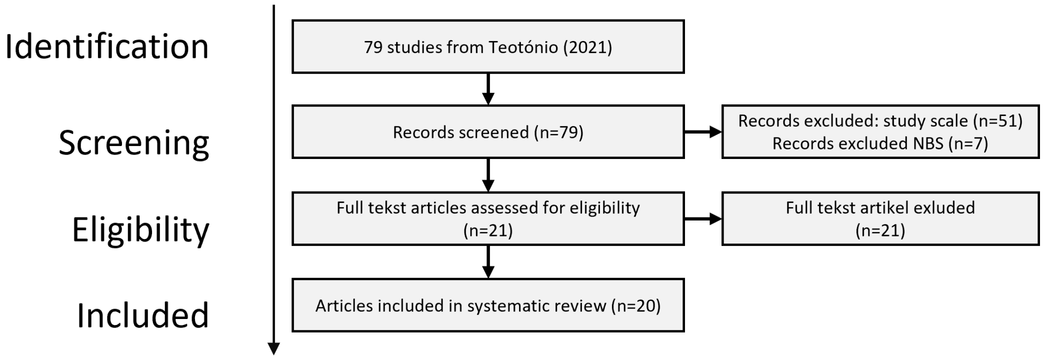

Figure 2.9: Flow diagram for the identification, screening, eligibility, and inclusion of studies. Reasons for full text exclusion was the duration of the study

The author is aware that there are several implication given this approach. The main downside is that the potential to leave out important sources. The biggest pitfall is the fact that all the sources identified by (Teotónio et al., 2021) are trying, in some manner, to determine the economic value of green infrastructure. This means that papers that provide valuable information, but do not try to assess the economic value, are left out. The choice of this approach was however substantiated mainly by the fact that it eliminates potential arbitrariness and randomness within the approach. On this basis the research is complete, and comprehensive, but only within the framework and scope of the choices made.

It was decided to filter Teotonio's selection of 79 papers to match the scope of this study. The first step was a screening based on the scale of the study, with a focus on including studies with the scale of a single building. This was done because that way the right information becomes available to make a judgement on the case study. Step two was to screen for the type of NSB, focusing on green roofs. The final step was to manually look at the scope of the studies and to what extent they matched the research data we needed. One study was excluded because of the the short time frame used, figure 2.9. This complete process is detailed in appendix A and in addition it also provides an overview of the used sources. The final list of papers is given in table 2.1.

2.6.2. RESEARCH STRUCTURE

To provide structure to the study, a comprehensive list of ecosystem services that a green roof can provide was compiled. This list of ecosystem services was classified, categorised and ordered in two ways. First, all services were classified based on the four categories of ecosystem services: supporting, cultural, providing and regulating services, as defined by the Millennium Ecosystem Assessment (2005). This framework was then further defined, see appendix B.

CLASSIFICATION OF THE SOCIAL CONTRIBUTION OF ECOSYSTEM SERVICES

Ecosystem benefits, or the welfare benefits people experience through interaction with natural systems, are defined as a complex set of interactions that vary in space, time and organisational units (Liu et al., 2007).

2

Table 2.1: Review literature: study author, year and title

Author (year)	**Title of peer reviewed paper**
Wong et al. (2003b)	Life cycle cost analysis of rooftop gardens in Singapore
Clark et al. (2008)	Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits
Carter and Keeler (2008)	Life-cycle cost–benefit analysis of extensive vegetated roof systems
Chang et al. (2011)	Optimal design for water conservation and energy savings using green roofs in a green building under mixed uncertainties
Claus and Rousseau (2012)	Public versus private incentives to invest in green roofs: A cost benefit analysis for Flanders
Ascione et al. (2013)	Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning?
Sproul et al. (2014)	Economic comparison of white, green, and black flat roofs in the United States
Macháč et al. (2016)	Green and blue infrastructure: An opportunity for smart cities?
McRae (2016)	Case study: A conservative approach to green roof benefit quantification and valuation for public buildings
Mahdiyar et al. (2016)	Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach
William et al. (2016)	An environmental cost-benefit analysis of alternative green roofing strategies
Ziogou et al. (2017)	Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region
Ulubeyli and Arslan (2017)	Economic viability of extensive green roofs through scenario and sensitivity analyses: Clients' perspective
Shazmin et al. (2017)	Property tax assessment incentive for green building: Energy saving based-model
Berto et al. (2018)	Enhancing the environmental performance of industrial settlements: An economic evaluation of extensive green roof competitiveness
Ziogou et al. (2018)	Implementation of green roof technology in residential buildings and neighborhoods of Cyprus
Kim et al. (2018)	Economic and environmental sustainability and public perceptions of rooftop farm versus extensive garden
Alves et al. (2019)	Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management
Niu et al. (2010)	Scaling of Economic Benefits from Green Roof Implementation in Washington, DC
Teotónio et al. (2018)	Eco-solutions for urban environments regeneration: The economic value of green roofs

The extent to which ecosystems can provide goods and services depends not only on their current health and diversity, but also on their resilience or ability to recover after disturbances. In the context of sustainability, it is important to ensure high levels of ecological resilience so that ecosystems can continue to function and provide goods and services for future generations (Shinderman, 2015). Promoting ecosystem health and diversity is therefore vital to the amount of goods and services an ecosystem can provide.

Despite the fact that numerous scientific studies have sought to examine the relationship between humans and nature, the complexity of integrated human and natural systems remains largely misunderstood (McPhearson et al., 2022). Therefore, it is crucial to learn how to handle interactions between people and nature appropriately and effectively. This will contribute to the creation of a more sustainable planet, which is crucial for both the present and following generations. By understanding and managing this interaction, we can ensure that the natural environment is maintained and even enhanced, while promoting human well-being. At the same time, this ensures that ecosystem services are fairly distributed among current and future generations, so that everyone has an equal opportunity to benefit from these services (Collins et al., 2011).

The Millennium Assessment classified ecosystem services based on their contribution to humanity. They can be divided into four categories: providing, regulating, supporting and cultural ecosystem services, see figure 2.10. Provisioning ecosystem services include the direct contribution of ecosystems, such as the production of food, water and raw materials. Regulatory ecosystem services include processes such as climate regulation, water purification and pollination, which play an important role in maintaining ecological balance and function. On the other hand, cultural ecosystem services include aspects such as recreation and aesthetic experiences that people experience in relation to natural environments. However, it should be noted that ecosystems not only provide direct services, but also contribute indirectly through supporting ecosystem services. These supporting services are crucial for sustaining and facilitating the direct ecosystem

Figure 2.10: Ecosystem services outline diagram. From Bath and Council (2021)

services. Examples include soil formation, photosynthesis and biodiversity conservation. Defining these various benefits and functions creates a bridge between human societies and natural systems, highlighting the interdependence and crucial role of ecosystems in human well-being (Millennium Ecosystem Assessment, 2005).

- **Provisioning services**
  Provisioning services encompasses the provision of finite tangible goods that are renewable and can be directly traded, consumed or quantified by humans (Maass et al., 2005; Costanza et al., 2017). Within the domain of improving the supply of these services, ecosystem services with a market value, such as food, fibre and biofuel, have been extensively studied. These services are studied from the perspective of improving supply to meet increasing demand. The provision of ecosystem services with a market value is very important for economic development and human welfare (Collins et al., 2011).

- **Regulating services**
  Regulatory ecosystem services are properties of ecosystems that result from complex interactions between their elements and contribute to a suitable human environment (Maass et al., 2005). The regulatory services that maintain the essential balance in terrestrial ecosystems are much less obvious to humans, and are therefore often neglected in decision-making processes (Costanza et al., 2017; Mengist et al., 2020). This, despite that Martínez-Harms and Balvanera (2012) found that regulating services were the most commonly mapped services.

- **Supporting services**
  Support services are ecological processes that form the basis for sustaining ecosystems and providing individual ecosystem services (Shinderman, 2015), without necessarily providing direct benefits to humans (Maass et al., 2005; Costanza et al., 2017). However, these services, such as photosynthesis and soil formation, are crucial for maintaining biodiversity and ecosystem stability. Despite their essential role, supporting ecosystem services can be overlooked in decision-making processes because they are less directly observable by humans than, say, food production or flood regulation (Collins et al., 2011).

- **Cultural services**
  Cultural services are often intangible in nature and arise from individual or collective perceptions that are highly dependent on the cultural context (Maass et al., 2005). It provides benefits for people's sense of community, place and well-being. These cultural services have an important impact on maintaining individual and communal identity. Understanding and preserving these cultural services is crucial for humanity as they contribute to the quality of life and sustainability of society. Recreational opportunities, spiritual renewal, historical reflection and scientific discovery are examples of these services provided by ecosystems (Shinderman, 2015). Improving the delivery of cultural ecosystem services has been extensively researched to better meet society's wants and needs (Collins et al., 2011; Costanza et al., 2017).

Gaining insights into the different types of ecosystem services is important in order to gain a deeper understanding of their role in enhancing human well-being and prosperity. This approach goes beyond simply focusing on the direct ways in which ecosystem services meet human needs and also considers the indirect contributions that bring value to people. Recognizing this is not only important for us as humans, but it's also crucial due to the interconnection and regulation of different ecosystem systems. The loss of these supporting and regulatory services can have a negative impact on the long-term availability of goods that can be sold in the market (Lant et al., 2008). The relationships between these different components create a complex landscape that can be organized and analyzed accordingly.

The strength of this distinction of various types of ecosystem services lies in its direct connection to the stakeholders involved through the social-ecological relationship. This is valuable because, except for provisioning services, ecosystem services are generally not excludable to specific individuals or groups. The fact that these services cannot be easily excluded often leads to instances of people benefiting without contributing, known as free-riding behavior. In a world where prioritizing sustainability is crucial, it is important to recognize the positive impact these ecosystem services have beyond the immediate stakeholders. This approach prevents investors from solely focusing on their own interests gained from interventions, without considering the potential costs associated with the decline of ecosystem services (Lant et al., 2008). The differentiation helps to put into perspective the unique contributions of ecosystems.

2.6.3. FOUNDATION OF THE ADOPTED CLASSIFICATION

To refine the classification of the specific ecosystem services associated with green roofs, a separate study took place. A detailed description of this entire process is included in appendix B. In shaping the categorisation and ensuring its accuracy and completeness first a review was made on macro scale ecosystem services, before the services of a green roof were looked at.

Multiple ways of classification were found for green roofs, each highlighting different aspects. The classification for a green roof proposed by Teotónio et al. (2021) was used as a basic reference. Moreover, relevant insights from the work of Zhang and He (2021) were integrated to validate and further refine the categorisation. The papers were used given their comprehensive categorisation and recent publication. This suggests that these papers likely incorporate the most current information available. Nevertheless, it is crucial to acknowledge that the similarity does not necessarily imply identical content value. Variations in the approach and interpretation of categorization between the two papers may exist. Hence, it was vital to consider not only the classification itself but also the underlying data in order to obtain a comprehensive understanding.

The paper by Zhang and He (2021) identifies various subcategories that arise from the motivations of different stakeholders seeking to achieve specific goals through the implementation of green roofs. These subcategories are further explained and supported with references in the paper. On the other hand, in the work of Teotónio et al. (2021), the different headers within the categories were derived from a study that analyzed the costs and benefits considered in 79 research papers. However, Teotonio et al.'s paper lacks detailed descriptions of these headers. Since Teotonio et al. conducted a systematic and comprehensive review of the relevant literature, it was assumed that their classification is comprehensive and can serve as a strong foundation for this research. Nonetheless, a comparison was made with Zhang et al.'s classification to draw insights from it.

GREEN ROOF ECOSYSTEMS SERVICE CATEGORISATION

This overview reveals a basic understanding of the potential ecosystem services of a green roof. Green roofs are multi-functional and contribute to various functions in different aspects. The resulting list comprises a total of 13 services, which are presented in figure 2.11. The services have been placed within the classification of Millennium Ecosystem Assessment (2005). However the literature review should prove the correctness of the combination of both classifications. A deliberate choice was made to display comparable services side by side, with the aim of enabling better comparison.

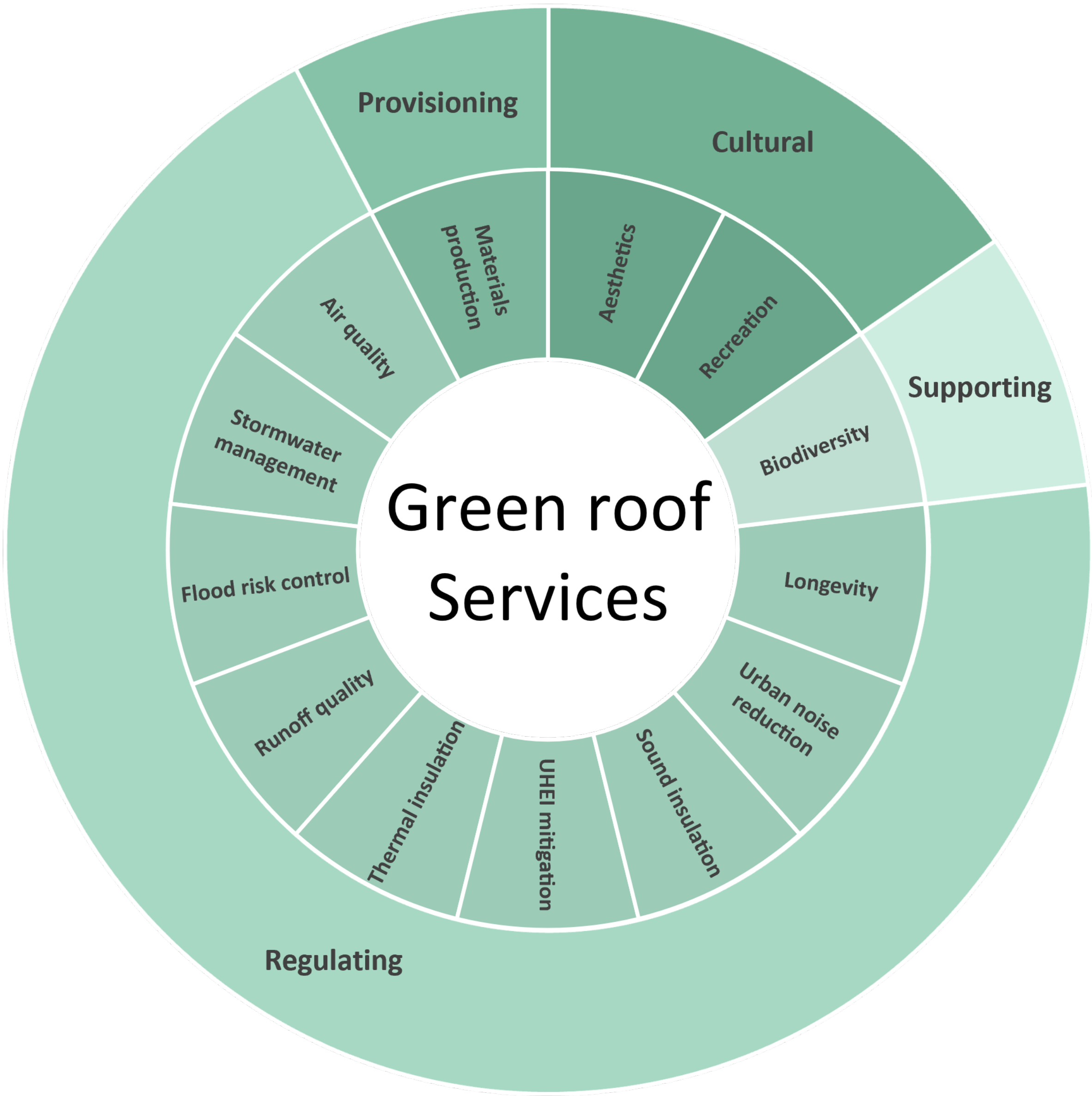

Figure 2.11: Classification of green roofs services used in the literature research. From own

2

2.7. (EXTERNAL) COST CALCULATION

In order to include the costs and external costs into the existing analysis the externalities have to be first determined. A life cycle assessment is one of the techniques developed to capture the externalities throughout the life cycle of the product (Standardization, 2006). It tracks the progress of a product through each stage of its life cycle, resulting in a document that is a kind of logbook of where materials have been, what they have done and what impact they have had on their environment. Materials can be seen as intrinsically involved in a triadic existence, namely an ecological, economic and social existence. These impacts can thus be diverse, including environmental impacts such as greenhouse gas emissions, social aspects such as employment, and economic aspects such as the price and value of materials and their contribution to production and trade (Ashby, 2022).

2.7.1. ENVIRONMENTAL, ECONOMICAL AND SOCIAL LIFE CYCLE ASSESSMENT

To obtain a deeper understanding of how materials impact these domains and to manage them effectively, specific measurement tools have been developed. These tools allow us to assess the ecological, social and economic aspects of materials. Within the domain of ecology, Environmental Life Cycle Assessment (E-LCA) focuses on measuring the ecological impact of materials. As a result, we gain insight into how materials affect the environment throughout their life cycle. The Social Life Cycle Assessment (S-LCA) focuses on the social impact of materials, covering aspects such as working conditions, social justice and community involvement. In addition, Life Cycle Costing (LCC) provides insight into the economics of materials, focusing on cost control and financial sustainability (Lin et al., 2020; Ashby, 2022).

Through LCA products or processes can be identified that have a major impact on the environment. In Europe, the principles and framework for establishing an LCA are laid down in ISO 14040 (ISO, 2022). This includes product development processes from cradle to grave (Singh et al., 2011). An LCA analysis provides a complete picture of the impacts obtained per product instead of just the cost price which can guide assistance in decision-making. The general framework for the three different analyses is the same and consists of: the scope definition, life cycle inventory (LCI), LCI assessment and an interpretation, see appendix E. By using these tools, we gain valuable insights into the role materials play within each of these three dimensions. As a result, we contribute to covering all pillars of sustainable development in a coherent and integrated way: People, Planet and Prosperity (Andrews, 2009; Reijnders, 2020)

Even though S-LCA a has a similar methodological frameworks and has made major advances in methodological development, practical application, and harmonisation (Toniolo et al., 2020), S-LCA is still in the early stages of development and improvement. This sets it apart from the widely used life-cycle cost analysis and environmental life-cycle assessment tools (Reijnders, 2020). The S-LCA faces several challenges (Rivela et al., 2022). Some of these challenges stem from the fact that the data required for S-LCA is different from that required for E-LCA. In E-LCA, the information is largely quantitative in nature, while the data required for S-LCA is qualitative and does not have a concrete, absolute scale. These data are influenced by cultural, normative and moral values that differ by location (Ashby, 2022). To date, there is no widely applicable tool for S-LCA that is equivalent in quality to existing conventional life-cycle cost calculations (Reijnders, 2020).

Given these considerations, this study decided not to incorporate Social Life Cycle Assessment, see figure 2.12. However, it is important to note that this study can act as a proof of concept, whereby the methodology currently developed for the environmental aspect may also be applied to the social aspect in the future. Thus, the framework can be extended once S-LCA is at a more advanced stage.

2.7.2. ENVIRONMENTAL COST BENEFIT ANALYSIS (E-LCA)

However, it is important to choose the right assessment tool that can encompass all the information from within this study. The LCA is recognised as a quantitative methodology, but the economic dimension is missing in the E-LCA, making it unsuitable for this study. Both the LCC and CBA methods rely on monetary valuation, but they differ in terms of their points of focus point, time span, and points of comparison. With regard to the environmental aspect, two levels are distinguished. The first, the Environmental Life Cycle Cost (eLCC), focuses on the total cost of a product's life cycle, including social costs (Biernacki, 2015). These costs are borne directly by various actors, including actual cash flows that are expected to be internalised in the future. Examples of such costs are waste disposal, carbon taxes and climate change adaptation costs. In addition, Full Environmental Life Cycle costing (feLCC) adds non-internalised environmental costs identified in an E-LCA (Hoogmartens et al., 2014). While CBA typically concentrates on projects or policies, LCC is used in the evaluation of products. At the same time, while the CBA focuses primarily on the lifetime of a specific

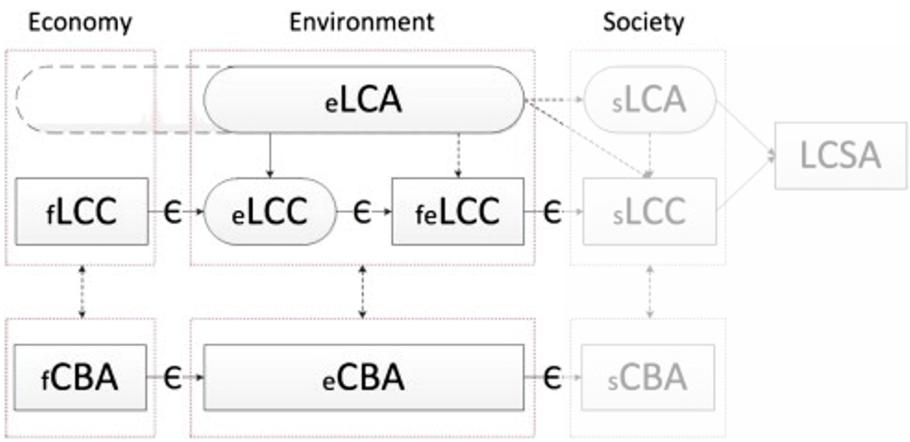

Figure 2.12: The integrated framework illustrates how different sustainability assessment tools interact. Full arrows denote the need for data from one methodology to carry out another methodology. Arrows with a dash show that while one methodology may be a useful input to another, they both remain stand-alone approaches. When the symbol "€" is used, it means that a methodology is a subset of another methodology. The social component has been faded because it is left out of the study. Adjusted from Hoogmartens et al. (2014)

project, the LCC focuses on the full or economic life cycles of the assessed products. Also when comparing products, LCC is a comparative assessment tools, whereas CBA is typically used in stand-alone project evaluations (Hoogmartens et al., 2014). Based on this the eCBA was chosen as the better fit for our research.

NET PRESENT VALUE

For this study, it was chosen to further shape the e-CBA by using the net present value (NPV), as previously done in the literature for CBA among others by McRae (2016); Mahdiyar et al. (2016); Teotónio et al. (2018). This method involves calculating future cash flows back to a present value by using discount rates (Fernando, 2023). This incorporates the value of time into the calculation, recognising that a euro today has a different value than a euro in the future. The use of this method is described as one of the most widely used and practical approaches (Mahdiyar et al., 2016).

The discounted cash flow is calculated based on the cash flow and a certain interest rate, as highlighted in equation 2.1 Finally, by adding all cash flows together, the NPV can be calculated.

$$DCF = \frac{CF_n}{(1+r)^n} \tag{2.1}$$

Where:
DCF : is the discounted cash flow to year t=0
CF : is the cash flow in year n
r : is the real discount rate

In addition, the discount rate as used in formula 2.1 is calculated by means of the real discount rate, as described in Mahdiyar et al. (2016). This takes into account both inflation and the discount rate used and thus provides more information within the calculation, see equation 2.2. This means that the outcome of the analysis is already corrected for both inflation and the respective discount values.

$$r = \frac{1+ndr}{1+ir} - 1 \tag{2.2}$$

Where:
r : is the real discount rate
ndr : is the nominal discount rate
ir : inflation rate

2.7.3. MONETIZING THE ENVIRONMENTAL IMPACT

ENVIRONMENTAL IMPACT CATEGORIES

The process of translating environmental impact data into monetary measures is not always trivial, as observed in Hoogmartens et al. (2014) work on bridging the two domains. It is crucial to comprehend the inputs and outputs of an LCA before attempting to calculate costs from an e-LCA. These inputs for an e-LCA include the materials utilized, the energy used, and the transportation of materials between various points in the production process (Ashby, 2022). From this list of product and related process inputs, we turn to the released emissions and pollutants. This list of emissions, classified according to the life-cycle inventory, should then be converted to a practically manageable quantity. On this basis, middle points (midpoints) are established. From July 2022, the environmental product declaration (EPD) EN-15804+A2 is the determination method designed by the European Union to determine the environmental impact of construction materials and products on sustainability (Durão et al., 2020; nationale milieudatabase, 2022). The newest EPD takes 19 environmental-impact-categories into account, the midpoints, see table 2.2. The EN15804 standard is important because it offers transparency and allows comparison. This offers legitimate opportunities for more sustainable products. Drawing up an EPD is produced on the basis of calculation methods of a life cycle assessment (LCA). To transition from different classes to midpoints, a categorisation factor is used. This factor reflects the relative impact of the class within one of the midpoints. In this way, all classes can eventually be converted to an equivalent value of the different environmental impact categories (NEN-EN 15804:2012+A2:2019/C1:2021 en, 2021), see figure 2.13.

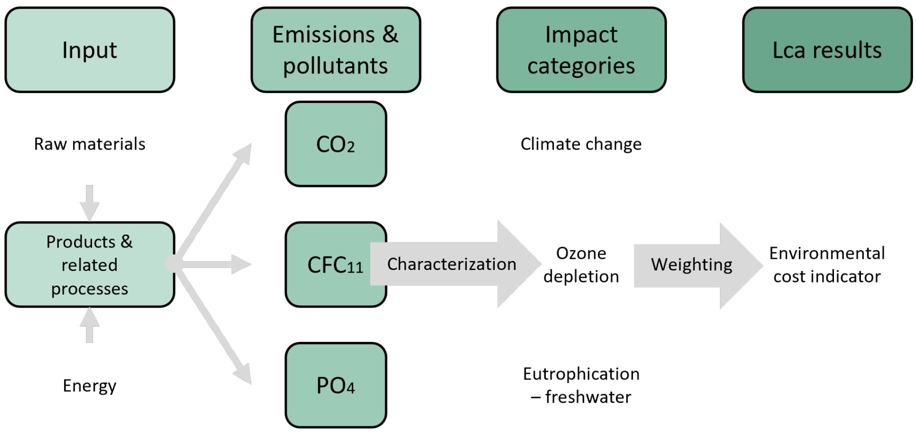

Figure 2.13: Environmental cost indicator. Adjusted from Quist (2021)

Table 2.2: New environmental impact categories, abbreviation, specific unit equivalent for each of the 19 'basic' environmental impact categories (EN15804 + A2 (2019))

	New Environmental impact categories	
Impact category	**Abbreviation**	**Unit equivalent**
Depletion of abiotic resources – minerals and metals	ADPE	kg Sb-eq
Depletion of abiotic resources – fossil fuels	ADPF	MJ, net calorific value
Climate change – total, fossil, biogenic and land use	GWP100	kg CO2-eq
Ozone layer depletion	ODP	kg CFC-11-eq
Photochemical oxidation	POCP	kg Ethene
Acidification	AP	kg mol H+
Human toxicity – cancer, non-cancer	HTP-c-nc	CTUh
Eco-toxicity (freshwater)	ETP-fw	CTUe
Eutrophication – freshwater	EP-freshwater	kg PO4-eq
Eutrophication – marine	EP-marine	Kg N-eq
Eutrophication – terrestrial	EP-terrestrial	mol N-eq
Ionising radiation, human health	IR	kBq U-235
Particulate matter emissions	PM	Disease incidence
Water use	WDP	m3 world eq. deprived
Land use	SQP	-

Environmental impact economic valuation tools

The LCA provides a list quantifying equivalent values of the 19 environmental impact categories as a result of the entire process of the material. Using a conversion method, the emissions released throughout the life cycle can be converted to a monetary value (Ingemarsdotter, 2022). In this way, the monetary value can be added to the e-CBA, as also described in (Arendt et al., 2020). However, this list cannot simply be monetised because these externalities have no direct market value. Another challenge is that the LCA offers an overview of generally defined potential impacts and therefore potential impacts must also be referred to in the monetary value calculation (Pizzol et al., 2015).

There are several methodologies for this, all of which have both strengths and weaknesses. Pizzol et al. (2015) gives a recommendation for which LCA impact categories the different methods are to be used. Nevertheless, the literature shows that not always the most appropriate method is applied. For example, for the impact category 'global warming', most methods use emission abatement costs (Arendt et al., 2020), while this method is not recommend because there are methods available, such as willingness to pay, that better reflect damage costs (Pizzol et al., 2015). In essence, the most important thing when LCA results are monetised, is that all impact categories are monetised in the same way using the same method (Arendt et al., 2020).

The consequence of the different assumptions and methods on which the calculation is based is that there is a difference in the accuracy, availability and application of the different calculation figures (Lindgreen and Vermeulen, 2023). Pizzol et al. (2015) compares 13 LCA applications and in them, on a relative scale, notes large differences in scientific foundation, documentation, completeness, uncertainty, complexity and relevance for LCA. However, this is a relative fact that partly relies on a subjective approach, however, it can be taken from this that the results from the different methods should not be taken as truth directly.

Ultimately, these variations lead to different values resulting from the different methods (Arendt et al., 2020; Amadei et al., 2021; Lindgreen and Vermeulen, 2023). Some of these differences can be attributed to the lack of knowledge about certain impact categories. For example, more research has been done on human health impacts than on biodiversity and natural resources. For these categories, more research and consensus is needed to determine the relevant impact. Arendt et al. (2020) also identifies several gaps in the literature regarding different approaches. Based on the results of that research, no suitable, complete and consistent method can be found to convert the impact categories of the environmental footprint impact into monetary terms. With the in this study used EN 15804+A2:2019 consistent with this environmental footprint assessment approach (Nationale milieudatabase, 2023).

Eco-cost

Generally, there is not one method recommended, but instead calls for a careful combination of techniques (Lindgreen and Vermeulen, 2023). In the choice, importance can be attached to different aspects. The decisive factor in the choice of method for this study was location. Arendt et al. (2020) has listed geographical reference as the most influential criteria. Because the valuation of these criteria is closely related to welfare, and in addition, the impact is also related to location. Based on this, it was therefore chosen to continue working with the Eco-cost/Value Ratio (EVR) as a method.

Most single indicators are based on damage. This emerged in the 1990s with the aim of making people aware of the damage caused by production and consumption (Arendt et al., 2020). However, these indicators are complex, vague to outsiders, based on assumptions, subjective assessments and difficult to communicate. Attempts to monetise results have been unsuccessful because of methodological shortcomings and uncertainties. Prevention-based indicators, such as the eco-cost system, are relatively new and have the advantage that calculations are simpler, more transparent and results can be expressed in monetary terms and concrete measures. This system focuses on decision-making processes and offers a single endpoint in euros, but does not emphasise reducing consumption (Pizzol et al., 2015; Amadei et al., 2021).

Eco-costs serve as a measurement tool to express a product's impact on the environment in terms of the cost required to reduce that impact to a level sustainable for the planet (Lindgreen and Vermeulen, 2023). The eco-cost methodology is based on the sum of marginal prevention costs and includes toxic emissions related to human health, ecosystems, climate change and natural resource depletion. The marginal prevention costs of toxic emissions are derived from the prevention curve. This assumes that countries take preventive measures to reduce emissions, implementing cheaper measures first. The level at which emissions are reduced below a safety threshold, the so-called no-effect level, is reached by using the marginal prevention cost of the last measure (Vogtlander, 2023).

The calculation of eco-costs is based on classification and characterisation tables, similar to Environmental Taxes. Normalisation is performed by calculating marginal prevention costs for a specific region. Unlike other systems, no separate weighting is needed in the eco-cost system, as the overall result is the sum of the eco-costs for all intermediate points. This has the advantage that the marginal prevention cost is linked to the

Table 2.3: The relationship between impact categories in EN 15804 and eco-costs 2023. Adjusted from Sustainability Impact Metrics (2023)

Impact Category in EN 15804 as well in EF (Environmental Footprint)	Quantity and Unit	Eco-costs 2023 per unit
Climate change - fossil	1 kg CO_2 equiv	€ 0.123
Climate change-biogenic	1 kg CO_2 equiv	€ 0.0
Climate change land-use and land-use change	1 kg CCR equiv	€ 0.123
Ozone Depletion	1 kg CFC II equiv	€ 0.00
Accidification	1 mol H+ equiv	€ 7.08
Eutrophication freshwater	1 kg P equiv	€ 15.32
Eutrophication freshwater	1 kg PO4 equiv	€ 5.0
Eutrophication marine	1 kg N equiv	€ 22.12
Eutrophication terrestrial	1 mol N equiv	€ 1.58
Photochemical ozone creation	1 kg NMVOS (= 1 kg NOx)	€ 5,67
ADP, abiotic depletion potential, metals and minerals	1kg Sb	note (a)
ADP, abiotic depletion potential, fossil fuels ("energy carriers")	1 MJ	note (b)
Water use, deprivation-weighted water consumption, WDP	1 m3 world require deprived	€ 0,18
Additional Impact Categories in EN 15804:2012+A2:2019		
Particulate Matter emissions (PM 2.5)	disease incidence (cases)	€ 147000
Particulate Matter emissions (PM2.5)	kg PM 2.5 equiv	€ 37.1
Ionizing radiation human health	kBq U235 equiv	0.0 note (c)
eco-toxicity	1 CTUe	€ 3.63E-3
eco-toxicity	1 kg Co equity	€ 360)
human toxicity cancer	1 CTUH (disease cases)	€ 920000
human toxicity cancer	1 kg benzo(a)pyrene equiv	€ 3750
human toxicity non-cancer	1 CTUH (disease cases)	€ 216000
human toxicity non-cancer	1 kg mercury equiv	€ 25500
soil quality	-	0.0 note (d)

Footnotes
(a) eco-costs has a different midpoint system for ADP, metals and minerals
(b) eco-costs has a different midpoint system for ADP, fossil. Note that eco-costs has a separate midpoint for uranium
(c) not in ecocosts (is dealt with in eco-costs of energy carriers)
(d) not in ecocosts (is dealt with in land-use, biodiversity)

cost of the most expensive Best Available Technology needed to achieve the target, as well as the level of tradable allowances required in the future. From a business perspective, eco-costs represent the costs associated with the risk of not complying with future government regulations (Vogtlander, 2023). However, Pizzol et al. (2015) places a comment on this method in that it does not rely on an actual demand but on an estimation of a hypothetical situation. As a result, uncertainty flows from the choice of mitigation techniques, the outline of the future and the lack of a causal relationship between damages and costs. The values for midpoints in the eco-cost 2023 are given in table 2.3

Phase B | Analysis phase

The next part in this study is the analysis phase. This phase consists of a thorough literature review based on the theoretical framework acquired in phase A. The literature review includes the theoretical information that provides insight into the current situation regarding the services of a green roof, the benefits and the translation to an economic value all linked to the stakeholders. This study broadens the theoretical knowledge, identifying and highlighting the common methods but also gaps in the literature.

3

GREEN ROOF LITERATURE REVIEW

3.1. INTRODUCTION

In this part of the research, a review was performed to provide insight into the existing black box of methods and assumptions that were used to determine the economic value of the services of green roofs. This critical review forms the basis for improving the current pool of information by allowing an open discussion and reflection upon from multiple disciplines. The literature analysis performed in chapter 2 provides the knowledge required for a structural and systematic conducted execution of the literature review as well as the list of reviewed literature. This theoretical framework was used to create a setup for the execution of the literature review, see appendix C. For this study, however, the methodologies used for the determination of the economic value for each of the ecosystem services within this literature review is important. Namely, for which ecosystem services can a statement be made on the basis of the existing literature, so that this can later be applied to the case study. This analysis phase of the research is dedicated to two sub-research questions:

- What are the private benefits of the ecosystem service of a green roof, and how can these benefits be expressed as an economic value?
- What are the benefits for society during the use stage of the ecosystem services of a green roof, and how can these benefits be expressed as an economic value?

To focus on answering the sub-research questions, the results of the literature review were highlighted. As a result, it was decided to move the supporting review and analysis to the appendix and present the conclusions of the study in this chapter. In particular, the appendix can be used for in-depth information behind the results and for specific studies on the different ecosystem services, see table 3.1. The appendices can be read as separate studies, following a logical structure to discussion, conclusion and recommendations. This chapter will cover the concise conclusions of the literature review in a systematic way, successively covering the provisioning, regulating, cultural and supporting services.

Table 3.1: Appendix number for the full literature review of different ecosystem services of a green roof

Provisioning services		**Regulating services**		**Cultural services**		**Supporting services**	
D.1	Materials	D.2	Air quality	D.10	Aesthetics	D.12	Biodiversity
		D.3	Stormwater management	D.11	Recreation		
		D.4	Floodrisk				
		D.5	Runoff quality				
		D.6	Thermal insulation				
		D.7	UHIE				
		D.8	Sound insulation / Urban noise reduction				
		D.9	Longevity				

3.2. PROVISIONING SERVICES

Based on the established classification of the ecosystem services of a green roof, only material production was identified as a providing service. The literature review was used to better contextualize and give interpretation to this. However, within the literature review an indication of the potential of a green roof to provide water was found. Nevertheless, it is important to note that substantial supporting evidence is lacking as the contribution of a green roof to purify and provide water is not fully clear due to the use of additional facilities. As a result, the current understanding of this aspect remains limited and the available information can only be attributed to the material facilities domain.

3.2.1. MATERIAL PRODUCTION

To date, the existing literature conducting cost-benefit analyses of green roofs has not extensively considered the presence of a rooftop farm. This gap in the literature is partly because the roof has to be designed in a specific way to benefit from this production of materials. The conventional extensive and intensive green roofs do not produce these goods and thus the benefits associated.

The current methodology provides general understanding of the benefits of green roofs with regard to material production. The knowledge reviewed provides insight into the potential of a roof top farm, where a quantifiable annual yield can be achieved. It is mentioned that the farming and cultivating could be done with the help of volunteers. However, it is recognized that the use of volunteers results in reduction of the annual yield. This annual yield, once harvested, has the potential to be monetised later by matching it to prevailing market price of the products, creating a tangible source of direct income. Creating a realistic price representation of the value of the goods.

However, the literature does not yet provide an unequivocal answer to the question of to whom this amount should accrue. This raises the question of whether revenue should be attributed to the building owner or benefit the community. The intended purpose of the roof should be considered, as the involvement of volunteers may reduce the annual revenue. Moreover, the presence of a rooftop garden offers social benefits not previously mentioned. Volunteers derive satisfaction from working in the rooftop farm, ranging from relaxation to social contact. This highlights the importance of green roofs in promoting community building, contributing to food security and providing educational opportunities within the local community. The value of a green roof thus extends far beyond the role of providing materials that can be sold and includes the cultural ecosystem services it provides. However these are, as of now, not yet quantified or monetized.

3.3. REGULATING SERVICES

Based on the classification found, the literature review was used to interpret the following regulating ecosystem services: air quality, storm water management, flood risk, runoff quality, thermal insulation, UHEI, sound insulation, urban noise reduction and the longevity. However, the study shows that the boundaries between the different categories are not always as strict as they may seem at first glance.

First, there are some similarities between water management, flood risk and water quality. These three are largely based on the physical aspect of the drainage coefficient of the green roof. In addition, similarities can also be found between thermal insulation and the UHEI. Finally, due to the scale level of this study, which focuses on the building level, there is hardly any distinction found between sound insulation and urban noise reduction. This is mainly caused because the numbers and values presented are not always used correctly, leading to overlap in the information. Based on this, both the analysis and the conclusion, as shown below, merge sound insulation and urban noise reduction. Nevertheless, additional information may help make these boundaries clearer and more understandable.

3.3.1. AIR QUALITY

A unified picture of how green roofs contribute directly and indirectly to improving air quality and how this can be translated into a monetary value emerges based on the information obtained from the literature. The method does not only demonstrate consistency for various pollutants, but it also demonstrates consistency across studies. This demonstrates that there is agreement on the methodology and estimation of the improvement in air quality brought on by green roofs. The outcomes of various studies in this area can be reliably compared and interpreted by employing consistent methodologies. This advances the idea that direct air quality improvement is a benefit of a green roof's overall ecosystem services and helps create a solid knowledge base.

For mapping green roofs on air quality, a number of substances have been addressed in the literature, these are; PM_x, SO_2, NO_2, O_3 and CO_2 for direct and CO_2, NO_x and SO_x for the indirect. It is noted that the indirect effect also reduce the amount of PM_x and O_3, however, these have not been elaborated.

Direct air quality regulation

The direct impact of adding a green roof on air quality comes from the fact that plants are able to absorb substances from the air. Plants come in different shapes and sizes and the uniqueness of different plants also creates a difference in their behaviour. The uptake potential of plants depends on air pollutant concentration, plant types and growth, and weather conditions (Berto et al., 2018). Nevertheless, the literature has tried to quantify the effect on air quality of plants on green roofs. In general, the method used in the literature is the same. First, the potential of the plant is determined. This is a property that shows to what extent the plant is able to uptake a given substance. This uptake capacity is usually expressed as a weight per area per time frame [g/m2/y]. Previous literature is used to determine this value, but in some cases the uptake potential is determined differently. Here, the potential uptake is determined based on the concentration of certain substances in the surrounding air. This is described as the better method, because the inclusion of local parameters in the calculation will result more specific to a certain location.

Indirect air quality regulation

Besides the direct impact on air quality through the uptake of substances, the literature also gives the indirect consequences of adding a green roof. In this, the literature tends to use a one-size-fits-all approach. The indirect impacts are derived from the saving of electricity or gas through the thermal effect of the roof package. The energy required for thermal comfort is directly related to a certain emission released when generating this energy. Making a distinction between energy produced from gas and energy produced from electricity is crucial to take into account the various emission profiles of energy generation, resulting in a more precise estimation of emission reductions. The saving of energy in turn ensures a reduced production of pollutants. The composition of the energy mix, which affects emissions and benefits of green roofs, varies depending on local conditions. Hence, local factors should be considered in the quantification of emission reductions. Furthermore, it is critical to consider the energy transportation losses when evaluating indirect pollutant reduction because these elements can have an impact on the actual savings realized. The indirect impacts of green roofs should be extended beyond energy savings from insulation and incorporate factors such as storm water treatment and the reduction of the UHEI.

According to the reviewed literature, it can be inferred that there is a lack of specific information and consistency in estimating the economic value of various substances. There is no consistent approach to determine the value of a substance, which leads to confusion and makes it difficult to use a uniform valuation. Both the avoided impact price, the substitute cost and the market price are addressed for monetizing the quantified substances, with the impact price looking at the damage to human health, agriculture, the environment and climate change. Making an informed decision between market price and impact price is challenging due to the lack of consistency, so there is a need for guidelines and tools for a consistent approach that take the interests of various stakeholders into account. Additionally, when using the impact price, the impact is often grouped together which yields little specific knowledge, a thorough understanding of the unique traits and effects of each substance is required, especially, when linking the values to the corresponding stakeholders.

3.3.2. Storm water management

Multiple methodologies were used in the literature that could be assigned to the storm water management ecosystem service of a green roof. The starting point of each of these methodologies is the fact that the green roof reduces the runoff. Because of this emphasis should be placed on the correctness of the runoff coefficient. Literature mentions multiple influences that could alter the real behaviour such as storms with a lower occurrence interval and the fact that green roofs might only delay the runoff. The annual rainfall, roof type, number of layers and depth of substrate layers were found to be significantly correlated with annual runoff. In contrast, the age of the green roof, slope angle and length were not found to be significantly correlated with annual runoff. Despite this, the literature still provided certain methodologies that could give an answer to the research question. It is important to note, that because of the valuation method, that the transportation and treatment, pipe dimension reduction and the incentive are mutually exclusive with the best management practise.

3.3.2.1. TRANSPORTATION AND TREATMENT COST

The proposed methodology for the transportation and treatment looks at the reduced volume of storm water through the sewer systems and could provide an answer to the research question. The amount of water that needs to be transported and treated is reduced as a result of this volume reduction. Therefore, the accountable party for the transportation and treatment of storm can benefit from avoided costs. It is crucial to consider the marginal costs in the production process associated with this same unit in order to accurately reflect this in the calculation. Therefore, a decrease in water volume should result in a decrease in the water treatment company's variable costs. The accountable local party should therefore be consulted when determining this cost estimate.

3.3.2.2. PIPE DIMENSION REDUCTION

The proposed methodology for the reduction of the dimension of pipe lines also looks at the reduced volume of storm water through the sewer systems. However, the current methodology was insufficient to give an answer to the research question. There is a current lack of understanding whether green roofs can cause a reduction of the pipes size. This is mainly due to the scale of this study which looks at the implementation on a single building. Even at a larger scale there is no consensus yet in the current literature whether green roofs can provide a benefit in terms of the reduction of pipe lines. A reduction in material costs is put forward as the aspect where savings can be made, in addition there would also be a reduction in maintenance costs. However, the literature does not yet offer a conclusive answer to this either on the larger scale.

3.3.2.3. INCENTIVE

Based on the review of the literature, the research question can be answered for the use of an incentive. This incentive is issued by the municipality to the owner of a building so that the owner can also benefit from the reduction in the discharge of water to the sewer. The incentive is in the form of a discount on the sewerage tax and can differ based on the reduction capacity. Because the incentive is issued by the local municipality, its availability and value depends on the location.

3.3.2.4. BEST MANAGEMENT PRACTISE

The methodology relying on the best management practise looks at the effect of green roofs and therefore the potential reduction of other interventions to manage storm water. The current methodology within the literature used the substitute cost method. It was shown that the use of the substitute cost method relied heavily on local conditions but could still provide an answer to the research question. The potential reduction is translated into a monetary value through savings on other projects. In addition, the opportunity costs are mentioned as an additional benefit. However, the current information on both are not enough to make a clear statement, the main shortcoming is the fact that these values cannot be easily transferred to other situations. Additionally the equivalent unit in which the measures are expressed is difficult to quantify, which is why follow-up research is needed to work out the potential of this.

3.3.3. FLOOD RISK

The proposed methodology looks at the reduction of pluvial flooding caused by the retention capacity of green roofs. The quantification of this value in the current pool of information is limited to advanced flood estimation models or the application on a bigger scale, instead of the scale of the scope of this study. In addition the values are highly dependent on the runoff coefficient as already discussed earlier in chapter D.3, paying little attention to the influence of the recurrence interval of storms.

Multiple approaches are found to translate the flood reduction into a value. Currently there is no consensus on the use of either the avoided impact or the substitution cost. The avoided impact cost should look at the influence on human health, environment, cultural heritage, economic activities, damages to buildings, infrastructure and transport. Avoided substitution costs explore proposed intervention plans that can be reduced or avoided due to the implementation of green roofs. The positioning of both values within the methodology as well as their impact on stakeholders should be the subject of further study, especially given the fact that both methodologies are mutually exclusive.

Within the framework of the current literature review, a noticeable gap appears in the available information that can adequately link the potential effects of implementing a green roof at the building level with the potential reduction in flood risk, especially when focusing on storm events with significantly higher return periods. As a result, a coherent picture of a methodological approach that is thorough enough to provide a convincing answer to the research question does not unfold.

3.3.4. Runoff quality

Based on the current literature reviewed no answer can be given to the research question. This is because the described method lacks substantiation and the provided information within the literature is not enough to make comprehensive statements about this. The current pool of information shows that there might be improvements, however the opposite could also be true. That is why future research is needed. In cooperation with the parties involved who control, monitor and regulate the water quality, a clearer picture of the effects and consequences needs to be drawn up. Based on this cooperation, the next step is to also arrive at figures for charging costs and revenues. The clean water could avoid additional measures that have to be taken by the property owner but it is likely that additional impacts are in place.

Once the water quality improvement is proven one can also look at the benefit of providing clean water as a provisioning service. For the project owner, benefits arise from the use of rainwater for irrigation and toilet flushing. However, this claim raises questions about scalability and applicability to other locations. Additional components, such as cisterns, that are needed for the system to function are mentioned. These components entail additional costs, which is described in the literature as an investment that may not outweigh the benefits. This influences the profitability, and raises an additional threshold of installation. However these benefits remain largely unknown due to the lack of information in the reviewed literature.

3.3.5. Thermal insulation

An answer to the research question could be formulated based on the current literature. The thermal insulation resulted in the benefit of reduced energy usage. The green roof increased the thermal mass and the roof's evapotranspiration and decreased the the absorption of solar radiation. In the literature, multiple ways of quantifying this energy reduction were used. Either numbers from other literature studies, by calculation, or software was used to quantify the amount of energy savings. The calculation method focused only on the thermal mass and local climate data. The use of basic calculations was substantiated because the evapotranspiration effect on roof cooling compared to its insulating effect is questioned. This is mainly because most green roofs use drought-resistant plants which naturally minimise evaporation processes to retain water. The size, roof-to-envelop ratio, use, and amount of floors were the influencing factors taken into account within some of the described software in addition to local climate data, the thermal mass, the evapotranspiration and absorption coefficient. Further research is needed to determine the influence of choosing either of the two methods to quantify the energy losses and also differences within different software. The quantitative data could be divided into the amounts of energy required for cooling and for heating. In some instances, a conversion factor was added to account for system losses. By selecting the appropriate price for either gas or electricity from the market, the values could finally be converted into a monetary value. The building owner/user received the benefit in this manner.

3.3.6. Urban heat island

Based on the current literature reviewed no answer can be given to the research question. The available literature does not provide sufficient guidance to properly incorporate the benefits of the UHEI into cost-benefit analysis. The method it presents focuses on the translation of the reduction of the UHEI on the energy demand of the city. However, this method only uses data related to large-scale applications, so no conclusions can be drawn about applicability at smaller scales, such as the focus of this study. Mainly because it is indicated that the effects are only exist when the green roofs are implemented at a larger scale.

To evaluate the benefits at the level of individual buildings, it is therefore necessary to have information on how to quantify the effects at this scale and how to translate them into a monetary value. The current methodology relies heavily on indicator values, while there are existing methods that can calculate the reduced energy loss at the level of an individual building, taking into account the decreasing outdoor temperature. Moreover, it should be recognised that the effects go beyond the energy consumption of the building alone. So far, however, no attempts have been made to include these aspects in the analysis. Therefore, it is of utmost importance that future research focuses on integrating these broader effects into the methodology, in order to better understand the climate impacts of green roofs and the broader ecological and health-related implications associated with them.

3.3.7. Sound insulation / Urban noise reduction

The present methodology shows that an answer can be formulated to the research question. The integration of a green roof results in an improved sound insulation of the roof, which in turn results in a reduction of indoor noise levels (dB/dB(A)). The literature shows that the reduction can be mapped in different ways. The use of these values therefore requires attention so that they can be correctly interpreted. The noise reduction can then be monetised in one of two ways. One can look at the prevented impact which is measured in terms of the property price (€% property value/dB) and a potential health cost, or at the prevented substitution of insulation panels (€/panel/m^2/dB). Since both approaches are mutually exclusive, follow-up research is needed to provide a proper economic interpretation of the method. In addition, there is some disagreement in the literature about whether this benefit applies only to the top floor or to the entire building. Therefore, further research is needed on the scale at which this noise reduction manifests itself within the building.

Moreover, noise propagation across the roof decreases, allowing adjacent buildings to also benefit from noise reduction. Depending on the spatial context, this results in a benefit in the form of increased property value in the surrounding area, which can be quantified in the same way using the method discussed earlier.

3.3.8. LONGEVITY

Based on the current literature reviewed an answer can be given to the research question. The current methodology allows translating life extension into a monetary value. The green roof and the plants provide protection from the elements. The result is that the green roof has a longer lifespan than the conventional roof. This leads to savings on replacement costs compared to conventional roofs at the time at which the conventional roof is normally replaced.

However, there is a lack of well-founded literary evidence to confirm the claimed lifespan. It is crucial to gather solid evidence to support this claim. Although the available stated examples all point in the same direction, it cannot be ruled out that there are examples that show the opposite. This is highlighted by the water accumulation in the low spots that can damage and affect the membrane. Part of the risk is mitigated by the fact that there are reports in the literature of companies offering guarantees for a certain lifespan of green roofs. Nevertheless, it is necessary to conduct further research and gather solid evidence to support this claim and gain a full understanding of the potential drawbacks and risks of green roofs.

3.4. CULTURAL SERVICES

Based on the defined classification, the literature review was used to interpret the following cultural ecosystem services: aesthetics and recreation. The study shows that the boundaries between the two categories are not always as strict as they may seem at first glance and that there is overlap between the different numbers. Community building and the potential for educational properties are also highlighted. Nevertheless, supporting evidence is lacking and thus requires additional research. On this basis, the information is limited to the aesthetic and recreational cultural services.

3.4.1. AESTHETICS

The research question cannot be answered based on the available literature. This is because the current proposed methodology in the literature does not yet rely on literature-proven relationships. The methodology attempts to depict the increase in property value based on the addition of the green roof. However, the causal link between property value and the presence of a green roof has so far only been substantiated by figures derived from the link of property value with parks and trees and a stated preferences method.

The values currently used in the literature, when all benefits are considered, can potentially lead to double counting of certain benefits. In particular, the overlaps between aesthetic value and recreational value deserve special attention here. Therefore, it is important that future research knows how to clearly distinguish between these two aspects so that aesthetic value can be adequately interpreted.

Moreover, the literature lacks an answer to the scale at which this price increase would apply. The current property value increase approach is applied to the entire building, but the author questions this, which warrants further research efforts.

Finally, it is important to also consider the potential increase in value of surrounding buildings as a result of green roof implementation. In this way, the application of green roofs can also make a positive contribution within urban areas. To date, these aspects have not been adequately investigated in the literature, so follow-up research should focus on these specific areas.

3.4.2. RECREATION

The research question cannot be answered based on the available literature. The present method for evaluating recreation value concentrates on the growth in property value. As a result, the entire increase in value accrues to the property owner. However, from the literature review it emerged that the current values still rely on the connection between the property value and parks and trees in the surrounding area. As a result, the causal relationship is lacking in the methodology used. Future research is needed to verify the fact that green roofs show a similar contribution. Especially given the fact that EGR are often not accessible.

There is also a lack of information on the cultural value of recreation of the green roof. Including the improvement of comfort and quality of life for users gives a more holistic picture of the value of recreation, by including the social value.

3.5. SUPPORTING SERVICES

Based on the defined classification of the ecosystem services of a green roof, only biodiversity was identified as a supporting service. The literature review was used to give interpretation this. The amount of information regarding the supporting services was very limited and thus no additional indication of services expect the biodiversity was found.

3.5.1. BIODIVERSITY

Based on the current literature no answer can be given to the research question. The literature looks at the increased biodiversity cause by the green roofs. The quantification of the effects of green roofs in the current pool of information is limited. There is an indication given of the positive effects on biodiversity on the building scale. Additionally the positive effect in creating a wildlife corridor is given, showing the valuable contribution on a bigger. Nevertheless, there is a lack of concrete values useful for making an informed and meaningful statement about the value of green roofs for biodiversity.

The valuation looks at the avoided substitution costs by the substitution of proposed biodiversity plans by the implementation of green roofs. However, the causal relationship between the quantification and the valuation is not yet scientifically proven.

Further research is needed to map this relationship, but the impact costs of these supporting services should also be considered. Only in this way will ecosystems be correctly valued.

3.6. LIMITATION IN THE CURRENT VALUATION METHODOLOGIES

One of the main things to emerge from the literature review is how the methodology should be set up in relation to the stakeholders. When looking at the different methods individually, these methods seem to rely on a logical flow within the cascade framework. However, when comparing the overview of the different methods within one ecosystem service, questions may already arise. This fact can be reinforced when the methods used of different ecosystem services are laid side by side. In this, it starts to be noticed that there are different approaches to provide an interpretation within the cascade framework. The problem lies in the fact that some of these methods are mutually exclusive. This means that using one method excludes the other. This is especially a problem in cases where both approaches have a relationship with a different stakeholder.

When comparing the different ecosystem services, two main approaches of the used methods emerged. On the one hand, one can determine the value based on a comparable intervention pre-implementation to determine the saved costs. Here, it is important to use an equivalent unit to enable comparison. On the other hand, one can look at the impact as a direct effect of implementing green roofs. This can look at the costs avoided or the revenue obtained. This first method, looking at comparable interventions, has been applied to storm water management, flood risks, noise insulation and biodiversity, among others. In contrast, impacts on material production, air quality, storm water management, flood risk, water quality, thermal insulation, noise insulation, the UHEI, recreation and aesthetics have been considered. In this, it is widely acknowledged that different methodologies have a significant impact on the results in environmental valuation (Jacobs et al., 2018).

However, it is unclear which method should be applied. For example, the study on sound insulation looks at both the impact of reduced noise levels and potential savings on sound insulation panels, while thermal insulation only looks at the impact of reduced energy loss. This lack of clarity on methodology is exacerbated when looking at the stakeholders involved. It is important to be aware of both methodologies, especially in situations where a stakeholder benefits from both one and the other. Take noise reduction, for example. For the owner, this could lead to an increase in property value or a reduction in the amount of soundproofing materials needed. Ultimately, the stakeholder will choose the method that brings the most financial benefit. However, noise reduction also brings social and health benefits to users, and these should be fairly considered in the trade-off. Fisher et al. (2009) already mentioned the conflicting nature of which different stakeholders perceive certain benefits and Jacobs et al. (2018) adds that no single method of valuation is capable of covering the full range of values found in nature.

Favouring one method over another may effectively result in another stakeholder benefiting from the service provided by the green roof. This can create a problem in which values can be manipulated. Additionally, as Fu et al. (2011) indicated, the difference methodologies could also cause a overlap leading to double counting. In a society where sustainable development plays an increasingly important role, it is important that these values are handled appropriately. Jacobs et al. (2016) stated that it is becoming more and more apparent, from an applied standpoint, the need for combining various disciplines and methodologies to represent the varied set of values of nature. In which a growing number of researchers and professionals have the same aspiration to investigate how combinations of ecological, sociocultural, and economic valuation tools can aid in actual resource and land use decision-making. where various value dimensions (ecological, cultural, economic, self-interest, electoral, or ethical) are either explicitly or implicitly considered in the decision-making process.

In this, the author does not suggest that one approach should be considered the right one, rather the current information shows that there are multiple methods available, however, it lacks awareness of this difference and the information that can support the use of one of the methods within a given context.

3.7. MONETIZING AND ASSESSING DIVERSE BENEFITS FOR STAKEHOLDERS

Based on the research, an overview of the ways in which various benefits of green roofs can be translated into monetary terms emerges. As described earlier, it is not equally clear for each benefit how to calculate it methodologically. In addition, there are also benefits that are mutually exclusive. Nevertheless, the potential of a significant number of benefits is highlighted. It is important to note that these monetary values are directly related to specific stakeholders who benefit from them. In order to present this information in a clear and understandable way, a complete overview of all benefits, whether or not they can be monetised, whether they are mutually exclusive, and which stakeholders are involved, is presented here.

BENEFITS FOR PRIVATE STAKEHOLDERS

There are several benefits for the private party, such as cost reduction, revenue generation and an increase in property value. A concrete revenue stream can be generated through the provisioning services offered by the roof. The production of materials here can lead to annual revenues through the sale of the generated materials. Moreover, green roofs can offer cost-reducing benefits on both a one-off and continuous basis. For example, incentives lead to a reduction in sewerage and wastewater treatment costs, and the potential use of water for toilet flushing, irrigation and drinking water can reduce a building's water requirements. In addition, the improved thermal insulation results in a reduction in the building's energy requirements, providing benefits throughout the life of the building. There are two cost-reducing benefits that are incidental in nature: the avoidance of noise insulation costs due to the use of prevented ceiling panels and the avoidance of conventional roof costs due to the increased lifespan. Finally, several benefits contribute to increasing property value. Aspects such as sound insulation, aesthetics and recreational opportunities can have a positive impact on property value.

BENEFITS FOR PUBLIC STAKEHOLDERS

Several benefits can be specifically attributed to certain parties. Regarding revenue generation, in some cases the annual revenue can be allocated to rooftop farm volunteers. These provisioning services result in a continuous cash flow. Moreover, these volunteers derive pleasure from working at the rooftop farm, resulting in social benefits, satisfaction, relaxation, social contact and community building. A similar effect can be achieved by setting up the rooftop for recreation rather than just for material gain. This contributes to residents' comfort and quality of life.

There are also benefits in the form of avoided substitution costs, mainly related to government agencies, given their relation to social issues. This includes prevented costs for best management practices for storm water reduction, flood reduction plans and environmental plans to promote biodiversity. Similarly, there are benefits in the form of avoided impact costs, also related to government agencies. These benefits include prevented impact costs for transportation and treatment, and the reduction of pipe size during future renovations.

Moreover, there are several benefits that can benefit multiple stakeholders. Nearby, the potential of the rooftop farm is highlighted as an educational resource, which can be considered a cultural service. Furthermore, there are savings in impact costs for human health, environment, cultural heritage, economic activities and building damage through the reduction of flood risk. Health and environmental benefits also emerge as aspects of the UHEI, along with the reduction in cooling needs of buildings in the immediate vicinity. The occupants of these buildings not only experience a reduction in energy needs, but the reduction in noise levels also contributes to improved health. In addition, the aesthetic improvement can lead to an increase in property value, which in itself is also seen as an independent value in the surrounding area.

Improving air quality has an impact that is both partial local and external. This is achieved by direct air purification by vegetation locally and indirectly by reducing emissions from power plants at external locations. This improvement in air quality sits between local influence and broader impact. However, it is important to note that the boundaries of air quality improvement benefits are often blurred, as impacts can shift due to air currents. This can be considered an omni-directional benefit in changing directions. The beneficial effects of air quality improvement have direct impacts on people, climate and the natural environment through positive influences on issues such as health, agriculture, flooding, ecosystems and climate change.

Finally, we can also attribute some benefits to society as a whole. These benefits are not exclusive to a specific group and their translation into a monetary value cannot be specifically assigned to one stakeholder. These mainly include food security and the avoided external costs incurred in the production of goods. The latter factor has been specifically highlighted in the context of the overall comprehensiveness of this study.

In translating the improvement in air quality quantitatively, a method of expressing the value using emissions trading prices is also mentioned. With this method, however, it is not clear which party benefits from this value.

PART C | SYNTHESIS PHASE

The next part in this study is the synthesis phase. This chapter discusses the calculation methodology for green roofs and data acquisition on the Betsy Perk case study. In doing so, the knowledge from the design and analysis phase is tested and used as a foundation to make statements and highlight limitations of the current knowledge. Additional sources of information used include literature review, database consultation and contact with Intermaris and Betsy Perk manufacturers. Finally, the financial overview is generated for the public and private party that serves to reveal outcomes and constraints.

4

Case study Betsy Perk

Figure 4.1: Adjusted front view Betsy Perk, with green roof. Adjusted from Intermaris and Gemeente Hoorn (2022)

4.1. Introduction

This part of the research applies the information gathered from the extensive literature review to a case study of an actual situation in the Netherlands. This takes a step beyond merely discussing theoretical methods and gaps in the literature. This knowledge is tested against practice in order to identify any bottlenecks in the translation to practice. The ultimate goal is to integrate all the information gathered and carry out an economic analysis of the benefits and costs of installing a green roof during all life-cycle phases.

This chapter is dedicated to translating the theoretical methods into a concrete case study with real figures. It starts with an introduction of the case study and its context. It then presents the various costs and economic values for the case study, based on the methodologies discussed earlier. Finally, the figures are juxtaposed to provide conclusions and insights from this research. It is important to emphasise that the focus here is not solely on the numbers. Rather, the research focuses on understanding the process that led to these numbers and the meaning and value to be attached to them. The lessons learned from this research will focus on the interpretation of these figures, taking into account the gaps identified in the literature.

4.2. CASE STUDY - BETSY PERK, HOORN

Betsy Perk is an complex that combines independent living while benefiting from care services for the elderly. The complex is located in Hoorn, South Holland, the Netherlands. As part of the renovation plan, efforts will be made to make the complex more sustainable, including a switch from gas to a heat network. In addition, the building will be fitted with a green roof, green facade and exercise garden. However, the renovation is not just limited to improving sustainability and climate adaptation. The aim is also to create high-quality housing in close cooperation with residents. There is also a focus on creating pleasant public spaces, the garden and facilitating meetings and social activities. By focusing on the social value and close involvement of residents, the aim is to create an environment where people can "goed ouder worden" (Intermaris, 2022).

The renovation of this building is part of a large-scale renewal in the Kersenboogerd. The centre area of Kersenboogerd is envisaged as one of the most attractive residential districts in the Netherlands, characterised by its spacious layout with plenty of greenery right up to the front doors, in addition to having a variety of housing types and facilities. Currently, the municipality of Hoorn ranks 240th on the sustainability score for ecological capital (Telos, 2022). This renovation can give a positive boost to the ecological contribution in the region. The vision is that residents will once again be proud to live here, with social cohesion, community spirit and communal activities promoting livability (Inbo, 2020).

4.2.1. NUMBERS AND FIGURE

Location:	Hoorn
Neighbourhood:	Kersenboogerd
Housing corporation:	Intermaris
Type of building:	Residential care complex
Number of dwellings:	200
Vegetation area:	4112 m^2

4.2.2. ROOF PACKAGE

An extensive green roof was chosen for the installation of the green roof on Betsy Perk. Zinco's Light Green Roof with Floraset FS75 was used for this purpose, see figure 4.2. This type of green roof offers the possibility of using a large number of different sedum plants on a piece of roof. The green roof is very suitable because of its low load on the roof's load-bearing capacity. Moreover, the green roof requires minimal maintenance and the purchase costs are also relatively low (Zinco, 2020).

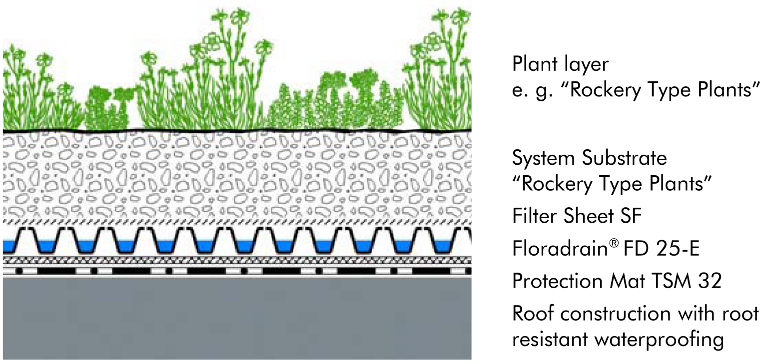

Figure 4.2: Roof section Betsy Perk - "Light Green Roof" with Floraset® FS 75. From Zinco (2020)

4.3. FULL LIFE CYCLE ECONOMIC COST ANALYSIS

4.3.1. COST PRICE

A clear picture emerged about the foreseeable purchase price of the green roof after consultation with Gijs Bakker. Intermaris received a detailed quotation that accurately specified materials, work to be carried out and the associated costs. Based on discussions with Mr Bakker, it has emerged that some of the work mentioned in the quotation is not directly necessary. This mainly concerns the cost of materials and the implementation of a specific layer whose further definition is deliberately not mentioned within this study.

Therefore, when determining the unit price for the materials and installation of the green roof, a conscious decision was made to exclude these costs, resulting in a downward correction of the total cost. This balancing process resulted in the estimated cost for the green roof ultimately being at a lower level. In order to avoid underestimating the cost, and still allow for possible additional expenditure to replace the eliminated cost item, a strategic choice was made to round up the estimated cost to the next multiple of ten. This approach allows a certain financial headroom so that any unforeseen expenses can be adequately addressed. In line with the aforementioned considerations and estimates, the cost per square metre of the green roof was finally set at €70.

4.3.2. MAINTENANCE

Through consultation with Gijs Bakker, a clear picture has emerged of the maintenance costs to be expected for Intermaris. In this, Intermaris received maintenance advice, indicating that it is recommended to carry out maintenance twice a year. This maintenance is essential to sustainably promote and ensure the healthy development of the sedum planting. Within this advice, a clear distinction is made between ensuring the growth guarantee during the first year, in which a carefully put together package of regular maintenance and a one-off replacement of any failed planting is implemented. In the subsequent years, the focus will be on routine maintenance to maintain the healthy and resilient growth of the sedum planting.

The financial cost of carrying out maintenance during the initial year has been calculated and amounts to about €2,25 per square metre. For subsequent years, the calculated cost for regular maintenance has been set at €1,75 per square metre.

4.3.3. ENVIRONMENTAL IMPACT

The Environmental Product Declaration results, as described according to EN 15804+A2, show the quantification of relative impacts in unit equivalents. Within this framework, a summary is compiled covering environmental impacts, resource use, output flows and waste categories, and additional impact categories. Often, resource use and output flows and waste categories are already included in the environmental impacts, and for this reason they are not further addressed within this study. For our specific study, the focus is on the environmental impacts and additional impact categories with the aim to convert these aspects into a monetary value, which is a crucial part of this study.

Figure 4.3 and 4.4 provide an overview of the impact by category and life-cycle stage. However, it is important to note that the EPD does not exactly match the roof installed on the Betsy Perk. The EPD used the 'Heater with lavender' type, rather than the sedum roof actually being installed. Nevertheless, this EPD can provide us with sufficient insight and a general impression, especially since the plants themselves have been excluded in the EPD. It is also important to note that the life-cycle modules maintenance (B2), operational energy use (B6) and operational water use (B7) are not declared, while the modules repair (B4), replacement (B5) and refurbishment (B5) are described as not relevant.

The information displayed shows that the additional impact categories, as shown in figure 4.4, have not been declared. Looking solely at the results of the most life-cycle phases for the impact categories, in figure 4.3, the results show that they have a negative impact, resulting in impacts on people, nature and resource use. In the figure, this is shown as positive values. Nevertheless, there are some points where certain impact categories actually show a positive contribution, indicated by negative values. This implies that during that specific phase, the impact, the use of materials or energy, is reduced in net terms. By adding up all the phases, it is possible to see for each impact category what the total contribution is, either positive or negative.

When looking at the quantitative values from the EPD, it is important to keep in mind what these values represent. These values represent a midpoint level and deal with assessments of environmental themes, such as climate change or acidification. A substance can have an impact on several impact categories (de Bruyn, 2017). It is therefore not a sound comparison to compare the quantitative values of air quality improvement with these values. This is because it involves a substance level and midpoints. The two are not directly equiv-

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT according to EN 15804+A2: 1 m² "Heather with Lavender" Green Roof System

Core Indicator	Unit	A1-A3	A4	A5	B1	C1	C2	C3	C4	D
GWP-total	[kg CO_2-Eq.]	-2.67E+0	4.76E-1	6.94E-1	9.94E-2	5.12E-2	2.38E-1	6.85E+0	1.15E+1	-3.66E-1
GWP-fossil	[kg CO_2-Eq.]	2.64E+0	4.74E-1	3.92E-1	9.65E-2	7.26E-2	2.37E-1	6.85E+0	2.17E+0	-3.66E-1
GWP-biogenic	[kg CO_2-Eq.]	-5.32E+0	1.90E-4	3.00E-1	2.82E-3	-2.36E-2	9.54E-5	-3.16E-4	9.31E+0	-9.54E-4
GWP-luluc	[kg CO_2-Eq.]	6.43E-3	1.99E-3	2.24E-3	7.05E-5	2.23E-3	9.93E-4	2.30E-4	4.53E-3	-3.29E-4
ODP	[kg CFC11-Eq.]	3.37E-14	1.16E-16	2.36E-16	6.16E-16	1.31E-16	5.82E-17	1.91E-15	6.81E-15	-4.94E-15
AP	[mol H^+-Eq.]	5.97E-3	3.94E-4	3.72E-4	6.94E-4	2.87E-4	1.97E-4	8.97E-4	1.31E-2	-5.90E-4
EP-freshwater	[kg PO_4-Eq.]	8.15E-6	1.03E-6	1.18E-6	2.26E-6	1.16E-6	5.17E-7	3.22E-7	4.58E-4	-6.06E-7
EP-marine	[kg N-Eq.]	2.43E-3	1.13E-4	7.42E-5	8.21E-5	4.94E-5	5.65E-5	2.41E-4	6.55E-3	-1.45E-4
EP-terrestrial	[mol N-Eq.]	2.68E-2	1.39E-3	1.09E-3	8.94E-4	7.01E-4	6.99E-4	4.01E-3	3.83E-2	-1.54E-3
POCP	[kg NMVOC-Eq.]	6.39E-3	3.16E-4	2.65E-4	2.58E-4	1.95E-4	1.58E-4	6.90E-4	1.33E-2	-4.10E-4
ADPE	[kg Sb-Eq.]	5.24E-7	3.94E-8	4.59E-8	1.91E-7	4.43E-8	1.97E-8	2.82E-8	1.75E-7	-7.23E-8
ADPF	[MJ]	4.74E+1	6.30E+0	7.24E+0	2.04E+0	7.08E+0	3.15E+0	2.56E+0	2.91E+1	-6.26E+0
WDP	[m³ world-Eq deprived]	1.44E-1	2.04E-3	6.74E-2	3.17E-3	2.30E-3	1.02E-3	7.09E-1	1.71E-1	-4.91E-2

Caption	GWP = Global warming potential; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential of land and water; EP = Eutrophication potential; POCP = Formation potential of tropospheric ozone photochemical oxidants; ADPE = Abiotic depletion potential for non-fossil resources; ADPF = Abiotic depletion potential for fossil resources; WDP = Water use

Figure 4.3: Result environmental impact categories according to EN 15804+A2. From ZinCo GmbH (2020)

RESULTS OF THE LCA – additional impact categories according to EN 15804+A2-optional: 1 m² "Heather with Lavender" Green Roof System

Indicator	Unit	A1-A3	A4	A5	B1	C1	C2	C3	C4	D
PM	[Disease Incidence]	ND	ND	ND	ND	ND	ND	ND	ND	ND
IR	[kBq U235-Eq.]	ND	ND	ND	ND	ND	ND	ND	ND	ND
ETP-fw	[CTUe]	ND	ND	ND	ND	ND	ND	ND	ND	ND
HTP-c	[CTUh]	ND	ND	ND	ND	ND	ND	ND	ND	ND
HTP-nc	[CTUh]	ND	ND	ND	ND	ND	ND	ND	ND	ND
SQP	[-]	ND	ND	ND	ND	ND	ND	ND	ND	ND

Caption	PM = Potential incidence of disease due to PM emissions; IR = Potential Human exposure efficiency relative to U235; ETP-fw = Potential comparative Toxic Unit for ecosystems; HTP-c = Potential comparative Toxic Unit for humans; HTP-nc = Potential comparative Toxic Unit for humans; SQP = Potential soil quality index

Figure 4.4: Result additional environmental impact categories according to EN 15804+A2. From ZinCo GmbH (2020)

alent in the calculation and may lead to an incorrect comparison. As a result, 1 kg of CO2 does not have to be equal to 1 kg of CO2 equivalent from the EPD.

The values derived from the environmental product declaration can be converted using the pricing per impact category as defined in section 2.7. This is done using the eco-cost which rely on the sum of marginal prevention costs. Due to missing data in the pricing or missing data in the environmental product declaration, the full environmental impact cannot be fully monetised. Nevertheless, it remains essential to present an indicative estimate of the possible results that can be expected, and for this reason the indicated outcome is still used. However, it cannot be stated with absolute certainty whether this indicative outcome underestimates or overestimates reality, as the impact, as mentioned earlier, can include both positive and negative values.

Visualising and comparing these values provides insight into the relative impact per impact category, as demonstrated in figure 4.5. A deeper analysis can use these results to identify moments and categories with significant impact, which can contribute to making the green roof production process more sustainable. For the purpose of this study, the distinction between the different impact categories was used to further distinguish "environmental impact". In doing so, no emphasis was placed on the relative impact per life stage, but rather looked at the total value per impact category.

The summation of the monetary value per impact category can be seen in table 4.1. By consulting this table, a more detailed understanding of the different aspects of the environmental impact emerges. Presenting these individual values aims to provide information while making the impact more specific and comprehensible. Based on the figures in this table, it can be concluded that the total environmental impact of the green roof package is equal to € 2,33.

4

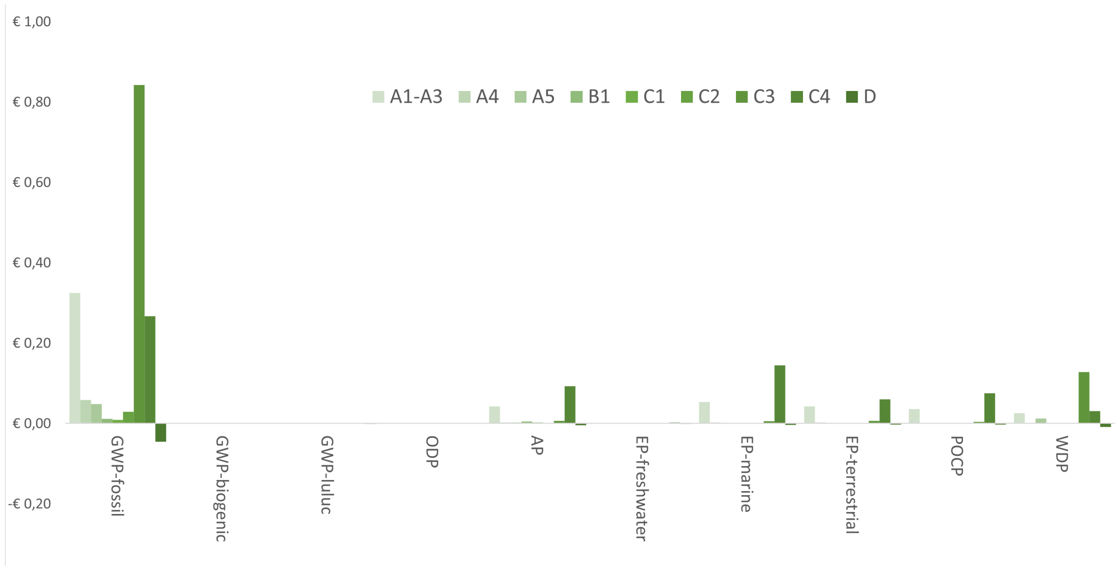

Figure 4.5: Visualising the monetary value of environmental impacts, broken down by impact category and life cycle stage.

Table 4.1: Monetization of environmental impact per category

Environmental impact category	Unit equivalent of measurement	Value
Global warming potential - fossil	[kg CO_2 -Eq,]	€ 1,55
Global warming potential - biogenic	[kg CO_2 -Eq,]	€ 0,00
Global warming potential - luluc	[kg CO_2 -Eq,]	€ 0,00
Depletion potential of the stratospheric ozone layer	[kg CFC_{11}-Eq,]	€ 0,00
Acidification potential of land and water	[mol H^+ -Eq,]	€ 0,15
Eutrophication potential - freshwater	[kg PO_4 -Eq,]	€ 0,00
Eutrophication potential - marine	[kg N-Eq,]	€ 0,21
Eutrophication potential - terrestrial	[mol N-Eq,]	€ 0,11
Formation potential of tropospheric ozone photo-chemical oxidants	[kg NMVOC-Eq,]	€ 0,12
Water use	[m^3 world-Eq deprived]	€ 0,19

4.4. FULL LIFE CYCLE ECONOMIC BENEFIT ANALYSIS

4.4.1. MATERIAL PRODUCTION

Green roofs have the potential to make contributions to the field of material production through rooftop farms. However, to make these contributions, additional conditions are required that are appropriate to the implementation of a rooftop farm. Necessarily, the benefits relevant to production are realised only through careful configuration of the green roof for this purpose. Unfortunately, Intermaris' green roof shows a lack of material production benefits, which can be attributed to the prevailing blueprint and layout characteristic of the vegetated roof structure. Intermaris' green roof was designed and implemented with the use of different species of sedum. Based on this, it must be concluded that there are no benefits for Intermaris within the category of provisioning services and, more specifically, material production.

4.4.2. THERMAL INSULATION

The addition of a green roof on an existing roof has the effect of increasing the thermal insulation of the green roof. This roof package results in less energy loss, giving a benefit to the user. The methodology for monetising this benefit is the same in all sources, the only difference is found in the quantification of the amount of energy savings. This can be done through hand calculations or through software. Whereby the accuracy of the software is higher because it includes more specific local and building characteristics that include the effect of evapotranspiration and absorption of thermal energy in the calculation. The quantified amount of energy saved based on either of the methods can be translated to a monetary value directly with the market price of energy or gas respectively.

The literature does not give detailed information or guidelines regarding the methodology to quantify of the energy savings. The calculation method chosen is based on an approximation as described in Center for Neighborhood Technology (2010), see equation D.8 and D.7. This choice is partly motivated because the literature review indicates a small influence of the evapotranspiration effect on the temperature compared to the insulating effect. On top of that the author believes that the use of software requires knowledge and skills to correctly operate the system and interpret the outcomes. Additionally, bounded by the time constraints involved in performing the calculation, the use of the basic calculation methods was substantiated.

The calculation of energy savings relies on the benefit created by the implementation of the green roof system. To perform this calculation, the additional insulation value is required. The calculation assumes that the roof system without a green roof has an R-value of 5,5 $[mK/W]$. This specific value was derived from communication with Gijs Bakker (Senior Project Leader/Buyer at Intermaris). The roof materials added as part of the vegetated roof add an average u-value of 0,632 $[W/m^2K]$ (Scharf and Zluwa, 2017). This means that with a u-value for a conventional roof equal to 0,182 $[W/m^2K]$ the u-value of a green roof becomes 0,141 $[W/m^2K]$, resulting in an improvement of Δ 0,041 $[W/m^2K]$. This slight improvement is also highlighted by van der Meulen (2019) and can be attributed to the strict requirements in place in the Netherlands.

4

The index for heating and cooling degree days is required to describe a building's thermal energy needs. These are calculated as average values based on data between 2018 and 2022 taken from Eurostat, the Statistical Office of the European Union. This uses a cooling degree day (CDD) of 26,6 and a heating degree day (HDD) of 2511,2 (Eurostat, 2023). Based on this, the total annual energy savings can be calculated in terms of energy loss. The total annual savings are 0,03 $[kWh/m^2]$ for cooling and 2,45 $[kWh/m^2]$ for heating.

Subsequently, it is possible to quantify this value using the energy price charged to customers. In de Kersenboomgaard, the area where Betsy Perk is located, a heat network is used to supply this energy. Consequently, a representative value for this type of electricity should be considered. Due to the significant impact of the war in Ukraine on energy prices in the Netherlands in the year 2022, it was decided to assume the 2021 energy price for district heating, i.e. €25,51 per GJ (Autoriteit Consument & Markt, 2023). Offsetting energy savings against this price and adjusted for inflation from 2021 with a factor of 1,13 results in a total monetary value for the reduced energy usage of €0,257/m2.

4.4.3. DIRECT MITIGATION OF AIR POLLUTION

Green roofs have a purifying effect on air, with the quantification of the uptake of air pollutants such as particulate matter (PM_{10}), sulphur dioxide (SO_2), nitrogen oxides (NO_2) and ozone (O_3) being possible using the calculation method described in Yang et al. (2008), see formula D.1. This method was chosen because of its ability to estimate the uptake potential of green roofs based using a formula that takes the concentration of that pollutant in the air and a given value for the dry deposition velocity of the particular air pollutant. This method is thus able to base the quantification based on recent and local data. For the quantification of carbon dioxide uptake (CO_2), previous data was used, as the previously mentioned calculation method does not have all the necessary data for CO_2. The choice was made to use the values as given in Getter et al. (2009). This is partly based on the range of values in this source and partly because of the lack of scientific evidence for other methods.

The local concentration values for PM_{10}, NO_2 and O_3 were taken from (Atlas Leefomgeving, 2023a). For PM_{10} and NO_2, the mean of the year 2020 was chosen as representative value due to the lack of more recent data. The relevant data source does not contain data related to SO_2. Therefore, the relevant data for SO_2 were obtained from Luchtmeetnet.nl (2023). As the specific information on SO_2 was not readily available at the site, average values from monitoring stations Amsterdam-Westerpark and Zaanstad-Hoogtij were used. For both monitoring stations, the values of the year 2022 were chosen as the most recent and representative values. Table 4.2 gives the values used for the quantification of the direct air pollution.

Regarding the O_3 concentration, the measurement time of 30-5-2023 at 12:40:00 was taken as the reference point for indicative purpose. However no monetary value was found for ozone and is therefore not included in further calculations.

For air pollution valuation, representative values were used for the different substances. The literature review highlights the potential use of the market value, the impact value or the use of the substitution costs, but lacks guidelines in which approach to use. In this study, from a societal perspective, we chose to use the impact value of the substances. This value was obtained from CE Delft's substance-level environmental pricing database. The value is based on damage to human health, ecosystem services, buildings, materials and infrastructure, resource availability and nuisance (CE Delft, 2023).

Table 4.2: Values used for the quantification of direct air pollution: particulate matter (PM_{10}), nitrogen oxides (NO_2), Ozone (O_3), sulphur dioxide (SO_2) and carbon dioxide (CO_2)

Air pollutant	**Unit**	$\mathbf{PM_{10}}$	$\mathbf{NO_2}$	$\mathbf{O_3}$	$\mathbf{SO_2}$	$\mathbf{CO_2}$
Concentration	$[\mu g/m^3]$	15,35	12,38	69	0,805	-
Pollutant flux min	$[g/m^2/y]$	0,472	0,152	0,212	0,002	594,54
Pollutant flux max	$[g/m^2/y]$	0,897	1,485	8,914	0,097	646,56

The use of environmental prices from CE-Delft is recommended by the Tweede Kamer for cost-benefit analyses and is also used to calculate external costs. These prices are presented as lower bound, central value and upper bound, see table 4.3. The lower bound and upper bound are mainly used to calculate the effects of policy measures, including government policies. For this analysis, the central value was selected as recommended for general users and specifically recommended for business cases (CE Delft, 2023).

Table 4.3: Price of direct air pollution in €/kg: particulate matter (PM_{10}), nitrogen oxides (NO_2), sulphur dioxide (SO_2) and carbon dioxide (CO_2). Values from CE Delft (2023)

€/kg	$\mathbf{PM_{10}}$	$\mathbf{NO_2}$	$\mathbf{SO_2}$	$\mathbf{CO_2}$
Low	41,4	12,4	33,7	0,05
Central	69,3	20,8	57,5	0,13
High	97,9	29,7	83,1	0,16

Using the formula from Yang et al. (2008), together with the values for quantification and the monetary values per substance, the prevented impact value of air pollution can be calculated. For the calculation, we chose to use the average value for quantification. The full overview per substance of the quantification, price and monetary benefits is shown in table 4.4.

Table 4.4: Overview direct mitigation of air pollution; quantification, unit price and monetary benefit

Direct mitigation of air pollution	**min [g/m2/y]**	**max [g/m2/y]**	**Price [€/kg]**	**Value [€]**
PM_{10}	0,472	0,897	69,30	0,047
NO_2	0,152	1,485	20,80	0,017
SO_2	0,002	0,097	57,50	0,003
CO_2	594,540	616,560	0,13	0,079

4.4.4. INDIRECT AVOIDANCE OF AIR POLLUTION

Likewise, a statement can be made regarding the indirect reduction of atmospheric pollutant emissions. The indirect quantity can be determined using the specific emission factor of the electricity grid in the Netherlands. Nevertheless, careful consideration should be given to the observation that in the Intermaris situation, the residences in Kersenboogerd, the residential area in which Betsy Perk is located, are connected to a thermal network whose renewable energy source is still unrevealed. To propel this study forward, values for geothermal energy have been observed. This distinction carries weight as the use of geothermal energy results in a lower need for primary energy to provide the same heating and cooling performance. For this application, the Coefficient of Performance (COP) is used and represents the ratio between the amount of energy supplied and the resulting amount of energy obtained. In this case study, the COP is set at 3,7 (Lensin et al., 2021).

As strikingly explained in the literature reviewed, considerable challenges are encountered in locating specific emission factors. While the literature only addresses the complexities associated with obtaining emission factors for O_3 and PM_x, a gap can also be observed in the available data for the Netherlands with regard to NO_x and SO_x. Taking this into account, the decision was taken to provide an indicative estimate based on previous literature sources. The data derived from the work of Center for Neighborhood Technology (2010) were retained as a conservative approach, with 0,87 $[kg/Mwh]$ for NO_x and 2,39 $[kg/Mwh]$ for SO_x, respectively. In this context, it should be emphasised that these numerical values should not be considered directly representative of the Dutch electricity grid. Nevertheless, these values provide a useful indication of the order of magnitude. As regards the specific emission factor in the Netherlands for carbon dioxide (CO_2), a report by the European Commission shows that it was set at 0,337 [kg/kwh] in the year 2020 (Bastos et al., 2020).

By using the available information regarding the specific emission factors for individual substances and the COP of the thermal network , through the energy savings of 2,45 [kwh/m^2] achieved as a result of the thermal insulation measures taken, a calculation method can be employed to determine the degree of emissions savings. This results in a decrease of $2,25*10^{-1}$ kg of CO_2, $5,82*10^{-4}$ kg of NO_2 and $1,60*10^{-3}$ kg of SO_2. These quantities can then be converted to a monetary value using the conversion method based on the impact value from CE-Delft as described earlier. The monetary values are expressed using the data from table 4.3. For completeness and overview, the quantification, price and value are shown in table 4.5.

Table 4.5: Overview indirect mitigation of air pollution

Indirect mitigation of air pollution	**Avoided pollutant [kg]**	**Price [€/kg]**	**Value [€]**
NO_2	$5,82*10^{-4}$	20,80	0,012
SO_2	$1,60*10^{-3}$	57,50	0,092
CO_2	$2,25*10^{-1}$	0,13	0,029

4.4.5. STORM WATER MANAGEMENT

Green roofs play a crucial role in preventing water from draining into the sewer system. This function is enabled by the ability of green roofs to retain water, after which this water is either absorbed by the vegetation, evaporates, or after some delay still runs off. Several approaches exist within the literature review for systematically mapping these benefits and their economic value. Herein emerges a lack of information and guidelines that can guide the decision for a specific approach. The "substitution method" can be employed, analysing savings on similar projects with a similar purpose. On the other hand, the "impact method" can be employed, looking at the impact of the intervention. For the current study, we opted to use the "impact method", based on available information and obstacles in defining the comparison within the "substitution method". Based on the literature review, two values can be generated for the impact method.

The amount of water retained can be quantified using the runoff coefficient. For our particular case, we found the runoff coefficient in the environmental product declaration document equal to 0,4. This means that, in theory, 60% of the water is retained. To calculate the annual amount of water retained, we use the average precipitation in the Netherlands for the period 1991-2020, which is 851 mm according to KNMI (2022). This means that in our case, the green roof can retain about 510.6 mm of water annually, diverting a significant amount of water from the sewer system. This helps relieves the sewer system during periods of rainfall.

4.4.5.1. TRANSPORT AND MAINTENANCE COST

To determine the impact of the green roof on reducing costs for transporting and treating water runoff, it is crucial to evaluate the costs associated with the prevented water runoff. This should use the marginal costs associated with this reduction. Based on the research conducted, it appears that obtaining specific and recent values for these factors can be difficult. It was therefore chosen to rely on somewhat dated data to still provide a rough estimate. These values will later be corrected for inflation to adjust them to the current value. Within this framework, there are costs associated with preventing the transport of rainwater through sewers, set at € 0,10 m^3 (van Moppes and Klooster, 2008). For energy consumption in wastewater treatment plants, this value is set at € 0,03 m^3 (Korving et al., 2015).

The estimated savings on transportation costs can be converted to a monetary value for this particular situation, based on the volume of storm water prevented. Similarly, the estimated savings on treatment costs can be converted to a monetary value based on the same volume. These values were then adjusted for inflation based on 2008 and 2015 figures, respectively, with factors of 1,394 and 1,222. The economic value of preventing storm water runoff through the sewer system is estimated at €0,071 per square metre of roof area, and the economic value of energy savings in sewage treatment plants for treatment is estimated at €0,019 per square metre of roof area.

4.4.5.2. INCENTIVE

The literature shows that some municipalities offer an incentive in the form of a reduction in the municipal rainwater charge when owners demonstrate that they achieve reduced discharge to the sewer. In this way, owners can share in the benefits enjoyed by the municipality. Following e-mail correspondence with the municipality of Hoorn, it was found that it does not operate such a scheme. On this basis, no economic value can be charged to the Betsy Perk on this aspect.

4.4.6. NOISE REDUCTION

Green roofs also contribute substantially to reducing noise levels both inside and around a building. This phenomenon has been a topic covered in the reviewed literature, with a methodology emerging that examines the impact of noise reduction on property valuation. This particular metric is referred to as the Noise Sensitivity Depreciation Index (NSDI), which quantifies the percentage loss in property value for each incremental increase of one decibel in noise levels (Udo et al., 2006).

The applicability of this methodology can also be used within the case study examined. In this context, the noise level around the Betsy Perk building shows a measured value of 52 dB (Atlas Leefomgeving, 2023b). This initial noise level can have a substantial impact on the property's depreciation when using the values as established in Udo et al. (2006). However, for this particular study, we decided to rely on the more recent findings presented in Ahlfeldt et al. (2019) and Kuehnel and Moeckel (2020), which state a NSDI of 0,4. These more recent studies show a lower NSDI, which leads to a result that is being characterised by smaller values, which fits a conservative approach.

The property price was determined on the basis of an estimate arrived at in consultation with Gijs Bakker. The outcome of this estimation resulted in an estimated property value of EUR 50 million. This valuation is based on an approximation taking into account the number of apartments and the estimated price of each apartment, which is expected to be around €250,000. When calculating the specific value resulting from noise reduction, the focus has been on the top floor of the building. This was done to provide a realistic assessment of the positive impact of noise reduction on the property value. In line with this approach, the total building area for this floor is 4112 square metres. Based on these calculations, a value of €2426 per square metre ultimately results.

Using the Noise Sensitivity Depreciation Index of 0.4 mentioned above and the property value per square metre, the economic value of noise reduction due to the installation of a green roof can now be evaluated. Here, it is assumed that a green roof produces a measurable improvement in indoor noise levels. Although no specific performance statement is available in the Environmental Product Declaration, it was decided to draw data from previous literature. An improvement of 3 decibels in the indoor noise level is assumed in the calculations. The choice of this value is a conservative approach, as the literature review has not provided an unambiguous picture of the exact extent of this benefit. To date, the literature has not reached a clear consensus on the actual magnitude of noise level improvement due to green roof installations. This approach ensures a careful and cautious assessment of the potential benefit to be gained from noise reduction using green roofs.

Based on the price per square metre of the roof and the increase in property value calculated from the NSDI, the increase in value per square metre due to the green roof can be calculated. This will increase the property value by 1,2%. This results in an amount of €29,11 per square metre.

4.4.7. LONGEVITY

The lifespan of the green roof can also be considered a separate benefit. Because a green roof has a longer lifespan compared to a conventional roof, it saves costs that would otherwise be spent on replacing the conventional roof. In the EPD provided by Zinco, the reference lifetime of the roof package is stated as 40 years, based on data from the German federal institute Bundesinstitut für Bau-, Stadt- und Raumforschung. This value was then compared with the service life used in the research articles from the literature review, as described in section D.9. Based on the similarities with previous studies, it was decided to use this value as a suitable indication. The cost of the conventional roof is set at € 46,00 per square metre (Homedeal, 2023). The calculation assumes that there is 1 avoided substitution cost in the first year, and an avoided substitution cost is included at half the life of the green roof, which is equal to about the service life of a conventional roof.

4.5. OVERVIEW

Based on the information obtained from the literature review, a statement was made about the expected economic values of the Betsy Perk case study. In addition, in consultation with Mr Bakker, an estimate of the cost of the purchase price and maintenance of the green roof was obtained. Lastly, the information from Zinco's EPD was passed on to the life-cycle environmental impact of the product used for the green roof. These can all be combined to provide an insight into the private and public costs and values of installing a green roof in this specific case. This overview of values can then provide us with a statement about the current state of the literature in combination with the case study.

As a first step in preparing the cost-benefit analysis, it is important to define the timeframe. This is the time window in which the costs and monetary benefits are included within the analysis. Based on the reference lifetime provided in the EPD, it was decided to use this value of 40 years as a suitable indication time frame in the CBA.

The price of time is taken into account in the real discount rate and is separately calculated for both private and public parties, because of differences in the value of time. Inflation is calculated as the average of the years 2003-2022 based on data from Triami Media (2022), and is 2,21%. For the discount rate of the public money flows, a value of 3% was used, based on the standard discount rate in the Netherlands (Nesticò et al., 2023). Leading to a real discount rate of 0,77%. A different discount rate is used for the private cash flows. The value of the private discount rate was found in the Annual report 2022 - bestuursverslag en jaarrekening from Intermaris and had a value of 5,9% (Intermaris, 2023). This leading to a real discount rate of 3,61% for the private party.

4.5.1. PRIVATE OVERVIEW

The first thing to consider is the economic values and costs for the private party, which in this case is considered the owner of the property. The costs come from the purchase price and maintenance costs, while the economic value come from the reduction of the building's energy needs, the increase in property value and the saved costs of a conventional roof, both in the initial phase and when the conventional roof is replaced. Since some of the monetary values are based on data from previous years, all revenues previously calculated have been adjusted for inflation to the year 2023. All future monetary values arising from energy savings and maintenance costs have been back-calculated to this base year based on the real discount rate of 3,61%. This results in the summary of costs and revenues shown in table 4.6.

Table 4.6: An overview of the discounted costs and benefits for the private party

Overview discounted private costs and benefits	**€/m^2**	**€**
Energy savings - thermal insulation	€ 5,54	€ 22.772,89
Property value increase - sound pressure level	€ 29,11	€ 119.708,88
Longevity - purchase price & replacement costs	€ 68,06	€ 279.843,85
Total value private benefits	€ 102,71	€ 422.325,61
Cost price	€ 70,00	€ 287.840,00
Maintenance cost	€ 38,53	€ 158.430,55
Total value private costs	€ 108,53	€ 446.270,55

According to the current calculation of the NPV, the total costs for the private party do not outweigh the economic values obtained over the lifetime of the green roof. Most of the value, € 68,06, come from the prevented cost of a conventional roof and its replacement. In addition, the increase in property value also contributes to the revenue. The revenues from energy savings are relatively small compared to these factors. The costs used result in a total value of €108,53 according to the calculation.

According to the current NPV calculation, it becomes clear that over the entire lifetime of the green roof, the cumulative costs for the private party do not outweigh the economic benefits generated. Most of these benefits, concretely €102,71, are from the avoided costs, € 68,06, from avoiding the expenses of a traditional roof and its associated replacement. Furthermore, the increase in property value also contributes substantially to the overall revenue. Revenues from energy savings are a relatively modest fraction compared to these influential factors. The calculated costs result in an estimated combined value of €108,53, as shown in the calculation done. Ultimately, the addition of the green roof results in a negative result of €23,944.94 for the private investor.

4.5.2. Public overview

Secondly, we can look at the values and costs to the public party, which in this case is considered society as a whole, or all values and costs minus those of the private party. The costs come from the environmental product declaration and have impacts in several areas. The values come from the reduction in energy requirements for sewage treatment, the reduction in transport costs for sewage and the direct and indirect improvement in air quality. Again, some of the monetary values are based on data from previous years, therefore all revenues previously calculated have been adjusted for inflation to the year 2023. Since all economic values to society are realised over the entire lifetime of the green roof, these have been back-calculated to the base year 2023 using the real discount rate of 0,77%. This results in the summary of costs and revenues shown in table 4.7.

Table 4.7: An overview of the discounted costs and benefits for the public party

Overview discounted public costs and benefits	**€/m^2**	**€**
Sewage treatment plant energy savings	€ 0,66	€ 2.714,35
Transport energy savings	€ 2,51	€ 10.321,34
Direct improvement of air quality	€ 5,82	€ 23.930,16
Indirect improvement of air quality	€ 5,31	€ 21.840,37
Total value public benefits	€ 14,30	€ 58.806,22
Global warming potential - fossil	€ 1,55	€ 6.355,63
Global warming potential - biogenic	€ 0,00	€ 0,00
Global warming potential - luluc	€ 0,00	€ 9,30
Depletion potential of the stratospheric ozone layer	€ 0,00	€ 0,00
Acidification potential of land and water	€ 0,15	€ 620,72
Eutrophication potential - freshwater	€ 0,00	€ 9,70
Eutrophication potential - marine	€ 0,21	€ 859,66
Eutrophication potential - terrestrial	€ 0,11	€ 470,02
Formation potential of tropospheric ozone photochemical oxidants	€ 0,12	€ 493,39
Water use	€ 0,19	€ 777,78
Total value public costs	€ 2,33	€ 9.596,20

Compared to the interests of the private party, the implementation of a green roof appears to be beneficial to the wider society. Current calculations show that the benefits to the public sector over the lifetime of the green roof far exceed the costs. In total, the benefits to society amount to €12,24, counterbalanced by a social cost of €2,33. However, it is important to clarify this distinction. For example, the realised savings of €10.321,34 on transport costs for the municipality (Ministerie van Infrastructuur en Waterstaat, 2023), as well as the saved costs of €2.714,35 for treatment processes by het Waterschap (STOWa, 2023). The remaining costs and benefits contribute to the overall society, benefiting both individual entities and the wider community as a whole.

4.6. Reflection and interpretation of the case study

Due to the lack of guidelines in the literature, we chose to approach this study from a societal perspective. Here, an emphasis has been placed on establishing values that are directly related to society as a whole. This is reflected in the choice of pricing prevented air emissions.

First of all, the case study shows that even with the available methodological data, it is not always feasible to express ecosystem services in a monetary value. A major obstacle here is the lack of accurate, site-specific and recent data. The study highlights that this problem stems partly from the fragmentation of information. Because of the different disciplines and stakeholders involved, this information is not always readily accessible. This lack of data is evident in both the EPD and the data required to calculate benefits.

In light of the limitations and assumptions used, these data can be interpreted further. This implies taking a broader view when all costs and benefits are taken together. This overview shows that a positive value emerges. This means that by not limiting the scope to just the private investor, a picture emerges of an economically profitable green roof, with a value of €6.14 per square metre, seen from the perspective of all stakeholders.

To accurately evaluate these values and examine the sensitivity and degree of influence of various parameters on these values a sensitivity analysis can be performed. As an illustration of this approach, Figure 4.6 presents an example analysis that examines the impact of both private and social discount rates on the NPV of both private and public values combined.

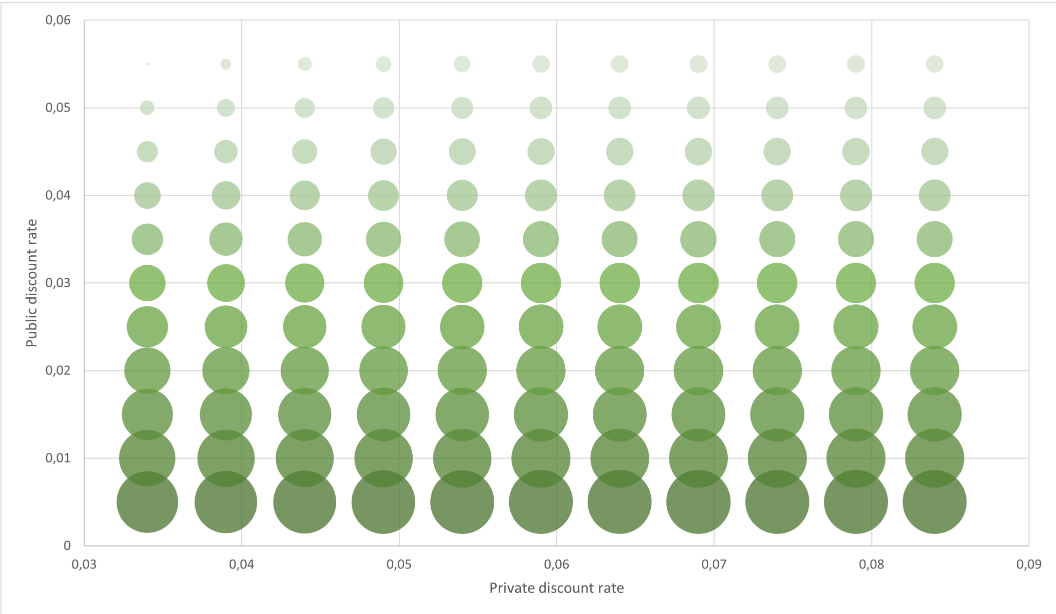

Figure 4.6: Total relative net present value indicated by the size of the dot for multiple discount rate combinations

Nevertheless, the bottleneck that arises is that, due to the observed lack of information in this study, conducting such analyses is unable to describe the full systemic sensitivity. It follows that this type of analysis could produce distorted conclusions, and a wrong indication towards stakeholders. At the current stage, conducting a sensitivity analysis is therefore discouraged, given that the already present lack of information introduces sufficient uncertainty in the final answer by itself, which a sensitivity analysis could not clear up. Especially considering that, in addition to the non economic valuated benefits of the green roof, there are also unmonetised costs. These unmonetised costs include not only environmental impacts, for which data are lacking for both quantification and valuation, but also the social costs cited earlier in the study. Because of this reason no sensitivity analysis will be performed.

The final result illustrates the importance of additional research to fill in the gaps in the literature. It also shows the value of cooperation and additionally shows the potential of green roofs for companies that want to profile themselves as active in "sustainable development".

Part D | Evaluation phase

The evaluation phase of the research comes next. The theoretical findings will be addressed in the final section, in addition to the flaws in the literature as it stands right now, their implications for the case study that was successfully carried out, and general conclusions. At the end of the study, recommendations have been provided for expanding upon and positioning this research into practice.

5

Discussion

This chapter will include a comprehensive discussion of the study conducted, along with an exploration of its associated limitations. It starts by outlining the interpretation of the results, while also introducing the perspectives of the study. Next, the limiting factors applicable to this study, together with the corresponding literature analysis, are discussed.

5.1. Discussion of the results

This research intends to positively contribute towards the position of green roofs as an alternative to conventional roofs within the boundaries of sustainable development. Thereby, the goal was that by providing a comprehensive overview of the cost benefit analysis of a green roof a fully informed, fair and transparent choice of this alternative could be made. This was accompanied by the objective of for the first time systematically analysing the current methodology in the literature and presenting it as an overview of prevailing views and perspectives. After going through the entire research, it can be concluded that an overview of all the costs and benefits of a green roof has been acquired, which entails not only the current pool of information regarding the ecosystem services of a green roof obtained from cost-benefit analysis, but also includes the environmental costs of a green roof. Furthermore, the information obtained from within the literature study has been proven applicable to a case study and shows the possibility to integrate green roof systems as an alternative to conventional roofs.

Implementing environmental costs into the analysis

A crucial aspect of this study involved refining the existing literature related to cost-benefit analysis. On the one hand, this study showed that methods are available within the literature to integrate external costs of materials into analyses. Specifically, the study illustrates that through environmental life cycle assessment, impacts can be assessed in 19 impact categories according to the EN15804 + A2 (2019). Ultimately, environmental impact costs can be embedded in an economic analytical framework through environmental cost-benefit analysis. This choice is motivated by its applicability as a stand-alone project evaluation. Nevertheless, it should be emphasised that there are also social external costs that can be mapped by social life cycle assessment. However, social values are mainly quantitative in nature and therefore this method is still in the early stages of continuous development. Due to the still early nature of this approach, it has not been taken into account in this study.

The environmental impact categories can then be monetised. This study indicates that several methods are available for this monetary translation, leading to divergent results due to the diversity of methodological approaches and the insufficient level of in-depth research. As a result, the methodology for this conversion is also still at an evaluative stage and continues to evolve constantly. Nevertheless, based on pre-existing literature, an indication of the values of these impact categories can be provided. In addition, the study highlights that reports are available from practitioners in the form of environmental product declarations that present these impacts quantitatively per product. This highlights the potential of using such environmental product statements in cost-benefit analyses, thus conveying a quantitative list of environmental impacts in a manner accessible to a wider audience. Contact with Zinco the owner of the environmental product declaration, shows that the environmental product declaration still considers some privacy aspects in terms of competitive advantage, resulting in the calculation of this research with the most comparable report available. However, in the future, its availability can also be used as a positive communication tool, allowing for a more open stream of information.

Ecosystem services literature review

The thorough literature review, implemented with a systematic approach, illustrates that there are still gaps in the current knowledge in the literature with regard to conducting a cost-benefit analysis for green roofs. The collected results show that if all methods from the literature were adopted without independent consideration, a catalogue of 13 ecosystem services would emerge, often accompanied by one and sometimes several benefits that can be converted to economic values. Based on these findings, it seems prima facie feasible to make informed statements, especially given that some approaches are implemented in multiple studies.

Nevertheless, when these approaches are thoroughly evaluated, their inherent shortcomings and assumptions are brought to the surface. Some methods are thoughtlessly adopted by different literary works, resulting in a compounding set of inaccuracies that may be considered valid over time. This study, by bringing together these various publications, shows that several approaches can be found in the literature and that a lack of knowledge regarding the correct approach can lead to the incorporation of mutually exclusive advantages. This in turn results in incorrect insights and outcomes. This is particularly noticeable in approaches such as the avoided cost method and the substitution cost method. Furthermore, this study reveals that there is also a lack of awareness about this issue, and also illustrates a lack of available guidelines for using these various approaches.

Ultimately, the critical approach of this study shows that within the 13 ecosystems, only for 6 (material production, air quality, noise and thermal insulation, storm water management and longevity) is a solid methodology available to translate services into benefits and then into economic value. In doing so, it is notable that there is especially a lack of cause-and-effect relationships that can adequately underpin these methods; current methods often rest on assumptions that do not fully directly represent the interrelationships. The research also shows that when these relationships are known, the right data is not always included due to availability. Parameters that particularly affect this are related to the specific case study, such as the location and composition of the green roof. However, discussing the availability of such information within the broader literature is beyond the scope of this study. Ultimately, the study shows that from a broader perspective, there are several co-existing benefits for some ecosystem services. In this, it is important to note that the ecosystem services as they emerge now, as well as the missing information, are a result of the scope of the study having focused on the scale of a single building. Therefore, care should be taken especially with the gaps related to ecosystem services that work beyond the scale of the study, such as, for example, the urban heat island effect, urban noise reduction, but also possibly biodiversity and others.

Insights and Considerations from the Betsy Perk Case Study: Ecosystem Services and Financial Assessment

Ultimately, the extensive effort of this research has resulted in gaining insights related to the Betsy Perk case study. The research highlights that not all ecosystem services mentioned in the literature are directly applicable to the case study, and that the specific design of this case does not allow for the provisioning service to be offered for material production. This highlights the importance of careful case-specific considerations. Nevertheless, the methodology derived from the literature appears to be relevant for other services. However, it is essential to note that a lack of relevant data has been demonstrated through the case study, resulting in the use of outdated data or data that is not directly representative of the site. This highlights the need for further research efforts and the provision of more accurate data for specific locations in addition to further refining methodologies. However, the case study does show that current data can lead to an understanding of a real situation in a systematic way.

The resulting financial overview presents the costs and benefits of a green roof for both public and private stakeholders. Even though these values give of the representation that the implementation of a green roof is beneficial for society, while it is not for the project developer. It is essential to note here that these figures represent what can currently be expressed within the existing knowledge base. In doing so, there is a large contrast between all potential like benefits and those that can actually be monetised. These figures should therefore not be considered in isolation, but should be understood in light of the potential of all ecosystem services. In addition, a the deeper refinement of external costs could also increase the costs for society associated with the implementation of the green roof. In this way, the current monetary values and the substantiation function as an important initial step to make the impacts of a green roof more accessible on a project basis. However, care should be taken when interpreting these values.

5.2. LIMITATION OF THE RESEARCH FRAMEWORK

In formulating the current research framework, specific choices and assumptions were made regarding the design and delineation of the study. All these choices affect the final results of the literature review. Therefore, it is essential to offer critical reflection on the choices made in order to reveal any limitations of the study. Moreover, these limitations play an important role in delineating the appropriate scope of the study. This chapter reflects in depth on the choices made regarding the selected literature and discusses their implications for the final results.

- Limitations and considerations in a multi-faceted study
  A major limitation of this research is its complex design, which interfaces with social, ecological and economic aspects, linking to both academic and practical fields. Moreover, various ecosystem services and external costs converge, resulting in a wide range of knowledge areas and fields of expertise coming together in this study. In doing so, an attempt has been made to operate cautiously by not drawing hasty conclusions based on the information already presented. The author is aware that preliminary statements can lead to distorted images, and acknowledges that not every section has been worked out in detail, which has at times limited the study's depth of treatment. Nevertheless, this does not affect the quality of the research, as it is precisely the merging of these different expertises that is essential. The limitations arise mainly because the study is not always able to draw concluding conclusions; instead, it often indicates that further research into various aspects is necessary.

- Unknown unknowns ecosystem services and benefits
  A possible limitation of the study arises from the combination of the identified ecosystem services and the sources used. Both the classification of ecosystem services and sources are based on Teotónio et al. (2021). This means that the ecosystem services categorisation are based on the same sources used to interpret these services. This may create 'unknown unknowns' within this study. Ecosystem services that were not included in the original study will also not be included when completing the ecosystem services. As a result, no addition can be made to the categorisation, nor can this categorisation be tested. However the fact that this study created a foundation of solid information allows future research to build on this.

- Complexities in translating benefits to the building scale
  The focus of this study on the building scale level provides a clear framework. Nevertheless, the literature review shows that the scale of different benefits is often mixed up. There are often attempts in the literature to translate the benefits at a larger scale back to the building scale. This can lead to debate, but this issue has been raised earlier in the study. However, it does mean that because the different scales sometimes do not have a clear delineation, methods emerge that are not fully suitable for the building scale level. Based on the available literature, it can be assumed that little information on these methods is available. However, this stems from the fact that researching these benefits is not the core of this chapter. When reading about these benefits, it should therefore be borne in mind that the information described here is not a complete representation of all available information when other scales are studied.

6
Conclusion

The research contributes to the provision of nature within cities through the use of green roofs as an alternative to conventional roofs by systematically identifying all costs and benefits associated with green roof implementation. The research objective is to indicate the current state of the literature and evaluate the currently used methods. The main research question is as follows:

What are the private and public costs and benefits of applying a green roof during all life cycle stages?

The primary research question is broken down into four sub-research questions in order to provide a structured answer to this question. First, a better understanding of the environmental impact of the production is obtained. After that, the current state of the literature is studied based on a systematic analysis. Once the current state of the literature was mapped, it was assessed whether the current state of the literature provided the information to determine the benefits for the case study. The case study was used as a proof of concept of the outcome of the current state of the literature in which the benefits were included together with the environmental costs to make a cost/benefit analysis. This chapter provides answers to the sub-questions first, before it proceeds to answer the main research question:

6.1. Sub-research questions

What is the environmental impact of the production of a green roof, and how can these be expressed in monetary terms?

In today's society, the environmental impact of products occupies an increasingly prominent position. To answer this sub-research question, an analysis of the existing methods in the literature aimed at assessing the external costs of green roofs was carried out. Based on this analysis, a methodology capable of quantitatively measuring the impact of a green roof was found.

On this basis, an attempt was made to examine the external costs that arise throughout the life cycle of green roofs. In the literature, the Environmental Life Cycle Assessment (E-LCA) is put forward as a method to assess the ecological impact of materials. The E-LCA is a structured approach that focuses on measuring the ecological impact of materials. As a result, quantitative insight is gained into how materials affect the environment throughout their life cycle. The outcome of the E-LCA is a quantification of the environmental impact throughout the life cycle, in accordance with ISO 14040. The EN15804 + A2 (2019) standard for environmental product declarations follows the methodology for LCA and distinguishes between 19 different impact categories, which can be subdivided according to their impact on human health, ecosystems or natural resource depletion.

In addition, the Social Life Cycle Assessment (S-LCA) is mentioned as a method to evaluate the social impact of materials, incorporating aspects such as working conditions, social justice and community involvement. The incorporation of the S-LCA is the next step towards pursuing sustainable development, by incorporating the cost aspect of each of the three representing pillars. Future research should focus on the incorporation, since this research is bounded by the fact that the S-LCA is still in a development phase.

The study found that the location is of significant impact in the choice of the methodology translating the environmental impact to an economic value, hence it was chosen do so using the Ecocost method of Vogtländer. In this, the marginal prevention costs of harmful emissions are linked to the emissions themselves. This approach has the advantage that calculations are simpler and more transparent, and results can be expressed in concrete measures and monetary values. The system is particularly focused on decision-making processes and provides a valuable toolkit for stakeholders.

The environmental product declaration EN-15804+A2 is the determination method designed by the European Union to determine the environmental impact of construction materials and products on sustainability according to the E-LCA. The environmental product declaration was obtained from Zinco. The availability of such reports on the market shows that there is increasing attention to this aspect from the market. This facilitates the integration of such reports within an E-LCA framework.

What are the private benefits of the ecosystem service of a green roof, and how can these benefits be expressed in monetary terms?

What are the benefits for society during the use stage of the ecosystem services of a green roof, and how can these benefits be expressed in monetary terms?

To answer the next sub-research questions, a thorough analysis of the existing methods in the literature aimed at assessing the ecosystem services and benefits was carried out. This analysis started with making a systematic analysis of the various steps used within the ecosystem cascade framework so that, in this way, a structured subdivision of the methods is created. Next, a list of 20 peer reviewed literary papers was determined based on filter criteria. This eventually formed the basis for formulating the framework for the analysis. The analysis focused on the identifying the methodologies that were used within the literature to translate the ecosystem services into benefits and next into a monetary value.

Through systematic analysis, this study examined 13 ecosystem services. The analysis showed that similar approaches are often used in the literature to quantify ecosystem services. However, this study showed that there are also ecosystem services that lead to different interpretations, especially in the methodology used to quantify values. The thorough research has tried to juxtapose these assumptions, focusing on the parameters that influence the value. Moreover, there is considerable variation in values, with location and local climate cited as among the most common factors. Additionally, the analysis shows that many assumptions are made in quantification, which reduces the accuracy of the values. On this basis, the value of this study is that it revealed the differences in methodology and the various assumptions that are made. Follow-up research requires experts in the various disciplines to carry out in-depth reflections in order to contribute to the advancement of these computational methods.

To monetise the quantitative benefits, this study has consistently looked at the valuation methods. In it, this study has shown that there is sometimes no consensus for the approach in the current literature and different sources use different valuation methods. A recurring problem is the distinction between the avoided impact cost method and the avoided mitigation cost method. The former method focuses on avoiding damage, while the latter looks at the cost savings from avoiding damage. In doing so, the study raises the issue of ambiguity about the methods. Because the two methods have different approaches, this often ensures that a different stakeholder benefits. In itself, this does not immediately pose a problem, but it is often the case that the benefits are mutually exclusive and therefore a choice has to be made for one of the two benefits. In doing so, the study identifies the importance of better guidelines and more research that can help in substantiating and making choices.

After completing the literature review, it can be concluded that there are several benefits for private parties, such as cost reduction, revenue generation and an increase in property value. However, due to methodological limitations, not all benefits can be expressed in financial terms. The literature lacks sufficient knowledge to fully integrate the potential of water use for toilet flushing, irrigation and drinking water that reduces a building's water requirements. Also, the benefits of increasing property value through aspects such as aesthetics and recreational opportunities are not fully understood.

Concrete economic value can be realised based on the knowledge from the literature for a number of benefits for the private party. A concrete revenue stream can be generated by multiplying the production of materials by the selling price. Incentives lead to a reduction in sewerage and wastewater treatment costs. In addition, improved thermal insulation leads to a reduction in the building's energy demand, yielding a reduction in energy demand throughout the life of the building. Furthermore, the avoided cost method can identify the cost savings of sound insulation through the use of pre-installed ceiling panels and the avoidance of conventional roof-related costs through longer life. Finally, there is a direct correlation between indoor sound level and property value, so improved sound insulation contributes to increasing property value.

After completing the literature review, it can be concluded that due to methodological limitations or unsubstantiated assumptions, not all benefits can be expressed in financial terms for public interests. Several benefits can be attributed specifically to certain stakeholders, despite their value still being unclear. Roof garden volunteers derive pleasure from their work there, leading to social benefits such as satisfaction, relaxation, social contact and community building. They could also benefit from the garden's annual revenue. A similar benefit for residents' comfort and quality of life is mentioned in relation to recreation.

There are also benefits in the form of avoidance of substitution costs, mainly related to public authorities because of their involvement in social issues. These include costs for best management practices for storm water mitigation, flood reduction plans and environmental plans to promote biodiversity.

In addition, there are benefits that can benefit multiple stakeholders. Nearby, the potential of the roof garden is highlighted as an educational resource. Furthermore, there are savings in impact costs for human health, environment, cultural heritage, economic activities and building damage due to flood risk reduction. Health and environmental benefits also occur in the urban heat island effect, along with reduced cooling needs of buildings in the immediate vicinity. Residents of these buildings also experience lower noise levels, contributing to better health. In addition, the aesthetic improvement can lead to higher property value, which in itself also constitutes as an independent value in the immediate area. Finally, there are some benefits that can be attributed to society as a whole. These benefits are not exclusive to a specific group and their future translation into a monetary value cannot be specifically assigned to one stakeholder. These mainly relate to food security and the avoidance of external costs incurred in the production of goods.

A number of benefits associated with avoiding impact costs for public authorities can be expressed in financial terms. These benefits include avoiding impact costs for transportation and treatment. There is also a good method available for improving air quality. This is achieved by direct air purification by plants at the local level and indirectly by reducing emissions from power plants at remote locations. These benefits can be quantified by multiplying the avoided cost price by the substitution cost price or avoided cost method. The beneficial effects of improved air quality have direct impacts on people, the climate and the natural environment. They have positive impacts on issues such as health, agriculture, floods, ecosystems and climate change.

6.2. MAIN RESEARCH QUESTION

What are the private and public costs and benefits of applying a green roof during all life cycle stages?
The answers to the sub-questions were used on the case study to form the final answer to the main research question.

In order to determine the public costs and benefits, the investigation of the first research question shows that the external environmental costs can be calculated by translating quantitative data from the environmental product declaration into a monetary value using the numbers from the Ecocost. In this way, the monetary impacts of different environmental impact categories due to the material production of the green roof were identified. In the end, this approach shows that the external costs of the green roof in the case of the case study are €2,33. These are also the only external costs identified in this study. This is offset by the benefits to society derived from sub-question 3. Here, the benefits of energy savings in sewage treatment plants, water transport savings, direct air quality improvement and indirect air quality improvement are discounted back to their present value, resulting in a societal benefit of €14,30.

The second research question provided information on green roof benefits relevant to the private party. The extensive literature review has shown that benefits such as energy savings, property value increase and the avoided costs of a conventional roof can be calculated as benefits for the private party. Using the net present value, the present value of these benefits can again be calculated, which amounts to €102,71. Against this are the costs for the purchase and maintenance of the green roof, obtained in close consultation with Intermaris. These costs result in a net present value of € 108,53.

The resulting financial overview presents the costs and benefits of a green roof for both public and private stakeholders. Even though these values give of the representation that the implementation of a green roof is beneficial for society, it is not for the project developer. It is essential to note that these figures represent what can currently be expressed within the existing knowledge base. The study emphasizes that these figures should therefore not be considered in isolation, but should be understood in light of the potential of all ecosystem services. Additional research is needed in to fill in the current gaps in order to make further statements regarding the private and public economic profitability.

In summary, this study provides an overview of the costs and benefits of green roofs, both for society and private parties, brings together various aspects and strands within both science and society and linked material and economic studies. The financial overview is the result of a critical analysis of current methodologies in the literature. Besides the benefits that can be monetised, the study also shows the gaps in the literature regarding methodologies for quantification and valuation. With this, the aim of the study has been achieved and progress has been made towards sustainable development. The insights from the study also contributed to achieving the broader research goal. Through communication with Intermaris, the research has made a positive contribution in the form of providing inside information.

By highlighting the information and methodologies used, this research can be reflected upon from many different perspectives. The current format promotes an intentional discussion. This deliberate discussion brings room for a dialogue on the value and appreciation of nature-based solutions. Starting such conversations ultimately contributes to the objective of this research, which is to promote a more just world where applications are always placed within a broader context. This requires the involvement of various stakeholders, which this research responds to. However in order to steer the future development, the author has guided future research by his offered recommendations in the last chapter.

7

Recommendation

The design of this study uncovered a lot of information, but did not have the scope to fully elaborate all the information. As a result, there are some open ends within the study that can serve as reference points for future research. Providing an overview of the current state of the literature can provoke discussion and reflection and contribute to the positioning of green roofs within both the social and physical domains. In addition, additions to current knowledge can follow. This chapter provides recommendations for future research. In addition, additional emphasis is placed on how the research should be used within practice so that guidance is also provided for this target group from the perspective of the author.

7.1. Recommendation for academia

- **Integration of social life cycle assessment into the current research framework**
  For future research, it is recommended that the current research design be broadened to incorporate the social costs of the product. Currently, the focus is exclusively on environmental impact, as the current tool for mapping this impact, the Environmental Life Cycle assessment (E-LCA), has reached an advanced stage compared to the Social Life Cycle assessment (S-LCA). As a result, current external costs remain inadequately captured. To obtain a more exhaustive overview of external costs, the S-LCA should also be integrated into the study once it reaches an advanced stage of development. Involving the S-LCA will make a valuable contribution to understanding the broader social impact of the product, enabling a more thorough evaluation of the overall external costs. This recommendation is based on the need to get a complete and holistic picture of the product's impact, incorporating both environmental factors and social aspects.

- **Enhancing clarity and integration in the use of avoided cost versus the substitution cost methods**
  It is of significant importance to address the existing knowledge gap in the literature, as highlighted in this study, regarding the use of the avoided cost method and the substitution cost method. Mainly, it is essential that clarification leads to a structured approach in applying these methods. This should take into account various perspectives in order to strive for an outcome that is socially responsible. In this, attention should be paid to the strengths of both approaches, but also to the stakeholders that emerge through both approaches. The question of what it means when one method is preferred over the other must be carefully considered. The investigation into the realisation of this approach should first accurately expose the dilemma involved, before proceeding to a final outcome. This process is ultimately crucial to fully ensure the integral value of such cost-benefit analyses.

- **Elaborating on ecosystem indications: A need for further development of unexplored benefits**
  Besides the question marks that can be placed on some current methodologies, there are also numerous benefits mentioned in the literature that have so far only been mentioned by name. Remarkably, these benefits often fall within the social and ecological domain, often involving health benefits, enjoyment of life or improvement/impact on ecology. It is therefore important to conduct targeted follow-up research to identify these benefits and further develop them to a level of quality equal to the rest. Here, it is essential to involve scientists from the social domain to put these benefits in the right perspective and then value them correctly. This is vital to achieve a more fair perception towards the various

stakeholders involved.

- **Investigate the specific impact of different roof layers in the green roof package**
  An optimistic future scenario, as outlined by the author, includes the development of a dashboard that links the benefits and impact of different green roof alternatives to the various layers of a roof package, using site-specific data. This dashboard would allow quick insight into different green roof options. To achieve this, future research should focus on analysing the specific effects of various roof layers within the green roof package, and their relationship with the performance of the overall system, both in terms of costs and benefits. This research would help optimise the designs of roof packages to meet specific requirements and goals, as well as gain a deeper understanding of the impact on other benefits.
  The direct feedback of these findings to potential users ensures that information on these relationships is exploited from multiple perspectives. This allows for valuable interaction between available information and stakeholder needs.

- **Incorporating temporal and spatial factors for enhanced stakeholder analysis**
  It is necessary to supplement the current information, which currently only uses values and calculates them back to a current value based on time. There is a need to move to a method that considers impacts in both time and location, in order to measure the impact of a green roof on the local situation at a specific time. This will allow a fairer assessment of the stakeholders involved. The proposed adaptation of the model will allow a more sophisticated and contextual evaluation, considering the effects of a green roof at a specific location and within a specific time frame. This will lead to a more accurate understanding of the impact on the stakeholders involved, especially with regard to demographic changes such as population growth within urban areas, as well as climate changes. Implementing this recommended approach will contribute to a more refined assessment of the benefits and costs of green roofs, and result in more holistic and relevant policy advice.

7.2. RECOMMENDATION FOR PUBLIC AND PRIVATE STAKEHOLDERS

This research offers both private and public stakeholders not only a financial overview, but also a valuable comprehensive understanding of the benefits of green roofs. The non-monetarily expressed benefits and obtacles in the current literature have been demonstrated of value by Intermaris through mutual discussions. There, the insights from the study have helped in valuing the green roof and in promoting external communication. Despite the fact that no comprehensive conclusions can be drawn based on the case study alone, the amount of interest and enthusiasm with which the study was embraced within the team and even the request to present it further to interested parties is an indication of the value of this study to such parties. It is therefore highly recommended that such parties use the findings of this research to support their consideration in selecting a green roof. The benefits of green roofs discussed in this study can serve as the basis for reaching an informed decision together with other local stakeholders. In this way, this research can provide insights to companies and entities that want to engage socially.

For government agencies, this research also provides considerable support in revealing the potential that green roofs offer. This can serve as a catalyst to encourage public authorities to actively participate in the ongoing refinement of existing knowledge. This will enable them to adapt policies and regulations with the aim of making the most of the benefits on offer. In this way, green roofs may be able to be used even more deeply as a means of achieving government objectives.

Moreover, this research has proven that it is possible to include external costs in such analyses. Governments can play a crucial role in the future, when these tools are further developed, by promoting their mandatory integration. By doing so, governments can encourage companies to operate in a more socially responsible manner. However, as already indicated by Vogtlander (2023), it is not expected that these external costs will be fully included in the cost price. The exact implementation thus remains speculative for the author, but its potential has been reaffirmed.

7.3. REFLECTION

This concluding section provides a reflection on the process of this research. This reflection is structured in three parts, namely a reflection on defining the research methodology, conducting the systematic literature review and the research findings obtained.

The examination of methodology proved instrumental in furthering the study. First of all, it provided a better understanding of the pitfalls that can arise in the different steps of making an economic analysis of green roofs. Adhering to the cascade framework from an early stage enabled a structured and systematic approach. A major challenge here was to represent the complexity of ecosystem services in a logical way, both for myself and the readers of the study. The literature offered numerous different perspectives and approaches, often involving ethical considerations, which added to the complexity. This understanding ensured that the research was conducted with caution and that every step taken was critically examined, given its crucial position within the social, economic and environmental domains. Secondly, this research has primarily provided an incentive to contribute to the existing body of knowledge in order to provide a valuable addition to the current literature. With these two aspects in mind, I have constantly considered the extent to which it is necessary to formulate a definitive answer to a gap in the literature, or whether raising this gap can be a valuable outcome in itself.

The second step involved conducting the literature review systematically. Here it became clear how challenging it is to conduct such a research. While organising and structuring information from different sources, it quickly became clear that one can easily get lost in the overwhelming amount of information. Unravelling data from one study often led to sifting through countless other studies. With each new publication, more papers were added that might contain valuable information for my research. The large number of papers sometimes made it difficult to make and justify a seemingly simple statement. Nevertheless, this thorough approach ensured that the result of this paper is what it is today. Fortunately, the thorough research also revealed some interesting findings, making the process more than rewarding.

7

In addition, it was sometimes challenging to stick strictly to the scope of my research. Of course, it is tempting to always look for new, ground-breaking findings. However, my approach was to let these innovations emerge from identifying gaps in the literature. Letting go of filling in these gaps was therefore a considerable challenge. This was particularly true as information was found during the research that could potentially provide answers to these gaps. However, it is essential to be aware of your role as a scientist and understand that the goal is not just to find answers to the gaps in the literature. It is more important to adequately address the gaps, rather than filling them in an unsatisfactory way. This realisation also emerged during my research, in which sometimes "weak" values took on a life of their own within the literature.

Finally, it is necessary to reflect on the results. Indeed, the design of my research put me in an awkward position. On the one hand, I wanted to be able to inform Intermaris that the green roof they implemented offers significant benefits, including financial ones. However, within the academic work and because of the deliberate position in which I placed myself, I also had to communicate that many of these benefits are not yet known or sometimes lack the means to express them in monetary values. This realisation makes it clear that while good values are important for research, sound research is of much greater value.

References

Acoustical Engineer (2019). Available at https://acousticalengineer.com/a-weighting-table/ (16-01-2023).

Aernouts, K. and Jespers, K. (2005). Energiekengetallen van de tertiaire sector in vlaanderen 2003-bijlage bij de energiebalans vlaanderen 2003: onafhankelijke methode. Available at http://www.emis.vito.be/sites/default/files/pagina~âÄę (15-07-2023).

Ahlfeldt, G. M., Nitsch, V., and Wendland, N. (2019). Ease vs. noise: Long-run changes in the value of transport (dis) amenities. *Journal of Environmental Economics and Management*, 98:102268.

Akbari, H. (1992). Cooling our communities. a guidebook on tree planting and light-colored surfacing.

Akbari, H. (2005). Energy saving potentials and air quality benefits of urban heat islandmitigation. *Lawrence Berkeley National Laboratory*.

Akbari, H., Pomerantz, M., and Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, 70(3):295–310. Urban Environment.

Albers, R., Bosch, P., Blocken, B., Van Den Dobbelsteen, A., Van Hove, L., Spit, T., Van de Ven, F., Van Hooff, T., and Rovers, V. (2015). Overview of challenges and achievements in the climate adaptation of cities and in the climate proof cities program.

Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., and Sanchez, A. (2019). Assessing the co-benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of environmental management*, 239:244–254.

Amadei, A. M., De Laurentiis, V., and Sala, S. (2021). A review of monetary valuation in life cycle assessment: State of the art and future needs. *Journal of Cleaner Production*, 329:129668.

Andrews, E. S. (2009). *Guidelines for social life cycle assessment of products: social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development.* UNEP/Earthprint.

Arendt, R., Bachmann, T. M., Motoshita, M., Bach, V., and Finkbeiner, M. (2020). Comparison of different monetization methods in lca: a review. *Sustainability*, 12(24):10493.

Ascione, F., Bianco, N., de'Rossi, F., Turni, G., and Vanoli, G. P. (2013). Green roofs in european climates. are effective solutions for the energy savings in air-conditioning? *Applied Energy*, 104:845–859.

Ashby, M. F. (2022). *Materials and sustainable development.* Butterworth-Heinemann.

Assembly, G. (2015). Sustainable development goals. *SDGs Transform Our World*, 2030:6–28.

Atlas Leefomgeving (2023a). Available at https://www.atlasleefomgeving.nl/kaarten?config=3ef897de-127f-471a-959b-93b7597de188&gm-x=150000&gm-y=460000&gm-z=3&gm-b=1544180834512,true,1;1544969872210,true,0.8;&activateOnStart=layermanager,info&activeTools=layercollection,search,info,bookmark,measure,draw,koeltorens (06-06-2023).

Atlas Leefomgeving (2023b). Available at https://www.atlasleefomgeving.nl/kaarten?config=3ef897de-127f-471a-959b-93b7597de188&activateOnStart=layercollection&gm-x=155000.00000000003&gm-y=456478.71437812824&gm-z=2.894059846274022&gm-b=1544180834512%2Ctrue%2C1%3B1544715737496%2Ctrue%2C0.8 (10-8-2023).

Autoriteit Consument & Markt (2023). Hoeveel betaal ik voor mijn warmte? Available at https://www.consuwijzer.nl/stadsverwarming-en-blokverwarming/warmtetarieven (25-06-2023).

autorità di bacino distrettuale delle alpi orientali (2023). Prra 2015-2021. Available at `http://www.alpiorientali.it/direttiva-2007-60/pgra-2015-2021/progetto-di-piano-di-gestione-del-rischio-alluvioni.html` (24-11-2022).

Bah, M., Chapman, E., and Gäckle, J. (2021). Stakeholder mapping report in each of the cultivating cities. Technical Report D3.2, Go Gren Routes.

Bai, X., Dawson, R. J., Ürge-Vorsatz, D., Delgado, G. C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D. C., et al. (2018). Six research priorities for cities and climate change.

Banting, D., Doshi, H., Li, J., Missios, P., Au, A., Currie, B. A., and Verrati, M. (2005). Report on the environmental benefits and costs of green roof technology for the city of toronto. *City of Toronto and Ontario Centres of Excellence—Earth and Environmental Technologies*.

Barker, T. and Rosendahl, K. E. (2000). Ancillary benefits of ghg mitigation in europe: So2, nox and pm10 reductions from policies to meet kyoto targets using the e3me model and externe valuations. *Ancillary benefits and costs of greenhouse gas mitigation*, pages 413–450.

Bastos, J., Lo Vullo, E., Muntean, M., Duerr, M., Kona, A., and Bertoldi, P. (2020). GHG Emission Factors for Electricity Consumption. *European Commission, Joint Research Centre (JRC)*.

Bath and Council, N. E. S. (2021). Ecosystem services. photo: Bath and north east somerset council. Available at `https://mayneconservancy.ca/what-are-ecosystem-services/` (04-02-2023).

Bello, J. P., Silva, C., Nov, O., Dubois, R. L., Arora, A., Salamon, J., Mydlarz, C., and Doraiswamy, H. (2019). Sonyc: A system for monitoring, analyzing, and mitigating urban noise pollution. *Communications of the ACM*, 62(2):68–77.

7

Berardi, U., GhaffarianHoseini, A., and GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied energy*, 115:411–428.

Berndtsson, J. C. (2010). Green roof performance towards management of runoff water quantity and quality: A review. *Ecological engineering*, 36(4):351–360.

Berto, R., Stival, C. A., and Rosato, P. (2018). Enhancing the environmental performance of industrial settlements: An economic evaluation of extensive green roof competitiveness. *Building and Environment*, 127:58–68.

Bertram, C. and Rehdanz, K. (2015). The role of urban green space for human well-being. *Ecological Economics*, 120:139–152.

Besir, A. B. and Cuce, E. (2018). Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 82:915–939.

Bianchini, F. and Hewage, K. (2012a). How "green" are the green roofs? lifecycle analysis of green roof materials. *Building and environment*, 48:57–65.

Bianchini, F. and Hewage, K. (2012b). Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. *Building and environment*, 58:152–162.

Biernacki, M. (2015). Environmental life cycle costing (elcc) in the aspect of cost management in the company. *Finanse, Rynki Finansowe, Ubezpieczenia*, 77:305–312.

Boadway, R. (2020). Economic evaluation of projects. In *Policy, Program and Project Evaluation*, pages 59–105. Springer.

Brachet, A., Schiopu, N., and Clergeau, P. (2019). Biodiversity impact assessment of building's roofs based on life cycle assessment methods. *Building and Environment*, 158:133–144.

Carter, T. and Keeler, A. (2008). Life-cycle cost–benefit analysis of extensive vegetated roof systems. *Journal of environmental management*, 87(3):350–363.

Castleton, H. F., Stovin, V., Beck, S. B., and Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and buildings*, 42(10):1582–1591.

CE Delft (2023). Handboek milieuprijzen 2023. Technical Report 23.220175.034, CE Delft.

Center for Neighborhood Technology (2010). The value of green infrastructure: A guide to recognizing its economic, environmental and social benefits. *Center Neighborhood Technology*.

Centraal Bureau Statistiek (2023). Population dynamics; birth, death and migration per region. Available at `https://www.cbs.nl/en-gb/figures/detail/37259eng?q=traffic%20density#shortTableDescription` (12-11-2022).

Centre, T. C. T. and Network (2016). Available at `https://www.ctc-n.org/technologies/insulation-buildings` (10-05-2023).

Cettner, A., Ashley, R., Viklander, M., and Nilsson, K. (2013). Stormwater management and urban planning: Lessons from 40 years of innovation. *Journal of Environmental Planning and Management*, 56(6):786–801.

Chan, A. and Chow, T. (2013). Energy and economic performance of green roof system under future climatic conditions in Hong Kong. *Energy and Buildings*, 64:182–198.

Chang, N.-B., Rivera, B. J., and Wanielista, M. P. (2011). Optimal design for water conservation and energy savings using green roofs in a green building under mixed uncertainties. *Journal of Cleaner Production*, 19(11):1180–1188.

Clark, C., Adriaens, P., and Talbot, F. B. (2008). Green roof valuation: a probabilistic economic analysis of environmental benefits. *Environmental science & technology*, 42(6):2155–2161.

Claus, K. and Rousseau, S. (2012). Public versus private incentives to invest in green roofs: A cost benefit analysis for flanders. *Urban forestry & urban greening*, 11(4):417–425.

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., Grimm, N. B., Grove, J. M., Harlan, S. L., Kaye, J. P., et al. (2011). An integrated conceptual framework for long-term social–ecological research. *Frontiers in Ecology and the Environment*, 9(6):351–357.

Connelly, M. and Hodgson, M. (2008). Sound transmission loss of green roofs. *Proceedings of the 6th Annual Greening Rooftops for Sustainable Communities. Baltimore, MD. April*.

Costanza, R. (2020). Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. *Ecosystem Services*, 43:101096.

Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., and Grasso, M. (2017). Twenty years of ecosystem services: how far have we come and how far do we still need to go? *Ecosystem services*, 28:1–16.

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., and Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global environmental change*, 26:152–158.

Currie, B. A. and Bass, B. (2008). Estimates of air pollution mitigation with green plants and green roofs using the ufore model. *Urban ecosystems*, 11(4):409–422.

Dai, L., Wörner, R., and van Rijswick, H. F. (2018). Rainproof cities in the netherlands: Approaches in dutch water governance to climate-adaptive urban planning. *International Journal of Water Resources Development*, 34(4):652–674.

Daily, G. C., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P. R., Folke, C., Jansson, A., Jansson, B.-O., Kautsky, N., et al. (2000). The value of nature and the nature of value. *Science*, 289(5478):395–396.

de Bruyn, S. (2017). Ce_delft_7. a761_handboek schaduwprijzen 2016. Technical report, CE Delft.

De Groot, R. S., Alkemade, R., Braat, L., Hein, L., and Willemen, L. (2010a). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological complexity*, 7(3):260–272.

De Groot, R. S., Fisher, B., Christie, M., Aronson, J., Braat, L., Haines-Young, R., Gowdy, J., Maltby, E., Neuville, A., Polasky, S., et al. (2010b). Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. In *The economics of ecosystems and biodiversity (TEEB): ecological and economic foundations*, pages 9–40. Earthscan, Routledge.

Durão, V., Silvestre, J. D., Mateus, R., and de Brito, J. (2020). Assessment and communication of the environmental performance of construction products in europe: Comparison between pef and en 15804 compliant epd schemes. *Resources, Conservation and Recycling*, 156:104703.

Ecomatters (2023). Life cycle assessment (lca). Available at `https://www.ecomatters.nl/nl/services/lca-epd/life-cycle-assessment/` (20-11-2022).

Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P. J., McDonald, R. I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K. C., et al. (2013). Urbanization, biodiversity and ecosystem services: challenges and opportunities: a global assessment.

Enríquez, E., Fuertes, V., Cabrera, M., Seores, J., Muñoz, D., and Fernández, J. (2017). New strategy to mitigate urban heat island effect: Energy saving by combining high albedo and low thermal diffusivity in glass ceramic materials. *Solar Energy*, 149:114–124.

Environmental Protection Agency (2022). Water quality management: Stormwater.

European Commission (2014). Guide to cost-benefit analysis of investment projects: Economic appraisal tool for cohesion policy 2014–2020.

European Commission (2016). Synthesis and dissemination of key outputs of the teeb initiative.

European Commission (2023a). Energy - environment - economy model for europe.

European Commission (2023b). Water framework directive.

Eurostat (2023). Cooling and heating degree days by country - annual data. Available at `https://ec.europa.eu/eurostat/databrowser/view/NRG_CHDD_A/default/table?lang=en` (05-04-2023).

Feitosa, R. C. and Wilkinson, S. J. (2018). Attenuating heat stress through green roof and green wall retrofit. *Building and Environment*, 140:11–22.

Felipe-Lucia, M. R., Martín-López, B., Lavorel, S., Berraquero-Díaz, L., Escalera-Reyes, J., and Comín, F. A. (2015). Ecosystem services flows: why stakeholders' power relationships matter. *PloS one*, 10(7):e0132232.

Fenger, J. (1999). Urban air quality. *Atmospheric environment*, 33(29):4877–4900.

Fernando, J. (2023). Available at `https://www.investopedia.com/terms/d/dcf.asp` (15-07-2023).

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., and Klüppel, H.-J. (2006). The new international standards for life cycle assessment: Iso 14040 and iso 14044. *The international journal of life cycle assessment*, 11:80–85.

Fisher, B., Turner, R. K., and Morling, P. (2009). Defining and classifying ecosystem services for decision making. *Ecological economics*, 68(3):643–653.

Fisk, P. (2010). *People planet profit: How to embrace sustainability for innovation and business growth*. Kogan Page Publishers.

Freeman, R. E., Harrison, J. S., Wicks, A. C., Parmar, B. L., and De Colle, S. (2010). Stakeholder theory: The state of the art.

Fu, B.-J., Su, C.-H., Wei, Y.-P., Willett, I. R., Lü, Y.-H., and Liu, G.-H. (2011). Double counting in ecosystem services valuation: causes and countermeasures. *Ecological research*, 26:1–14.

Gaffin, S. R., Khanbilvardi, R., and Rosenzweig, C. (2009). Development of a green roof environmental monitoring and meteorological network in new york city. *Sensors*, 9(4):2647–2660.

Gaffin, S. R., Rosenzweig, C., and Kong, A. Y. (2012). Adapting to climate change through urban green infrastructure. *Nature Climate Change*, 2(10):704–704.

Getter, K. L. and Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. *HortScience*, 41(5):1276–1285.

Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., and Andresen, J. A. (2009). Carbon sequestration potential of extensive green roofs. *Environmental science & technology*, 43(19):7564–7570.

Ghomeishi, M. (2021). Aesthetic preferences of laypersons and its relationship with the conceptual properties on building façade design. *Journal of Asian Architecture and Building Engineering*, 20(1):12–28.

Giama, E., Papageorgiou, C., Theodoridou, I., and Papadopoulos, A. M. (2021). Life cycle analysis and life cycle cost analysis of green roofs in the mediterranean climatic conditions. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pages 1–14.

Godish, T., Davis, W. T., and Fu, J. S. (2014). *Air quality*. CRC Press.

Goh, C. S., Chong, H.-Y., Jack, L., and Faris, A. F. M. (2020). Revisiting triple bottom line within the context of sustainable construction: A systematic review. *Journal of cleaner production*, 252:119884.

Gómez-Baggethun, E. and Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological economics*, 86:235–245.

Gómez-Baggethun, E., Gren, Å., Barton, D. N., Langemeyer, J., McPhearson, T., O'farrell, P., Andersson, E., Hamstead, Z., and Kremer, P. (2013). Urban ecosystem services. In *Urbanization, biodiversity and ecosystem services: Challenges and opportunities*, pages 175–251. Springer, Dordrecht.

Goodpaster, K. E. (1991). Business ethics and stakeholder analysis. *Business ethics quarterly*, pages 53–73.

Grimm, N. B., Grove, J. G., Pickett, S. T., and Redman, C. L. (2000). Integrated approaches to long-term studies of urban ecological systems. *BioScience*, 50(7):571–584.

Grooten, M., Almond, R. E., et al. (2018). *Living planet report-2018: aiming higher.* WWF international.

Haines-Young, R., Potschin, M., et al. (2010). The links between biodiversity, ecosystem services and human well-being. *Ecosystem Ecology: a new synthesis*, 1:110–139.

Handel, S. N., Saito, O., and Takeuchi, K. (2013). Restoration ecology in an urbanizing world. *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment*, pages 665–698.

Hein, L., Van Koppen, K., De Groot, R. S., and Van Ierland, E. C. (2006). Spatial scales, stakeholders and the valuation of ecosystem services. *Ecological economics*, 57(2):209–228.

Helander, H., Petit-Boix, A., Leipold, S., and Bringezu, S. (2019). How to monitor environmental pressures of a circular economy: An assessment of indicators. *Journal of Industrial Ecology*, 23(5):1278–1291.

Helpdesk water (2023). Gemeentelijk rioleringsplan. Available at `https://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/handboek-water/wetgeving/wet-milieubeheer/gemeentelijk/` (12-11-2022).

Hendriks, C., Snep, R., de Vries, E., and Brolsma, R. (2016). Groene daken in tilburg: operationele handvatten voor ontwikkeling van gemeentelijk beleid. Technical report, Alterra, Wageningen-UR.

Herath, H. and Mittal, M. (2022). Adoption of artificial intelligence in smart cities: A comprehensive review. *International Journal of Information Management Data Insights*, 2(1):100076.

Hilten, R. N. (2005). *An analysis of the energetics and stormwater mediation potential of greenroofs*. PhD thesis, University of Georgia.

Hirsch, J., Gates, S., Criswell, S., Addison, M., Winkelmann, F., Buhl, W., and Ellington, K. (1998). Doe 2.2 and power doe. *The new generation in DOE-2 building energy analysis, building energy simulation program.*

Hobbie, S. E. and Grimm, N. B. (2020). Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B*, 375(1794):20190124.

Homedeal (2023). Dakrenovatie kosten. Available at `https://www.homedeal.nl/dakbedekking/dakrenovatie-kosten/` (20-05-2023).

Hoogmartens, R., Van Passel, S., Van Acker, K., and Dubois, M. (2014). Bridging the gap between lca, lcc and cba as sustainability assessment tools. *Environmental Impact Assessment Review*, 48:27–33.

Hop, M. E. C. and van Wetten, J. (2010). *Dak en gevelgroen*.

Howard, L. (1818). *The climate of London: deduced from meteorological observations, made at different places in the neighbourhood of the metropolis*, volume 1. W. Phillips, George Yard.

Huang, J., Franconi, E., et al. (1999). Commercial heating and cooling loads component analysis. *LBL-37208, Lawrence Berkeley National Laboratory, Berkeley, CA*.

Huizinga, J., de Moel, H., and Szewczyk, W. (2017). Global flood depth-damage functions. methodology and the database with guidelines. Scientific Report EUR 28552 EN. doi: 10.2760/16510, European Commission, European Commission, Joint Research Centre, Edificio Expo; C/ Inca Garcilaso, 3, E-41092 Sevilla, Spain.

Inbo (2020). Toekomstvisie centrumgebied van de kersenboogerd (2020-2035). Technical report, Gemeente Hoorn & Intermaris.

Ingemarsdotter, E. (2022). A guide to life cycle costing.

Intermaris (2022). Goed ouder worden in betsy perk. Brochure.

7

Intermaris (2023). Jaarverslag 2022 bestuursverslag en jaarrekening. Technical report.

Intermaris and Gemeente Hoorn (2022). Centrumgebied kersenboogerd. Available at `https://hoornkersenboogerd.nl/` (01-02-2023).

ISO (2022). Iso 14040:2006.

Jacobs, S., Dendoncker, N., Martín-López, B., Barton, D. N., Gomez-Baggethun, E., Boeraeve, F., McGrath, F. L., Vierikko, K., Geneletti, D., Sevecke, K. J., et al. (2016). A new valuation school: Integrating diverse values of nature in resource and land use decisions. *Ecosystem services*, 22:213–220.

Jacobs, S., Martín-López, B., Barton, D. N., Dunford, R., Harrison, P. A., Kelemen, E., Saarikoski, H., Termansen, M., García-Llorente, M., Gómez-Baggethun, E., et al. (2018). The means determine the end–pursuing integrated valuation in practice. *Ecosystem services*, 29:515–528.

James J. Hirsch and Associates. (2015).

Jawad, N., Abidi, S. R. T. Z., and Jahangir, A. J. (2022). Green roofs: More than just a pretty face. *Journal of Arts & Social Sciences*, 9(1):111–120.

Jones, R., Bathgate, R., Symons, J., and Williams, N. (2019). Quantifying the benefits of green infrastructure: Literature review and gap analysis.

Jonkers, H. (2021). Reader cie4100 - materials and ecological engineering. Technical Report DOE-SLC-6903-1, Delft University of Technology, Delft.

Kadykalo, A. N., López-Rodriguez, M. D., Ainscough, J., Droste, N., Ryu, H., Ávila-Flores, G., Le Clec'h, S., Muñoz, M. C., Nilsson, L., Rana, S., et al. (2019). Disentangling 'ecosystem services' and 'nature's contributions to people'. *Ecosystems and People*, 15(1):269–287.

Kim, E., Jung, J., Hapsari, G., Kang, S., Kim, K., Yoon, S., Lee, M., Han, M., Choi, Y., and Choe, J. K. (2018). Economic and environmental sustainability and public perceptions of rooftop farm versus extensive garden. *Building and Environment*, 146:206–215.

King, D. and Mazzotta, M. (2023). Available at `https://www.ecosystemvaluation.org/cost_avoided.htm` (10-11-2022).

Kleerekoper, L., Van Esch, M., and Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling*, 64:30–38.

KNMI (2014). Knmi'14: Climate change scenarios for the 21st century – a netherlands perspective. Scientific Report WR2014-01, KNMI, De Bilt, The Netherlands.

KNMI (2022). Het regent niet vaker, wel harder. Available at `https://www.knmi.nl/over-het-knmi/nieuws/het-regent-niet-vaker-wel-harder#:~:text=Totale%20hoeveelheid%20neerslag%20per%20jaar%20is%20met%209%25%20toegenomen&text=De%20jaarsom%20is%20sinds%201906,71%20millimeter%20oftewel%209%20procent.` (25-06-2023).

Köhler, M. (2006). Long-term vegetation research on two extensive green roofs in berlin. *Urban habitats*, 4(1):3–26.

Köhler, M., Schmidt, M., Grimme, F. W., Laar, M., and Gusmão, F. (2001). Urban water retention by greened roofs in temperate and tropical climate. *Technology Resource Management and Development*, 2:151–162.

Korving, H., Korving, J. L., Langeveld, J., and Van Der Biezen, S. (2015). *Reductie hydraulische belasting RWZI*. Number 05. Stichting RIONED en STOWA.

Kosareo, L. and Ries, R. (2007). Comparative environmental life cycle assessment of green roofs. *Building and environment*, 42(7):2606–2613.

Kuehnel, N. and Moeckel, R. (2020). Impact of simulation-based traffic noise on rent prices. *Transportation Research Part D: Transport and Environment*, 78:102191.

Köhler, M. and Kaiser, D. (2021). Green roof enhancement on buildings of the university of applied sciences in neubrandenburg (germany) in times of climate change. *Atmosphere*, 12(3):382.

La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M. L., Liquete, C., Egoh, B., Geneletti, D., and Crossman, N. D. (2017). Ecosystem services classification: A systems ecology perspective of the cascade framework. *Ecological indicators*, 74:392–402.

Lagstrom, J. (2004). Do extensive green roofs reduce noise. *International Green Roof Institute*.

Lankhorst, G., Arts, J., Terwel, K., and Jonkers, H. (2019). Life cycle analysis: Load-bearing structures of high-rise buildings in western europe. *CTBUH*, 3:28–35.

Lant, C. L., Ruhl, J., and Kraft, S. E. (2008). The tragedy of ecosystem services. *BioScience*, 58(10):969–974.

Lee, J. H. and Bang, K. W. (2000). Characterization of urban stormwater runoff. *Water research*, 34(6):1773–1780.

Legesse, F., Degefa, S., and Soromessa, T. (2022). Valuation methods in ecosystem services: A meta-analysis.

Lensin, S., Koen Smekens, K., Groen, B. i. t., Mijnlief, H., and Tolsma, S. (2021). Conceptadvies sde++ 2022 geothermie. *Planbureau voor de Leefomgeving*, 4382.

Li, J., Song, C., Cao, L., Zhu, F., Meng, X., and Wu, J. (2011). Impacts of landscape structure on surface urban heat islands: A case study of shanghai, china. *Remote sensing of environment*, 115(12):3249–3263.

Li, X., Zhou, Y., Yu, S., Jia, G., Li, H., and Li, W. (2019). Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy*, 174:407–419.

Li, Y. and Babcock Jr, R. W. (2014). Green roof hydrologic performance and modeling: a review. *Water science and technology*, 69(4):727–738.

Liberalesso, T., Cruz, C. O., Silva, C. M., and Manso, M. (2020). Green infrastructure and public policies: An international review of green roofs and green walls incentives. *Land use policy*, 96:104693.

Lin, R., Man, Y., and Ren, J. (2020). Framework of life cycle sustainability assessment. In *Life Cycle Sustainability Assessment for Decision-Making*, pages 155–173. Elsevier.

Lindgreen, E. R. and Vermeulen, W. J. (2023). In search for ground rules for product-oriented full cost accounting methods: Ensuring construct validity. *Environmental and Sustainability Indicators*, page 100275.

Liu, H., Kong, F., Yin, H., Middel, A., Zheng, X., Huang, J., Xu, H., Wang, D., and Wen, Z. (2021a). Impacts of green roofs on water, temperature, and air quality: A bibliometric review. *Building and Environment*, 196:107794.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., et al. (2007). Complexity of coupled human and natural systems. *science*, 317(5844):1513–1516.

Liu, K. K. Y. and Baskaran, B. A. (2004). Green roof infrastructure - technology demonstration, monitoring and market expansion project. Technical Report 121 p.

Liu, W.-Y., Fang, B.-S., and Hsieh, C.-M. (2021b). Evaluating the recreation value of alishan national forest recreation area in taiwan. *Forests*, 12(9):1245.

Luchtmeetnet.nl (2023). Luchtmeetnet.nl meetpunt Amsterdam-Westerpark. Available at `https://www.luchtmeetnet.nl/meetpunten?component=SO2&station=NL49016` (04-05-2023).

Maass, J. M., Balvanera, P., Castillo, A., Daily, G. C., Mooney, H. A., Ehrlich, P., Quesada, M., Miranda, A., Jaramillo, V. J., García-Oliva, F., et al. (2005). Ecosystem services of tropical dry forests: insights from long-term ecological and social research on the pacific coast of mexico. *Ecology and society*, 10(1).

Macháč, J., Louda, J., and Dubová, L. (2016). Green and blue infrastructure: An opportunity for smart cities? In *2016 Smart Cities Symposium Prague (SCSP)*, pages 1–6. IEEE.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M., and Kjeldsen, T. (2014). Review of trend analysis and climate change projections of extreme precipitation and floods in europe. *Journal of Hydrology*, 519:3634–3650.

Mahdiyar, A., Tabatabaee, S., Sadeghifam, A. N., Mohandes, S. R., Abdullah, A., and Meynagh, M. M. (2016). Probabilistic private cost-benefit analysis for green roof installation: A monte carlo simulation approach. *urban forestry & urban greening*, 20:317–327.

Mahdiyar, A., Tabatabaee, S., Yahya, K., and Mohandes, S. R. (2021). A probabilistic financial feasibility study on green roof installation from the private and social perspectives. *Urban Forestry & Urban Greening*, 58:126893.

Maibach, M., Schreyer, C., Sutter, D., Van Essen, H., Boon, B., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., and Bak, M. (2008). Handbook on estimation of external costs in the transport sector. *Ce Delft*, 336.

Manso, M., Teotónio, I., Silva, C. M., and Cruz, C. O. (2021). Green roof and green wall benefits and costs: A review of the quantitative evidence. *Renewable and Sustainable Energy Reviews*, 135:110111.

Marien, K., Duerinck, J., and Torfs, R. (2002). Economic impact modules for the euros model. *WIT Transactions on Ecology and the Environment*, 53.

Martínez-Harms, M. J. and Balvanera, P. (2012). Methods for mapping ecosystem service supply: a review. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 8(1-2):17–25.

Mayrand, F. and Clergeau, P. (2018). Green roofs and green walls for biodiversity conservation: a contribution to urban connectivity? *Sustainability*, 10(4):985.

McDonald, R. I., Marcotullio, P. J., and Güneralp, B. (2013). Urbanization and global trends in biodiversity and ecosystem services. *Urbanization, biodiversity and ecosystem services: challenges and opportunities: a global assessment*, pages 31–52.

McPhearson, T., Cook, E. M., Berbes-Blazquez, M., Cheng, C., Grimm, N. B., Andersson, E., Barbosa, O., Chandler, D. G., Chang, H., Chester, M. V., et al. (2022). A social-ecological-technological systems framework for urban ecosystem services. *One Earth*, 5(5):505–518.

McRae, A. M. (2016). Case study: A conservative approach to green roof benefit quantification and valuation for public buildings. *The Engineering Economist*, 61(3):190–206.

Mengist, W., Soromessa, T., and Feyisa, G. L. (2020). A global view of regulatory ecosystem services: Existed knowledge, trends, and research gaps. *Ecological processes*, 9:1–14.

Mentens, J., Raes, D., and Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and urban planning*, 77(3):217–226.

Millennium Ecosystem Assessment (2005). Ecosystem and human well-being - biodiversity synthesis.

Miller, J. D. and Hutchins, M. (2017). The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the united kingdom. *Journal of Hydrology: Regional Studies*, 12:345–362.

Ministerie van Binnenlandse Zaken en Koningrelaties (2023). Afdeling 3.1. bescherming tegen geluid van buiten, nieuwbouw.

Ministerie van Infrastructuur en Waterstaat (2022). Deltaplan ruimtelijke adaptatie. Available at `https://www.deltaprogramma.nl/themas/ruimtelijke-adaptatie/deltaplan` (12-11-2022).

Ministerie van Infrastructuur en Waterstaat (2023). Available at `https://www.infomil.nl/onderwerpen/lucht-water/handboek-water/activiteiten/lozen-biologisch/behandeling-stedelijk-afvalwater/lozen-rwzi/zorgplicht-zuivering-stedelijk-afvalwater/` (15-07-2023).

Mommer, L. (2022). Six reasons why we need biodiversity. Available at `https://www.wur.nl/en/newsarticle/six-reasons-why-we-need-biodiversity.htm` (08-01-2023).

Morillas, J. M. B., Gozalo, G. R., González, D. M., Moraga, P. A., and Vílchez-Gómez, R. (2018). Noise pollution and urban planning. *Current Pollution Reports*, 4(3):208–219.

Morse, W. C. (2020). Recreation as a social-ecological complex adaptive system. *Sustainability*, 12(3):753.

Mougeot, L. J. et al. (2000). Urban agriculture: definition, presence, potentials and risks. *Growing cities, growing food: Urban agriculture on the policy agenda*, 1:42.

Müller, A., Österlund, H., Marsalek, J., and Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of the Total Environment*, 709:136125.

Murphy, E. and King, E. A. (2022). *Environmental noise pollution: Noise mapping, public health, and policy*. Elsevier.

Nabielek, K. and Hamers, D. A. F. (2015). *Destad verbeeld: 12 infographics over de stedelijke leefomgeving*.

National Research Council et al. (2009). *Urban stormwater management in the United States*. National Academies Press.

nationale milieudatabase (2022). Europese normalisatie. Available at `https://milieudatabase.nl/milieuprestatie/europese-normalisatie/` (10-02-2023).

Nationale milieudatabase (2023). Van 11 naar 19 milieueffectcategorieën, stand van zaken. Available at `https://milieudatabase.nl/nl/actueel/projecten/versnellingsactie/` (2-03-2023).

NEN-EN 15804:2012+A2:2019/C1:2021 en (2021). Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. Correction sheet, NEderlandse Norm (NEN).

Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., et al. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of the total environment*, 579:1215–1227.

Nesticò, A., Maselli, G., Ghisellini, P., and Ulgiati, S. (2023). A dual probabilistic discounting approach to assess economic and environmental impacts. *Environmental and Resource Economics*, 85(1):239–265.

New Jersey Future (2020). What is stormwater? Available at `https://stormwaterutilities.njfuture.org/what-is-stormwater-2/` (02-02-2023).

Nguyen, C. N., Muttil, N., Tariq, M. A. U. R., and Ng, A. W. (2022). Quantifying the benefits and ecosystem services provided by green roofs—a review. *Water*, 14(1):68.

Niu, H., Clark, C., Zhou, J., and Adriaens, P. (2010). Scaling of economic benefits from green roof implementation in washington, dc. *Environmental science & technology*, 44(11):4302–4308.

Noor, N. M., Asmawi, M. Z., and Abdullah, A. (2015). Sustainable urban regeneration: Gis and hedonic pricing method in determining the value of green space in housing area. *Procedia-Social and Behavioral Sciences*, 170:669–679.

Nurmi, V., Votsis, A., Perrels, A., and Lehvävirta, S. (2013). Cost-benefit analysis of green roofs in urban areas: case study in helsinki.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K. K., and Rowe, B. (2007). Green roofs as urban ecosystems: ecological structures, functions, and services. *BioScience*, 57(10):823–833.

Office of Air Quality Planning and Standards, Office of Atmospheric Programs U.S., and Environmental Protection Agency (1998). *REGULATORY IMPACT ANALYSIS FOR THE NOx SIP CALL, FIP, AND SECTION 126 PETITIONS*, volume 2 of *Health and Welfare Benefits*.

Omer, M. A. and Noguchi, T. (2020). A conceptual framework for understanding the contribution of building materials in the achievement of sustainable development goals (sdgs). *Sustainable Cities and Society*, 52:101869.

Orsini, F., Dubbeling, M., De Zeeuw, H., and Gianquinto, G. (2017). *Rooftop urban agriculture*. Springer.

Ottelé, M., van Bohemen, H. D., and Fraaij, A. L. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological engineering*, 36(2):154–162.

Pal, A., He, Y., Jekel, M., Reinhard, M., and Gin, K. Y.-H. (2014). Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle. *Environment international*, 71:46–62.

Pascual, U., Muradian, R., Brander, L., Gómez-Baggethun, E., Martín-López, B., Verma, M., Armsworth, P., Christie, M., Cornelissen, H., Eppink, F., et al. (2010). The economics of valuing ecosystem services and biodiversity. *The economics of ecosystems and biodiversity: Ecological and economic foundations*, pages 183–256.

Peck, S. W., Callaghan, C., Kuhn, M. E., and Bass, B. (1999). Greenbacks from green roofs: forging a new industry in canada.

Peng, L. L. and Jim, C. Y. (2015). Economic evaluation of green-roof environmental benefits in the context of climate change: The case of hong kong. *Urban Forestry & Urban Greening*, 14(3):554–561.

Pizzol, M., Weidema, B., Brandão, M., and Osset, P. (2015). Monetary valuation in life cycle assessment: a review. *Journal of Cleaner Production*, 86:170–179.

Planbureau voor de Leefomgeving (2021). Reflectie op de leefomgevingsthema's in het coalitieakkoord 2021-2025.

Porsche, U. and Köhler, M. (2003). Life cycle costs of green roofs. *World Climate & Energy Event*, pages 461–67.

Potschin-Young, M., Haines-Young, R., Görg, C., Heink, U., Jax, K., and Schleyer, C. (2018). Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. *Ecosystem Services*, 29:428–440.

Proost, S. and Rousseau, S. (2007). *Inleiding tot de milieueconomie*. Acco.

Quist, Z. (2021). De bepalingsmethode (mki) is aangepast: Wat de EN15804 + A2 betekent voor jouw bedrijf. Available at `https://ecochain.com/nl/knowledge-nl/wat-en15804-a2-voor-jou-betekent/` (30-04-2023).

Rabl, A. and Eyre, N. (1998). An estimate of regional and global o3 damage from precursor nox and voc emissions. *Environment International*, 24(8):835–850.

Ramírez, A. Z. and Muñoz, C. B. (2012). Albedo effect and energy efficiency of cities. In *Sustainable Development-Energy, Engineering and Technologies-Manufacturing and Environment*. IntechOpen.

Raouf, A. M. and Al-Ghamdi, S. G. (2020). Framework to evaluate quality performance of green building delivery: construction and operational stage. *International Journal of Construction Management*, pages 1–15.

Rasul, M. and Arutla, L. (2020). Environmental impact assessment of green roofs using life cycle assessment. *Energy Reports*, 6:503–508.

Redwood, M. (2012). *Agriculture in urban planning: generating livelihoods and food security*. Routledge.

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., and Stringer, L. C. (2009). Who's in and why? a typology of stakeholder analysis methods for natural resource management. *Journal of environmental management*, 90(5):1933–1949.

Reijnders, L. (2020). Life cycle assessment of microalgae-based processes and products. In *Handbook of microalgae-based processes and products*, pages 823–840. Elsevier.

Rivela, B., Kuczenski, B., and Sucozhañay, D. (2022). Life cycle sustainability assessment-based tools. In *Assessing Progress Towards Sustainability*, pages 93–118. Elsevier.

Roe, D., Seddon, N., and Elliott, J. (2019). Biodiversity loss is a development issue. *International Institute for Environment and Development. Available at: https://pubs. iied. org/pdfs/17636IIED. pdf (accessed 22 February 2021)*.

Romijn, G. and Renes, G. (2013). *Algemene leidraad voor maatschappelijke kosten-batenanalyse*. Centraal Planbureau (CPB).

Roorda, N. (2017). *Fundamentals of Sustainable Development*. Routledge.

Rosenzweig, C., Gaffin, S., and Parshall, L. (2006a). Green roofs in the new york metropolitan region: research report. *Columbia University center for climate systems research and NASA Goddard institute for space studies*, 59.

Rosenzweig, C., Solecki, W., and Slosberg, R. (2006b). Mitigating new york city's heat island with urban forestry, living roofs, and light surfaces. *A report to the New York State Energy Research and Development Authority*.

Rosenzweig, C., Solecki, W. D., Hammer, S. A., and Mehrotra, S. (2011). *Climate change and cities: First assessment report of the urban climate change research network*. Cambridge University Press.

RTL Nieuws (2014). Available at `https://www.rtlnieuws.nl/nieuws/nederland/fotoserie/1579461/beeld-wateroverlast-nederland` (15-02-2023).

Sabeh, N. (2020). Rooftop plant production systems in urban areas. In *Plant factory*, pages 129–135. Elsevier.

Saiz, S., Kennedy, C., Bass, B., and Pressnail, K. (2006). Comparative life cycle assessment of standard and green roofs. *Environmental science & technology*, 40(13):4312–4316.

Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., Dirks, K. N., Heaviside, C., Lim, S., Macintyre, H., et al. (2016). Health and climate related ecosystem services provided by street trees in the urban environment. *Environmental Health*, 15(1):95–111.

Sattler, S., Zluwa, I., and Österreicher, D. (2020). The "pv rooftop garden": Providing recreational green roofs and renewable energy as a multifunctional system within one surface area. *Applied Sciences*, 10(5):1791.

Schafft, M., Wegner, B., Meyer, N., Wolter, C., and Arlinghaus, R. (2021). Ecological impacts of water-based recreational activities on freshwater ecosystems: a global meta-analysis. *Proceedings of the Royal Society B*, 288(1959):20211623.

Scharf, B. and Zluwa, I. (2017). Case study investigation of the building physical properties of seven different green roof systems. *Energy and buildings*, 151:564–573.

Schrieke, D., Lönnqvist, J., Blecken, G.-T., Williams, N. S., and Farrell, C. (2021). Socio-ecological dimensions of spontaneous plants on green roofs. *Frontiers in Sustainable Cities*, 3:777128.

Scolaro, T. P. and Ghisi, E. (2022). Life cycle assessment of green roofs: A literature review of layers materials and purposes. *Science of The Total Environment*, page 154650.

Shafique, M., Azam, A., Rafiq, M., Ateeq, M., and Luo, X. (2020). An overview of life cycle assessment of green roofs. *Journal of Cleaner Production*, 250:119471.

Shafique, M., Kim, R., and Rafiq, M. (2018). Green roof benefits, opportunities and challenges–a review. *Renewable and Sustainable Energy Reviews*, 90:757–773.

Shazmin, S., Sipan, I., Sapri, M., Ali, H., and Raji, F. (2017). Property tax assessment incentive for green building: Energy saving based-model. *Energy*, 122:329–339.

Shinderman, M. (2015). Introduction to sustainability as a distinct worldview with emphasis on the ecological domain. In *Reference Module in Earth Systems and Environmental Sciences*. Elsevier.

Shushunova, N. S., Korol, E. A., and Vatin, N. I. (2021). Modular green roofs for the sustainability of the built environment: The installation process. *Sustainability*, 13(24):13749.

Simmons, J. and Lovegrove, I. (2005). Bridging the conceptual divide: lessons from stakeholder analysis. *Journal of Organizational Change Management*, 18(5):495–513.

7

Singh, A., Berghorn, G., Joshi, S., and Syal, M. (2011). Review of life-cycle assessment applications in building construction. *Journal of architectural engineering*, 17(1):15–23.

Smith, K. R. and Roebber, P. J. (2011). Green roof mitigation potential for a proxy future climate scenario in chicago, illinois. *Journal of applied meteorology and climatology*, 50(3):507–522.

Soukka, R., Väisänen, S., Grönman, K., Uusitalo, V., and Kasurinen, H. (2020). Life cycle assessment. *Encyclopedia of Sustainable Management*.

Sproul, J., Wan, M. P., Mandel, B. H., and Rosenfeld, A. H. (2014). Economic comparison of white, green, and black flat roofs in the united states. *Energy and Buildings*, 71:20–27.

Stache, E., Jonkers, H., and Ottelé, M. (2019). Integration of ecosystem services in the structure of the city is essential for urban sustainability. *Ecological wisdom inspired restoration engineering*, pages 131–150.

Standardization, I. (2006). Environmental management: life cycle assessment: principles and framework. *Vol. ISO*, 14040.

Standish, R. J., Hobbs, R. J., and Miller, J. R. (2013). Improving city life: options for ecological restoration in urban landscapes and how these might influence interactions between people and nature. *Landscape ecology*, 28(6):1213–1221.

STOWa (2023). Transport van afvalwater. Available at `https://www.saniwijzer.nl/technieken/transport-afvalwater` (15-07-2023).

Sugimoto, K., Matsui, K., and Takabayashi, J. (2016). Uptake and conversion of volatile compounds in plant–plant communication. In *Deciphering Chemical Language of Plant Communication*, pages 305–316. Springer.

Sun, T., Bou-Zeid, E., and Ni, G.-H. (2014). To irrigate or not to irrigate: Analysis of green roof performance via a vertically-resolved hygrothermal model. *Building and Environment*, 73:127–137.

Suryasari, N., Antariksa, L. D. W., and Santosa, H. (2022). Formal aesthetics of the facades of historical public buildings (dutch east indies architecture in malang).

Susca, T., Gaffin, S. R., and Dell'Osso, G. (2011). Positive effects of vegetation: Urban heat island and green roofs. *Environmental pollution*, 159(8-9):2119–2126.

Sustainability Impact Metrics (2023). Available at `url={https://www.ecocostsvalue.com/lca/eco-costs-estimate-epds/}` (10-7-2023).

Tan, P. Y. and Sia, A. (2005). A pilot green roof research project in singapore. In *Proceedings of third annual greening rooftops for sustainable communities conference, Awards and Trade Show, Washington, DC*. Citeseer.

Telos, H. P. . (2022). Duurzaamheidsscore nederlandse gemeenten 2022 [fact sheet]. Technical report.

Ten Brink, P. (2012). *The economics of ecosystems and biodiversity in national and international policy making*. Routledge.

Teotónio, I., Cabral, M., Cruz, C. O., and Silva, C. M. (2020). Decision support system for green roofs investments in residential buildings. *Journal of Cleaner Production*, 249.

Teotónio, I., Silva, C. M., and Cruz, C. O. (2018). Eco-solutions for urban environments regeneration: The economic value of green roofs. *Journal of Cleaner Production*, 199:121–135.

Teotónio, I., Silva, C. M., and Cruz, C. O. (2021). Economics of green roofs and green walls: A literature review. *Sustainable Cities and Society*, 69:102781.

Teotónio, I., Oliveira Cruz, C., Matos Silva, C., and Morais, J. (2020). Investing in sustainable built environments: The willingness to pay for green roofs and green walls. *Sustainability*, 12(8):3210.

The Economics of Ecosystems and Biodiversity (TEEB) (2010). Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of teeb. *United Nations Environment Programme*.

Tomalty, R. and Komorowski, B. (2010). *The Monetary Value of the Soft Benefits of Green Roofs*. PhD dissertation, Smart Cities ResearchServices, Montreal.

Tong, Z., Whitlow, T. H., Landers, A., and Flanner, B. (2016). A case study of air quality above an urban roof top vegetable farm. *Environmental Pollution*, 208:256–260.

Toniolo, S., Tosato, R. C., Gambaro, F., and Ren, J. (2020). Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment. In *Life Cycle Sustainability Assessment for Decision-Making*, pages 39–56. Elsevier.

transitieteam circulaire bouweconomie (2018). transitie-agenda circulaire economie.

transitieteam circulaire bouweconomie (2022). transitieteam advies circulaire economie.

Triami Media (2022). Historische inflatie nederland – historische cpi inflatie nederland. Available at `https://www.inflation.eu/nl/inflatiecijfers/nederland/historische-inflatie/cpi-inflatie-nederland.aspx` (15-07-2023).

Tribe, J. (2020). *The economics of recreation, leisure and tourism*. Routledge.

Tripathy, D. P. (2008). *Noise pollution*. APH Publishing.

Turner, R. K., Paavola, J., Cooper, P., Farber, S., Jessamy, V., and Georgiou, S. (2003). Valuing nature: lessons learned and future research directions. *Ecological economics*, 46(3):493–510.

Udo, J., Janssen, L., and Kruitwagen, S. (2006). Stilte heeft zijn'prijs'. *Silence has its price), Economisch Statistische Berichten*, 83:14–16.

Ulubeyli, S. and Arslan, V. (2017). Economic viability of extensive green roofs through scenario and sensitivity analyses: Clients' perspective. *Energy and Buildings*, 139:314–325.

United Nations (2022). Cities - united nations sustainable development action 2015.

van den Bos, S. (2021). How green is the rotterdam roofscape?

van der Meulen, S. H. (2019). Costs and benefits of green roof types for cities and building owners. *Journal of sustainable development of energy, Water and Environment Systems*, 7(1):57–71.

van Moppes, D. and Klooster, J. (2008). Groene daken rotterdam maatschappelijke kosten-baten analyse.

Van Renterghem, T. and Botteldooren, D. (2008). Numerical evaluation of sound propagating over green roofs. *Journal of sound and vibration*, 317(3-5):781–799.

Van Renterghem, T. and Botteldooren, D. (2009). Reducing the acoustical façade load from road traffic with green roofs. *Building and environment*, 44(5):1081–1087.

Van Renterghem, T. and Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. *Building and environment*, 46(3):729–738.

Van Renterghem, T., Hornikx, M., Forssen, J., and Botteldooren, D. (2013). The potential of building envelope greening to achieve quietness. *Building and Environment*, 61:34–44.

van Riel, W. (2011). *Exploratory study of pluvial flood impacts in Dutch urban areas.* Deltares.

Vermeulen, S. and Koziell, I. (2002). Integrating global and local values: a review of biodiversity assessment.

Versini, P.-A., Gires, A., Tchiguirinskaia, I., and Schertzer, D. (2020). Fractal analysis of green roof spatial implementation in european cities. *Urban Forestry & Urban Greening*, 49:126629.

Vijayaraghavan, K. and Raja, F. D. (2014). Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption. *Water research*, 63:94–101.

Vogtlander, J. (2023). *Lca: a practical guide for students, designers and business managers*. Delft Academic Press, sixth edition.

Vogtländer, J. G. (2023). *Eco-efficiënt Value Creation, Sustainable Strategies for the Circular Economy*. Delft Academic Press, third edition.

Walters, S. A. and Stoelzle Midden, K. (2018). Sustainability of urban agriculture: Vegetable production on green roofs. *Agriculture*, 8(11):168.

Wang, J. and He, D. (2015). Sustainable urban development in china: Challenges and achievements. *Mitigation and adaptation strategies for global change*, 20(5):665–682.

Wang, M. Q. and Santini, D. J. (1995). Monetary values of air pollutant emissions in various us regions. *Transportation Research Record*, (1475).

Wang, X., Li, H., and Sodoudi, S. (2022). The effectiveness of cool and green roofs in mitigating urban heat island and improving human thermal comfort. *Building and Environment*, 217:109082.

Wang, Y., Ni, Z., Hu, M., Li, J., Wang, Y., Lu, Z., Chen, S., and Xia, B. (2020). Environmental performances and energy efficiencies of various urban green infrastructures: A life-cycle assessment. *Journal of Cleaner Production*, 248:119244.

William, R., Goodwell, A., Richardson, M., Le, P. V., Kumar, P., and Stillwell, A. S. (2016). An environmental cost-benefit analysis of alternative green roofing strategies. *Ecological Engineering*, 95:1–9.

Williams, N. S., Rayner, J. P., and Raynor, K. J. (2010). Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in australia. *Urban forestry & urban greening*, 9(3):245–251.

Wong, N. H., Cheong, D. W., Yan, H., Soh, J., Ong, C., and Sia, A. (2003a). The effects of rooftop garden on energy consumption of a commercial building in singapore. *Energy and buildings*, 35(4):353–364.

Wong, N. H., Tay, S. F., Wong, R., Ong, C. L., and Sia, A. (2003b). Life cycle cost analysis of rooftop gardens in singapore. *Building and environment*, 38(3):499–509.

Wooster, E., Fleck, R., Torpy, F., Ramp, D., and Irga, P. (2022). Urban green roofs promote metropolitan biodiversity: A comparative case study. *Building and Environment*, 207:108458.

World Health Organization (2018). *Environmental noise guidelines for the European region.* World Health Organization. Regional Office for Europe.

World Health Organization (2021). What are the who air quality guidelines?

worldpopulationreview (2023). Available at `https://worldpopulationreview.com/country-rankings/countries-by-density` (5-07-2023).

WTCB (2006). volume technische voorlichting. 229 edition.

Xi, L., Zhang, M., Zhang, L., Lew, T. T., and Lam, Y. M. (2022). Novel materials for urban farming. *Advanced Materials*, 34(25):2105009.

Xue, J., Shen, G. Q., Yang, R. J., Wu, H., Li, X., Lin, X., and Xue, F. (2020). Mapping the knowledge domain of stakeholder perspective studies in construction projects: A bibliometric approach. *International journal of project management*, 38(6):313–326.

Yang, J., Yu, Q., and Gong, P. (2008). Quantifying air pollution removal by green roofs in chicago. *Atmospheric environment*, 42(31):7266–7273.

Yang, L., Qian, F., Song, D.-X., and Zheng, K.-J. (2016). Research on urban heat-island effect. *Procedia engineering*, 169:11–18.

Yao, L., Chini, A., and Zeng, R. (2020). Integrating cost-benefits analysis and life cycle assessment of green roofs: a case study in florida. *Human and Ecological Risk Assessment: An International Journal*, 26(2):443–458.

Zachariadis, T. and Hadjikyriakou, C. (2016). *Social costs and benefits of renewable electricity generation in Cyprus.* Springer.

Zhang, C., Li, J., and Zhou, Z. (2022a). Ecosystem service cascade: Concept, review, application and prospect. *Ecological Indicators*, 137:108766.

Zhang, G. and He, B.-J. (2021). Towards green roof implementation: Drivers, motivations, barriers and recommendations. *Urban forestry & urban greening*, 58:126992.

Zhang, X., Han, L., Wei, H., Tan, X., Zhou, W., Li, W., and Qian, Y. (2022b). Linking urbanization and air quality together: A review and a perspective on the future sustainable urban development. *Journal of Cleaner Production*, page 130988.

Zhang, Y., Zhao, W., Chen, X., Jun, C., Hao, J., Tang, X., and Zhai, J. (2020). Assessment on the effectiveness of urban stormwater management. *Water*, 13(1):4.

Zihlmann Sánchez, V. (2023). Stakeholder analysis on the current situation and possible integration of nature-based solutions in zurich and investigation of cooling efficiency and improvement of outdoor thermal conditions with nature-based solutions in novi sad.

Zinco (2020). System data sheet “light green roof” with floraset® fs 75. Technical report, ZinCo GmbH.

ZinCo GmbH (2020). “heather with lavender” green roof system. Technical Report EPD-ZIC-20200082-CCA1-EN, Institut Bauen und Umwelt e.V. (IBU), Berlin.

Ziogou, I., Michopoulos, A., Voulgari, V., and Zachariadis, T. (2017). Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm mediterranean region. *Journal of Cleaner Production*, 168:346–356.

Ziogou, I., Michopoulos, A., Voulgari, V., and Zachariadis, T. (2018). Implementation of green roof technology in residential buildings and neighborhoods of cyprus. *Sustainable cities and society*, 40:233–243.

Zuo, J., Pullen, S., Rameezdeen, R., Bennetts, H., Wang, Y., Mao, G., Zhou, Z., Du, H., and Duan, H. (2017). Green building evaluation from a life-cycle perspective in australia: A critical review. *Renewable and Sustainable Energy Reviews*, 70:358–368.

A

KEY LITERATURE IDENTIFICATION

The section below discusses how the bibliography from Teotónio et al. paper 'Economics of green roofs and green walls: A literature review' was filtered into a list suitable for the application in this research. The base step is provided to clearly define the scientific framework of Teontonio's approach upon which this research could work in advance. Constraint by limited time available for this study, it was decided to put reliance on the manual filtering done from 370 to 79 reports. Hence, the content analysis of the different reports in the paper could be used likewise. The next steps continue to reduce the list based on content information as it emerged in the paper. Finally, a manageable list emerged that directly related to this study. The steps taken substantiate the argument that a self made literature filter set-up from scratch, would emerge a similar list of reports.

A.1. LITERATURE SELECTION PROCESS: TEOTONIO'S INITIAL PROCESS

The approach of Teotonio's initial methodology took the following steps:

- First stage: Publications from Web of Science
  Search term: *cost-benefit analysis green infrastructures of ecosystem services*
- Second stage: Publications from Science Direct
  Search term: *cost-benefit analysis green infrastructures of ecosystem services*
  Due to the broad and extensive content of this database, only papers on green roofs and walls were included

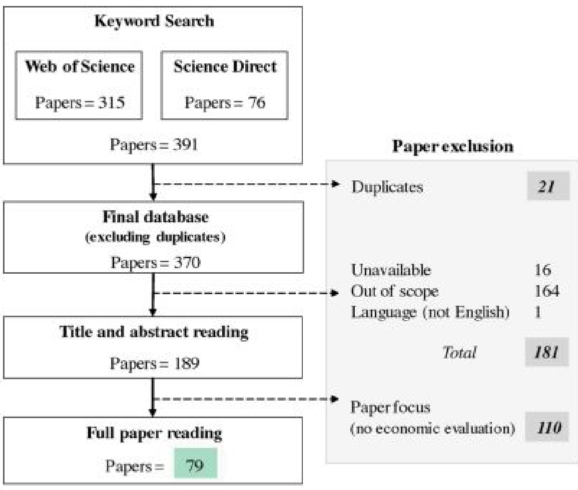

Figure A.1: Screening procedure of papers, From Teotónio et al. (2021)

Both stages searched for the search terms in the papers and identification of the terms in title, abstract or keywords. Duplicates were excluded which resulted in 370 papers published until the end of 2019. Unavailable papers or those not written in English were excluded. The papers were then assessed for relevance based on the abstract and title. The list of 189 papers that remained was fully examined in terms of content and on this basis, the final sifting was done. The final number of papers that met the requirements was 79, see figure A.1. These sources were then developed in their entirety within Teotonio's paper. These sources can be found in Appendix C Table C1 of the study.

A.2. LITERATURE SELECTION PROCESS: FILTERING OF SCOPE SPECIFIC PAPERS

In the elaboration of the 79 papers, numerous categories and subdivisions were identified. Because these offer insight into the various papers, it was chosen to use this information as a guideline to steer the screening part of the filtering of the literature. Different aspects of the papers were highlighted and the ones that were chosen were based on the scope of this study. Additionally the list as emerged from this screening procedure were read in entirety, and the eligibility was finally based on the research scope, see figure A.2.

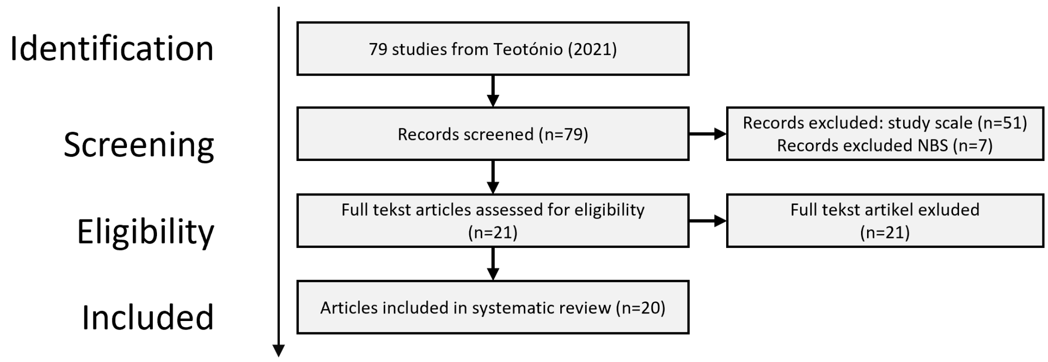

Figure A.2: Flow diagram for the identification, screening, eligibility, and inclusion of studies. Reasons for full text exclusion was the duration of the study

A.2.1. SCREENING: RESEARCH SCALE

Teotónio et al. distinguished between 3 different scale levels; building, site and urban scale. The case study followed an approach for the effects of implementing a green roof on a single building, therefore, only the studies related to the scale of a building were included the rest were filtered out. Despite the fact that the omitted studies can offer insights on the behaviour of green roof application, it is expected that there is a difference between a large-scale implementation and the effects of a single individual. This includes the effect of cooperation between different roofs.

It was expected that many of the values identified in studies on bigger scales cannot be linearly scaled back to the scale level of a building. Teontonio describes this as follows: ''Most benefits have a significant impact on a district-urban scale project. However, if the analysis is downscaled to a single building, some benefits lose their significance as they have limited contribution towards city-scale goals. For example, the potential of a 200 square meter green roof towards improving the air quality of a city is negligible." However, on the other hand, there are studies that have tried to scale the environmental benefits of green roofs from individual buildings to the city scale (Teotónio et al., 2021). In this case, however, we chose to exclude site- and city-scale studies.

For this study, the impact of applying a green roof to a single building is considered. This drops off studies that are outside this scope:

- 12 Urban Studies
- 2 Urban/Site Studies
- 35 Site Studies
- 2 Undefined studies

After this step, 28 studies are left.

A

A.2.2. SCREENING: NATURE BASED SOLUTION

The focus of the next step looks at the specific interpretation of green infrastructure in the papers. As a result of Teontonio's research design, the list of studies now consists of studies with different interpretations of GI. In it, there are studies comparing alternatives GI infill, or comparing a single GI solution with a null test. Teontonio identified the environmental solution used for each study. Common ones are nature-based solutions, green roofs, green facades/living walls, street trees and porous pavements. The focus of this study is on green roofs only, therefore all studies investigating EGR and/or IGR were considered. The other studies were excluded through this criteria. Subsequently, only studies investigating green roof:

- 7 studies

After step 3, 21 studies are left.

A.2.3. ELIGIBILITY

The literature list was run through to identify in advance any sources outside the scope of the analysis. Based on an initial scan of the list of literature, 1 more source was found that should not be included in the further literature study. This is the source from Sun et al. (2014). Based on the analysis by Teontonio, it emerged that the time horizon of this study is only 63 days. In view of the design of this study, it was decided that the paper therefore has insufficient connection with this study and will not be included.

A.3. FINAL LIST OF PAPERS

A list of 20 papers is the result of the focus and filtering of the original list provides by Teotónio et al. (2021). The list of their respective location can be found in table A.1, a figure highlighting the location of the countries in A.3, and a figure of the location of the cities in A.4. These sources will form the basis in further analysis.

Table A.1: Literature list

Study	Location	Time [years]
Wong et al, 2003	Singapore	40
Clark et al., 2008	Michigan	40
Carter and Keeler, 2008	Athens (USA)	40
Chang et al., 2011	Florida	50
Claus and Rousseau, 2012	Flanders	50
Ascione et al., 2013	Spain, Italy, Netherlands, United Kingdom, Norway	-
Sproul et al., 2014	Illinois, Washington DC, New York, Virginia, Georgia, Florida, Orlando, Texas, California, Arizona	50
Machác et al., 2016	Prague-Jinonice	50
McRae, 2016	San Antonio	25
Mahdiyar et al, 2016	Kuala Lumpur	50
William et al., 2016	Illinois	39
Ziogou et al., 2017	Larnaca, Limassol, Nicosia, Paphos	20
Ulubeyli and Arslan, 2017	Turkey	40
Shazmin et al., 2017	Kulai, Johor	-
Berto et al., 2018	Trieste	40
Ziogou et al., 2018	Nicosia, Larnaca, Limassol, Paphos	30
Kim et al., 2018	Seoul	40
Alves et al. 2019	Sint Martin Island	30
Niu et al., 2010	Washington DC	40
Teotónio et al., 2018	Lisbon	40

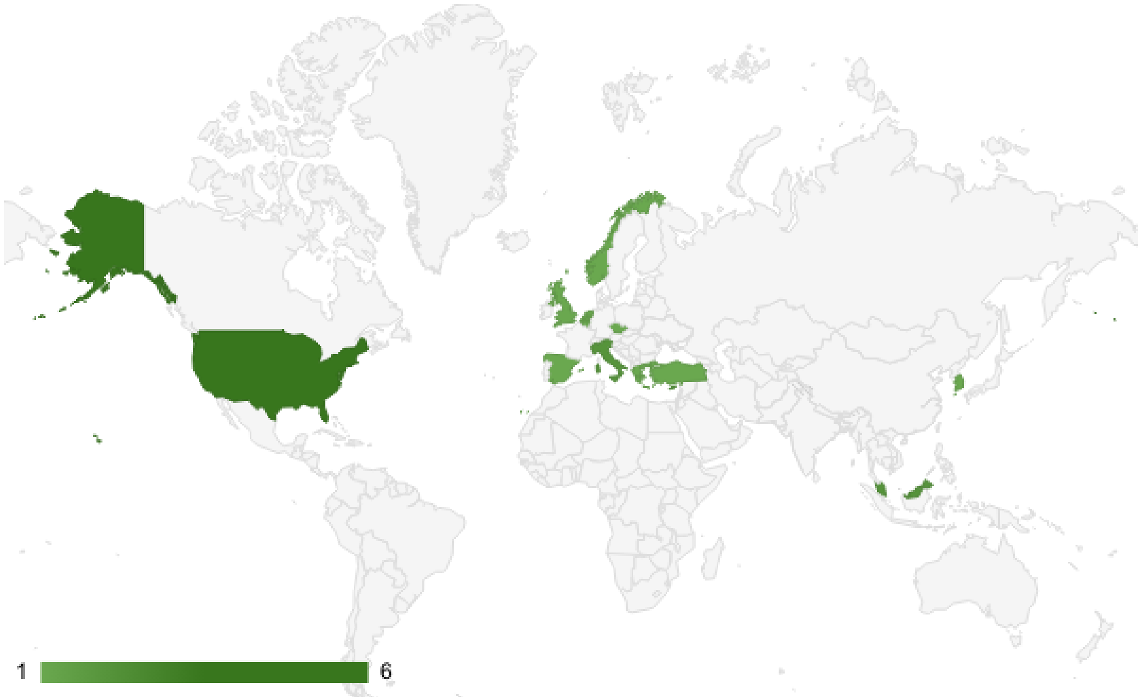

Figure A.3: Location the countries of the twenty studied sources, duplication countries within one study have beeen counted as 1

A.3.1. LIMITATIONS WITH REGARDS TO THE IDENTIFIED LITERATURE

In formulating the current literature to be analysed, specific choices and assumptions were made regarding the design and delineation of the study. All these choices affect the final results of the literature review. Therefore, it is essential to offer critical reflection on the choices made in order to reveal any limitations of the study. Moreover, these limitations play an important role in delineating the appropriate scope of the study. This chapter reflects in depth on the choices made regarding the selected literature and discusses their implications for the final results.

- **Reliability regarding potential bias used methodologies**
  Within the design of this study, it was decided to extract computational methods from existing peer-reviewed literature reviews that have focused on the economic analysis of green roofs. Within this, there is the possibility that potential bias is unknowingly present in the studies. Efforts have been made to identify potential conflicting interests of the authors of the various studies, but in many cases this is not explicitly stated. It has been assumed that the papers are of reliable nature based on their publication in recognised scientific journals. Nevertheless, it is important to be critical of the information provided. A critical view on each of the methodologies is used as a way to eliminate this potential bias within the information.
- **Reliability regarding potential used information**
  By relying on these existing studies, considerable preliminary work has already been done, allowing for comparison of existing methodologies. However, it is important to note that this choice skips a step in the process. This is because each of these studies has interpreted economic analysis in a unique way, based on existing literature knowledge. This implies that some of the existing information will not be included in this study based on the earlier made choices. In particular, this includes information related to the quantification and valuation of ecosystem services and ecosystem benefits. The design of these studies is mainly aimed at conducting an economic analysis, and therefore the information used will also be specifically aimed at providing insights for this analysis. This means that some of the information in the literature based on this study may not be explicitly highlighted. That is why this study cannot give of a representative overview of the existing information regarding the quantitative information. Careful consideration of the claims made within this research is used as a way to eliminate the potential to make incorrect claims about the availability of information within the literature.

A

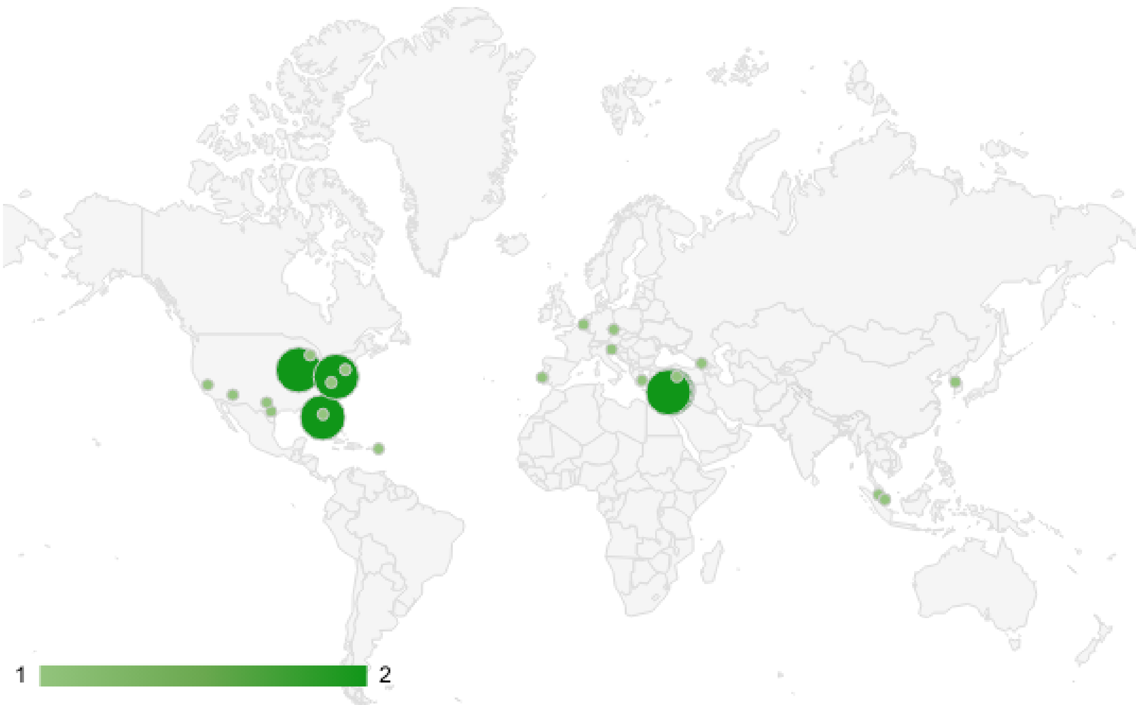

Figure A.4: Location the cities of the twenty studied sources

B
Ecosystem services

This appendix finds a classification for the ecosystem services of a green roof. First, the importance of this is mapped through a brief introduction then the ecosystem services in general were first looked at on a macro level. Then, using various studies, we zoomed in on the services of a green roof.

B.1. Importance of ecosystem services in cities

The growth of cities and urbanisation are complex processes with strong links to biophysical and ecological processes. On the one hand, cities exert influence on the biophysical environment, for example through changes in land use, management of water and waste streams and greenhouse gas emissions. On the other hand, cities also depend on the services provided by the biophysical environment, such as climate regulation and water management. Understanding these interactions is crucial for developing sustainable urban systems that support and sustain people and nature. Green roofs can add additional green within the cities. Examining the dependence of city dwellers on biodiversity and ecosystem services is seen by McDonald et al. (2013) as one of two ways of analysing city-environment interactions. General classifications must be adjusted to fit particular types of ecosystems since different habitats offer various sorts of ecosystem services (Gómez-Baggethun and Barton, 2013), see figure B.1.

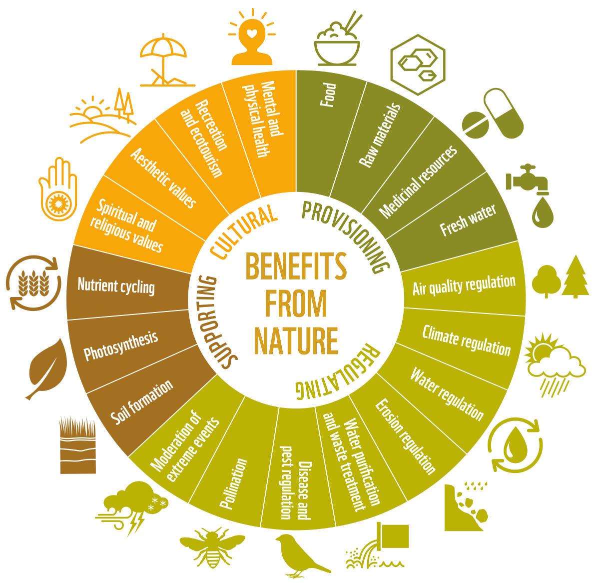

Figure B.1: Different types of ecosystem services or benefits from nature. From Grooten et al. (2018)

B

B.1.1. CATEGORISATION OF ECOSYSTEM SERVICES

First, we looked at the general services we obtain from nature. In this, different classifications can be found. These classifications indicate the importance of these systems by making them understandable. In this, nature offers a wide range of services and goods that benefit human well-being (Grooten et al., 2018). A commonly used distinction in these services is that of Millennium Ecosystem Assessment (2005) and adapted by De Groot et al. (2010a), distinguishing between supporting, cultural, provisioning and regulating services, see table B.1.

Table B.1: Potential indicators for determining (sustainable) use of ecosystem services. Adjusted from De Groot et al. (2010a)

Services comments	**Ecological process and/or component**	**State indicator**
Provisioning		
Food	Presence of edible plants and animals	Total or average stock in kg/ha
Water	Presence of water reservoirs	Total amount of water (m3/ha)
Fiber & Fuel & other raw materials	Presence of species or abiotic components with potential use for timber, fuel or raw material	Total biomass (kg/ha)
Genetic Materials	Presence of species with (potentially) useful genetic material	Total “gene bank” value
Biochemical products and medicinal resources	Presence of species or abiotic components with potentially useful chemicals and/or medicinal use	Total amount of useful substances that can be extracted (kg/ha)
Ornamental species and/or resources	Presence of species or abiotic resources with ornamental use	Total biomass (kg/ha)
Regulating		
Air quality regulation	Capacity of ecosystems to extract aerosols & chemicals from the atmosphere	Leaf area index NOx-fixation, etc.
Climate Regulation	Influence of ecosystems on local and global climate through land-cover and biologically-mediated processes	Greenhouse gas-balance (esp. C-sequestration); Land cover characteristics, etc.
Natural Hazard mitigation	Role of forests in dampening extreme events	Water-storage (buffer) capacity in m3
Water regulation	Role of forests in water infiltration and gradual release of water	Water retention capacity in soils, etc. or at the surface
Waste treatment	Role of biota and abiotic processes in removal or breakdown of organic matter, xenic nutrients and compounds	Denitrification (kg N/ha/y); Immobilization in plants and soil
Erosion protection	Role of vegetation and biota in soil retention	Vegetation cover Root-matrix
Soil formation and regeneration	Role of natural processes in soil formation and regeneration	E.g. bio-turbation
Pollination	Abundance and effectiveness of pollinators	Number & impact of pollinating species
Biological Regulation	Control of pest populations through trophic relations	Number & impact of pest-control species
Habitat or supporting		
Nursery habitat	Importance of ecosystems to provide breeding, feeding or resting habitat for transient species	Number of transient species & individuals (esp. with commercial value)
Genepool protection	Maintenance of a given ecological balance and evolutionary processes	Natural biodiversity (esp. endemic species)
Cultural & amenity		
Aesthetic	Aesthetic quality of the landscape	Number/area of landscape features with stated appreciation
Recreational	Landscape-features Attractive wildlife	Number/area of landscape & wildlife features with stated recreational value
Inspiration for culture, art and design	Landscape features or species with inspirational value to human arts, etc.	Number/area of Landscape features or species with inspirational value
Cultural heritage and identity	Culturally important landscape features or species	Number/area of culturally important landscape features or species
Spiritual & religious inspiration	Landscape features or species with spiritual & religious value	Presence of Landscape features or species with spiritual value
Education & science	Features with special educational and scientific value/interest	Presence of features with special educational and scientific value/interest

This distinction offers insight into the different categories to which ecosystems can contribute in both direct and indirect ways. The ecosystem services is the table also show the multidimensional contribution of nature. However, this multi-functional nature also means that this classification is not directly generally applicable as stated above.

B.2. CATEGORISING GREEN ROOF SERVICES

The previous chapter showed that ecosystems have a multidimensional nature. However, this also ensures that there are chances of overlooking certain services. Therefore, we chose to look at multiple studies in order to arrive at an accurate understanding for this study.

Within various fields, green roofs offer a valuable contribution and solution, making them a multi-purpose tool. In the various literary papers that have been published on the ecosystem services of green roofs, various services have been included in the evaluation (Teotónio et al., 2018). In 2014, a research was conducted by Li and Babcock Jr (2014), covering 350 papers related to diverse fields such as engineering, environmental sciences, agronomy, architecture and ecology. Based on these papers, 10 topic areas were identified, including thermal effects, runoff quality, hydrology and more. The services included were determined by the specific perspective of the research and the availability of relevant information to support the claims. The fact that sometimes certain services have been excluded based on their relevance to the study was also found by Teotónio et al. (2018). This strengthens the claim of the multi functionality of green roofs. In addition, it stated that some of the studies also show that the scale level may affect the ecosystem services included. In other cases, however, it is not immediately clear why certain services were included and others not. This can lead to a degree of arbitrariness and detract from the comprehensiveness of the study, where all options are considered.

Within the literature, there has been a significant amount of research on the various ecosystem services provided by green roofs. A number of papers, including Oberndorfer et al. (2007), Shafique et al. (2018), Jones et al. (2019) and Nguyen et al. (2022) have tried to provide an overview of the benefits of green roofs, distinguishing between different categories, see table B.2. However, the classification of these papers lack depth in terms of the social and economic benefits of green roofs as seen in De Groot et al. (2010b), preventing a proper foundation for categorisation. The papers which do name and provide a certain amount of information on the social and economic benefits of green roofs, cannot be used as an holistic foundation, especially when the content is compared to other papers. Thus, these classifications have not been found to be comprehensive and leave room for own interpretation.

Table B.2: Green roof services from Jones et al. (2019), Oberndorfer et al. (2007), Nguyen et al. (2022) and Shafique et al. (2018).

Author	**Jones et al. (2019)**	**Oberndorfer et al. (2007)**	**Nguyen et al. (2022)**	**Shafique et al. (2018)**
Title	Quantifying the benefits of green infrastructure in Melbourne	Green roofs as urban ecosystems: ecological structures, functions, and services	Quantifying the benefits and ecosystem services provided by green roofs—a review.	Green roof benefits, opportunities and challenges – A review.
Services	Storm water	Storm-water management	Runoff reduction	Stormwater retention to reduce peak flow and runoff
		Water quality	Runoff quality improvement	Water quality enhancement for water utilization
	Cooling buildings and cities	Summer cooling	Energy use reduction	Thermal benefits to improve the environment and reduce energy costs
		Urban heat island	HTC improvement	
	Biodiversity	Urban habitat values		Ecological benefits
	Health and well being	Community and landscape properties	Ecological, social and economic	Social benefits
				Economic benefits
		Improving roof membrane longevity		
		Air quality	Air quality improvement	Air cleaning for easy comfort into urban areas
		Ecosystems services and community properties		
			Noise reduction	Noise reduction

ADOPTED CATEGORISATION FOR GREEN ROOF SERVICES

Two categorisations finally emerged that were used together with the knowledge of previous categorisations as the basis for this research. The first paper, called "Towards green roof implementation: drivers, motivations, barriers and recommendations" by Zhang and He (2021), describes various factors influencing the implementation of green roofs and provides recommendations for promoting the adoption of this technology. The categorisation is extracted from, what is in the paper described as the motivations to green roof implementation. This categorisation provides insight into a wide variety of services including the social and economic services of green roofs and is therefore of great value.

The second paper, called "Economics of green roofs and green walls: A literature review" by Teotónio et al. (2021), focuses specifically on the economic benefits of green roofs. This research included a systematic review of 79 scientific papers, with a special focus on qualitative and quantitative analysis of these papers. This paper describes the various costs and benefits of green roofs and provides insight into the financial viability of this technology. Also, the categorisation made herein can serve as an important starting point for understanding the full range of benefits of green roofs.

Table B.3 presents the different headers from the two papers side by side, with corresponding headers placed next to each other. These analyses show that multiple categorisations of ecosystem services of green roofs are available within the literature. By combining and analysing these, we can gain a better understanding of the various benefits that green roofs provide and contribute to the development of sustainable solutions to urban challenges.

Table B.3: Categorisation used by Teotónio et al. (2021) and Zhang and He (2021)

Zhang and He (2021)	**Teotónio et al. (2021)**
Energy efficiency	Energy consumption
Urban heat island mitigation	Urban heat island mitigation
Longevity prolongation	Longevity (system)
Air purification	Air quality
Runoff control	Flood risk control
Water purification	Runoff quality
Urban infrastructure improvement	Storm water management
Sound insulation and noise reduction	Sound insulation
	Urban noise reduction
Biodiversity increase	Biodiversity / habitat creation
Recreation and aesthetics	Recreation
	Aesthetics
Property value enhancement	-
Employment improvement	-
-	Health and well-being
-	Production (eg. food, wood)

Comments based on the two categorisations:

- First of all, it is worth noting that both papers have certain categories that are not mentioned in the other. Specifically, the categories of "property value enhancement" and "employment improvement" are absent in Teotonio's paper. In Zhang's paper, the concept of property value enhancement is discussed as a direct result of green roofs, highlighting their role in achieving this outcome. This assertion is supported by data from Bianchini and Hewage (2012a). However, in the context of the cascade framework, property value enhancement can be seen as a consequence of an ecosystem service rather than an ecosystem service itself, the same can be said about employment enhancement. Therefore, it is more appropriate to classify it as a benefit rather than a separate category within the ecosystem services framework.

- From a content perspective, a critical evaluation was carried out regarding the title of the "Energy efficiency/consumption" section. This process was guided by the description of this specific service as outlined in Zhang et al. (2021). According to this description, the energy efficiency improvement of a building is attributed to the reduction of cooling load in summer and its positive effects in winter. The reduction in energy demand is thus associated with the impact of the green roof on the thermal insulation of the building. Given the central focus on the social-ecological aspect in this study, it is crucial that these intermediate steps are adequately highlighted so that the actual mechanism can be unravelled.
Based on these findings, it is concluded that the chosen title "Energy efficiency/consumption" is misleading. Indeed, this title may lead to double counting of energy saving effects already covered in one of the other subcategories. To avoid this, it was decided to change the title to "Thermal insulation".

This new title gives a more accurate indication of the actual contribution of the green roof, while the resulting benefit can still be described as energy savings. This approach also resonates with the similar subcategory of sound insulation. It is therefore essential to use the correct title so that the study is presented and interpreted correctly.

- In Teotonio's categorization, a specific order of arrangement is not evident. However, when considering the content, it is important to present similar groups in close proximity to enhance clarity and coherence. This approach is effectively demonstrated in Zhang's study, where various benefits related to a specific theme are presented side by side. For example, Zhang organizes the benefits associated with water impact as "runoff control," "water purification," and "urban infrastructure improvement," which are listed together. Similarly, the advantages of sound insulation and noise reduction are also placed adjacent to each other in Zhang's study. In contrast, Teotonio's categorization does not place "sound insulation" and "urban noise reduction" in immediate succession. From a substantive standpoint, arranging similar groups in close proximity is beneficial for a more coherent representation of the content.

C
SETUP LITERATURE ANALYSIS GREEN ROOF BENEFITS

The design of the study results in new insights by systematically reviewing the existing literature. The author specifically chose not to reinvent the wheel, but to summarise existing practice. From this, standard methods can be derived that are used to assign a value to the various ecosystem services. The knowledge obtained from the literature can then be reflected upon to answer the research question whether an answer can be given based on the current literature. The aim is not to reach definitive conclusions; rather, the open-ended format is intended to encourage conversation about how the literature deals with these ecosystem services and the value judgements associated with them. Moreover, this knowledge is not directly taken as truth, but rather points of discussion are raised and recommendations are given for follow-up research. The research is complete when the full content of the literature from the list, as described in table 2.1, has been identified.

The literature is analysed with the goal to convert the services of a green roof into benefits and a monetary value. For this purpose, the ecosystem services as described in figure 2.11 have been analysed based on the earlier given information regarding the cascade framework, project evaluation tools and the involved stakeholders. The ecosystem services according to this classification will be dealt with systematically.

This includes a trade-off between the level of detail to be covered and the scope of this study. An economic analysis mainly looks at the outcomes and benefits provided by a green roof. Therefore, the physics behind the services have only been treated superficially, and not stepped into every level of detail.

Each of the chapters of the ecosystem services have been setup using the same structure. The introduction aims to provide a general introduction for each service, including any relationship with existing decisions and plans. To give the framework of the importance of the ecosystem service, the relationship with the green roof has been given in advance in the introduction. This places the green roof within the field of application of the respective ecosystem service. The literature was then reviewed and various benefits were extracted with their values and calculation methods. In this way, a picture of how it is converted into money was obtained for each benefit. As part of the economic analysis, an attempt was also made here to extract the stakeholders. Based on all this, statements were made where necessary and recommendations and discussion points were given.

C.1. INTRODUCTION

The introduction defines the (social) importance of the field of ecosystem service work. This has been done by analysing how reality manifests itself in practice. Therefore, the introduction will provide background information on the basis of which the implementation of a green roof can make a positive contribution. The reason for approaching it this way is that in this way a better picture of the importance of the service can be formed. The introduction offers a simplified representation of reality, but at the same time already provides a lot of information about the parties involved. In this way, the introduction can be placed in a social context so that it can be properly assessed in relation to stakeholders. Here, the link can be made to decision-making and plans, to bring out the seriousness of the situation even more clearly. In this process, the role of a green roof as a solution to a specific problem is always defined separately. Herein, the properties and physical behaviour of a green roof are described, so that a complete picture of both the problem and how a green roof can contribute as part of the solution emerges.

The purpose of the introduction is to provide a condensed view of the ecosystem service. This has been done in a way that balances the depth on the topic with the frameworks of this study. Ultimately, then, the introduction serves as an introduction to the service described and the relationship of a green roof to this service for a broadly accessible audience.

C

C.2. BENEFIT IDENTIFICATION: NUMBERS, CALCULATION AND STAKEHOLDERS

In order to define an answer to the research question the different used methodologies to translate ecosystem services into a monetary value should be determined. There are many possibilities for translating these services into benefits and accordingly into monetary values. To provide consistency throughout the different services, it was chosen to systematically evaluate each service. A substantiation was made between the used methodology, the use of values for the quantification and the use of values for the valuation. The assessment on which these were assessed for the research question is adhoc, this was done mainly based on the large differences in the quality of the methodologies and values. However, the focus of this study has been on finding a causal connection between the different steps in the cascade framework and that this can be substantiated by literary papers. In this, it is important to note that the assessment was done purely on the basis of the information available from the literary papers themselves. Thereby, supporting information from other literary papers has not been used to keep the scope of the study manageable. For example, the enumerated results have already been juxtaposed in Manso et al. (2021). However, the design does give the opportunity to test and make this review based on other papers, this is however something that follow-up research should focus on.

BENEFIT QUANTIFICATION

In order to correctly quantify the amount of a given service that comes from that system, it is crucial to first understand the ecosystem services that are used and then precisely measure how well they are functioning (Costanza et al., 2017). These services form the basis for the value judgment and are therefore crucial to the methodology. The first step is to explore the methods to quantitatively assess these services. Reliable data are necessary to develop the methodology. When evaluating quantification, we did not just focus on the isolated numbers, but instead paid attention to the context and specific situation in which these numbers were obtained. This avoided blindly adopting numbers without the necessary context.

The intent of presenting values is not for them to be used by themselves as a starting point for future economic analysis. Additional research is always required.

- The availability of numerical data that can serve as benchmarks for quantifying green roofs.
- The quality of these data, their recentness and their fit with the benefit described.
- The delineation and limitations of these data, as well as the context within which they can be applied.
- The provision of order magnitudes regarding the values used, with the aim of encouraging follow-up research that allows for reflection and can place these values in a broader literary spectrum.

BENEFIT VALUATION

In converting to monetary values, careful attention was paid to how the significance of the values used was established. The focus was on the creation and substantiation of these values. Through thorough research, efforts were made to gain a deep understanding of the essence and realisation of these values. Understanding their meaning and realisation provides insight into both the quality of the value in the given situation and the extent to which the conversion to monetary values is consistent with the methodology described. This can also help in assessing consistency with stakeholder interests as described in the methodology.

The inclusion of specific values in numerical terms, if any, is not intended to base follow-up research on those values. Such values are included only to form a picture that may be of service in reflecting on the methodology. However, avoiding the inclusion of monetary values is preferred because of the implications of local currency and the temporal nature of value.

- The availability of numerical data that can serve as a benchmark for the valuation of green roofs.
- How this value was economically arrived at and how this value connects to quantification.

C

Stakeholders

Ultimately, a general overview of the stakeholders involved can be obtained. Stakeholders are involved both in the identification of benefits and in the feedback of monetary values to these parties. Within the study, an inclusive approach is sought in which all stakeholders identified are examined throughout the process. In this way, values can later be correctly attributed to the right stakeholders and gaps within this process can be highlighted. When identifying stakeholders, consideration is also given to how money flows are created and when this takes place.

- Obtaining a comprehensive overview of affected stakeholders with respect to benefit identification and monetary value feedback.
- Conducting an inclusive review that closely examines all stakeholders throughout the process, with the aim of ensuring the appropriate allocation of values to the relevant stakeholders.
- Systematically identifying stakeholders and thoroughly analysing the creation of financial flows, including their temporal aspects.

Methodology

By comparing the information from the various studies side by side, it provides insight into the methodology used to translate ecosystem services into monetary values. Here, the overall assumptions, quantification, calculation methods, value determinations, stakeholders involved and the relationship between all of these can be put side by side. The aim of this was to identify patterns and similarities in the literature, which can ultimately serve as a basis for the discussion, conclusion and recommendation. The overarching goal was to get an overview of the current state of the art used in the literature, revealing both usability and limitations. Additionally, this approach looks for gaps in the literature. It is important to note that methodology by itself says little, and that a methodology based on good assumptions on paper does not necessarily lead to good outcomes in terms of values.

C.3. Discussion

The discussion critically reflects on the methodology used in the 20 studied peer reviewed papers, and poses important questions concerning the approaches used in various sources and whether they are an honest representation of reality. It is crucial to keep in mind the original scope and purpose of this research. The process for identifying ecosystem service benefits and using valuation tools to translate them into a value that justifies the current situation and the involved stakeholders is the main topic of discussion. Examining the methodology employed in this process, together with the values and metrics given to this methodology, is crucial for our study. This involves distinguishing between the quantification of ecosystem benefits and their valuation. But it also draws attention to the entire informational process and how values are related. It primarily addresses the shortcomings of existing approaches in doing so. Comparing the studies side by side provided insight into the methodologies used as well as potential information that is still undiscovered or still based on assumptions. This exchange of ideas forms the basis for formulating the conclusions and recommendations for future research.

C.4. Conclusion

The final conclusion answers to what extent the sub-questions can be answered using current knowledge. This follows as a logical consequence of the points as discussed in the discussion. The conclusion provides an overview of the current state of the literature by presenting all methods side by side and indicating the assumptions and limitations therein. The conclusion has been carefully crafted as a self-contained read, using concise statements and sufficient precision to provide direction for future research. This exposes the current state of the literature, having reviewed 20 papers spread over a 15-year period, and allows this study to serve as a starting point for improving, supplementing and further developing the existing literature.

C.5. Recommendation

The recommendations follow logically from the conclusions and provide focused direction for follow-up research. In conjunction with the conclusion, it can be determined what contribution follow-up research can make to the current state of the literature. In doing so, the author is encouraged to have other researchers fill in these gaps in the literature so that steps can be taken towards a more equitable and comprehensive valuation of green roofs.

D

Literature review

This chapter has taken a systematic approach to identify all ecosystem services by thoroughly reviewing the available information as presented in the papers listed in Appendix A. The literature review has been organised according to the classification of provisioning, regulating, cultural and supporting services. Each of these ecosystem services was elaborated in detail using the framework shown in Appendix C. The subsequent discussion highlights the considerations that led to the study's conclusions. Collectively, these concluded results provide an overview of the current status of methodologies in the literature and have been deployed to make statements in relation to the Betsy Perk case study. In addition, recommendations have been formulated for each individual ecosystem service based on current research, with the aim of guiding future research. The specific ecosystem services are summarised in Table D.1.

Table D.1: Chapters ecosystem services green roof

Ecosystem service categorisation	**Page**
Provisioning services	100
Regulating services	105
Cultural services	154
Supporting services	160

PROVISIONING SERVICES

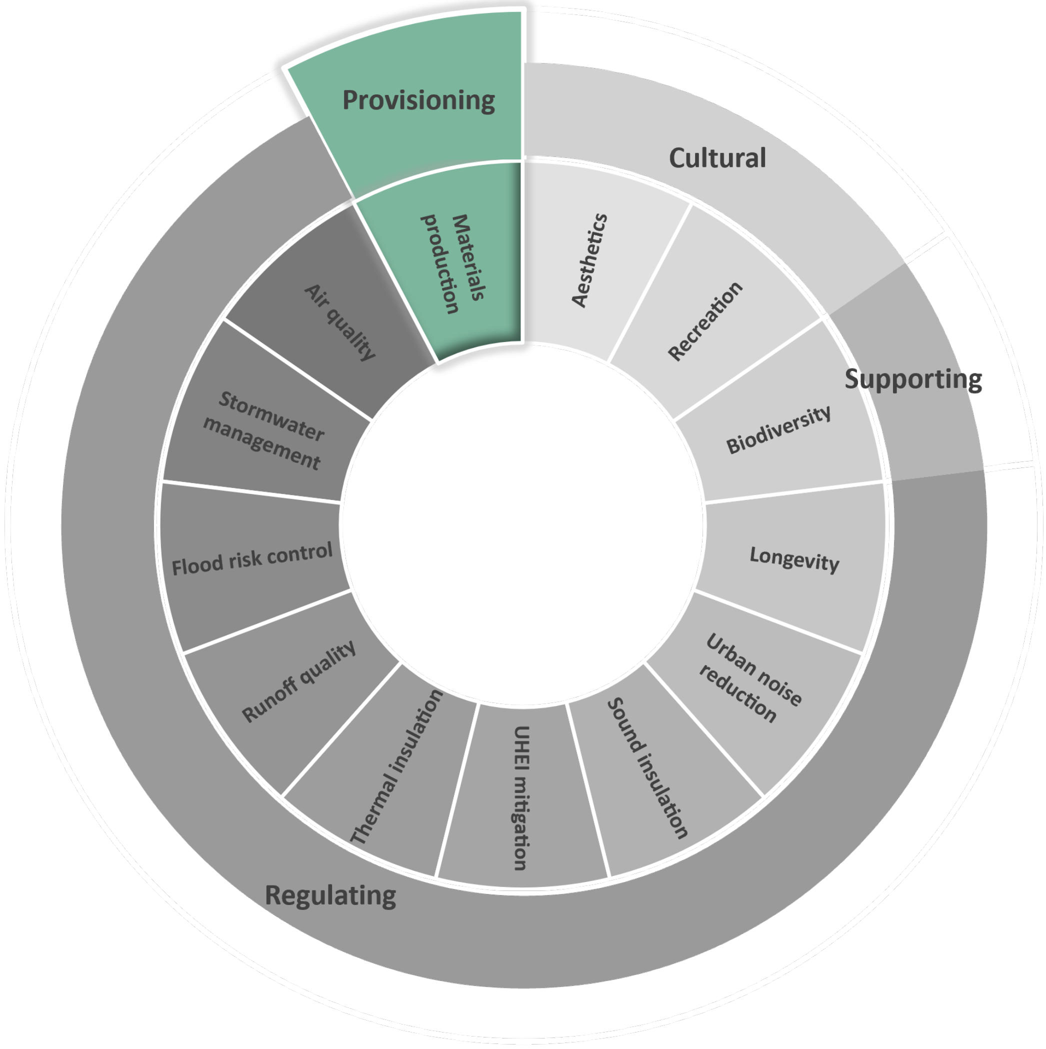

Figure D.1: Provisioning services

Provisioning services		
Appendix	**Title**	**Page**
D.1	Material production	101

D.1. MATERIAL PRODUCTION

Urban agriculture, an economic sector located within or on the outskirts of cities, embraced the potential of the local environment and transformed it into a thriving source of growing, processing and distributing varied food and non-food products. This can help address the current problem of provisioning services, which are spread globally. By using low-cost transport, it is possible to utilise ecosystem services from outside urban areas, as they are not available within the city limits leading to increased energy usage, biodiversity loss (Stache et al., 2019) and pressure on the sustainability and land use of our environment Xi et al. (2022). However, urban agriculture mainly utilises the available human and material resources, products and services in and around the respective urban area. Moreover, urban agriculture in turn mainly meets the needs of the same urban area through the provision of human and material resources, products and services. Urban agriculture rested on three essential principles that enabled its success. First, it provides opportunities within the urban environment by using local resources. In this way, it helps create new opportunities and recycle waste streams. The second principle of urban agriculture focused on production. Not only did the sector produce food, but it also provided various other goods, services and products. Finally, local production of food and non-food products reduces the distance between producer and consumer, resulting in more efficient delivery of products and services (Mougeot et al., 2000). Thanks to its versatility, urban agriculture could be applied in different ways and used flexibly within the urban area (Xi et al., 2022), see figure D.2.

Figure D.2: Different types of urban farming. Adapted from (Xi et al., 2022)

Feeding the world's growing population presents a complex issue. Guided by climate change, scarce natural resources, a shift in demography and increasing waste, the shortage of natural goods is growing. By 2030, 660 million people are expected to go hungry, a number that is likely to grow. This requires the search for smart innovative solutions that can improve productivity and sustainability of production. Urban agriculture provides a contribution to food production, which leads to an increase in supply and thus a decrease in price. A lower price on food, given the ratio of income expenditure on food, can contribute significantly to mitigating the effects of poverty. Moreover, urban agriculture creates employment and business opportunities within the urban environment (Redwood, 2012).

On top of that, from an economic perspective, more and more valuable countryside is being used for industries, commercial activities or houses rather than for urban farming. This spread is partly driven by national and local government policies. The associated benefits are often higher because non-market benefits such as civic and community engagement are often overlooked. Yet the use and hence demand of materials derived from nature is growing. With this, the importance of the viability of urban agriculture is also growing (Xi et al., 2022).

MATERIAL PRODUCTION ON GREEN ROOFS

Green roofs are a valuable addition to the concept of urban agriculture and provide numerous benefits to city residents. As an alternative location for plant growth, the roof provides both food- and non-food-related materials. Rooftops are a suitable location for plants that require a lot of sunlight, horizontal space or pollination. However, the plants selected should be able to withstand variations in temperature and humidity, together with high temperatures (Sabeh, 2020).

As rooftops are a previously relatively unused part of the city, there are numerous opportunities and possibilities for large-scale applications. However, not all roofs are equally suitable for production of natural materials. This is because the growing conditions for these plants are essential to ensure their productivity and efficiency. Many vegetables prefer deeper soil to allow their roots to grow fully. This makes only IGR suitable, which often contains more nutrients as an added benefit. Structurally, however, not all roofs can apply IGR. As a result, attention is growing to the potential of urban farming on EGR. Plants with superficial roots are a good solution for application on extensive roofs, these can achieve high productivity with minimal effort of resources (Walters and Stoelzle Midden, 2018). For both types of roofs, some challenges appear to be present besides the load-bearing structure: roof access, health and safety issues, and the need for water and electricity. For new roofs, these can be taken into account in design, but can pose problems when renovating existing buildings (Orsini et al., 2017).

D.1.1. LITERATURE REVIEW

The available literature on green roofs and their contribution and potential in terms of material production is limited. This can be partially explained by the fact that the roof needs to be designed specifically for this purpose (Carter and Keeler, 2008), while most research publications focus on the use of a different kind of vegetation, which is sedum in most cases. As a result, there are only a limited amount of statements about the material production in this context. Nevertheless, the stated statements on material production are detailed below.

GR agriculture is identified as an attractive solution to the shortages of available agricultural land. This is reinforced by its integral position in the energy, water and food spectrum, by both maximising used precipitation and minimising a building's energy needs. However, the lack of the lack of up-to-date studies that can provide information on the topic is highlighted. Different stakeholder perspectives are raised, including a section that sees urban agriculture as a form of sham agriculture and intended only for social activities, while another section perceives the positive effects on food production. Community cohesion, increased food security, and the provision of educational opportunities are some of the additional social advantages of urban farming (Kim et al., 2018).

QUANTIFICATION OF MATERIAL PRODUCTION

The study from Kim et al. (2018) is based on a realistic situation, allowing reliable statements to be made. One of the conclusions is that operational and maintenance costs of urban farming are relatively low. This is partly due to the fact that maintenance is carried out by local parties involved in the building, on a voluntary basis. It is worth noting that the study takes place in the context of a university, where many people are involved, but there is also contribution from local residents on a voluntary basis. However, the comparison between the actual yield and the average yield shows that the efficiency of voluntary farming is not high and is even half of the average yield in the area. As a possible solution, better education of farmers is raised as a way to increase production, however, due to the voluntary basis, it is not a cost-effective solution. Instead, it refers to better and cheaper soil composition to increase yields.

VALUATION OF MATERIAL PRODUCTION

Based on the actual harvest, the total yield can be calculated. Two hypothetical scenarios were considered in Kim et al. (2018). The first in which the amount of potato harvest is doubled to match the average harvest of urban agriculture in the region. The second scenario, plant cucumbers in addition to potatoes during the summer months. Both scenarios show that more returns can be achieved through more efficient farming. The report only describes the annual yield in kilograms, while not providing any information on the conversion from kilograms to euros. The social costs were also included in the calculation. The environmental impact of producing the same quantity of potatoes at another location has been included as a benefit. However, there is again insufficient substantiation for this to say anything meaningful about it.

Despite the lack of actual numbers for the yield of the building, Teotónio et al. (2018) makes a simplified calculation using core values. The annual profit of food production is calculated based on an national indicator of minimal production productivity and the market price in Portugal. This shows that a minimum harvest yield is also taken into account here, an assumption that, based on Kim et al. (2018), takes into account a reduced yield and is therefore well-founded.

Stakeholders
Urban farming is seen as an opportunity to generate additional income around a building. According to current literature, urban farming offers opportunities for contributing to food production, where the resulting harvest can be sold at market prices to generate additional income. In the work of Teotónio et al. (2018), selling the harvest is described as an annual benefit that increases annually. Moreover, Kim et al. (2018) considers the yield from production as an income source for the project owner that returns annually.

D.1.2. Discussion
Methodology
Although the current methodology was based on limited amount of literature a few discussion point could be highlighted. Within current calculation methods, the yield of urban farming is attributed to the project owner. Nevertheless, the question arises whether this assumption is correct. Kim et al. (2018) showed the use of volunteers to farm and cultivate vegetables. It is therefore questionable whether revenues can be attributed to the building owner, or whether they should rather benefit the community. The question should be asked what the intended purpose of the roof is. The use of volunteers decreases the yearly yield. Looking solely at this aspect this might be seen as a bad thing. However, it is uncertain whether a project owner is willing to take responsibility for the management and maintenance of a roof farm himself, in order to improve the yearly yield. This would in any case require additional staff with expertise in the field. This may require a specific set-up for the management and maintenance of the roof garden. However this information could not be extracted from the sources

Moreover, Kim et al. (2018) highlights another important benefit of roof gardens that has not been mentioned so far. Namely, volunteers derive a lot of satisfaction from working in the roof garden. This can range from a certain level of relaxation to socialising, so the presence of a green roof also provides social benefits. Besides promoting community building, urban farming contributes to food security within the community and provides educational opportunities. Thus, the roof not only fulfils a role as a provisioning materials that can be sold, but also plays an important role within the local community by providing cultural ecosystem services.

quantification
When looking purely at provisioning services, the current literature offers a method for making an assumption of the amount of material production. In both sources it can be seen that a reduced quantity is used, however, the degree of influence cannot be clearly determined from the one example. At the moment, the existing literature does not yet provide an unequivocal answer to this issue.

valuation
When looking strictly at providing services, the current literature provides a method for making a solid statement with regard to pricing. This value is related to the market price and has a direct relationship with the product. On this basis, there can be little discussion about the valuation method itself. However, the main question is to whom this value should be attributed. Who should benefit from the value generated? This question relates to the distribution and attribution of economic benefits and may be subject to debate.

D.1.3. Recommendation
To answer the research question, follow-up research should focus on:

- Investigate revenue sharing:
  The literature does not yet provide a single answer to the question of to whom the proceeds of a rooftop farm should accrue. Follow-up research should focus on exploring the different stakeholders and their rightful claim to the revenues. This could help create clear guidelines and policies on the distribution of revenues from green roofs with a rooftop farm.
- Investigate the impact of cultural ecosystem services:
  No answer has yet been found on the impact of cultural ecosystem services associated with a rooftop farm, such as community building, food security and educational opportunities. It is important to conduct further research on these aspects to better understand and assess their value and impact. This research can help raise awareness of the wider benefits and positive impacts of a rooftop farm on green roofs.

- Investigate the influence of volunteers and professionals on returns and additional costs:
  It is important to investigate further the influence of volunteers and professionals on the yield of a rooftop farm on a green roof, as well as the possible additional costs. The use of volunteers can play a positive role in the realisation of a rooftop farm, but it can also affect the yield and efficiency of farming activities. It is essential to examine the impact of volunteer use and compare it with the use of professionals. This research can help understand the optimal mix of volunteers and professionals and identify potential savings or cost increases associated with using both groups.

REGULATING SERVICES

Figure D.3: Regulating services

Regulating services		
Appendix	**Title**	**Page**
D.2	Air quality	106
D.3	Stormwater management	120
D.4	Floodrisk	126
D.5	Runoff quality	130
D.6	Thermal insulation	133
D.7	UHIE	140
D.8	Sound insulation / Urban noise reduction	145
D.9	Longevity	151

D.2. AIR QUALITY

Our world is surrounded by an atmosphere composed of various elements in the gas and particle phase. This composition is influenced by various physical forces and phenomena that occur on and in the atmosphere. Examples include gravity, air density and pressure, and the movement of the atmosphere and individual air molecules. The interactions between the atmosphere and the environment, and within the atmosphere itself, contribute to changing the chemical composition of the atmosphere. Besides the physical principles that influence the composition of the atmosphere, solar radiation and thermal energy also play a role in the energy balance of the atmosphere. All these elements work together to make the atmosphere increasingly complex (Godish et al., 2014).

This complexity of the atmosphere affects the functioning of our planet. For instance, the chemical composition of the atmosphere directly affects climate and weather conditions. Changes in atmospheric composition can lead to consequences such as climate change and acid rain.

DECLINING AIR QUALITY AND THE DEVELOPMENT OF REGULATIONS

For centuries, air pollution has been a problem for mankind, mainly caused by the use of fire as a source of heat and energy (Godish et al., 2014). The smoke released by burning fuel has had a negative impact on both the environment and human health. The development of cities has led to improvements in the material prosperity and quality of life of urban dwellers in a relatively short period of time, but has also led to serious environmental problems, such as air pollution caused by intensive human activity (Zhang et al., 2022b). Cities, by their very nature, are concentrations of people, materials and activities, so they exhibit the highest levels of pollution and experience the greatest impact (Fenger, 1999). Environmental degradation is largely attributed to urban development with excessive expansion and consumption of natural resources, especially the use of fossil fuels. The industrial revolution in the nineteenth century and subsequent technological developments, such as the invention of motor vehicles, led to increased pollutant emissions and hence the current air pollution. Air pollution resulting from rapid urbanisation and economic development is considered one of the main causes of the global burden of disease and therefore one of the biggest public health challenges (Zhang et al., 2022b). Economic growth also has a clear impact on the level of air pollution in a country. This impact can be explained by the relationship between average income and air pollution in urban areas. At the onset of economic growth, this relationship first increases for a long time, causing an increase in the amount of air pollution. When a maximum is reached, there will then be a decrease in air pollution, due to effective control of this pollution. Most of the cities in the industrialised West are currently in this latter, declining phase of air pollution. However, in many emerging economies, the stabilisation phase has just been reached or this declining trend is not yet in place, so the amount of air pollution continues to increase (Fenger, 1999).

In today's era of increasing urbanisation and industrialisation, air pollution poses a serious threat to public health. Not surprisingly, policymakers and scientists around the world are making efforts to regulate and improve air quality. An important aspect of this effort is the accurate measurement and calculation of the levels of pollutants in the air and to understand the extent to which people are exposed to measured or calculated pollution levels. However, measurement of these levels alone is not sufficient to assess health risks, as the actual exposure of individuals to pollutants depends on several factors, such as their location and behaviour (Fenger, 1999). For this reason, there is a need for accurate measurements of air quality and the development of effective regulations. For this reason, the World Health Organisation (WHO) has developed air quality guidelines. WHO's Air Quality Guidelines act as a global target for national, regional and city governments to help their citizens improve their health by reducing air pollution. These guidelines are based on scientific evidence and recommend limit values for specific air pollutants. Since the first publication in 1987, WHO continues to update the guidelines regularly to ensure their continued relevance and to support a wide range of policy options for managing air quality in different parts of the world (World Health Organization, 2021).

The World Health Organization has introduced air quality guidelines, which delineate thresholds and interim goals for the ubiquitous solid particles and liquid droplets constituting air pollutants, particulate matter (PM_x), sulphur dioxide (SO_2), nitrogen oxides (NO_2), Ozone (O_3) and carbon dioxide (CO_2). These guidelines provide countries with a framework to devise policies aimed at enhancing air quality and safeguarding public health.

GREEN ROOF AIR QUALITY REGULATION

Green roofs and plants in general have the ability to filter the air and absorb harmful substances. It is possible to improve the quality of the air in a local area through the addition of plants. The quantity in which

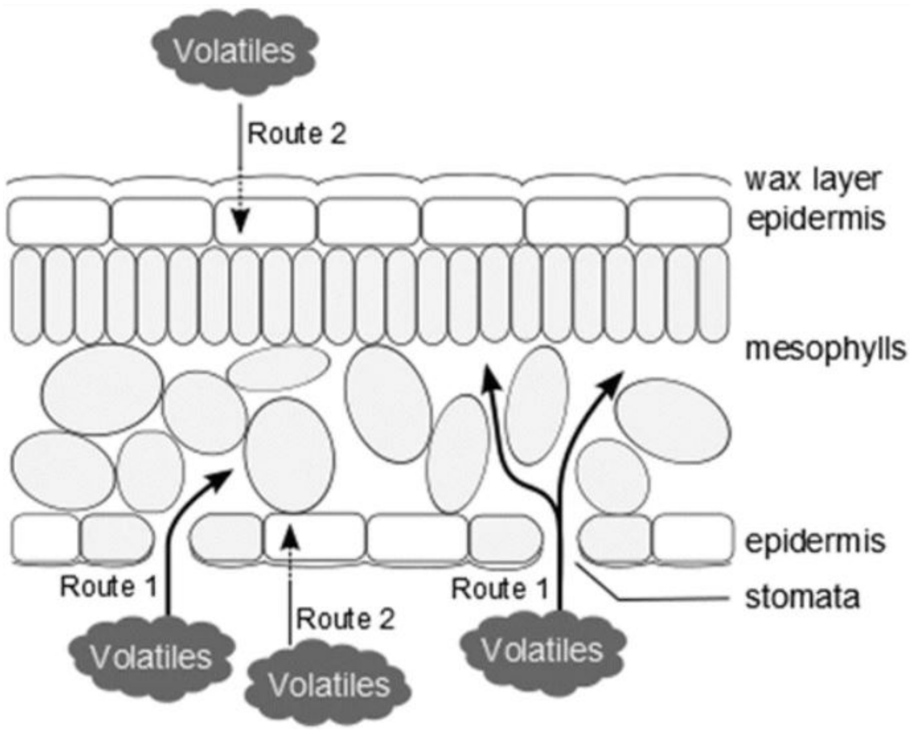

Figure D.4: Deduced routes of volatile uptake in leaf tissue (Sugimoto et al., 2016)

health-damaging substances are absorbed depends on a number of parameters (Ottelé et al., 2010). In order to effectively evaluate the air-purifying capabilities of plants, it is necessary to consider a range of factors, including the deciduous or evergreen nature of the plant, the size and shape of its leaves, and the shape and structure of the plant itself. These elements directly impact the plant's capacity for uptake. Additionally, the micro-climate and growing conditions within a specific environment must be taken into account, as well as the design of the surrounding area and the distance of the plant from the source of pollutants. External influences, such as the type and concentration of pollutants, must also be considered.

Plant have the capacity to take up pollutants through stomatal uptake (figure D.4: route 1) and non-stomatal deposition (figure D.4: route 2). The stomatal uptake takes place through absorption and non-stomatal deposition through adsorption. Part of these volatile compounds will be re-emitted in the air over time but the rest is transferred into the plant tissue. In this way, plants in the urban area can serve as a natural filter (Sugimoto et al., 2016).

D.2.1. LITERATURE REVIEW

A total of 12 sources make a statement on the impact of green roofs on air quality. In them, a distinction is made between direct impacts on air quality and indirect impacts. Direct effects refer to the capture of substances by the plant. 8 sources make a statement on this. Indirect effects on air quality refers mainly to the effect due to prevented emissions.

DIRECT AIR QUALITY REGULATION

The direct impact of adding a green roof on air quality comes from the fact that plants are able to absorb substances from the air. The literature uses different calculation methods for the underlying value of different compounds. It was decided to organize the subject matter by substance because of the shared methodologies utilized in the numerous publications and the range of substances. This is so because every substance behaves differently and has a different effect. Even though the focus of this research is to show insight on the described methods, presenting the literature in this systematic way also provides a good picture of the magnitude of values used in the numerous articles for each specific chemical.

The following substances have been addressed in the literature in the context of the direct effects, through uptake, of a green roof on air quality; particulate matter (PM_x), sulphur dioxide (SO_2), nitrogen oxides (NO_2), Ozone (O_3) and carbon dioxide (CO_2).

INDIRECT AIR QUALITY REGULATION

Besides the direct impact on air quality through the uptake of substances, the literature also gives the indirect consequences of adding a green roof. In this, the literature tends to use a one-size-fits-all approach. The indirect impacts are derived from the saving of energy through the thermal effect of the roof package. The energy required for thermal comfort is directly related to a certain emission released when generating this energy. Because the literature uses a consistent approach for each of the substances, it was chosen to address the indirect effects in a single section.

D.2.1.1. BENEFIT: DIRECT CAPTURE OF PARTICULATE MATTER

Only a few studies in the literature reviewed for this study offer information on the uptake potential of green roofs on Particulate matter in the air. The uptake potential of a green roof is considered first, looking at the quantification. In general, the values as described and used in the sources are in the same order of magnitude. With the uptake potential of a 1 square meter green roof compared to the particulate matter emissions of a car in a year (Claus and Rousseau, 2012). The valuation of these adverse effects are discussed next. Generally, the environmental and health damage caused by particulate matter is referred to. This is an important problem that is increasingly targeted by policy makers. Studies in Flanders estimate the external health effects from 483 to 546 euro per inhabitant per year (Claus and Rousseau, 2012), showing the importance and potential of the matter.

QUANTIFICATION OF CAPTURED PARTICULATE MATTER

Most papers refer back to Yang et al. (2008), who quantified, using a dry deposition model based on local concentration, the level of air pollution removal by green roofs. The study revealed that the particulate matter uptake value accounted to 14% of the total mass uptake. The annual removal rate, in Chicago, was determined for different vegetation types. The canopy covers have an uptake of 1,12 $[gm^{-2}yr^{-1}]$ for short grass, 1,52 $[gm^{-2}yr^{-1}]$ for tall herbaceous plants and 2,16 $[gm^{-2}yr^{-1}]$ for deciduous trees. In addition to just the local uptake velocity value, the study also provided insight on the steps taken, as well as the values in which the local influence factors are omitted. These values can be converted to a local value using formula D.1, these values are given in table D.2.

$$\textbf{Polutant flux}[gm^{-2}s^{-1}] = Vd * C * 10^8 \tag{D.1}$$

Where Vd = dry deposition velocity of a particular air pollutant (cm s^{-1})
C = concentration of that pollutant in the air (µg m^{-3})

Table D.2: The minimum and maximum modeled monthly average deposition velocities of Particulate Matter. The numbers inside the parenthesis were standard errors. Adjusted from Yang et al. (2008)

PM_{10}	**Short grass**	**Tall herbaceous plants**	**Deciduous trees**
Minimum (cms^{-1})	0,10 (0,005)	0,10 (0,006)	0,13 (0,008)
Maximum (cms^{-1})	0,19 (0,003)	0,25 (0,004)	0,36 (0,006)

The annual removal rate of Yang et al. (2008) is mentioned in Claus and Rousseau (2012), Berto et al. (2018) and Kim et al. (2018). Claus and Rousseau (2012) also mentions a scenario where a 20% green roof coverage would achieve 21,7 million square feet of green roofs accounting for an uptake of 5,66 metric tonnes of particular matter, which amounts to 2,8 $[gm^{-2}yr^{-1}]$. Despite this, Claus has found that the available information regarding the absorption of PM, or particulate matter, to date is insufficient to quantify and value it. The absorption potential of (Yang et al., 2008) is similarly mentioned in Kim et al. (2018). But, the study does similarly not address air pollution reduction since the essential information to estimate its advantages was not gathered or made available for the entire five years that the green roof was in operation at the study location. Berto et al. (2018) supports the use of the values from Yang by comparing that the monthly mean values and annual trends for the concentration series are similar between the two areas. This justification admits that the uptake potential depends on the concentration of air pollutants, plant species and growth, and weather conditions.

In addition, the upper value from Nurmi et al. (2013), a case study in Helsinki, is also based on the data from Yang. The uptake margin is given as a value between 0,8-1,2 g/m2 of PM_{10}. The lower value comes from Currie and Bass (2008), who tried to make an estimation of the air pollution mitigation potential in

Toronto (Canada). In the calculation of the air pollution values in the model, the UFORE-model, a prediction was made for grass, because data from similar other vegetation that is also usually widely used on extensive green roofs was not available. The approach of both Currie and Bass (2008) and Yang et al. (2008) rely on dry deposition velocity values from the literature (Tong et al., 2016), where the estimates of Yang were found to be around 18% higher compared to the estimates from Currie (Nurmi et al., 2013).

However, Nurmi et al. (2013) provides no justification on the basis of which these values were adopted as maximum and minimum. The paper does refer to the influence on air pollutant removal uptake affected by the air pollutant concentrations, weather conditions and the growth of plants as stated by Yang. The annual uptake capacity from Nurmi is referenced and used in the paper of Macháč et al. (2016), who made an estimation of a single-family house in Prague-Jinonice.

The information from both Yang et al. (2008) and Currie and Bass (2008) are also used in the quantification of the air quality in Center for Neighborhood Technology (2010), which is used as the basis to determine the improvement in air quality in Alves et al. (2019), a case study in the Dutch side of Sint Maarten Island, located in the Caribbean region. The upper limit and lower limit of the calculation are determined by Yang and Currie's values, respectively. Based on the surface area, the total uptake can be accurately calculated. The outcome is stated as a preliminary estimation of the magnitude of a substance's annual uptake rate. However, it is questionable to what extent the absorption potential of green roofs in Chicago and Toronto can be used as an indicative value for absorption in St Maarten.

VALUATION OF CAPTURED PARTICULATE MATTER

For mapping the economic impact of particulate matter, the literature is quite unanimous. A quantification of air pollution mitigation emerges from all sources as an intermediate step in the economic analysis. This involves calculating a value that expresses the uptake potential given as a weight that a square area unit is capable of absorbing during a year. The obtained capture potential can then be converted to an amount of substance by weight, after which it can be translated into an economic value. Within the literature, this economic value is calculated for all sources of particulate matter on the basis of impact costs. This cost is attributed to the damage caused by the emission of the pollutant.

In Berto et al. (2018), the translation to money is calculated based on the projected cost of damages as determined by the Energy-Environment-Economy Model for Europe (E3ME). The original version of the model was developed by a European team and compiled in accordance with various contracts concluded in the 1980s and 1990s as part of EEC/EU research programmes. However, the current version of the model was developed by Cambridge Econometrics (European Commission, 2023a). The model includes physical impacts on human and animal health and welfare, materials buildings and other physical capital, and vegetation (Barker and Rosendahl, 2000).

In Teotónio et al. (2018), a translation is also made to the economic value of PM_x. The value used to convert the amount of PM_x is based on its impact cost. It is noted from Maibach et al. (2008) that the impact cost was calculated using HEATCO 2006. However, contrary to what is reported in Teotónio et al. (2018), this value is not representative of disposal of the substance, but looks at the social costs and benefits. The main objective of the Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO) was to provide guidance for conducting social cost-benefit analyses (Barker and Rosendahl, 2000). This value ultimately emerges by quantifying health effects, crop losses and building/material damages. In this, health costs caused by PM_x provide the largest share in terms of cost category (Maibach et al., 2008).

In Macháč et al. (2016) and Alves et al. (2019), the meaning of the used monetary value is given as a reduction of negative effects on health (heart and respiratory diseases, cancer), the environment and climate change. Some of the referenced sources are not accessible, which made it difficult to make a well-grounded statement about them. Nevertheless, a statement has been made based on the information that is available. Based on Center for neighbourhood technology by Center for Neighborhood Technology (2010), which uses information both direct and indirect from Wang and Santini (1995). Wang presents two general methods for estimating the monetary value of air pollutants, namely the damage value method and the control cost method. The damage value method is based on direct estimation of the value of air pollutants through simulation of air quality. The effects of air pollution on health and other welfare impacts are identified and valued. This method involves many assumptions in the estimation steps and there is uncertainty associated with each step, even-though the method is well-grounded in theory. The control cost method requires less uncertainty and estimates the marginal cost of emission control. These opportunity costs represent the avoidance of more expensive spending of available emission control measures intended to meet regulatory requirements. The information from Wang and Santini (1995) provides further elucidation on the application of different methods, with their flaws.

D.2.1.2. BENEFIT: DIRECT CAPTURE OF NITROGEN OXIDES

Only a few studies in the literature reviewed for this study offer information on the uptake potential of green roofs on NO_2 in the air. The uptake potential of a green roof is considered first, looking at the quantification. The values found mostly rely on the same source of information, however, studies have also been mentioned using multiple samples in controlled conditions or studies relying on modelling software. The valuation of these adverse effects are discussed next.

QUANTIFICATION OF CAPTURED NITROGEN OXIDES

D

One study relied on the extensive research of Morikawa et al (1998), it was used in Clark et al. (2008) to quantify the Nitrogen oxide uptake by plants. In that study, the NO_x uptake potential of 217 plants taxa were evaluated under controlled conditions in a greenhouse environment, with published results expressed as mg N g-1 dry weight per 8 h of daylight exposure. The study made assumptions about the water percentage of plant mass, the leaf thickness, leaf area index and the average daily daylight hours. An average uptake capacity per unit area of 270 - 440 $[gm^{-2}yr^{-1}]$ NO_2 was obtained this way. The traditional vegetated roof plants of choice, sedums, was not evaluated, but the study did included a member of the same family.

Claus and Rousseau (2012) clearly illustrates the difference in the two approaches that can be used to assign a value to the uptake potential of NO_x. One approach uses a core value from the literature, while the other uses local concentrations. Based on numbers from Clark et al 2005, an uptake of 48,82 $[gm^{-2}yr^{-1}]$ was found. On the other hand, according to Clark et al 2008, an uptake of about 5-10% of the surrounding NO_x concentration was given. Applied to the specific location, an average uptake of 50-100 g NO_2 per m2 per year was derived.

Table D.3: The minimum and maximum modeled monthly average deposition velocities of NO_2. The numbers inside the parenthesis were standard errors. Adjusted from Yang et al. (2008)

NO_2	**Short grass**	**Tall herbaceous plants**	**Deciduous trees**
Minimum (cms^{-1})	0,01 (0,001)	0,01 (0,001)	0,01 (0,001)
Maximum (cms^{-1})	0,39 (0,006)	0,49 (0,007)	0,58 (0,008)

Most papers refer back to Yang et al. (2008), who quantified, using a dry deposition model based on local concentration, the level of air pollution removal by green roofs. The study revealed that the nitrogen dioxide uptake value accounted to 27% of the total mass uptake. The canopy covers have an annual removal rate in Chicago of 2,33 $[gm^{-2}yr^{-1}]$ for short grass, 2,94 $[gm^{-2}yr^{-1}]$ for tall herbaceous plants and 3,57 $[gm^{-2}yr^{-1}]$ for deciduous trees. Besides the local uptake velocity value, the study also gives the values in which the local influence factors are omitted. These values can be converted to a local value using formula D.1, these values are given in table D.3. The uptake values from Yang et al. (2008) are mentioned in Claus and Rousseau (2012), Berto et al. (2018) and Kim et al. (2018).

But, Kim et al. (2018) does not address air pollution reduction since the essential information to estimate its advantages was not gathered or made available for the entire five years that the green roof was in operation at the study location. Berto et al. (2018) supports the use of the values from Yang by comparing that the monthly mean values and annual trends for the concentration series are similar between the two areas. This justification admits that the uptake potential depends on the concentration of air pollutants, plant species and growth, and weather conditions.

In addition, the upper value from Nurmi et al. (2013), a case study in Helsinki, is also based on the data from Yang. The uptake margin is given as a value between 1,6-2,3 g/m2 of NO_x. The lower value comes from Currie and Bass (2008), who tried to make an estimation of the air pollution mitigation potential in Toronto (Canada). In the calculation of the air pollution values in the model, the UFORE-model, a prediction was made for grass, because data from similar other vegetation that is usually also widely used on extensive green roofs was not available. The approach of both Currie and Bass (2008) and Yang et al. (2008) rely on dry deposition velocity values from the literature (Tong et al., 2016), where the estimates of Yang were found to be around 18% higher compared to the estimates from Currie (Nurmi et al., 2013).

However, Nurmi et al. (2013) provides no justification on the basis of which these values were adopted as maximum and minimum. The paper does refer to the influence on air pollutant removal uptake affected by the air pollutant concentrations, weather conditions and the growth of plants as stated by Yang. The annual uptake capacity from Nurmi is referenced and used in the paper of Macháč et al. (2016), who made an estimation of a single-family house in Prague-Jinonice.

The information from both Yang et al. (2008) and Currie and Bass (2008) are also used in the quantification of the air quality in Center for Neighborhood Technology (2010), which is used as the basis to determine the improvement in air quality in Alves et al. (2019), a case study in the Dutch side of Sint Maarten Island, located in the Caribbean region. The upper limit and lower limit of the calculation are determined by Yang and Currie's values, respectively. Based on the surface area, the total uptake can be accurately calculated. The outcome is stated as a preliminary estimation of the magnitude of a substance's annual uptake rate. However, it is questionable to what extent the absorption potential of green roofs in Chicago and Toronto can be used as an indicative value for absorption in St Maarten.

Using a SEDUM model, the NO_x uptake capacity of 20 $[gm^{-2}yr^{-1}]$ NO_2 is calculated in Niu et al. (2010). Due to the omission of certain input parameters such as the concentrations of HNO_3, NO and NO_2 in air-soil and initial vegetation, the results are subject to uncertainty. The uncertainty arises from the possibility that the concentrations may fluctuate and increase over time, leading to a varying uptake over time. As a consequence, the estimation is likely to underestimate the actual uptake. Furthermore, the experimental data indicates that the measured values for NO_x uptake are higher. Additionally, in the greenhouse studies, there is an underestimation attributed to SEDUM, which can be attributed to the increased air concentrations of NO_x. Moreover, the model's underestimation arises from equilibrium assumptions and general transfer rates between compartments in the multimedia.

VALUATION OF CAPTURED NITROGEN OXIDES

The monetary value associated with NO_x emissions in Clark et al. (2008) was derived from a health benefit. For this, two estimates were made based on methods developed by the U.S. Environmental Protection Agency (EPA) as part of the regulatory impact analysis of NO_x reductions in 1998. This analysis showed that reducing NO_x would result in lower O_3 and PM_x emissions in the eastern United States. These emissions were linked to premature mortality, hospital admissions, bronchitis, acute respiratory symptoms, worker productivity, worker loss days and minor restricted activity days (Office of Air Quality Planning and Standards et al., 1998).

It is described in Claus and Rousseau (2012) that the calculation of NO_x uptake can be performed in two ways. One calculation uses a core value from the literature, while the other uses local concentrations. Since both methods are based on different sources from the literature, different translations to money are also used for both methods. However, one source is no longer available online, so no statements can be made about the significance of this value. For the calculation method based on local concentrations, the translation to money is based on Marien et al. (2002), according to Clark et al. (2008). They calculated the value based on an exponential cost curve for NO_x reduction compared to the benefits of this reduction. The benefits come from the health benefits from reducing concentrations of PM10 by reducing nitrates.

In Macháč et al. (2016) and Alves et al. (2019), the meaning of the used monetary value is given as a reduction of negative effects on health (heart and respiratory diseases, cancer), the environment and climate change. The reduction of NO_2 is based on the values from Center for Neighborhood Technology (2010) and is not explained individually in the calculation but the reduction of this air pollutant is shown together with SO_2, O_3 and PM_x. The full course of action in the literature is therefore further presented in PM_x section D.2.1.1.

In Berto et al. (2018), the translation to money is calculated based on the projected cost of damages as determined by the Energy-Environment-Economy Model for Europe. The original version of the model was developed by a European team and compiled in accordance with various contracts concluded in the 1980s and 1990s as part of EEC/EU research programmes. However, the current version of the model was developed by Cambridge Econometrics (European Commission, 2023a). The model includes physical impacts on human and animal health and welfare, materials buildings and other physical capital, and vegetation (Barker and Rosendahl, 2000).

D.2.1.3. BENEFIT: DIRECT CAPTURE OF SULPHUR OXIDES

Only a few studies in the literature reviewed for this study offer information on the uptake potential of green roofs on SO_2 in the air. The uptake potential of a green roof is considered first, looking at the quantification.

These studies show that green roofs can have a positive effect on air quality. The use of green roofs can reduce the amount of SO_2 in the air by absorbing and retaining this harmful substance. It contributes substantially to the formation of sulphate aerosols and is the primary pollutant in the generation of acid rain. Moreover, it can contribute to respiratory damage in human individuals Maibach et al. (2008). Tan and Sia (2005), as referenced in Claus and Rousseau (2012), indicated the potential of green roofs to help reduce the level of atmospheric pollutants arising from traffic emissions in the vicinity of the roof. The level of sulphur dioxide was reduced by 37% after installation of the green roof. However, no concrete uptake potentials can be extracted from this study, which is needed to serve as the basis for follow up studies. The values found mostly rely on the same source of information. The valuation of these adverse effects are discussed next.

QUANTIFICATION OF CAPTURED SULPHUR OXIDES

D

Most papers refer back to Yang et al. (2008), who quantified, using a dry deposition model based on local concentration, the level of air pollution removal by green roofs. The study revealed that the sulphur oxides uptake value accounted to 7% of the total mass uptake. The canopy covers have an annual removal rate in Chicago of 0,65 $[gm^{-2}yr^{-1}]$ for short grass, 0,83 $[gm^{-2}yr^{-1}]$ for tall herbaceous plants and 1,01 $[gm^{-2}yr^{-1}]$ for deciduous trees. Besides the local uptake velocity value, the study also gives the values in which the local influence factors are omitted. These values can be converted to a local value using formula D.1, these values are given in table D.4. The uptake values from Yang et al. (2008) are used in Claus and Rousseau (2012), Berto et al. (2018) and Kim et al. (2018).

Despite this, Claus and Rousseau (2012) has found that the available information regarding the absorption of SO_2 to date is insufficient to quantify and value it. The absorption potential is similarly mentioned in Kim et al. (2018). But, the study does similarly not address air pollution reduction since the essential information to estimate its advantages was not gathered or made available for the entire five years that the green roof was in operation at the study location. Berto et al. (2018) supports the use of the values from Yang by comparing that the monthly mean values and annual trends for the concentration series are similar between the two areas. This justification admits that the uptake potential depends on the concentration of air pollutants, plant species and growth, and weather conditions.

In addition, the upper value from Nurmi et al. (2013), a case study in Helsinki, is also based on the data from Yang. The uptake margin is given as a value between 0,4-0,6 g/m^2 of SO_2. The lower value comes from Currie and Bass (2008), who tried to make an estimation of the air pollution mitigation potential in Toronto (Canada). In the calculation of the air pollution values in the model, the UFORE-model, a prediction was made for grass, because data from similar other vegetation that is usually also widely used on extensive green roofs was not available. The approach of both Currie and Bass (2008) and Yang et al. (2008) rely on dry deposition velocity values from the literature (Tong et al., 2016), where the estimates of Yang were found to be around 18% higher compared to the estimates from Currie (Nurmi et al., 2013).

However, Nurmi et al. (2013) provides no justification on the basis of which these values were adopted as maximum and minimum. The paper does refer to the influence on air pollutant removal uptake affected by the air pollutant concentrations, weather conditions and the growth of plants as stated by Yang. The annual uptake capacity from Nurmi is referenced and used in the paper of Macháč et al. (2016), who made an estimation of a single-family house in Prague-Jinonice.

The information from both Yang et al. (2008) and Currie and Bass (2008) are also used in the quantification of the air quality in Center for Neighborhood Technology (2010), which is used as the basis to determine the improvement in air quality in Alves et al. (2019), a case study in the Dutch side of Sint Maarten Island, located in the Caribbean region. The upper limit and lower limit of the calculation are determined by Yang and Currie's values, respectively. Based on the surface area, the total uptake can be accurately calculated. The outcome is stated as a preliminary estimation of the magnitude of a substance's annual uptake rate. However, it is questionable to what extent the absorption potential of green roofs in Chicago and Toronto can be used as an indicative value for absorption in St Maarten.

Table D.4: The minimum and maximum modeled monthly average deposition velocities of SO_2. The numbers inside the parenthesis were standard errors. Adjusted from Yang et al. (2008)

SO_2	**Short grass**	**Tall herbaceous plants**	**Deciduous trees**
Minimum (cms^{-1})	0,04 (0,005)	0,04 (0,006)	0,05 (0,006)
Maximum (cms^{-1})	0,39 (0,006)	0,48 (0,007)	0,57 (0,007)

Valuation of captured sulphur oxides

In Macháč et al. (2016) and Alves et al. (2019), the meaning of the monetary used value is given as a reduction of negative effects on health (heart and respiratory diseases, cancer), the environment and climate change. The reduction of SO_2 is based on the values from Center for Neighborhood Technology (2010) and is not explained individually in the calculation but the reduction of this air pollutant is shown together with NO_2, O_3 and PM_x. The full course of action in the literature is therefore further presented in PM_x section D.2.1.1.

In Berto et al. (2018), the translation into monetary terms is made based on the projected cost of damages as determined by the Energy-Environment-Economy Model for Europe (E3ME). The original version of the model was developed by a European team and compiled in accordance with various contracts concluded in the 1980s and 1990s as part of EEC/EU research programs. However, the current version of the model was developed by Cambridge Econometrics (European Commission, 2023a). The model includes physical impacts on human and animal health and welfare, materials buildings and other physical capital, and vegetation (Barker and Rosendahl, 2000).

D

In Teotónio et al. (2018), a translation is also made to the economic value of SO_2. The value used to convert the amount of SO_2 is based on its impact cost. It is noted from Maibach et al. (2008) that the impact cost was calculated using HEATCO 2006. However, contrary to what is reported in Teotónio et al. (2018), this value is not representative of disposal of the substance, but looks at the social costs and benefits. The main objective of the Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO) was to provide guidance for conducting social cost-benefit analyses (Barker and Rosendahl, 2000). This value ultimately emerges by quantifying health effects, damage to crops and ecosystems by acid deposition and building/material damages caused by corrosive processes due to acidity.

D.2.1.4. Benefit: direct capture of ozone

Only a few studies in the literature reviewed for this study offer information on the uptake potential of green roofs on O_3 in the air. These studies show that green roofs can have a positive effect on air quality. The use of green roofs can reduce the amount of O_3 in the air by absorbing and retaining this harmful substance. The uptake potential of a green roof is considered first, looking at the quantification. The values found mostly rely on the same source of information, however, studies have also been mentioned using multiple samples in controlled conditions or studies relying on modelling software. The valuation of these adverse effects are discussed next.

Quantification of captured ozone

Most papers refer back to Yang et al. (2008), who quantified, using a dry deposition model based on local concentration, the level of air pollution removal by green roofs. The study revealed that the ozone uptake value accounted to 52% of the total mass uptake. The canopy covers have an annual removal rate in Chicago of 4,49 $[gm^{-2}yr^{-1}]$ for short grass, 5,81 $[gm^{-2}yr^{-1}]$ for tall herbaceous plants and 7,17 $[gm^{-2}yr^{-1}]$ for deciduous trees. Besides the local uptake velocity value, the study also gives the values in which the local influence factors are omitted. These values can be converted to a local value using formula D.1, these values are given in table D.5. The uptake values from Yang et al. (2008) are used in Claus and Rousseau (2012), Berto et al. (2018) and Kim et al. (2018). Claus and Rousseau (2012) also mentions a scenario where a 20% green roof coverage would achieve 21,7 million square feet of green roofs accounting for an uptake of 6.00 metric tonnes of ozone, which amounts to 3,0 $[gm^{-2}yr^{-1}]$. Despite this, Claus has found that the available information regarding the absorption of ozone to date is insufficient to quantify and value it. The absorption potential is similarly mentioned in Kim et al. (2018). But, the study does similarly not address air pollution reduction since the essential information to estimate its advantages was not gathered or made available for the entire five years that the green roof was in operation at the study location. Berto et al. (2018) supports the use of the values from Yang by comparing that the monthly mean values and annual trends for the concentration series are similar between the two areas. This justification admits that the uptake potential depends on the concentration of air pollutants, plant species and growth, and weather conditions.

In addition, the upper value from Nurmi et al. (2013), a case study in Helsinki, is also based on the data from Yang. The uptake margin is given as a value between 3,0-4,4 g/m^2 of O_3. The lower value comes from Currie and Bass (2008), who tried to make an estimation of the air pollution mitigation potential in Toronto (Canada). In the calculation of the air pollution values in the model, the UFORE-model, a prediction was made for grass, because data from similar other vegetation that is usually also widely used on extensive green roofs was not available. The approach of both Currie and Bass (2008) and Yang et al. (2008) rely on dry deposition velocity values from the literature (Tong et al., 2016), where the estimates of Yang were found to be around 18% higher compared to the estimates from Currie (Nurmi et al., 2013).

However, Nurmi et al. (2013) provides no justification on the basis of which these values were adopted as maximum and minimum. The paper does refer to the influence on air pollutant removal uptake affected by the air pollutant concentrations, weather conditions and the growth of plants as stated by Yang. The annual uptake capacity from Nurmi is referenced and used in the paper of Macháč et al. (2016), who made an estimation of a single-family house in Prague-Jinonice.

The information from both Yang et al. (2008) and Currie and Bass (2008) are also used in the quantification of the air quality in Center for Neighborhood Technology (2010), which is used as the basis to determine the improvement in air quality in Alves et al. (2019), a case study in the Dutch side of Sint Maarten Island, located in the Caribbean region. The upper limit and lower limit of the calculation are determined by Yang and Currie's values, respectively. Based on the surface area, the total uptake can be accurately calculated. The outcome is stated as a preliminary estimation of the magnitude of a substance's annual uptake rate. However, it is questionable to what extent the absorption potential of green roofs in Chicago and Toronto can be used as an indicative value for absorption in St Maarten.

Table D.5: The minimum and maximum modeled monthly average deposition velocities of O_3. The numbers inside the parenthesis were standard errors. Adjusted from Yang et al. (2008)

O_3	**Short grass**	**Tall herbaceous plants**	**Deciduous trees**
Minimum (cms^{-1})	0,01 (0,001)	0,01 (0,001)	0,01 (0,001)
Maximum (cms^{-1})	0,42 (0,007)	0,54 (0,008)	0,65 (0,008)

VALUATION OF CAPTURED OZONE

In Macháč et al. (2016) and Alves et al. (2019), the meaning of the used monetary value is given as a reduction of negative effects on health (heart and respiratory diseases, cancer), the environment and climate change. The reduction of O_3 is based on the values from Center for Neighborhood Technology (2010) and is not explained individually in the calculation but the reduction of this air pollutant is shown together with NO_2, SO_2 and PM_x. The full course of action in the literature is therefore further presented in PM_x section D.2.1.1. An equal impact emerges in the calculation of Berto et al. (2018). According to the concentration-response function and economic assessment suggested by the ExternE Project of the European Commission, the negative impact of O_3 was determined. While the influence on materials was discovered to have too much uncertainty in addition to their tiny size, the harm was described in terms of its impact on agriculture and human health. To avoid double counting NO_x-derived ozone, only the O_3 contribution from volatile organic compounds is taken into account (Rabl and Eyre, 1998).

D.2.1.5. BENEFIT: DIRECT CARBON DIOXIDE SEQUESTRATION

Only a few studies in the literature reviewed for this study offer information on the uptake potential of green roofs on CO_2 in air. The uptake potential of a green roof is considered first, looking at the quantification. The studies provide information on the impact of green roofs on the concentration of CO_2 in air. Carbon dioxide is the greenhouse gas significantly affected by green infrastructure. The ability of vegetation to sequester CO_2 depends on local factors, such as specific practices, species and climate (Center for Neighborhood Technology, 2010), as well as the location of the green roof and surrounding air quality (Macháč et al., 2016). The valuation of these adverse effects are discussed next.

The sources contradict each other regarding the main stumbling block in the calculation. According to Carter and Keeler (2008), CO_2 uptake is well documented, but uncertainty regarding the improvement in air quality remains. Despite this, by integrating Sedum green roofs as a component of an emissions trading scheme, basic estimations for the economic quantification of these gains are still feasible. While this has been done for the indirect reduction in CO_2, Claus and Rousseau (2012) contends that it is not viable to place a monetary value on the direct CO_2 effect.

QUANTIFICATION OF CARBON DIOXIDE SEQUESTRATION

To calculate the benefits of CO_2 capture, Alves et al. (2019) refers to the calculation method described in Center for Neighborhood Technology (2010). Here, a value is given for the uptake potential per square unit area by weight. The information presented is sourced from a study conducted by Getter et al. (2009), which conducted two experiments. The first experiment consists of eight extensive green roofs located in Michigan and four in Maryland. The study focused on quantifying carbon sequestration by measuring above-ground biomass of the green roofs. The total of twelve green roofs, varying in age from one to six years, consisting predominantly of Sedum species. The substrates of the green roofs exhibited a range of depth, spanning from 2,5 cm to 12,7 cm. On average, the aforementioned rooftops accumulated 162 [gm^{-2}] of carbon within their above ground biomass. The second experiment was performed on the rooftop of a structure situated in East Lansing, Michigan. A total of twenty plots were designated, with a substrate-only control as the baseline, the remaining plots were seeded with one species of Sedum, which, alongside the substrate depth of 6,0 cm, represent conventional extensive green roofs in the United States. The results obtained at the termination of the second year manifested that the storage of above-ground plant material varied with the species, culminating in an average of 168 [gm^{-2}] of carbon. The MLCan software, as used by William et al. (2016), provided a similar Carbon uptake [kgC/d] representing an intermediate storage. However, no efforts were taken to convert this carbon absorption into a monetary value for carbon dioxide.

The final range of carbon uptake from Getter et al. (2009) is between 162 and 168 g/m2 C. The said quantity is subsequently transformed into the corresponding quantity of CO_2 avoided in the atmosphere via a conversion factor of 3.67 that translates stored carbon into avoided CO_2. Notably, the employed values are suspected to constitute an underestimation of the authentic uptake potential since one of the two studies failed to account for below-ground biomass. It is important to note that this calculation method is only an approximation and there are other factors that affect such as the age and the condition determine the final CO_2 uptake. Ultimately, this amounts to a range of the uptake potential of 594,54 and 616,56 g/m2. In terms of order size, this corresponds to the value mentioned in Teotónio et al. (2018), which talks about an uptake potential of about 390 g/m2. However, this value has not been scientifically substantiated.

VALUATION OF CARBON DIOXIDE SEQUESTRATION

Monetizing the amount of carbon dioxide captured by the green roof should be done through a financial evaluation. The literature reveals two approaches for this. The first approach examines the socio-economic impact cost of CO_2. This is documented in the works of Macháč et al. (2016), Teotónio et al. (2018) and Alves et al. (2019). This analytical method estimates the average socio-economic cost resulting from emissions over the lifetime of the green roof. In Center for Neighborhood Technology (2010), this value acts as an upper bound. In contrast, the lower bound is derived from the average price of the European Union carbon cap-and-trade system. However, it is important to note that this market is not global and is subject to regulatory parameters.

D.2.1.6. BENEFIT: INDIRECT AVOIDANCE OF EMISSIONS

Besides the direct impact on air quality through the uptake of substances, the literature also gives the indirect consequences of adding a green roof. In this, the literature tends to use a one-size-fits-all approach. The indirect impacts are derived from the saving of energy through the thermal effect of the roof package. The energy required for thermal comfort, either from gas or electricity, is directly related to a certain emission released when generating this energy. Therefore, the saving of energy in turn ensures a reduced production of pollutants. This energy saving would deliver a significant reduction in environmental impact. The impact of energy savings would provide up to 66,7-92,3% of the total impacts in all environmental categories (Saiz et al., 2006), and therefore air pollution would provide greater environmental benefits than storm water runoff reduction (Clark et al., 2008).

Several important considerations need to be made when dealing with this literature. The author is aware that presenting emission factors side by side may lead to undesirable comparisons, because the amount of pollutants released during power generation expressed as these factors are indicative of specific locations at specific times. Further research therefore requires searching for new, site-specific values within the literature anyway. Based on this, the author has decided to only make statements about the procedures in different sources to provide a roadmap that can be used for future research. In this way, the current literature can be used as a guide in future research rather than providing values.

QUANTIFICATION OF AVOIDED EMISSIONS

The literature suggests a method for calculating the quantity of emissions avoided. The approach for determining the avoided emissions of criteria air pollutants based on using utility-specific emission factors is used by Claus and Rousseau (2012) and Berto et al. (2018) for CO_2 and by Niu et al. (2010), Sproul et al. (2014), Ziogou et al. (2017), Ziogou et al. (2018) and Alves et al. (2019) for CO_2, NO_x and SO_x. However, it should be noted that this presents a distorted picture. The energy production also creates ozone and particulate matter, but no emission factors for either of these substances could be found (Center for Neighborhood Technology, 2010). The utility specific emission factors that were used in each of the studies rely on the composition and properties of the electricity grid or the space-heating equipment and is therefore different for study. This is seen back in a different use of sources and values accordingly. The method is best expressed by the formulae taken from (Center for Neighborhood Technology, 2010) as used in (Alves et al., 2019). The energy needed for thermal comfort, which is typically expressed in KWh, is directly correlated with a certain emission generated during the energy's generation. Consequently, energy conservation ensures that fewer pollutants are produced, see formula D.2.

$$\textbf{Avoided pollutant emissions}(kg) = \text{Electricity reduction}(kWh) \times \text{emission factor}(kg/kWh) \tag{D.2}$$

D

A similar structure is applied when gas is used instead of electricity for heating buildings. The additional insulation layer of the green roof reduces gas consumption, resulting in reduced emissions due to reduced use, see formula D.3.

$$\textbf{Avoided criteria pollutant emissions}(kg) = \text{Heating natural gas saving}(mJ) \times \text{emission factor}(mJ/kWh) \tag{D.3}$$

The distinction in the calculation between gas and electricity is dependent on the available information, and local customs. A statement about both gas and electricity is made by Niu et al. (2010), Sproul et al. (2014) and Berto et al. (2018), while Claus and Rousseau (2012), Ziogou et al. (2017), Ziogou et al. (2018) and Alves et al. (2019) only make a statement about electricity. In Macháč et al. (2016) the avoided emissions of air pollutants from the application of green roofs were mentioned. However, no further statements can be made since neither these values and nor the specific emissions were specified.

In the papers of Ziogou, based of the nationally representative conversion emission factor, the quantity of kg of matter/kWh is determined. In addition, the losses that occur are taken into account in Ziogou et al. (2017) and Ziogou et al. (2018). This can be a loss due to transmission and distribution, or through the national conversion factor that reflects the ratio of primary energy to electricity energy. This factor is again based on local parameters.

VALUATION OF AVOIDED EMISSIONS

The next step is to translate the indirect consequence denoted in terms of a quantity of prevented emissions, into a monetary amount. For this, the matching monetary value is found for the emissions. There is some disagreement in the literature about what this value should represent. A number of sources look at the traded market price of these substances, in addition the impact value is also included as indicative of the reduced substance. Claus and Rousseau (2012) is the only source that gives no clear indication on the meaning of the used value.

Looking at the market trading price, a number of sources use it to capture costs. Berto et al. (2018) assumes the value based on the carbon reduction tax according to the Kyoto Protocol. Which is the price that emitters must pay for each ton of greenhouse gas emissions they emit.

In Niu et al. (2010), for NO_x and SO_x, this is based on the allowance market price according to the U.S. Environmental Protection Agency (EPA), estimated by the CAIR (Clean Air Interstate Rule) project. For CO_2, the value is from the Chicago Climate Exchange (CCX) and the European Climate Exchange (ECX). The reason for using different databases for the different substances, is because of the specification of the databases on only a few substances. Sproul et al. (2014) adopts the value from Niu for the valuation of NO_x and SO_x. The valuation of CO_2 is done based on the assumption of a linear price increase over the lifespan of the green roof.

Unlike Niu et al. (2010), in Ziogou et al. (2017) and Ziogou et al. (2018) the translation into monetary terms is based on the impact value of the substances. These studies use detailed information drawn from the work of Zachariadis and Hadjikyriakou (2016), in which the marginal damage costs of CO_2 were calculated by the U.S. Environmental Protection Agency. This included the long-term costs of climate change, such as damage to human health, agricultural production, floods, ecosystems and others. To calculate the costs of NO_x and SO_2 emissions, the European project CASES (FEEM 2008) was used, in which the total external costs of each pollutant were composed of the sum of damage to human health, crops, materials and biodiversity.

In Alves et al. (2019), the meaning of the used monetary value is given as a reduction of negative effects on health (heart and respiratory diseases, cancer), the environment and climate change. Some of the referenced sources are not accessible, which made it difficult to make a well-grounded statement about them. Nevertheless, a statement has been made based on the information that is available. Based on Center for neighbourhood technology by Center for Neighborhood Technology (2010), which uses information both direct and indirect from Wang and Santini (1995). Wang presents two general methods for estimating the monetary value of air pollutants, namely the damage value method and the control cost method. The damage value method is based on direct estimation of the value of air pollutants through simulation of air quality. The effects of air pollution on health and other welfare impacts are identified and valued. This method involves many assumptions in the estimation steps and there is uncertainty associated with each step, even-though the method is well-grounded in theory. The control cost method requires less uncertainty and estimates the marginal cost of emission control. These opportunity costs represent the avoidance of more expensive spending of available emission control measures intended to meet regulatory requirements. The information from Wang and Santini (1995) provides further elucidation on the application of different methods, with their flaws.

D.2.2. DISCUSSION

METHODOLOGY

It has been demonstrated that the common methodology, consistently used in numerous articles, offers a reliable mechanism for converting the ecosystem service of regulating air quality into the benefit of both direct air pollutants uptake and the indirect avoidance of emissions and the valuation of both accordingly. The method entails calculating a monetary value based on the absorption and avoided quantity of a green roof, which is then represented by a conversion into money. The fundamental approach taken in the literature for this purpose seems to be the same in all studies. Some sources do, however, provide helpful modifications to this approach that raise accuracy and should be discussed.

- It is still unclear, based on the literature reviewed, why some sources mention particular compounds while ignoring them in others. When a justification is offered, it is often attributed to the lack of necessary information for an adequate calculation. However, a compilation of all studies has revealed that, in the current state of the literature, there is sufficient information available to make indicative statements about all compounds in this area.
- In the current approach to the indirect impacts of green roofs, only energy savings due to insulation value have been considered. However, there are other aspects that could be considered to get a more complete picture of the impact of green roofs. For example, an extension of the approach could look at the savings realised from storm water treatment and the reduction of the Urban Heat Island effect, as also described in Center for Neighborhood Technology (2010). By integrating these additional factors, a more holistic picture of the positive effects of green roofs on the energy savings can be obtained.
- In addition, for indirect avoided air pollution, we see that certain sources make a distinction between energy generated from gas and electricity within the methodology used. It is important to take this distinctive approach, as gas and electricity power plants have different emission profiles. By taking into account the specific energy sources avoided by green roofs, a more accurate estimate of the emission reductions achieved can be made. This more detailed approach contributes to a more specific valuation, allowing a more realistic calculation of avoided emissions.

QUANTIFICATION

Similarities can be seen in the quantification of both direct uptake and indirect emissions that were prevented. The uptake potential of a specific area of plants is needed for the direct calculation. Utilizing particular emission factors, indirect effects on air quality have been quantified. Looking at the information from all sources, there are a number of points that are not consistently considered. The method used therefore raises a number of discussion points.

- The uptake potential of a specific area of plants is needed for the direct calculation, while the indirect effects on air quality have been quantified utilizing particular emission factors. It seems possible to adopt these values out of context. However, a debate about the appropriateness of their use in various contexts arises when looking at the annotations associated with these values. This is because the on-take potential is indicative of certain conditions, including location. As a result, both the uptake potential and the emission factor are indicative of a particular location.

The use of a fixed value across multiple studies for the uptake potential can be questioned because of the lack of consideration for local conditions. Additionally, the literature also noted the dependence of the uptake potential on plant species, growth and weather conditions. Several sources rely on the uptake potential as described in Yang et al. (2008). This value is derived from a formula that considers the local concentration of pollutants in the air. Nevertheless, the various sources do not use this formula, but only use the final result based on the local case specific data. Determining the uptake based on local concentrations is described as the better method (Claus and Rousseau, 2012), thus in this the approach of some of the literature falls short. Although resources are available for a specific approach, they remain unused. In order to fit the numbers of the uptake potential to the site, then, the use of this formula is already a step in the right direction.

The existing methodology for calculating emission reductions assumes that energy production comes from a specific combination of power plants, nuclear reactors and renewable energy sources. However, the composition of this energy mix varies depending on local conditions. This variation has direct implications for emissions and hence the benefits of green roofs. Fortunately, this aspect is already recognised in the literature, as shown by the fact that different sources use various local factors.

- When assessing indirect pollutant reduction, it is important to look at the source of energy production. This needs to take into account the losses that occur during energy transport, which means that the actual savings may be lower than the amount of energy produced. Fortunately, some sources include this principle in their approach, which is a step in the right direction to get a more complete picture of the actual savings. By considering these losses and transport factors, we can make a more realistic estimate of the actual impact and savings that come from green roofs.

VALUATION

Deriving the value of different substances from the studied literature still proves to be a challenge due to a lack of detailed information and consistency.

- In the current literature, there is no consistent approach to determining the value of a substance. Most studies determine the value based on the impact of the substance, while some studies use the market price or the avoided mitigation cost. The lack of consistency in the existing literature makes it difficult to make an informed choice between market price and impact price. There is a need for future research that focuses on developing guidelines and tools to adopt a consistent and considered approach. These guidelines should take into account the interests of different stakeholders.
- If the impact price is chosen in the literature, often, the impacts of all substances are lumped together, while there are actually differences between them. This lack of distinction leads to little specific knowledge emerging regarding individual substances and their impacts. This undermines the potential to actually improve air quality, as it is essential to have a detailed understanding of the specific characteristics and effects of each substance.

D.2.3. RECOMMENDATION

To improve the knowledge required to answer the research question, follow-up research should focus on:

- Extension to other substances and factors
  Although certain pollutants (PM_x, SO_2, NO_2, O_3 and CO_2) and indirect effects have already been named in the literature, it is interesting to consider other pollutants and factors. Follow-up research could focus on quantifying the impact of green roofs on a wider range of substances.
- Extending the calculation of energy savings
  In addition, the indirect effects should go beyond energy savings from insulation to include factors such as storm water treatment and the reduction of the Urban Heat Island effect. This way a more complete overview is generated, which could prove to be more adaptive and represent a more holistic picture in a wider variety of contexts.

QUANTIFICATION

- Refine methods for quantifying direct and indirect impacts
  The current quantification methods provide a basis for calculation, follow-up research can be of a controlling and verifying nature on the one hand. Whereby the use of the figures from the literature and the use of, for instance, Yang's formula should be investigated. In addition, follow-up research should also

supplement the current knowledge pool. In which the influence of specific factors can be investigated. In this way, when considering local values, their influence can be taken into account by, for example, also considering the time factor.

Valuation

- Develop guidelines and tools for consistent valuation
  To determine the economic value of different substances, there is a need for guidelines and tools that enable a consistent approach. Researchers can work on developing a uniform methodology to determine the value of substances, taking into account both market prices and impact prices. It is also important to consider the interests of different stakeholders when determining economic value.
- Investigate specific properties and effects of each substance
  To better understand the unique properties and impacts of each substance, further research is needed. Researchers should delve deeper into the properties of different substances in line with their valuation method. This will help improve the connection of the valuation method with the involved stakeholders and gain more specific knowledge on the contribution of green roofs to improving air quality.

D.3. STORMWATER MANAGEMENT

Coping with precipitation is a major challenge in cities. In an urban environment, natural systems are disrupted by the process of urbanisation. Changes in land use and land cover, such as the removal of vegetation and fertile soil for agriculture or urban infrastructure and the introduction of an engineered drainage system, cause a shift in the hydrology of the local area both above and below ground. As a result, receiving waters in the catchment are exposed to significantly different flow regimes than before urbanisation (National Research Council et al., 2009). Serious environmental problems are caused by the combination of the effects of climate change with rapid urbanisation. This is because impervious surfaces convert precipitation into storm water runoff, causing various water quantity and quality problems (Zhang et al., 2020).

The main causes of these problems are the loss of water-holding and evaporative functions of soil and vegetation. Due to the large amount of hard surfaces, such as buildings and roads, the total amount of precipitation in urban areas is prevented from penetrating the soil. In undeveloped areas with more greenery, such as forests and gardens, rainwater can infiltrate into the soil or evaporate through vegetation, while in an urban landscape these processes are reduced, see figure D.5. Vegetation and soil absorb and filter the water, reducing the amount of runoff that enters sewage systems or natural water bodies. This water can cause problems if not treated properly, which is why these impervious surfaces require the addition of alternative routes for runoff water to leave the city (National Research Council et al., 2009). Globally, the use of piped drainage systems has been under debate, as they are considered less sustainable than alternatives. One issue is the increasing amount of polluted water runoff from impermeable surfaces in urban areas. The poor quality causes environmental damages while the excessive flows cause property damages (Cettner et al., 2013).

There are two types of sewage systems: separate and combined (figure D.6). In a separate system (MS4), the sanitary sewage is the combination of wastewater from homes and businesses. The sanitary sewage is transported via pipes to a treatment facility, while stormwater is transported through distinct pipes to a natural water body or drainage system. In a combined system (CSS), both wastewater and stormwater are conveyed through the same pipes to a treatment facility. When a sewage system experiences an overflow, the consequences can be severe for both the environment and public health. In the case of combined sewer systems, this can lead to sanitary sewage entering natural waters (New Jersey Future, 2020).

During an overflow in a separate sewage system, the sanitary sewer system remains unaffected by the increased volume of stormwater. A local flooding may take place if the pipes designed for storm water runoff cannot cope with the increased water volume, causing localised water damage. However, in a combined sewage system an overflow may happen when the treatment facility or the pipes are unable to process the volume of water. The overflow is resulting in the release of raw sewage into the environment. This can pose a significant threat to public health (National Research Council et al., 2009). It is essential to properly design and maintain sewage systems, to prevent overflow and protect public health and the environment, particularly in the case of combined sewer systems.

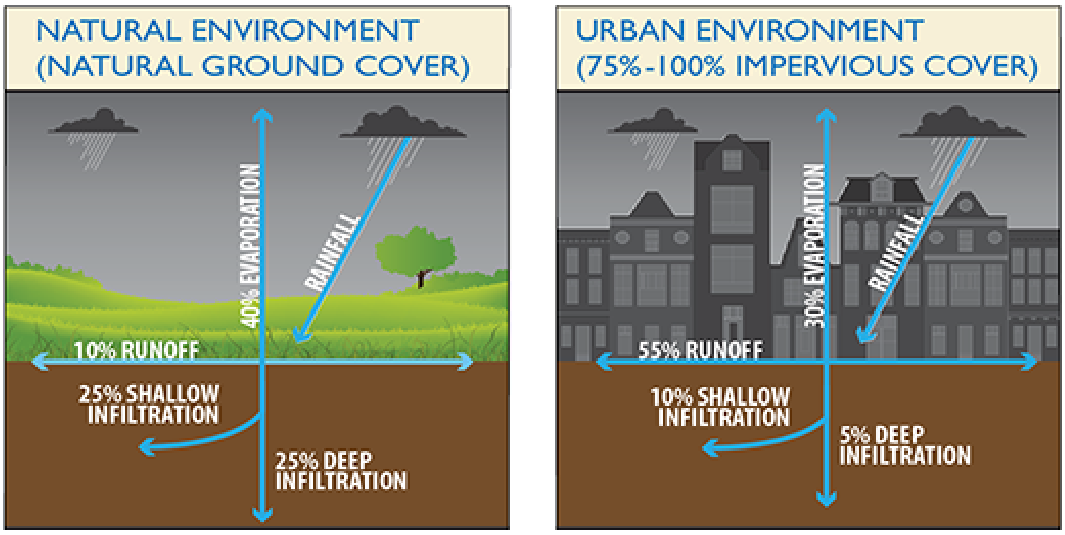

Figure D.5: Comparison runoff natural environment and urban environment. From New Jersey Future (2020)

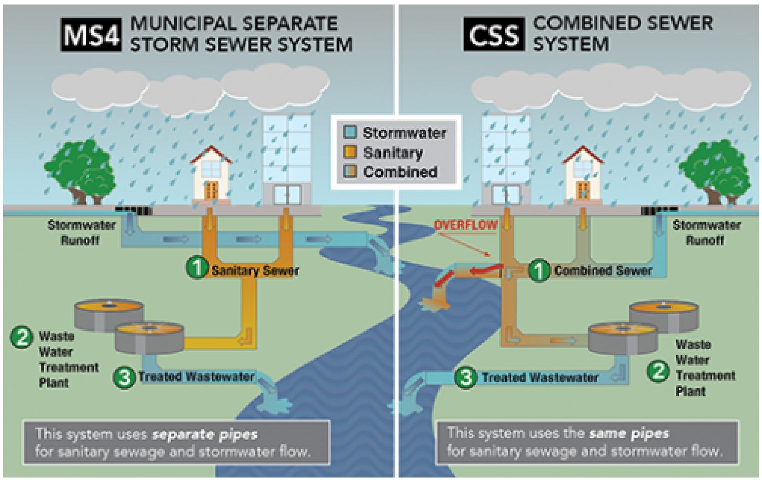

Figure D.6: Comparison municipal separate storm sewer system and combined sewer system. From New Jersey Future (2020)

GREEN ROOF STORM WATER MANAGEMENT

Stormwater control might potentially benefit greatly from green roofs. The large amount of roofs in cities means that there is a lot of surface area for the implementation. Rainfall that falls on the roof can be collected, stored, and released using green roofs. When it rains, a portion of the moisture is absorbed by the soil and plants on the green roof, where it is utilized to support plant development or is gradually released back into the atmosphere through evapotranspiration. The remaining water is retained in the soil layer or directed to a drainage system to form the runoff (Berto et al., 2018). This process of water management helps reduce the volume and rate of stormwater runoff, which can otherwise cause flooding and erosion in urban areas (National Research Council et al., 2009). By intercepting and retaining a significant portion of the precipitation that falls on the roof, green roofs can act as a sponge to soak up excess water and mitigate the impacts of heavy rain events. The amount of water that can be retained is determined by soil properties as well as moisture conditions. When all the pores inside the soil are filled with water the soil is in a saturated condition, meaning it can hold no more water. The water content after a free drainage is called the field capacity, with the volume drained being called the specific yield (Berndtsson, 2010).

D.3.1. LITERATURE REVIEW

Several advantages of using a green roof are mentioned in the literature. The main benefit is to reduce the volume of water that is discharged as runoff. A variety of methods were found to exist in literature to determine the financial benefit in terms of storm water reduction of a green roof.

Most of the literature refers to a runoff coefficient which indicates the ratio of runoff to precipitation. A higher coefficient value indicates a greater proportion of runoff, while a lower value indicates a higher potential for water infiltration into the soil. The value of this runoff coefficient can vary depending on the source used, with values ranging from 0,5 (Carter and Keeler (2008), Macháč et al. (2016) and Claus and Rousseau (2012) respectively) to 0,4-0,2 for a vegetated layer of 8cm thick (Macháč et al., 2016). Compared to a conventional roof, this represents an improvement of 48% to 52% (Carter and Keeler (2008) and Claus and Rousseau (2012) respectively). The difference in values can be attributed to the fact that the studies took place in different conditions: rain intensity, duration of rain, substrate thickness, length of study period. As a result, these values can hardly be compared with each other, without including the context of the study. On this basis, it was also decided not to present the figures in a clear tabular form.

The quantity of runoff is determined by both local and roof-specific parameters. Local parameters, such as the quantity and frequency of precipitation (Macháč et al., 2016) and drought periods (Berto et al., 2018), have an impact on the reduction of runoff. In addition, the amount of transpiration by the canopy is influenced by vegetation type and coverage rate (William et al., 2016). The substrate's thickness and type, as well as the drainage equipment (Macháč et al., 2016), influence runoff and determine the amount of soil evaporation (William et al., 2016). Depending on the infiltration rate of the applied soil, runoff increases as the green roof becomes saturated, making it equivalent to a bare-roof system (Chang et al., 2011). A thicker substrate mix increases storage capacity, but as a result, causes the moisture to be retained for a longer time, limiting the effectiveness of retention during subsequent storms (Clark et al., 2008). These factors result in a differences in the runoff capacity between EGR and IRG, with the latter having a lower runoff coefficient (Teotónio et al., 2018). The roof slope is also a parameter that affects runoff (Macháč et al. (2016), Berto et al. (2018)). A larger slope will cause the retention of the roof to decrease, and thus the peak flow rate of the roof increases. In general, the influence of the roof slope is found to be lower than the moisture content (Clark et al., 2008).

A more general attempt to specify the relation between a green roof and its runoff is illustrated in equation D.4, linking rainfall amount (prec), substrate layer thickness (sub) and annual runoff (Claus and Rousseau, 2012).

$$\textbf{Annualrunoff} = 693 - 1,15prec + 0,01prec^2 - 0,8sub \qquad \text{(D.4)}$$

D

This formula is based on measured values of runoff from green roofs, with most of the data coming from Germany. The formula provides insight into the physical processes affecting the determination of runoff. The annual rainfall, roof type, number of layers and depth of substrate layers were found being significantly correlated with annual runoff. In contrast, the age of the green roof, slope angle and length were not found to be significantly correlated with annual runoff. This means that both the roof package and local parameters such as climate with annual rainfall play a role in determining runoff (Mentens et al., 2006). However, due to their low sizing, especially for extensive green roofs, they are only effective against storms with a recurrence interval of 1-2 years. For larger storms, the roofs quickly become saturated, causing large portions of precipitation to still run off as runoff. Typically, storm water systems are sized based on storms with a recurrence interval of 25-100 years Carter and Keeler (2008).

Green roofs are not only capable of reducing but also in postponing the peak volume of downpours. The ability of green roofs to reduce and delay peak runoff can be as high as 65% and extend the time it takes to leave the site by 3 hours, in wet weather (Sproul et al., 2014). An alternative study demonstrated marginally less favorable results, wherein the delay of heavy rainfall was observed to be postponed by a duration of 8 minutes, with a volume reduction of 52%, when a substrate layer of 4cm is compared to a classic roof cover (Claus and Rousseau, 2012). Moreover, the use of green roofs does not completely eliminate the impact of all storms, but rather delays and reduces peak runoff (William et al., 2016). Nevertheless, the study of Alves et al. (2019) shows that it is possible to draw conclusions based on rainfall events with different recurrence intervals.

Various methods exist to determine the financial benefit of a green roof, as shown in the literature. Despite possible differences in the methods, all calculations have the same basic premise: by reducing the volume of water, the amount of water to be transported and treated can be reduced. This can lead to avoidable costs. Because of this it was chosen to analyse the benefits one by one instead of analysing them based on quantification and valuation as done in previous chapters.

D.3.1.1. Transportation and treatment cost

The calculation of the revenue from avoided transport and treatment costs is always set up in the same way. The prevented runoff is converted into a quantity (often denoted in m^3) and then multiplied by a unit price (often denoted in €/m^3). This price can be based on the cost of pumping and purifying of the water, Niu et al. (2010) and Macháč et al. (2016), or more specifically the reduced energy consumption and the cost associated in Berto et al. (2018) or in some cases, as in Claus and Rousseau (2012), derived on the basis of the supra-municipal sanitation contribution passed on to small users. In the case of Teotónio et al. (2018), no statement can be made on the meaning of the value as the original source is not available in English.

D.3.1.2. Pipe dimension reduction

The runoff coefficient of a green roof therefore determines how much water needs to be drained. A reduction in this runoff results in less water having to be transported, less water having to be treated and therefore the sizing of treatment facilities can be lower. These are advantages for the sewerage owner (Carter and Keeler, 2008). The storm water management system consists of a collection of pipes, inlets and junction boxes that make up the storm drain system. By stopping storm water before it reaches the system, it is possible to avoid having to increase the size of the pipes during maintenance and repair (Carter and Keeler, 2008). In calculation, this is reflected in only a few sources. The water volume reduction factor is also applied to the annual storm water infrastructure management budget, in the paper of Berto et al. (2018). However, in practice, the volume decrease means that only the cost of materials decrease. Looking at the total cost of a project (materials, equipment, contingencies, transportation, labour costs, overheads, extra parts, mobilisation/clearance of the site), this would only lead to savings on material costs (about 23-29% of the total cost in a typical tunnel project) (Niu et al., 2010). Smaller installations, especially smaller cisterns (Sproul et al., 2014), also reduce maintenance costs. This relationship between the cost of pipe per unit length and the diameter of the pipeline is discussed most extensively in Carter and Keeler (2008). While studying the feasibility of replacing 15.9% of the total land cover in an urban catchment with green roofs, it found that these reductions are not significant enough to lead to a change in pipe sizing as a result of implementing green roofs. However, the outcome of the calculation may differ in other locations depending on the density of buildings that lend themselves to adding a green roof and the rainfall profile. When the literature does include the value in the calculation, a 1-time storm water equipment down sizing is charged as a benefit, based on best management practice equipment cost (Sproul et al., 2014). However, the origin of the value used from this source is unknown, nor is the time when the value was taken into account.

D.3.1.3. Incentive

To pay for the cost of sewerage, municipalities charge a fee to landowners. There are examples where owners are encouraged and rewarded for reducing the volume of water they deliver to the sewer (Clark et al., 2008; Carter and Keeler, 2008; Niu et al., 2010). They receive a discount on the sewerage tax for this, which also results in a cost saving for the owner. This rebate can range from 35% in Portland (USA) (Carter and Keeler, 2008; Niu et al., 2010) to as much as 50% , for a reduction in the volume of water in a 10-year 24-hour storm, and 100%, for a reduction in the volume of water in a 100-year 24-hour storm in Minneapolis (USA), off the original sewerage fee payable for development (Clark et al., 2008).

D.3.1.4. Best management practices

Finally, the literature compares green roofs in storm water management compared to other solutions. Using retention data, the costs of different storm water best management practices (BMPs) for controlling storm water runoff in an urban area have been compared. The costs of these alternative BMPs were compared with the costs of using green roofs, with the aim of determining the cost savings that could be achieved by using the alternative BMPs. Sand filters, bioretention areas and porous paving were considered in the analysis of Carter and Keeler (2008), which are typically used in an ultra-urban application.

Since other BMPs for storm water reduction take up valuable land, there are also opportunity costs involved here. It also provides opportunities because the use of roofs in an urban area can be applied in many places. Green roofs provide practical solutions in densely built-up urban areas, where conventional solutions have to compete with other infill solutions. However these opportunity cost were not taken into account.

The analysis was conducted in line with compliance with a storm water ordinance adopted to establish minimum requirements and controls for storm water management to protect and ensure the general health, safety and welfare of the public. In this way, it justifies the use of public funds to encourage and contribute financially to individuals so that green roofs are used for runoff mitigation. The benefits of use over the alternative BMPs have been included in a social cost-benefit analysis and are for the county (Carter and Keeler, 2008).

D.3.1.5. Stakeholders

Based on the literature, there are a number of benefits related to storm water management when a green roof is applied, for both private and public stakeholder.

Most of these benefits are to society. Due to the runoff retention capacity the runoff flow is reduced during downpour. This reduces the need of transportation and treatment costs. These cost are assigned to the local sewage management party. This reduction can be seen as a continues benefit during the entire lifespan of the green roof. Additionally this also reduces the need of bigger storm water management systems. When looking at future pipe enlargements, a reduced size of storm water outlets due to the reduced volume are benefits for the owner of the sewer system. The benefits can be attributed to a saving on materials, given the fact that labour and other costs will still occur during maintenance work. As a result of the smaller dimensions, upkeep of the system will also be lower, especially the upkeep of cisterns.

It can also be seen that storm water management as a whole is expressed in an economic value by means of best management practices. Again, the benefit lies with social parties who bear responsibility for this, the local county in the case of Carter and Keeler (2008). This benefit evaluation is again made with the economic avoided cost method, and is assigned to year zero in the calculation.

For the project owner, two benefits were obtained from literature. The project owner enjoys a benefit based on a 'reduction fee', which is essentially a social benefit passed on. Traditionally, storm water management costs are covered by property taxes or fees for drinking water use. However, municipalities can credit the use of green roofs (Clark et al., 2008), thus distributing the benefits more equally. The main advantage of this is that it still provides a benefit to the owner of the sewer system, but this benefit is then also partly returned to the private owner in the form of the abatement fee. In addition, the potential of using storm water for other purposes such as irrigation and toilet flushing is addressed. This too means savings for the project owner, since it reduces the need to buy tap water. Both savings are a direct representation of the market prices, either through the substitute cost method or market price-based approach. They will benefit the owner during the entire lifespan of the green roof.

D.3.2. DISCUSSION

D

The current literature evaluates the benefits of storm water management and identifies different benefits for various stakeholders, with different incentives designed to pass on these benefits. The literature reveals some important aspects worth noting.

Current calculation methods for the financial benefit of storm water management are based on the assumption of a specific runoff coefficient. Therefore, the estimation of this coefficient greatly affects the outcome of the financial benefits generated by storm water management. There is a wide range of indication values in literature for the runoff coefficient of a green roof. Care should be taken that the right indicative value is chosen, given all local conditions. But also the consideration between the retention capacity en roof load structure.

In addition, comments must be added to the runoff coefficient, such as the influence of the storm's recurrence interval and the fact that a green roof does not reduce the runoff but only slows it down. These influences are not taken into account within the methods described so far.

Different benefits arise from the green roof service storm water management. However, some counterarguments have been presented in the literature that challenge some of the assumptions on which the calculation methods are based. For the purpose of a clear overview of the various methodologies, it was chosen to deal with them separately.

TRANSPORTATION AND TREATMENT COST

The first methodology relies on the reduction of the amount of water that has to be transported and treated. These cost should correctly link the cost of transportation and treatment to a unit price of water [m^3]. To correctly reflect this in the calculation, it is important to look at the marginal costs in the production process linked to this same unit. In the current literature, this value is sometimes still based on values that are not a one-to-one representation of what needs to be mapped. Due to this erroneous assumption, the final outcome is also not an accurate reflection of reality. The main issue here is the misalignment of the value and the stakeholder involved, in which the party bearing the costs and benefits is not truly reflected.

When determining the financial benefit of a green roof, it is also important to look at the type of sewerage system present at the location in question. As indicated earlier, there are two types of sewerage systems: the combined sewer system and the municipal separate stormwater sewage system (MS4). Depending on which system is present at the site, it can be determined whether the calculation for avoiding conveyance and treatment costs can be applied. In the case of MS4, stormwater is discharged directly to nearby water bodies and therefore does not reach the sewage treatment plants. In such cases, there are little to no benefits based on transport and treatment costs.

PIPE DIMENSION REDUCTION

The stormwater management systems consists of a collection of multiple components. Decreasing the amount of runoff would lead to a decreased flow, and thus the potential to decrease the size of the pipe. Multiple attempts were found within literature. The first attempt using the stormwater reduction value to the stormwater infrastructure cost will most likely result in an overestimate since it does not take fixed cost into account. Another opted approach looks only at the reduction of the material cost. However, in addition to the statement that the contribution of green roofs to pipe dimension reduction is negligible, several arguments can be found in the literature that question the described benefit. The composition of green roofs makes them effective in retaining and reducing runoff during smaller storm events, while the dimension of the pipes is based on bigger storms.

These methods, however, don't fit the size of the study's scope. The size of a single building is the main topic of this study. Therefore, the possible reduction of the components that are directly impacted by the size of the building should be the main focus of the pipe dimension reduction.

INCENTIVE

In terms of methodology, the use of an incentive is pretty well grounded. Because it relies on actual numbers and values, the benefit can be directly included in the analysis. However, the use depends on the availability of the incentive within the municipality, therefore it depends per location whether the benefit is present. This should be included in the calculation so that no virtual benefit is created from actual cash flows that do not exist in reality.

BEST MANAGEMENT PRACTICES

There is currently only one indication of the methodology used for the best management practices. The methodology relies on the capacity of green roofs to reduce the need for other practices. The advantage achieved is therefore relative to other means. However, based on current information from the literature, no well-formulated statement can be made to properly highlight this methodology.

D

D.3.3. RECOMMENDATION

To improve the knowledge required to answer the research question, follow-up research should focus on:

- Further research on correct calculation of runoff coefficient
  The runoff coefficient is responsible for the impact on stormwater management. On that basis, properly mapping the runoff coefficient is an important consideration. The effect of the annual rainfall, roof type, number of layers and depth of substrate layers on the annual runoff should be better mapped. Additionally for single storms follow-up research should focus on determining the influences that can alter the behaviour of green roofs, such as the frequency of storms and the fact that green roofs can only slow down runoff. By considering these factors, more accurate methods can be developed to calculate the runoff coefficient and better quantify the impact of green roofs on stormwater management.

TRANSPORTATION AND TREATMENT COST

- Determination of marginal transport and treatment costs
  The current methodology for determining the transport and treatment costs of storm water through the sewer system can be further improved. It is important to link the costs associated with transport and treatment of water to the reduced amount of water due to green roofs. This can be achieved by working with responsible local parties, such as water treatment companies, to accurately estimate the variable costs saved from reduced water runoff. Developing guidelines and standards for determining these costs can help create a consistent approach and obtain reliable results.

PIPE DIMENSION REDUCTION

- Study on the effect of green roofs on pipe sizing
  The quantification should focus on looking at the potential gains on a small scale, from probably the reduction of materials. This should take into account the effects of storms with different recurrence intervals. The follow-up step should elaborate valuation data regarding how this pipeline reduction will impact maintenance costs. The reduced maintenance cost can be seen as an additional benefit arising from the reduced dimension.

BEST MANAGEMENT PRACTICES

- Identifying the best management practises for the effects of a single building
  Identifying the potential of best management practises on the scale of a single building applicable for multiple situations. Obtaining data is essential for both the quantitative comparison as well as the valuation of the benefit. Research could demonstrate the effectiveness of the method in both theory and practise. The next step should go into more detail about the potential for the extra opportunity cost. Once more, it is still unclear how to translate this into a numerical value. In order to further fill in the advantages of a green roof, further research can be done to determine the potential of this and add to the existing knowledge pool.

D.4. FLOODRISK

Floods are a natural event in which an area that is normally dry is flooded with water. This can happen as a result of heavy rainfall, storm surges, meltwater from snow and ice, or other causes. Floods can happen slowly or swiftly, and their magnitude and intensity can change depending on the situation. There are various forms of floods, including floods along rivers and coasts, floods brought on by rising groundwater, floods caused by reservoirs breaching, and floods brought on by heavy rainstorms and flash floods. Floods can do a great deal of harm to the environment and the communities that inhabit it. They can result in the destruction or damage of buildings, roads, bridges, farms, and other infrastructure, as well as the loss of human life. Moreover, floods can result in a variety health problems, including the spread of diseases and infections, and psychological stress and trauma to affected communities.

PLUVIAL FLOODING

Apart from flooding caused by rivers and water bodies flowing outside their banks, there is another risk of flooding in urban areas (Dai et al., 2018). Pluvial flooding occurs when the surface runoff generated exceeds the infiltration rate and drainage capacity. The dimension of the infrastructure meant for storm water runoff is then too small and therefore some of the precipitation cannot be drained in a controlled manner. This often occurs during heavy rainstorms of short duration (Miller and Hutchins, 2017), see figure D.7.

Urban areas are increasingly affected by extreme weather events and are among the most vulnerable human habitats in terms of climate change impacts. Scientific literature indicates trends in observed extreme precipitation and flood runoff in recent years. Climate models predict an increase in extreme precipitation in the future, consistent with the observed trend in extreme precipitation observed in recent years (Madsen et al., 2014). As a result of climate change, annual precipitation in the Netherlands increased by about 26% between 1910 and 2013. In addition, the intensity of weather events has increased significantly (KNMI, 2014).

Extreme rainfall affects cities more because of the large percentage of areas covered with asphalt or other sealing materials (Dai et al., 2018). The implementation of these materials lead to a reduction in the water absorption capacity into the soil, resulting in an increased stress on drainage systems.

The recent increase in pluvial flooding in urban areas can have severe economic consequences. with a growing population in cities it is necessary to analyse these impacts accurately. To achieve this, the identification of a wide range of impacts of water on infrastructure in urban areas is important. As demonstrated in the classification of impacts in Dutch urban areas formulated by van Riel (2011), multiple material and immaterial impact are identified, affecting economics, health, services and comfort.

In the Netherlands, municipalities and water boards have the task of discharging rainwater. For the proper functioning of the water treatment plant, this water is not meant to end up in the waste water sewer, as it is a clean water stream that has to be discharged to the surface water or soil. Traditional infrastructure in Dutch cities, such as canals and sewer systems, appears to have insufficient capacity to cope with the increase in storm water. Especially in densely populated urban areas, infiltration systems have been found to have insufficient capacity to drain stormwater (Dai et al., 2018). Together with the water board, the municipality can set policy goals, which are further elaborated in the Municipal Sewerage Plan. Within the package of measures aimed at preventing such flooding, either increasing the infiltration rate or the drainage capacity

Figure D.7: Pluvial flooding in the Netherlands. From RTL Nieuws (2014) should therefore be considered (Helpdesk water, 2023). The Delta Plan on Spatial Adaptation sets seven ambitions for a water-robust and climate-resistant design of the Netherlands in 2050. One of these ambitions is the smart linking of climate adaptation measures with other tasks in the physical living environment. This offers many opportunities, especially in the urban area, speeding up climate adaptation measures, enabling multiple measures to be implemented simultaneously and offering financial benefits (Ministerie van Infrastructuur en Waterstaat, 2022).

GREEN ROOFS

Among their other benefits, green roofs also have the ability to retain water, which further helps reduce the negative effects of storm water on urban environments. The soil and plants on a green roof act like a sponge, absorbing and storing water during rainstorms. The retained water is then either slowly returned to the atmosphere through a process known as evapotranspiration, which is the sum of the water vapour released to the air by transpiration through their leaves and evaporation through the soil. The remaining water in the soil will release the water with some delay after which it is still drained through sewer systems or infiltration. Looking at the water balance, green roofs increase the storage capacity of the urban area during a storm. The storage capacity depends on the thickness of the substrate (see chapter D.3). The saturation of the soil at the start of the downpour is also influential. After all, a saturated soil cannot retain additional water. Ultimately, this helps regulate the amount of runoff water. By storing and releasing water in this way, green roofs play a vital role in managing storm water in urban environments and contribute to the overall sustainability of the city. In this way, the likelihood of pluvial flooding decreases and thus material and immaterial damage.

D

D.4.1. LITERATURE REVIEW

Three papers tried tried to make a statement and translate the flood risk control into a monetary value. Literature links heavy precipitation resulting in flooding and subsequent damage. Green roofs are used as a solution in order to decrease the risk of urban flooding.

D.4.1.1. FLOOD DAMAGE REDUCTION

One advantage of reducing the volume to the sewer system is the reduction of the probability of a combined sewer overflow. As the name suggests, this benefit is only applicable in the case of a CSS. Severe storms can lead to a water overflow in natural water bodies during heavy rainfall. This water, a combination of rainwater and wastewater from households and businesses, can lead to wastewater in natural bodies of water. In the city of Toronto, this could already save $46.6 million in infrastructure costs (Banting et al., 2005). This value looks at avoided costs for a similar proposed underground storage capacity, in which the estimation of the reduction for the same level of CSO control had a unit cost of $1,340/m3. This does not include the reduction of damage with high environmental impact in many larger cities, as described in the Carter and Keeler (2008).

Teotónio et al. (2018) is discussing a similar municipal intervention plan to change precipitation flow to prevent combined sewer overflow events, especially since Lisbon, the case study of the paper, has suffered serious flooding in the last years. Green roofs can play an important role in this solution due to their water buffering capacity. This can be justified as green roofs offer a multidisciplinary solution and because the budget for the flood intervention package is known. The whole annual cost of the intervention proposal is considered for intensive green roofs, for extensive roofs an average reduction of the pick flow is applied. Given their lower water absorption capacity.

The methodology to monetise the flood damage reduction can also be based on the flood impact, as done by Berto et al. (2018). Mapping these impacts and analysing the prevention capacity of green roofs can save on impact costs. In the region, various rivers are causing urban flooding with a known cost. The exact origin of the value in the catchments is unknown. However, the most recent general framework directive of the region does talk about reducing the negative impacts of floods on human health, the environment, cultural heritage and economic activities (autorità di bacino distrettuale delle alpi orientali, 2023).

A much more comprehensive and labour-intensive calculation of a system composed by open channels follows from Alves et al. (2019). Using a flood estimation model in Storm Water Management Model (SWMM), the expected annual damage can be determined as a benefit derived from the decrease in flood damage. The anticipated probabilistic flood cost, expressed in monetary terms, represents the yearly damage as the summation of all possible flooding events. The reduction is computed as the difference between scenarios that involve the application of additional flood reduction measures and those that do not. The expected annual damage was determined for each location, for different flood depths. The number of affected buildings was looked at on the one hand and the damage cost per affected building on the other. This made it possible to calculate the total building damage for different return periods. The model takes the main drainage pipes into account in relation to surfaces and streets. The monetary value on which this calculation relies is based on depth-damage curves. Here, water depth is used to make a statement about the damage to different asset or land-use classes. This value comes from surveys of construction costs completed by multinational construction companies (Huizinga et al., 2017), and includes damages to residential and commercial buildings, infrastructure damage and transport damage.

D.4.1.2. STAKEHOLDERS

The monetary values resulting from flood risk control have different natures. Some of the studies approach the issue from the impact side. Looking at the damage that can be prevented by applying green roofs. This damage due to flooding has been mapped with the use of the avoided cost method. Two papers looked at the damage cost, while one paper looked at the substitution cost of alternative options. All benefits flow back to public stakeholders.

Berto et al. (2018) probably bases the value on a reduction of the negative impacts of floods on human health, the environment, cultural heritage and economic activities. Benefits are thus estimated based on the avoided cost method looking at the damage cost. These benefits flow back to a wide variety of local stakeholders, and because of the uncertainty of origin no further statements can be made other than just assigning them as annually to society as a whole. The avoided cost method is also used in Alves et al. (2019), who bases the benefit looking at the potential avoided damage to residential and commercial buildings, infrastructure and transport. Based on these damages the social benefits flow to a wide variety of local property owners, as well as local municipalities. The benefit is seen as yearly occurring during the entire lifespan.

In addition, valuation methods can also look at the preventive side as an approach to determine the financial cost, since green roofs play a part in preventing combined sewer overflow. Current benefits are again for social parties who take steps to prevent this. The current assessment method in Carter and Keeler (2008) looks at the available budget reserved to prevent combined sewer overflows from happening. Little information is available on the scale in which green roofs are capable of addressing this problem. The avoided costs were assigned to the year zero, in which the roof was finished. Teotónio et al. (2018) also compares the use of a green roof as a direct equally contribution to the problem. Given the fact that there is an budget for an intervention proposal, the social benefits of adding green roofs is that according to the avoided cost method looking at the substitution cost of alternative options. Based on this assumption, there is an advantage when green roofs are applied because these conventional solutions no longer need to be implemented. In the paper, this advantage is for the municipal council, given that they control the budget of the intervention plan. This benefit is defined as yearly equal during the proposed intervention period, of 15 years.

D.4.2. DISCUSSION

There are a number of debatable points in the current literature. It is crucial to pay attention to the methodologies used to quantify and and value the benefits.

When looking at the methodology of the flood damage reduction, Berto et al. (2018) focuses on flood impacts, there is reason to believe that the damage as used originates, partially, from river flooding. On that basis, the impact of green roofs may be an overestimate. Especially when taking into account the size of the catchment area, 9073 km2 in the case of the source. The influence of installing green roofs at this scale cannot be estimated as such, or its feasibility should be questioned. This does bring additional awareness to what needs to be considered in the flood risk calculation. That it is about the parameters that can be controlled, and therefore especially about pluvial flooding. The inability of cities to transport water outside the city impose damage on local infrastructure and more. Green roofs play their part in allowing a additional storage capacity, within the scope of this study the influence of a single building should be studied.

QUANTIFICATION

As described in the section D.3: storm water management, it should be noted that the runoff reduction is not undisputed. Storms with higher recurrence intervals will still discharge significant amounts of water as surface runoff. As a result, this water can still contribute to the occurrence of flooding, which is typical in such storm events.

VALUATION

In the literature, there is an awareness of the impact of implementing green roofs on reducing flooding. The benefit is defined as an avoided damage cost, which is directly related to the effects of flooding that can be prevented by using green roofs. However when looking at the combined sewer overflow the damage is based on the avoided mitigation cost. This involves looking at the potential cost savings at the front end of the problem. Using this value should take into account the fact that a uniform measure of utility is used, e.g. preventing flooding with a recurrence interval of x number of years.

The author believes that the two methodologies can both provide valuable information and are not mutually exclusive, allowing for situations where both benefits are taken into account. In this way, from a social point of view, the impact that can be avoided in an area can be looked at. This is important as it affects local people and mapping this impact can cause awareness. Presenting this data to local stakeholders can trigger them to take initiative and (collectively) address the problem. However, correctly implementing this methodology requires close cooperation with parties who place value on this application. Including the avoided financial mitigation benefits can help create new opportunities, especially given the limited budgets of public agencies. In this way, new opportunities can be generated by involving stakeholders in the process.

D.4.3. RECOMMENDATION

To answer the research question, follow-up research should focus on:

- Research on the quantification of pluvial flood reduction
  Since the literature provides limited information on quantifying the reduction of pluvial flooding by green roofs, further research is needed at the scale of this study. Follow-up research could focus on developing methods to accurately quantify the impact of green roofs on reducing pluvial flooding. This should take into account factors such as rain runoff coefficient and storm recurrence. It is important to examine the influence of these factors and integrate them into the methodology to get a realistic picture of the contribution of green roofs to reducing pluvial flooding at the desired scale.
- Comparison of different valuation methods
  The literature mentions both avoided impact costs and avoided mitigation costs as possible approaches to determine the value of pluvial flood reduction from green roofs. Follow-up research could focus on comparing these two approaches and assessing their suitability in different contexts. This should take into account the interests of different stakeholders. In addition, it is important to determine the position of these values within the methodology and further investigate their impact on stakeholders. Developing guidelines and criteria for selecting the most appropriate valuation methodology should contribute to a consistent and reliable approach to determining the value of pluvial flood mitigation.

Figure D.8: avoided vs avoidable cost

D.5. RUNOFF QUALITY

Mostly all precipitation that falls within the urban area is either drained by runoff or permeates the soil by infiltration. With the transport of storm water, a lot of waste is also drained into nature. Changes in land use and land cover have resulted in hydrological changes. The disruption of natural systems can lead to deterioration of water quality and habitat for plants and animals that depend on these waterways. It is therefore crucial to understand and manage the effects of urbanisation on the environment to protect the health of ecosystems and human health (National Research Council et al., 2009).

This urban runoff can lead to increased levels of nutrients, posing a risk to water quality and aquatic communities (Environmental Protection Agency, 2022). Most of the pollution in this discharge is absent from street solids and sewer-deposited materials (Lee and Bang, 2000). Furthermore, the atmospheric pollution is also considered an important source of pollutants in urban runoff water. These substances are not only released into the air locally from both natural and anthropogenic sources, but can also originate from outside the city due to wind. This allows many different substances to be present in the air, and their composition and quantity may change over time. In general, atmospheric pollutants are an important environmental source of solids and any conventional and surface pollutants carried by urban stormwater (Müller et al., 2020). This ultimately affects the physical, chemical and biological conditions of downstream waterways (National Research Council et al., 2009).

Due to urban runoff ending up in open natural waterways, it has an impact on the flora and fauna found in these water bodies. Pollution of these waters results in the deterioration of the natural balance of these waters. The European Union has designed a framework directive with the Water Framework Directive, which lays down the most important laws for water protection in Europe. By regulating individual pollutants and setting corresponding regulatory standards, an integrated approach is ensured (European Commission, 2023b). In addition, the amending directive on priority pollutants (Directive 2013/39/EU) expands the list of substances to be included in water quality studies (Müller et al., 2020).

D.5.1. LITERATURE REVIEW

There are two studies that comment on green roofs' impact on water quality. First, the information from the study by Claus and Rousseau (2012) is evaluated as it includes the most comprehensive pool of information.

In order to make a statement about the influence on water quality, it refers the research of Berndtsson (2010). This research shows that there is some disagreement within the literature, underpinned by conflicting results. This partly arises from different factors affecting runoff quality, such as; type, age and geometry of the green roof, soil moisture characteristics, season, weather and rainfall characteristics, and the type of vegetation. In addition, this study addresses an important difference between the results arranging from the setup of the different studies. It describes that the influence on runoff quality can be measured from two basic principles. The first looks at the concentration of certain substances compared to the concentration in rain, however, this can give a distorted picture because the green roof reduces the runoff volume. Because the volume is lower, the concentration in which these substances are found is likely to become higher. The second way therefore looks at a certain mass of pollution discharged by a square metre of roof surface, compared to the amount of mass falling on that same surface. It then follows from this whether the green roof causes an increase or decrease in the amount of measured substance. Thus, depending on the study, an increase or decrease in the concentration or total amount of a given substance can be measured. The statement in Claus and Rousseau (2012) omits some important subcategories from Berndtsson, so an overview is given here for completeness:

- **Phosphates**
  Phosphates come from fertilisers and bird and animal faeces. As a result, green roofs are often a source of phosphorus due to nutrient-enriched soil and fertiliser use. Studies give conflicting results when it comes to the amount and form in which it occurs, with some measuring that all phosphorus released is in the form of phosphates, and there are even roofs with no phosphorus runoff, and some measuring that the total concentration of phosphorus is significantly higher than the concentration of phosphate phosphorus. Part of the load reduction is attributed to the reduction in water volume, but may also be linked to the age of the roof.
- **Nitrogen**
  Nitrogen concentrations in green roof runoff may be related to soil type, age of the green roof and maintenance. Some studies indicate that concentrations of various forms of nitrogen are lower in green roof runoff than in rainwater. They did however, postulated that organic nitrogen may be released from

vegetated roofs. Causing the total nitrogen concentrations in rain and vegetated roof runoff water to be very similar. Also a load reduction was shown, which was dependant on the water volume reduction. Other studies found high nitrogen release from green roofs.

- **Heavy metals**
  Available studies show that extensive green roofs reduce heavy metals in urban runoff. The concentrations found in runoff water are often the same as those in precipitation. One study shows that, in both summer and winter months, the semi-intensive and extensive systems with grass stopped significant amounts of loadings of lead, zinc, and copper and of cadmium. Another study shows that taking into account the annual water interest that a green roof can retain chromium, manganese, lead and zinc and increase the load copper and iron.
- **pH-value**
  Green roofs affect the quality of runoff water by increasing the pH values of rainwater, which are typically between 5 and 6, to over 7 and 8 in the runoff water from green roofs. This function contributes significantly to lowering the acidity level of natural water receivers. As a result, green roofs have a mitigating effect on mild acid rain.
  The neutralising effect on the PH value is also confirmed in the study by De Cuyper and Dinne cited by Claus and Rousseau (2012). Other than that, in this study, based on the concentration of substances in the runoff water, an increase is mostly found for the studied substances.

D

Despite paying extensive attention to the amount of substances present in the discharge water, the source calculation looks at Biological Oxygen Demand, as also measured in de cuyper. This looks at the amount of oxygen used by bacteria. In the conversion to a monetary value, the limit value is used as a starting point for the calculation. There is a charge for the annual measurement, and if the value is too high, additional measures must be taken, however, this value is not specified. The source of Teotónio et al. (2018) also only mentions benefit through "clean" water treatment costs. However, the substantiation of which substances, and which calculation methods are used are missing.

D.5.1.1. LAWN IRRIGATION AND TOILET FLUSHING

Wong et al. (2003b); Chang et al. (2011) take a step forward and also try out smart ways to apply that water to partially meet domestic needs. In the design of the Chang et al. (2011), water is used directly for the need of toilet flushing and garden irrigation. In this way, the water is used smartly and thus saves money by reducing clean drinking water usage. Using a cistern, the water is stored, forming a buffer that can be used when there is demand. By including the entire water balance, the study has enough information to make a meaningful statement on this. The amount of water that is saved by reusing the storm water and gray water for flushing toilets and irrigating the backyard is monetized by the tap water price.

D.5.1.2. STAKEHOLDERS

Little is still known about the influence of green roofs on water purification. The improvement of water quality can provide a provisioning service of cleaner water that can be used for multiple purposes, but this needs to be determined first. As a result, in terms of stakeholders, it cannot yet be determined who will benefit from improved water quality.

D.5.2. DISCUSSION

Based on current pool of information, it can be noted that there is still a lot to be gained in terms of water quality. The improvement of the water quality is only highlighted in a couple of sources with little information given. Nevertheless, it is noteworthy that the amount of substances present is not yet included in the calculation of Claus and Rousseau (2012), and any indication of substantiation in Teotónio et al. (2018) is missing. The current state of the literature seems to be only an indication of the possibilities. The current calculation methods seem rather focused on the fact that one value from the project owner's perspective should be arrived at in a way, however, without the proper information and practices to do so. Instead, there needs to be a basis for an integrally determined calculation methods for mapping values. This could later also determine the potential of water provisioning. Which is currently described in the literature as an investment that may not outweigh the benefits (Chang et al., 2011). However it currently lacks the information of the influence of the green roofs, since additional systems are required.

D.5.3. RECOMMENDATION

- Deepen the methodology and obtain substantial evidence
  Since the current literature does not provide sufficient information to provide a clear answer to the research question, it is necessary to create and strengthen a methodology and obtain substantial evidence. Researchers can work on developing a sound methodology that can substantiate the quantification and valuation of the impact on the runoff quality. This could include, for example, more detailed measurements and analysis. The focus of research should stick with the scale of a single building.
- Cost analysis
  Researchers should work on developing methods to monetise the benefits. By working closely together, researchers and stakeholders can work together to collect data and conduct studies to understand and translate the impacts of water quality improvements into money. This will contribute to a better understanding of the financial aspects and economic benefits of green roofs, and help make informed decisions when implementing them.
- Investigate scalability and applicability of clean water provision
  Once the improvement in water quality has been demonstrated, further research can be done on the benefits of providing clean water as a provisioning service. This should specifically consider the use of rainwater for irrigation and toilet flushing, as mentioned in the literature. It is important to explore the applicability of these benefits in different contexts and locations. In addition, the costs and benefits of additional components, such as cisterns, required for the system should be included in the analysis. Research can focus as well on the potential barriers to installation.

D.6. THERMAL INSULATION

Buildings play a vital role in providing protection from natural influences. A crucial aspect of this is creating an indoor climate that differs from the outside temperature to meet our comfort needs. Although buildings act as physical barriers that allow us to regulate the indoor climate, the outside temperature continues to play a significant role due to leaks and heat losses. Therefore, the design of a building is an important aspect that must take external temperature into account. To effectively manage and control this, it is necessary to understand the application of thermal protection layers, which reduce the influence of external temperature. Gaining such knowledge is essential to ensure the desired thermal conditions within a building (Centre and Network, 2016).

Heat transfer can occur through three physical mechanisms. First, there is thermal conduction, where heat is transferred by a temperature gradient in a solid material. This mechanism is known as conduction or conduction. Second, there is heat transfer through liquids or gases, where heat is transferred by the flow of the medium. This is called convection. Last is thermal radiation, where thermal energy is radiated from surfaces.

Implementing insulation measures in a building brings several benefits. First of all, it results in a reduction of heat loss in winter and the need for cooling in summer. In addition, it contributes to cost savings and increased comfort. Increased thermal insulation results in a lower energy requirement of the building, which in turn reduces the demand for fossil fuels. The indirect consequence is a relief of pressure on the natural ecosystem (Centre and Network, 2016).

Buildings account for a significant proportion, i.e. 31% global energy demand, and adding extra insulation to buildings can therefore have a significant impact (Li et al., 2019). This impact is partly reflected in regulations, such as the Buildings Decree in the Netherlands, which sets stricter standards for insulation values in both renovation and new construction. Moreover, residential energy labels are used to visualise performance, in addition to established standards and target values for home insulation. In this way, an important contribution is made to achieving climate goals, reducing CO_2 emissions in the built environment and lowering energy costs.

GREEN ROOFS

Green roofs are part of the boundary of a building and thus add to the physical properties of this outer layer. They protect the interior against exterior influences, including temperature fluctuations of the outside air. The vegetation and the substrate layers of the green roof acts as a natural insulation layer helping to reduce the transmission of heat entering and leaving the building. Green roofs can also reduce the energy demand of buildings by the effect of evapotranspiration. Finally the green roof also provides a shading effect on the building, which reduces the fluctuation of the the indoor temperature (Besir and Cuce, 2018).

D.6.1. LITERATURE REVIEW

Through passive techniques, green roofs provide numerous benefits that can help reduce the level of energy requirement and improve the thermal-energy performance in buildings (Ulubeyli and Arslan, 2017) or the thermal comfort in the building (Claus and Rousseau, 2012). The addition of the green roof covering adds plants and materials that deliver properties, which in turn can provide physical phenomena during the operation of the roof (Ascione et al., 2013). Three main categories were found in which green roofs influence the energy consumption of a building.

- **Inertial mass for storing heat**
  The inclusion of green roofs leads to the addition of thermal insulation, by increasing the thermal inertia. The presence of both the plants and the substrate contributes to an increase in the R-value of the building's roof (Wong et al., 2003b). This insulation effectively lowers the energy intensity of the building, thereby regulating energy consumption. The insulating properties a green roof possesses depends greatly on the depth of the thermal mass. The greater the depth of thermal mass, the greater the thermal insulation (McRae, 2016). Because intensive green roofs have an increased soil depth over extensive green roofs, generally speaking IGR are a better temperature moderator than the EGR (William et al., 2016). The additional insulation is especially useful during the winter months, and reduces the need for building heating during the winter season (Chang et al., 2011; Macháč et al., 2016; Berto et al., 2018).
- **Absorption of thermal energy for vital processes of vegetation through photosynthesis**
  A high degree of absorption of solar radiation is used for the purpose of facilitating vegetation-based

biological functions (Wong et al., 2003b; Ziogou et al., 2018), while only a minimal portion of the radiation is conveyed to the ground (Ascione et al., 2013). Research shows that of the total solar radiation absorbed by planted roofs, 27% is reflected, 60% is absorbed by the plants and soil, and 13% is transmitted into the soil. Compared to a bare roof that receives 100% of direct exposure to solar radiation, the plant layer of a green roof together with the layer of substrates can shield up to 87% of solar radiation, thus making significant contributions to reducing the warming of a building (Wong et al., 2003b).

- **Evapotranspiration**
  The green roof can help cool a building during the summer due to the evapotranspiration effect from plants and the evaporation of moisture in the soil (Carter and Keeler, 2008; Chang et al., 2011; Ziogou et al., 2017, 2018). The phenomenon of evapotranspiration refers to the sum of the absorption of heat by plants as liquid water vaporizes through the stomata (transpiration) and the vaporising of surface water on top of the plants (evaporation) (Ascione et al., 2013). The evaporation of water collected in the substrate and vegetation layer induces a cooling effect that not only decreases the need for air conditioning within buildings, but also cools the surrounding microclimate (Macháč et al., 2016). Although evapotranspiration seems to be a benefit of green roofs, its effect on roof cooling compared to its insulating effect is questioned. A slight decrease in soil temperature is caused by the irrigation (William et al., 2016), this is mainly because most green roofs use drought-resistant plants, such as Sedum, which naturally minimise evaporation processes to retain water (McRae, 2016). The process of quantifying evapotranspiration is tricky anyway. Where different models use different procedures. Some literature considers vegatation as an equivalent uniform material composed of air and leaves. Others consider heat exchange between plant leaves and the surrounding air (Ascione et al., 2013).

In general, these three phenomena reduce the energy requirements of a building with respect to heating and cooling (Carter and Keeler, 2008). Ultimately, they all cause the temperature fluctuation on the roof surface to decrease. Compared to a conventional roof, the temperature of the lower layer is closer to that of the air temperature. This bottom layer temperature ultimately determines the amount of energy required for heating or cooling the building, regardless of any other insulation layers (William et al., 2016). As a result, the effect of outside on the indoor temperature in the building also decreases Wong et al. (2003b); Mahdiyar et al. (2016).

Besides the characteristics of the roof itself, environmental characteristics also affect the amount of energy that can be saved for maintaining the indoor temperature in the building. For example, under certain circumstances, the addition of a green roof may cause the amount of energy demanded to increase (Ascione et al., 2013). It is therefore important to properly evaluate the energy demand in the larger framework. Building characteristics can influence this, such as size (Claus and Rousseau, 2012; Macháč et al., 2016), roof-to-envelope ratio (Mahdiyar et al., 2016), number of floors (Macháč et al., 2016) and building use (Chang et al., 2011; Ascione et al., 2013; McRae, 2016). However, characteristics of the building's location should also be considered, such as climate (Claus and Rousseau, 2012; McRae, 2016; Mahdiyar et al., 2016)) and weather characteristics (Mahdiyar et al., 2016).

D.6.1.1. QUANTIFICATION

Almost all sources use data from previous sources to substantiate statements regarding energy savings. Some of these sources apply this information to estimate energy consumption impacts in a relatively time-efficient manner. The reasoning usually takes into account the influential parameters described earlier and refers to studies that are as similar as possible to the current study. However, this is not always fully feasible. Nevertheless, some sources apply this approach to make statements on the impact of green roofs on energy savings. This approach is explained below, focusing on the parameters that are decisive in choosing figures from similar studies.

In fact, data are not always available that fully correspond to the specific situation under investigation in a study. For this reason, Claus and Rousseau (2012) decided to rely on studies that took place in similar climates. For example, to make a statement about a building in Belgium, data from Athens (Greece) and Madrid (Spain) by Saiz et al. (2006) are used, while information from Athens (America) (Carter and Keeler, 2008) and Singapore (Wong et al., 2003a) is excluded. A value for the average savings is found in the calculation as a percentage of the usual energy consumption for the 'offices and administrations' sector (Aernouts and Jespers, 2005). This value can then be converted into a value in kWh/m2, using the average annual energy consumption of buildings with a similar function.

The use of studies that took place in similar climates can also be seen in Mahdiyar et al. (2016)'s methodology. First, a number of studies are mentioned that also took place in Malaysia, the country where Mahdiyar also conducted his research. However, these studies do not directly provide data that can be used one-to-one in the calculation. In addition, a number of studies, including that of Wong et al. (2003a) in Singapore, are also mentioned. However, the final data comes from a study in Malaysia that combined different types of roofs with different amounts of air conditioning during the day. The results of this study are already expressed in kWh/m2 and therefore do not need further conversion. In the study by Ulubeyli and Arslan (2017), the energy savings is similarly based on a previous study with similarities in the location and also the dimensions of the green roof. The values emerging from this study are expressed in a range of kWh per year. A similar rate of annual energy savings is collected in Shazmin et al. (2017). Data was gathered from various empirical studies conducted under climatic conditions similar to Malaysia, and to convert these rates to annual energy savings, average monthly electricity data were collected from buildings with similar residential use. Chang et al. (2011) also looks at the use of the building. Due to the lack of information from studies on residential buildings, this information was extracted through personal communication with the Florida Solar Energy Centre. From this, the reference of the proportion of the roof in relation to the total energy demand is extracted. Because the data is extracted from a local data source, it is assumed that this also incorporates the local climate. Climate is also used in Teotónio et al. (2018) as a basis when looking for figures in previous studies. Here, climate conditions similar to those of the site under study are taken into account. In addition, the annual use of residential and commercial buildings is differentiated when calculating energy savings. This differentiation enables a more accurate picture of the potential energy savings of green roofs in different types of buildings. Finally, Macháč et al. (2016) also relies on figures from previous studies, but it does not specifically state which studies were used for this purpose, nor does it indicate which parameters were considered when selecting these studies.

D

The different approximation methods result in different values obtained from the different sources. The main difference between these values is due to the distinction between heating and cooling. All sources that use software for their calculations provide values for both cooling and heating. However, among the sources that use calculation methods, only McRae (2016) does not have this distinction, while Teotónio et al. (2018) is the only one that does make this distinction among all sources that use key figures. The sources that do not use this distinction use a single value for both heating and cooling requirements. This distinction allows for a more focused calculation of a monetary value. In most cases, energy for heating is provided by gas, while for cooling, air conditioning is mostly used which requires electricity. However, references Ziogou et al. (2017) and Ziogou et al. (2018) are an exception, as the energy for both heating and cooling is provided by electricity.

BASIC CALCULATION

The method of Clark et al. (2008) uses a simplified, one-dimensional heat flow equation to calculate the annual heat loss. Therein, it uses formula D.5, in which the relationship between the heat flux (Q $[W]$) through the roof with the material resistance flow (R $[mK/W]$) is given by means of the heat transfer coefficient (h $[W/m^2K]$) and the area (A $[m^2]$) and the temperature (T $[K]$). The approach of the Center for Neighborhoud Technology is based on the calculation method as described in Clark. To identify energy savings, both Alves et al. (2019) and McRae (2016) use the Center for Neighborhood Technology's calculation method. This method provides a simple estimate of energy savings by considering the green roof as an extra layer of insulation (Alves et al., 2019). The extra insulation value is directly translated into the benefit it provides in the form of reduced energy loss, by looking at the energy it takes to maintain the required indoor air temperature.

$$\dot{Q} = h \times A \times \Delta T = \frac{A \times \Delta T}{R} \tag{D.5}$$

The method uses a systematic roadmap to identify the amount of savings in this way. To estimate the heat in a climate and the energy required to keep buildings cool, cooling degree days (CDD) are used. Cooling degree days are calculated by subtracting the balance temperature from the average daily temperature and adding only the positive values together over a year. Conversely, heating degree days (HDD) measure the energy required to heat a building. Heating degree days are used to estimate the cold in the climate and the amount of energy that may be needed to keep buildings warm. HDDs are calculated by subtracting the average daily temperature from a balance temperature and adding only the positive values over an entire year. CDD and HDD indicate how intensively a building must operate to maintain a desired indoor temperature. The balance temperature used can vary. The CDD and HDD were obtained from the National Oceanic and Atmospheric Administration in McRae (2016). They provide the information of over 9800 national weather stations in the United States. Alves et al. (2019) uses a more approximate approach where the annual cooling savings were done based on a four-month average of 27 celsius degrees, with 20 celsius degrees as the balance temperature. This way also provides an estimate of the amount of energy required to keep a building comfortable. However, the source only mentions CDD, this is probably due to the tropical climate at the location studied, however, this is not specifically mentioned.

Then, based on the R-value, the ΔU is calculated. The R-value represents the thermal resistance of a material, where a higher R-value means that heat does not pass through the material as easily. The U-value is the inverse of the R-value and represents the overall heat transfer coefficient. When calculating, it is important to take into account the extra insulation value provided by a green roof by considering the difference between a conventional roof and a green roof, see equation D.6.

$$\Delta \mathbf{U} = \frac{1}{R_{\text{conventional roof}}} - \frac{1}{R_{\text{green roof}}} \tag{D.6}$$

D

The CDD and HDD can than both be used with D.6 in equation D.7 and D.8 respectively to calculate the annual cooling and heating savings. These savings apply per unit area and can therefore be extended to the total roof area to arrive at total savings. However, it is common in many studies to report savings per unit area, often in m2.

$$\textbf{Annual cooling savings}(Btu/SF) = \text{annual number of cooling degree days}(^\circ Fdays) \times 24\ \text{hrs/day} \times \Delta U \tag{D.7}$$

$$\textbf{Annual heating savings}(Btu/SF) = \text{annual number of heating degree days}(^\circ Fdays) \times 24\ \text{hrs/day} \times \Delta U \tag{D.8}$$

Berto et al. (2018) probably also estimates the energy savings based on heating degree days as well as local climate data, such as average summer and winter temperatures, and average rainfall. A distinction is made here between the amount of natural gas used as a primary heating fuel and the use of electricity for indoor cooling. However, the researchers did not provide further information on the methodology used, so no specific statements can be made about the used methodology.

MODELING SOFTWARE

The literature shows that several methods are available for simulating energy systems in buildings. Some of these methods are Powerdoe, applied by Wong et al. (2003b), Energyplus, used by Clark et al. (2008), Niu et al. (2010), Ascione et al. (2013), Ziogou et al. (2017) and Ziogou et al. (2018), Equest and HYDUS-1D, by Carter and Keeler (2008), and finally MLCan, by William et al. (2016). Each method has both strengths and weaknesses. An important consideration when choosing a method is the availability of information and the time required in relation to the accuracy of the outcome.

Energyplus

EnergyPlus is an US Department of Energy-supported building energy simulation software programme. The programme is designed to model various energy flows, such as heating, cooling, lighting, ventilation and water, based on climate and building use data, material and size (Niu et al., 2010). This model also takes into account radiative exchanges at both high and low wavelengths, and the effects of vegetation on convective heat flow, evapotranspiration through soil and vegetation, heat transfer through soil with change in soil thermophysical properties and humidity (Ascione et al., 2013). In this way, it combines several technical advantages, such as coupled models for heat and mass transfer, analysis tools for heat balance by radiation and convection mechanisms, and adjustable calculation time steps (Ziogou et al., 2017).

In the elaboration of Energyplus, information was mainly taken from sources Ziogou et al. (2017) and Ziogou et al. (2018), as these sources are more recent and therefore work with newer information. For Energyplus to work, a number of data are needed. This data can be divided into three main categories; information on the use of the building, information on the properties of the building itself and information on the climate and conditions in which the building is located. To make this transparent, the building is divided into independent thermal zones. This takes into account the orientation and use within each zone. Depending on the usage distribution, daily, weekly and monthly values are prepared of the desirable values of internal winter and summer temperatures, ventilation rates, lighting levels, number of occupants and efficiency of electrical appliances. In addition to the internal conditions, local climate data are also taken into account.

EnergyPlus offers the possibility of attaching a so-called "eco-roof" to a building, this can be done with the EcoRoof model included in the simulation core of the programme (Ziogou et al., 2018). According to Ziogou et al. (2017) the basic features of this model are as follows:

- The energy balance between the substrate and foliage is established through the use of FASST vegetation models
- A simultaneous calculation of the temperature equations for both the foliage and the substrate surface
- a water balance mainly dependent on precipitation, irrigation, and moisture transfer between the upper and lower layers of the soil

Due to certain instability problems in the conductivity transfer scheme of EnergyPlus, some important properties are currently missing from the model. In particular, the moisture-dependent properties of wet soil, such as thermal conductivity, volumetric specific heat capacity and thermal diffusivity, are not included in the Ecoroof model. Moreover, only the vegetation layer and the growing medium layer of the green roof are used in the calculations. The other layers, including drainage materials, are simulated separately in accordance with the software's standard procedures.

In the approach of Ascione et al. (2013), the modelling of the green roof is mainly carried out using the EnergyPlus numerical procedure. Based on this, a model is created that takes into account the radiative exchanges at both high and low wavelengths. In addition, the effects of vegetation on convective heat flow, evapotranspiration through soil and vegetation, heat conduction transfer through soil taking into account changes of soil and humidity are also included. The choice to deviate from the standard use of EnergyPlus, was made because this approach was seen as the only one that allows for a comprehensive and parametric analysis (Ascione et al., 2013).

PowerDOE
Wong et al. (2003b) uses the computer software programme PowerDOE. This was the first interactive and graphical environment for DOE-2.2 aimed at providing a complete and user-friendly experience. Within the software, it is possible to enter local weather data from a database. In addition, a description of the building must be entered, distinguishing between architectural and HVAC features. The building can be divided into different zones, where data such as the amount of daylight, lighting levels, number of users, ventilation rates and efficiency of electrical appliances can be entered for each zone. Finally, periods of use can be defined for the building, which can also include the HVAC (Hirsch et al., 1998).

eQuest
In Carter and Keeler (2008), EQuest (Quick Energy Simulation Tool), the successor of PowerDoe (James J. Hirsch and Associates., 2015), was used in combination with HYDRUS-1D for energy load simulation. To create the model, laboratory measurements were combined with measurements of air temperature, wind speed, humidity, radiation and soil temperature. For EQuest to work properly, specific input data are required, such as the thermal conductivity, density, heat capacity, thickness and surface absorption of the roof layer. However, determining the thermal properties of green roof soils is challenging due to the lack of available data. For this reason, some of the parameters were estimated using a combination of HYDRUS, laboratory experiments and Fourier equation. To obtain thermal conductivity, HYDRUS was used as a tool to estimate soil moisture. This estimate was then validated using on-site measurements. The output of these was used to estimate thermal conductivity, which was obtained by averaging three methods. The volumetric heat capacity and density were obtained from observations in the laboratory. In addition, it was necessary to include the effects of evapotranspiration in EQuest, which was also done using HYDRUS and using the typical meteorological year data (Hilten, 2005).

MLCan
William et al. (2016) used the MLCan model to run simulations for green roofs. The aim was to capture the interactions between soil, vegetation and climate and investigate how water and energy balances evolve through coupled soil and vegetation layers. From the model analysis comes the temperature of the bottom of the soil layer. The simulations were conducted during a 72-day drought period in central Illinois in the United States. In addition, the effect of irrigation on vegetation during this period was simulated to evaluate the benefit of irrigation as part of regular maintenance. In addition, the effects of green roofs on both ambient and indoor temperatures were compared with those of traditional and cool roofs using the MLCan model.

The vertical-resolution MLCan model is a modelling tool used to simulate the ecological processes of above-ground and below-ground systems. The model includes both C3 and C4 photosynthetic pathways and resolves the vertical radiation, thermal and environmental regimes within the canopy and soil-root system. The subsurface system includes the solution of soil moisture and soil heat in the vertical soil domain, using soil temperature and moisture distribution to evaluate the effectiveness of green roof strategies. The model has been validated for both C3 and C4 vegetation and has demonstrated its ability to capture acclimatising responses of vegetation to elevated CO_2 (William et al., 2016).

It emerges from the model analysis that the ground temperature is important to calculate heat loss. This is done for the building in question using a simple conductivity model, using the equation D.5 as previously used by Clark et al. (2008). This formula states that the heat flux in the building is determined by the thermal resistance (R-value) of the roof package, without the green system in this case, and the temperature difference between the ground and the desired interior temperature of the building. This does not take into account the complexity of modelling the building's internal HVAC system (William et al., 2016).

D

CONVERSION FACTOR

In Clark et al. (2008), the addition of a system factor is discussed. The system factor considers the efficiency of the air handling system (Huang et al., 1999). The required energy is the sum of the amount of energy for heating or cooling of the building, as well as the energy lost by inefficient systems, and by the duct supply system. The system factor can be described as the ratio of the building load to the system load. The building load represents the energy requirement of the building, while the system load indicates how much heating or cooling the system must provide to meet this energy requirement.

When calculating energy loss in a building, a value emerges, but this value does not equal the amount of energy required to compensate for this loss. This is caused by several losses occurring before the energy actually provides the required heat or cooling. This phenomenon is described in several sources, with Clark et al. (2008) referring to Huang et al. (1999), which distinguishes between the losses that occur in the machines that provide cooling or heating and the energy losses, plus the amount of energy needed to get the temperature to the destination (such as fans and pumps). These two losses are represented as one value in Ascione et al. (2013) and William et al. (2016), even distinguishing between the losses occurring in heating and cooling.

In Ziogou et al. (2017) and Ziogou et al. (2018), the entire energy requirement is provided by electricity. It is therefore only logical that only one value is taken into account for these sources. In Ziogou et al. (2017), this is represented as a national primary energy conversion factor due to the use of a central heating and cooling system. In Ziogou et al. (2018), system specifications were considered, where the characteristic curves of the coefficient of performance or energy efficiency ratio were extracted. Here, electricity consumption depends on hourly values of ambient air temperature and heat pump load.

D.6.1.2. VALUATION

Using one of the three aforementioned methods, the loss of energy is determined. Some of the sources additionally use conversion factors to account for the losses between the energy demanded and the energy required. For the other sources, the amount of energy demanded is equal to the energy loss. However, the green roof has a positive impact on all sources and thus provides the benefit. For all sources, the calculation to a monetary value is the same. The amount of energy demanded is converted by means of a price unit, usually expressed in €/kWh, taken from the market price. The distinction between the use of gas and electricity is reflected in the calculation of the price per kWh, as the prices of gas and electricity differ. Moreover, the price may also depend on the user, as described in Niu et al. (2010), where a distinction is made between tariffs passed on to commercial and residential users. Ultimately, the savings in terms of money are obtained by multiplying the amount of energy saved by the market price of this amount. The result reflects the financial benefits of the different energy sources.

D.6.1.3. STAKEHOLDERS

Based on the existing literature, an overview of the relationship between the effect of green roofs on energy reduction and the possibilities of expressing this in monetary value is presented. The stakeholders involved can be identified from both the methodology applied and the monetisation process, and these are consistent with each other. The benefits of energy reduction can be converted directly into a demonstrable market value. This allows building owners to benefit from the reduced energy consumption throughout the life of the building and therefore gain financial benefits during this phase.

D.6.2. DISCUSSION

Within the analysed sources, a consistent method is used to translate the thermal benefit of green roofs into a monetary value. However, the literature shows that there are a number of different ways to get the numbers for infill.

Quantification

Looking at the parameters that can have an impact, we see that building-specific parameters such as size, roof-to-envelope ratio, the amount of floors and uses, as well as local climate must be taken into account. These are largely reflected when using software for quantification. However, the literature shows that this is not consistently the approach taken. Most of these influences are omitted when calculation methods are used. These mainly assume the thermal mass of the roof package. The literature shows that the influence of absorption and evaporation is small. On this basis, the choice of using a calculation method can be supported. However, this fact should be more strongly substantiated with more research that could possibly show the difference. Additionally the differences between the various software and the impact on the results should also be further investigated.

D.6.3. Recommendation

The current methodology provides the means to include thermal insulation in the cost-benefit analysis. However, follow-up research is needed to strengthen and validate the current methodology. This follow-up research should focus on:

- Investigating the influence of different methods and software
  The literature describes different approaches and software to quantify the energy savings of green roofs. Further research is needed to determine the influence of these different methods but also the differences between various software on the results. It is important to understand how choosing between old literature, calculations and different software tools can affect the quantitative estimation of energy savings. Follow-up research can focus on comparing these methods and analysing the differences and similarities in the results they produce. This will contribute to a better understanding of the most appropriate approaches and tools for quantifying energy savings from green roofs.

D.7. URBAN HEAT ISLAND EFFECT

The urban heat island effect (UHIE) is a heat accumulation phenomenon, which is a characteristic of the urban climate, caused by urban construction and human activities. Human intervention has impacted the heat balance in cities. As a result, cities become significantly warmer than surrounding rural areas, which has an influence on both humans, and buildings (Yang et al., 2016).

The climate exerts a significant influence on the ways in which urban spaces are utilised and on the climatic performance and needs of buildings. At the same time, the city as an environment in turn equally impacts climate. This reciprocal influence process between climate and city implies that it is essential to consider the interactions and dynamics between these factors when designing sustainable and climate-resilient urban environments (Kleerekoper et al., 2012).

Several factors were extracted from Kleerekoper et al. (2012), that contribute to higher temperatures in urban areas compared to surrounding rural areas. A visual representation of this phenomenon can be found in figure D.9.

1. In addition, the reflectivity of surfaces also plays a role. Surfaces with a higher albedo have a greater capacity to reflect incoming radiation directly, reducing the amount of heat entering the urban area (see figure D.10).
2. Air pollution in urban areas has the effect of raising the temperature. This is due to the absorption of solar radiation by the pollutant particles in the atmosphere and its subsequent conversion into heat, causing this heat to be retained in the atmosphere.
3. Cities and the surface have a harder time radiating heat back into the atmosphere due to a reduction in heat loss caused by sky obstruction. Instead, the obstructive structures trap heat or reflect long-wave radiation back at it.
4. Internal heat production from combustion processes for the purpose of industries, cars and space heating release anthropogenic heat.
5. During the day, surfaces in cities absorb incoming solar radiation and internal heat, causing them to heat up. Materials, such as concrete and asphalt, are commonly used in the construction of buildings and roads, and are because of their thermal diffusivity highly effective at transferring heat, considering both the thermal conductivity and heat capacity of a material when evaluating its ability to conduct and retain heat. In combination with a high thermal capacity these materials are able to store a lot of heat. At nighttime the energy flow works the other way around, releasing the stored heat to the environment.
6. Compared to rural regions, urban environments use less permeable materials and have less vegetation, which reduces evaporation. As a result, these areas turn more energy into sensible heat rather than latent heat.
7. The decrease in wind speed due to various obstacles and causes restricts the turbulent heat transport from within streets.

GREEN ROOFS

Vegetation can mitigate the UHIE or more specifically the cooling effect of vegetation on a roof or facade affects both the building and the surrounding area (Kleerekoper et al., 2012). The effect of green roofs can

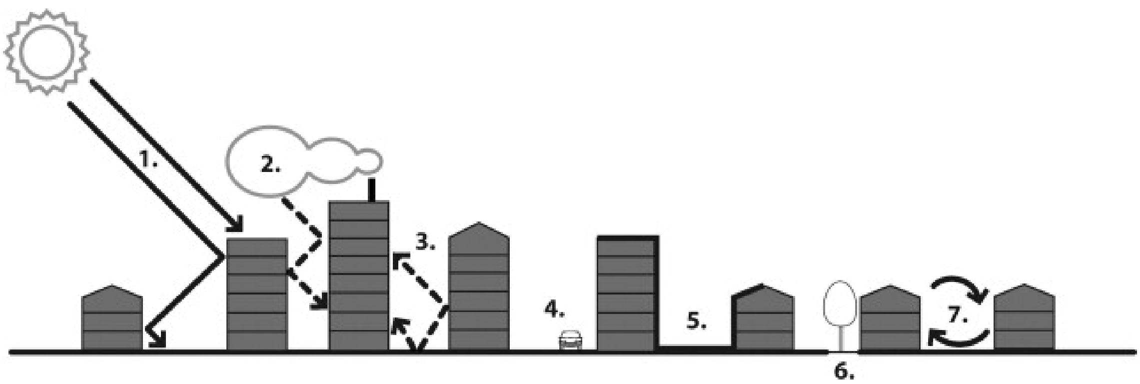

Figure D.9: Causes of urban hat island (Kleerekoper et al., 2012)

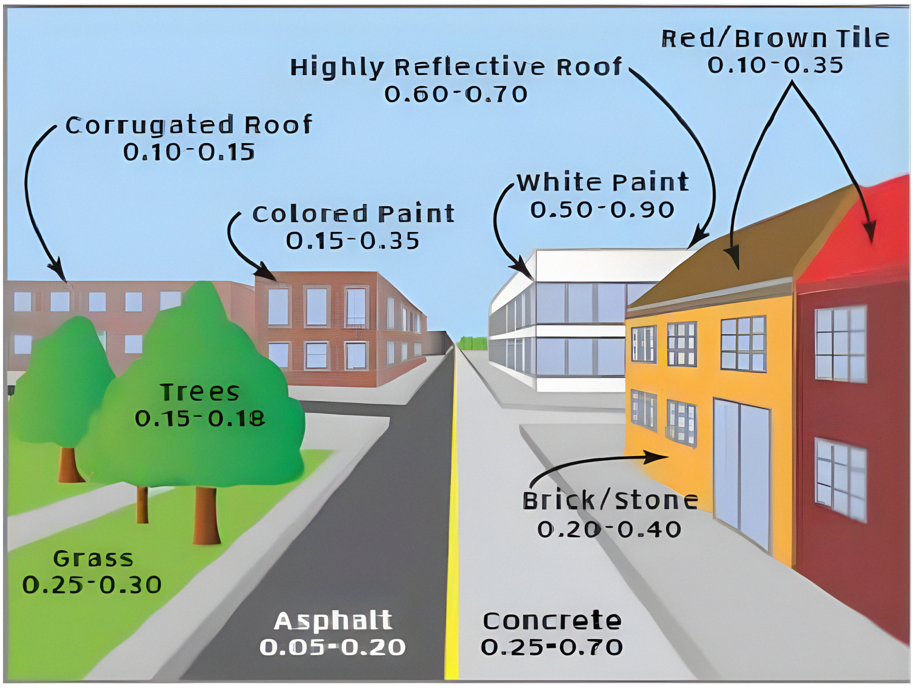

Figure D.10: Albedo ranges of various surfaces typical to urban areas (Ramírez and Muñoz, 2012)

have a greater impact because of the spatial distribution of roofs throughout the urban landscape, compared to when the same amount is applied in a concentrated manner Li et al. (2011). Green roofs have the advantage that the albedo value of plants is higher (0,2) compared to conventional roofing (0,05) (Gaffin et al., 2009; Susca et al., 2011). This reduces net radiation by reflecting more incoming solar radiation, which reduces the perceptible heat flux and absorbed heat on the surface. The concept of combining high albedo materials with low thermal diffusivity properties opens new possibilities for temperature reduction in cities (Enríquez et al., 2017). Another factor is that cities with less vegetation are less able to lose heat through evaporation (Wang et al., 2022). In rural areas, trees and other plants absorb water from the ground and evaporate it through their leaves, helping to lower temperatures. In cities, however, there is often less vegetation, which means less evaporation and thus temperatures stay high for longer. Finally the lower temperature of the vegetation cover has the benefit of having a lower radiation temperature than impervious surfaces with the same albedo (Salmond et al., 2016). The radiant heat transfer is an equation with the temperature to the power of four. A lower surface temperature thus significantly influences the amount of energy that is transferred through radiation between two surfaces.

A greater vegetation cover increases urban albedo, has a lower radiation temperature, increase evaporation and thus reduce the average air temperatures and extreme temperatures during heat waves (Salmond et al., 2016). So adding a green roof affects temperature regulation in two areas. On the one hand, it lowers the amount of energy that net reaches the city and, on the other hand, it can increase the city's heat loss capacity.

Combining these properties a commonly found albedo of green roofs in literature is found, which has the range of 0,7-0,85 as used by Castleton et al. (2010), Getter and Rowe (2006), Manso et al. (2021) and Berardi et al. (2014). The problem here, however, is that the original study of Rosenzweig et al. (2006a) asked the question what albedo equivalent for a white roof is required to reproduce the surface temperatures observed on the green roofs. The outcome of this question indicates the range of equivalent albedo including, for example, the evaporation effect on temperature. As a result, it steps away from the original meaning of the word albedo. The value should therefore be used carefully and with appropriate indication of the original assumptions.

D.7.1. LITERATURE REVIEW

There are several perspectives in the literature for assigning a value to the reduction of the UHEI. Green roofs have an impact on the microclimate in cities. The positive effects on pedestrian thermal comfort through a reduction in daily air temperature is in the order of 0,4 °C at pedestrian level and can even reach 2 °C when green roofs are combined with greenery at pedestrian level. Additionally, green roofs can be an efficient mitigation of the UHEI (Ziogou et al., 2018). According to energy models, the application of a widespread 50% extensive green roof could lead to a city-wide temperature reduction of 0,1 to 0,81 Celsius (Carter and Keeler, 2008; Niu et al., 2010). However, this temperature reduction was considered negligible given the uncertainty inherent in these models. The study discounted potential energy cost savings and stated that the potential is rather speculative until more reliable and comprehensive studies are conducted. The assertion that green roofs do not appear to significantly affect ambient temperatures in the urban canyon is also brought to light in Ziogou et al. (2018). The UHIE includes air quality, urban temperature and precipitation Claus and Rousseau (2012) but also heat-related deaths, respiratory illness, increased peak electricity use, and other ecologically adverse impacts Sproul et al. (2014), however only information about the relation between the UHEI and energy use was elaborated in the literature.

D

D.7.1.1. Quantification of the UHEI mitigation

It is crucial to quantify the impact of green roofs on the urban heat island phenomenon before placing a value on that impact. Several sources in the literature review make this claim based on earlier research, but the design of William et al. (2016) allows for specific claims about the UHEI to be made within the study's findings.

The study of William et al. (2016) evaluates several roofing strategies in terms of their performance in multiple categories, including urban heat island mitigation. Because of the design of the study, it is possible to obtain direct values of the surface temperature of a green roof compared to a normal roof. It shows that the surface temperature of a green roof approaches the air temperature, while a conventional roof can be up to 25 degrees Celsius warmer during the day. Since the study took place during a dry period, the case of an extensive green roof with irrigation was presented. The study relates the temperature difference with a conventional (non-reflective) roof to a drastic effect on the UHEI. It is emphasised here that this effect is only applicable on a large scale.

Berto et al. (2018) also discusses the benefit a green roof can provide on counteracting the UHEI. The outline of the study compares green roofs and cool roofs. Considering an equivalent effect between the two applications, it does not make a calculation for the benefits of green roofs. This is partially substantiated by the statement that these positive externalities are not all easily monetised.

The rest of the studies focus on evidence from previous studies to quantify the effect of green roofs. The literature mostly suggests that the effect of green roofs on the UHEI is highly dependent on the scale at which it is applied. That the addition of green roofs on the UHEI has an impact only on a large scale can be found in Claus and Rousseau (2012), William et al. (2016) and Teotónio et al. (2018). Claus and Rousseau (2012) describes a reduction of 2 degrees Celsius when 50% of the roofs in Toronto become green roofs. The original paper emphasises that this reduction only applies to irrigated roofs (Banting et al., 2005). For non-irrigated roofs, the reduction is only 1 degree Celsius and only affects a smaller area. In Porto, a reduction of 1 degree Celsius is stated when green roofs are applied to 75% of the urban area, and for Lisbon a reduction in air temperature of 0,3-4,2 degrees Celsius is mentioned by Teotónio et al. (2018), with the benefit of the influence on the air temperature being dependent on the local environment.

There are some inaccuracies in the piece written about the UHEI of Teotónio et al. (2018). An air temperature reduction of 2,25 °C is chosen based on a range between 0,3 and 4,2 degrees Celsius. However, the justification for this is sloppy. When referring to Wong, an incorrect article is referenced, "Life cycle cost analysis of rooftop gardens in Singapore" Wong et al. (2003b) instead of "The effects of rooftop garden on energy consumption of a commercial building in Singapore" Wong et al. (2003a). In addition, the referenced value cannot be found in the cited article by Saiz et al. (2006). The study does mention a 1 °C change in urban temperature in Toronto obtained over one-third of the city if half of the buildings had green roofs and at least 3% of them were fully saturated. This inaccuracy therefore highlights the need to comment and question the aforementioned range.

D.7.1.2. Valuation of the mitigation of the UHEI

It can also be seen in the calculation in the different studies that the scale of green roof implementation has an influence. The scale of implementing 50% of the roofs with green roofs was found to be very unlikely by Claus and Rousseau (2012) and therefore this study did not include monetary savings for urban heat island mitigation.

The studies that do calculate a monetary value make a link between cooling requirement and surrounding ambient temperature. Teotónio et al. (2018) uses the correlation that a 0,6 °C increase in ambient temperature increases the cooling requirement by 1,5-2%. In substantiating this, reference is made to Akbari (2005). However, the exact values cannot be found in the source. Akbari (2005), just like Akbari et al. (2001) does refer to an increase in energy demand in cities of 2-4% per degree, for a 1K rise in daily maximum temperature above a threshold of 15-20 degrees Celsius (Akbari, 1992), following figures from US cities. The value of the city wide temperature reduction is used with the decrease in energy usage in Teotónio et al. (2018), in order to calculate the value of the city's potential reduction in energy consumption (€/m^2).

D.7.1.3. Stakeholders

Only a few sources actually monetise the link between the impact of green roofs and the UHEI. Almost all sources suggest that the effect is only noticeable with large-scale implementation, this also affects the scale at which the benefits work. The sources reviewed indicate that lowering the ambient temperature has the direct effect of lowering the energy requirement for cooling. This means that within this urban area, all building owners benefit from this reduction in ambient temperature. The benefits from the energy reduction can directly be translated into a verifiable market values. The property owners can benefit from this reduced energy usage during the entire lifespan.

D.7.2. Discussion

Based on the literature reviewed, a conceptual understanding of the intended goals emerges. However, it should be noted that this approach has several shortcomings.

This study highlights the incompleteness of the current methodology at the city level and the lack of relevant data. The methodology used is based on temperature reduction and the resulting impact on energy consumption. This reduction is expressed as a value per square metre of roof area. Nevertheless, this can give a misleading picture as the methodology described does not correspond to what should actually be studied. The limitations of this study emphasise papers that make statements about individual buildings, while the methodology focuses on the application of green roofs on a larger scale. Reducing the application to a value per square metre can be questioned based on the information in the literature, as the effect is only noticeable in large-scale application. Therefore, this should be considered a side note to the calculation. An approach should therefore be sought within the methodology that is capable of identifying the effects of a green roof on an individual building.

In addition, the current methodology focuses exclusively on energy-related impacts, while the literature also refers to other, partly social, effects of the increased urban climate. Aspects such as heat-related deaths, respiratory diseases, air quality, and precipitation, increased peak electricity consumption and other ecologically adverse effects are also mentioned in relation to the UHEI.

Quantification

Based on the available information, it is difficult to make a definitive statement on the effect of green roofs on the temperature around a building. The literature studied mainly shows a lack of information. Part of these shortcomings can be attributed to the fact that the effects of temperature reduction only become noticeable when green roofs are implemented on a large scale. The literature often talks about applications on 50% or 75% of roofs, but the feasibility of this is questioned. However, it is essential to evaluate these values within the scope of this study and within the limits of the sources consulted. After all, the domain of mitigation of the UHEI uses a different scale than the studies reviewed themselves. Based on the current information, an incomplete but positive effect is demonstrated, just not for the scale of our study.

Valuation

Moreover, the fundamentals of the energy issue also have some shortcomings. The value currently used dates from 1992, which means that the data may be outdated and no longer provide accurate information. It is necessary to supplement this data with more recent information, taking into account the changes that have occurred between 1992 and the present, such as changed needs, consumption patterns and installations. Moreover, building construction regulations have changed, which may also have changed the influence of the external climate. Therefore, it is essential to consult new sources that reflect a similar relationship, based on more recent data.

Nevertheless, one may question the extent to which it is necessary to work with indicator values, while there are also possibilities to include direct temperature reduction in the calculation or to use a model that analyses a building's energy losses. In this way, the UHEI is no longer considered as a separate factor, but integrated into the calculation of a building's energy demand. This provides a more holistic approach, taking into account the interaction between green roofs and the broader contextual framework of the urban climate.

D.7.3. RECOMMENDATION

The potential of reducing the UHEI on urban energy demand is still in its preliminary stages. Future research should focus on:

QUANTIFICATION

To answer the research question, follow-up research should focus on:

- UHIE mitigation effect of green roofs on individual buildings
  Follow-up research should focus on a methodology specifically for quantifying the effects of green roofs on individual buildings. By developing a methodology specific to individual buildings, a more accurate and detailed assessment of the climate benefits of green roofs at this scale can be obtained. This would allow local and climate-related parameters to be included in the calculation
- Inclusion of wider impacts in the analysis
  Follow-up research should focus on including broader effects of green roofs in the analysis. For example, researchers can investigate how green roofs improve air quality, influence the urban microclimate, promote stormwater management and affect the health and well-being of residents. Integrating these broader impacts into the methodology will provide a more complete picture of the climate and environmental benefits of green roofs, and can help make informed decisions about their application.

D.8. SOUND INSULATION/URBAN NOISE REDUCTION

Sound is a physical phenomenon caused by vibrations in a source and then propagates as longitudinal waves through a medium, such as air or water. The sound we hear is a change in air pressure due to these waves. Sound can be considered as noise if there is no agreeable musical quality or as an unwanted sound (Tripathy, 2008). Noise pollution was first recognized as a significant form of pollution at the World Environment Congress in Stockholm in 1972 (Morillas et al., 2018). Since then, the World Health Organization (WHO) has published numerous reports based on global research showing the negative impact of noise pollution on human health. In 2011, the WHO also identified noise pollution as one of the most significant environmental stressors with negative effects on public health (Morillas et al., 2018). Humans being exposed to noise can suffer from auditory and nonauditory health effects (World Health Organization, 2018; Morillas et al., 2018).

Sound is being produced as a byproduct of all sorts of activities. The main causes of the sound pollution are from roads, airports and noisy areas (Mahdiyar et al., 2016). This mainly forms a problem in cities, where a lot of people are subjected to these sound levels, but also localized sources could cause a significant disturbance. To prevent excessive levels of noise disturbance, many rules and regulations can be found. These are most commonly backed by fines and penalties to raise the cost of emitting noise. However, controlling and enforcing these rules to a level that effectively reduces the noise pollution is difficult (Bello et al., 2019). There is evidence that coping with noise pollution is increasingly more difficult for regulators as cities increase in size (Murphy and King, 2022).

Looking at the physical characteristics, sound can be defined by multiple properties. Sound in general can travel in multiple frequency, typically measured in Hertz (Hz). Different sound sources produce different sound pressure levels within this frequency spectrum. In normal atmospheric pressure and at 20 ^{o}C sound will travel at a velocity of 340 m/s. Sound is expressed in decibels (dB) which has a logarithmic scale, an increase of 3 dB will be caused by a doubling of the sound pressure level. As a result, sounds pressure levels cannot be directly subtracted from each other. This requires expertise of how sound works through different mediums and interaction between them.

Once the sound levels of different frequencies are mapped indoors, they need to be correctly translated to human perception. The human ear is more sensitive to certain frequencies, which is why the different frequencies are corrected by a-weighting, see figure D.11. This is also taken into account in multiple national standards, as for example the Dutch Bouwbesluit (Ministerie van Binnenlandse Zaken en Koningrelaties, 2023). In order to determine A-weighted decibel values (dB(A)), the A-weighting factor for the corresponding frequency band is added to the unweighted decibel level (dB) (Acoustical Engineer, 2019).

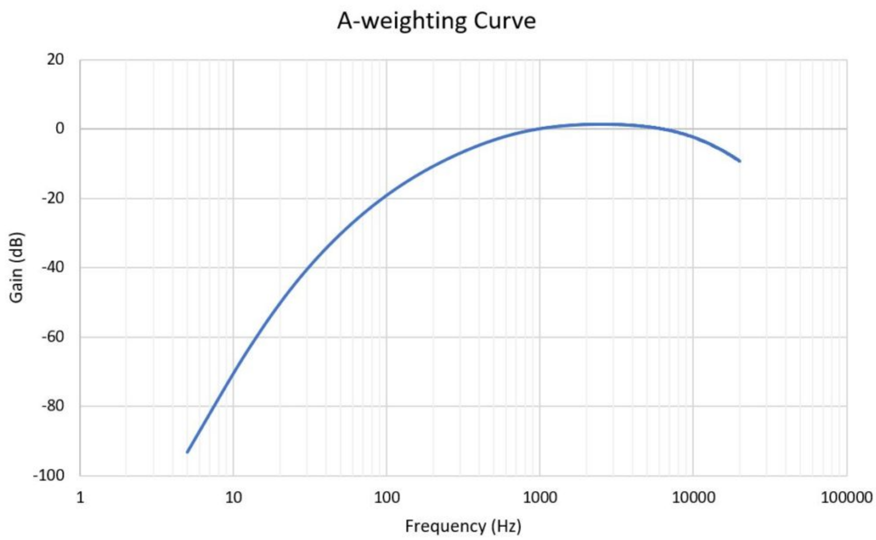

Figure D.11: The A-weighting curve for human perception. From Acoustical Engineer (2019)

GREEN ROOFS

Green roofs are part of the boundary of a building. They protect the interior against exterior influences, including an improved sound insulation. The vegetation on a green roof acts as a natural sound absorber, helping to reduce the transmission of sound waves from outside sources. Additionally, the soil and plants on a green roof can provide additional mass, which can help to block and absorb sound waves (Claus and Rousseau, 2012). The absorption capacity is influenced by multiple different parameters and determines the amount of noise insulation (Mahdiyar et al., 2016).

This can help to reduce the amount of noise that is transmitted into a building, making it a more comfortable and quiet space. The improved sound insulation provided by a green roof can be particularly beneficial in urban environments, where noise pollution can be a significant problem.

D.8.1. LITERATURE REVIEW

In the assessed literature, 5 papers have aimed to make a statement about the influence of green roofs on the sound insulation. In this, the literature gives varying values for the acoustic insulation value. Multiple economical techniques have been used in order to translate the benefit of the sound insulation of a green roof into a value.

D.8.1.1. QUANTIFICATION OF SOUND PRESSURE LEVEL REDUCTION

First, the quantification of the sound insulation of a green roof is discussed, before the calculation is addressed. There are a number of studies that focus on the impact of the substrate and plants on sound transmission. However, lot of misuse of values in the literature is seen. At first glance, the values seem to vary widely, with values between 6 and 50 dB (Mahdiyar et al., 2016). The main cause of this is that various literature measure different physical behaviours. The first thing that should be addressed is the difference in sound insulation and the reduction of sound propagation (figure: D.12). The physical behaviour of the roof system is different in both, leading to a different outcome. The second point of notice is found when looking at the sound insulation, which is a feature determined by the multi-layered system. The value can thus look at the impact of the addition of the green roof package, or the sound insulation value of the total roof package including the green roof.

The upper limit of the found values is obtained from Mahdiyar et al. (2016), which states that EGR can reduce the noise around 40 dB and between 46 and 50 dB for IGR. The original substantiation for this dates from the 1980's and 1990's and is not accessible online. It has been assumed, based on Claus and Rousseau (2012), that these values come from the complete roof package, including the green roof. Claus and Rousseau (2012) mentions an acoustic insulation value of about 38-40 dB(A). This value is based on research done by WTCB (2006), where the relationship between weight and overall acoustic insulation was found (figure: D.13). The addition of the substrate, drainage layer and plants from adding a green roof add additional weight to the roof package and thus increase the noise muffling.

Claus and Rousseau (2012), Mahdiyar et al. (2016) and Macháč et al. (2016) use the values from Van Renterghem and Botteldooren (2008, 2011). Who conducted studies on the effect of extensive green roofs on sound propagation. These studies focused on the impact of the substrate and plants on sound transmission parallel over the medium, rather than the effect of external factors on sound transmission perpendicular to the medium,

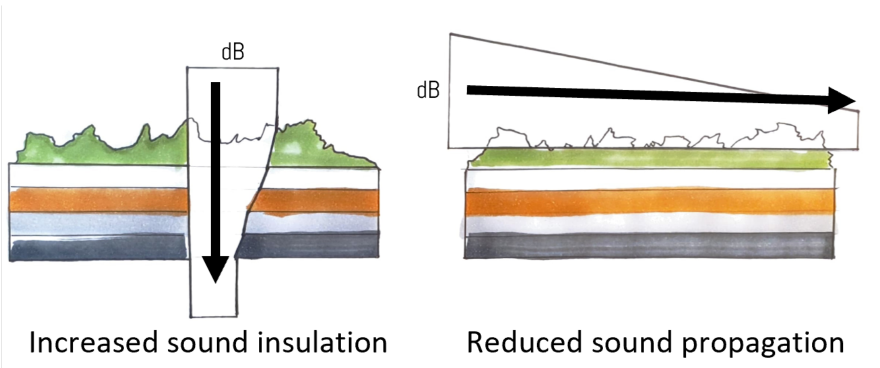

Figure D.12: Acoustic benefits of a green roof on the sound pressure level. (Own figure) from outside to inside. For completeness, the results of the two studies are presented below related to the aforementioned transmission:

- Van Renterghem and Botteldooren (2008) discovered that, when the layer thickness is changed, extensive green roofs have a damping peak of 10 dB when compared to an acoustically hard roof for the 1000 Hz octave band. Near the maximum layer thickness (15–20 cm), a good overall efficiency for this type of green roof is seen. The beneficial effects are no longer impacted by the substrate thickness for an intensive green roof with a substrate layer thickness of more than 20 cm.
- Van Renterghem and Botteldooren (2011) observed a single instance of diffraction with a green roof's acoustic performance improving by more than 10 dB at sound frequencies between 400 Hz and 1250 Hz. The improvement of the green roof is less frequency-dependent in double diffraction cases, and a case with gains of up to 10 dB was discovered.

However the outcome as presented by Claus and Rousseau (2012) of the results of Van Renterghem and Botteldooren (2011) is wrong, quoted it wrote: 'Van Renterghem and Botteldooren (2011) measured acoustic levels inside houses in several settings and found reduction up to 10 dB for particular sound frequencies'. The justification, "inside houses," does not align with the research referenced, which look at the propagation of sound over the roof. This incorrect usage is used along with WTCB (2006), as described above, in what appears to be the substantiation for: 'With outside noise levels of 76–80 dB(A) and estimated inside levels of 50–60 dB(A), we assume that the studied green roof decreases noise levels with some 23 dB(A) during daytime.' As a result, both studies appear to be measuring the same phenomenon, when in fact, this is not the case.

A similar inconsistency is seen in the application of the values from Van Renterghem and Botteldooren (2008) in Macháč et al. (2016). The values are again a representation of the reduction of noise over the roof medium. The maximum noise control achieved with a substrate thickness of 15-20 cm, in the range of 6-10dB, is used. However the value is later compared to a noise reduction through the layer, using drywall boards.

There is some ambiguity in the presentation of the values in Mahdiyar et al. (2016). Despite the fact that the described results of Van Renterghem and Botteldooren (2008) are not wrong, it lacks the research framework in which these results should be placed. By placing the results alongside the papers of Lagstrom (2004) and Connelly and Hodgson (2008), which are looking at the additional insulation value of adding a green roof from outside to inside through the entire package, the ambiguity of the results could cause confusion. The further substantiation of the noise reduction shows that the author has not included the results from Van Renterghem and Botteldooren (2008) in this either, which strengthens the indicated difference. So although the author did take the right considerations, it could cause confusion for future researchers.

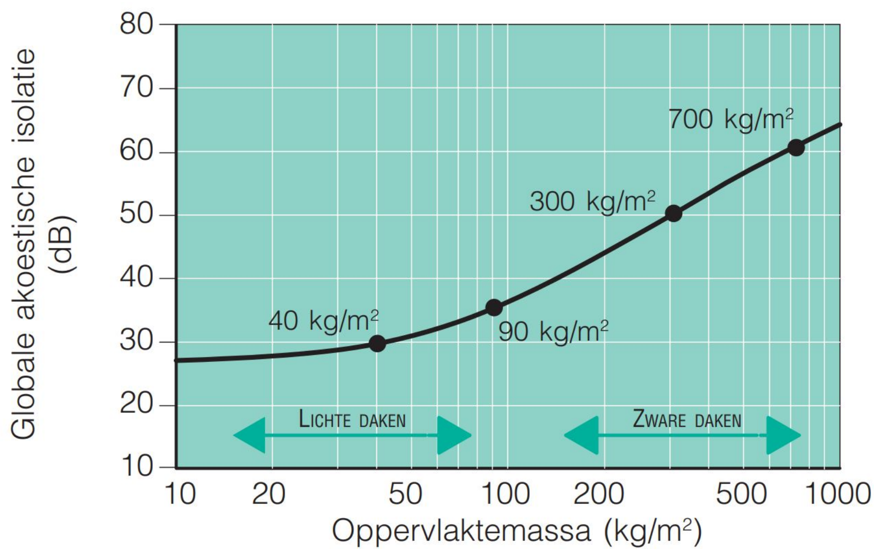

Figure D.13: Airborne sound insulation depending on the surface mass : empirical relationship in the case of single walls. From WTCB (2006)

Additional comments can be placed by the use of Lagstrom (2004). The results are more complex than they appear. These values are however calculated for a lightweight roof, with the additional comment that the effects would presumably have been lower on heavier roofs. Since the case study of Mahdiyar et al. (2016) is located in Kuala Lumpur, this lightweight roof may be applicable. It should however be noted for the context of this study.

However, it should be noted that the reduction value as used in Mahdiyar et al. (2016) from Connelly and Hodgson (2008) is wrong. The capability of extensive green roofs to reduce noise from 5 to 21 dB within frequency range of 50–4000 kHz, is described in Mahdiyar. In reality, the conclusion of Connely talks about an increase, above a reference roof, in the low and mid frequency range (50 Hz to 2000 Hz) of 5 to 13 dB in transmission loss, and 2 dB to 8 dB increase in transmission loss in the higher frequency range for EGR. Additionally, Teotónio et al. (2018) references Connely and discusses a 4 dB reduction for EGR and an 8 dB reduction for IGR. However, the paper only provides a representative value for EGR and does not offer a value for IGR.

D

D.8.1.2. VALUATION

As illustrated above, it is difficult to predict the behaviour of a green roof on noise reduction. Because this behaviour is not yet immediately clear, literature shows different approaches for the calculation to a monetary value. For completeness, the sources described above have also been worked out.

PROPERTY VALUE INCREASE

The approach of Claus and Rousseau (2012) makes the connection between the noise level in the environment and the market value of the property. In the calculation to monetary values, the chosen calculation method utilizes an estimated value of a 0.6% decrease in property market, this calculation takes into account that this noise level only applies to the highest floor. This value is valid when the ambient noise level increases by 1 dB(A). As already described above there is some inconsistency in the paper of Claus and Rousseau (2012), in which a reduction over the roof medium is used together with a value through the medium in order to make a statement about the reduction through the medium. By now comparing this with the relation of the outside noise level an overall weak chain of relations forms the foundation of this valuation method. Teotónio et al. (2018) adopts this approach and thus uses the same inconsistency.

SOUND INSULATION MATERIAL

Macháč et al. (2016), Mahdiyar et al. (2016) and Ulubeyli and Arslan (2017) base the value on an substitution cost of sound insulation material. The insulating properties of the green roof ensure that there is a less obligation of other sound insulating material. The cost price was derived by looking at the reduction value that a green roof can add to the roof package, insulation material with similar properties are chosen as substitution costs. This value also benefits the project owner in the first year.

A similar inconsistency as Claus and Rousseau (2012) is seen in the calculation of Macháč et al. (2016). The use of values from Van Renterghem and Botteldooren (2008) map the reduction of noise over the roof medium. However, in the calculation this is compared to a fictitious avoided cost for ceiling insulation using drywall boards. Which assumes that the reduction value over the roof medium can be equally applied for insulation through the roof medium.

URBAN NOISE REDUCTION

For calculation purposes, the sound insulation value of the roof package is applied as a means of achieving noise reduction in the city. In the context of the chosen case study in Teotónio et al. (2018), there is a municipal action plan to reduce noise by 10dB. A budget has therefore been made available for this purpose from the municipality. Since green roofs can serve as part of this solution, the benefit is applied using the avoided cost method. In this, the application of an IGR is equated to the entire available budget, for EGR the noise reduction capacity is estimated to be lower and hence it saves only 80% of the cost.

D.8.1.3. STAKEHOLDERS

Despite there being many differences in the values and calculation methods, they are essentially all identical. The addition of a green roof produces a degree of noise reduction. This reduction is translated into a monetary value next. In some sources, this is calculated on the assumption of avoided costs that would otherwise have to be put into soundproofing material or the cost that would have been occurred to reduce the urban noise level. For the project owner, this means that costs can be saved during the execution of the work and for the municipality, because the addition of green roofs can achieve the same desired effect as the budget is meant to achieve, this budget is no longer needed. Another section of sources looks at the impact that the addition of extra noise reduction has. Based on this, it was found that the price of property can increase. Again, this benefit is supposed to be for the project owner. These benefits accrue directly to the property owner in the first year. However, there is also an indication of a potential social benefit. The computational values used by Teotónio et al. (2018) and Claus and Rousseau (2012) in fact show the relationship between a reduction in ambient noise level with property value, but also the impact of noise pollution on health (Lagstrom, 2004). There is, however, too little information available within current research frameworks to support this statement.

D.8.2. Discussion

Essentially, the methodology is already in place, but to date there is much inconsistency in the literature and the distinction in physical behaviour is often neglected, leading to ambiguity. However, when all the information is systematically reviewed, two benefits that green roofs offer emerge. These benefits can be linked to the previously mentioned distinction between sound insulation and reduced noise propagation.

D

Quantification

First, it is worth bearing in mind what the description of the physical meaning is of these values. They can present a reduction of the indoor sound pressure level, the reduction through all layers, the reduction through just the additional green roof components or a reduction over the roof surface. For each of the methodologies it is essential to use the right physical property in order to rely on well-grounded statements. However, literature has showed that these are used out of context and that the original physical meaning gets lost within the process. This leads to inconsistency and an overall weak substantiation of the used methodologies. A distinction must be made between the impact on the building the green roof is located on due to increased sound insulation, and surrounding buildings that can also benefit from the prevented sound propagation.

Valuation

The analysed literature reveals two methods of expressing the benefit of noise reduction in monetary terms. The difference lies in the fact that one method looks at avoided damage costs, while the other looks at avoided mitigation costs. However, because these two methods are mutually exclusive, attention should be paid to their proper elaboration. This aspect was covered earlier in section D.4, which we refer to for the discussion that arises when using these values. In addition, a point of discussion arose from literature whether the property value increase should be applied to the top floor alone or over the entire building. Claus and Rousseau (2012) stated that the noise reduction does not cover the whole building. Applying this value may therefore lead to an overestimation, however, more research is needed on this as the statement is not based on literary evidence. So far, the elaboration of avoided damage costs focuses only on property depreciation, but there is also evidence in the literature of human health impacts. To date, however, this aspect is not considered.

D.8.3. Recommendation

The current methodology provides the means to determine the monetary benefits of sound insulation. However, follow-up research is needed to strengthen and validate the current methodology. This follow-up research should focus on:

- Refinement of noise reduction quantification
  Since there is inconsistency and confusion in the literature regarding the quantification of noise reduction by green roofs, further research is needed to refine the methods and approaches. It is important to use appropriate physical properties and context when quantifying noise reduction so that reliable and well-supported results can be obtained. Follow-up research can focus on developing standardised methods and criteria for quantifying noise reduction at different levels, such as within a building and in surrounding buildings. This should also take into account the physical behaviour of different noise components and the specific properties of green roofs that contribute to noise reduction.
- Comparison of valuation methods
  Although there are two methods mentioned in the literature to express the value of noise reduction in monetary terms, namely avoided damage costs and avoided mitigation costs, there is a need for further comparison and refinement of these methods. Follow-up research can focus on analysing the advantages and disadvantages of both methods and developing guidelines for their proper application.

This should take into account various aspects, such as the impact on property value and the costs and benefits of health benefits. By examining these aspects and integrating them into the quantification, a more complete picture of the economic value of noise reduction by green roofs can be obtained.

D.9. LONGEVITY

The concept of useful life is essential in maximizing the benefits of a product. This concept differentiates between the technical lifetime, which is the duration for which a product can function properly, and the economic lifetime, which is the time period during which the costs of maintenance and operation do not outweigh the benefits of using the product.

The project owner has his own rationale for making a particular choice. However, from a social point of view, it is increasingly important to also consider the social impact of using materials. After all, building materials place a heavy burden on the environment and society. Producing building materials and carrying out construction work requires most of the 21% of global CO2 emissions (Raouf and Al-Ghamdi, 2020). The 2018 transition agenda circular construction economy states the goal of halving CO_2 emissions in construction by 2030 (transitieteam circulaire bouweconomie, 2018). The elaboration, advisory route to a circular economy in construction 2022, even talks about reducing CO_2 50-60% (transitieteam circulaire bouweconomie, 2022). That also means a hefty task for the construction industry. Longevity is part of the circular economy. Where longevity is defined as "Increase resource use through prolonging the time materials remain in the economic system" (Helander et al. (2019) - p6). Provided that the stock of materials replaces the raw materials that go into production, improved longevity helps reduce input flows and also directly defer and/or reduce output flows.

D

GREEN ROOFS

The design and construction of a green roof should therefore take into account how the longevity changes compared to a normal roof. When conducting an economic analysis, this value is also taken into account. So, for both the society as well as the project owner, the life time of a green roof plays a mayor influence.

D.9.1. LITERATURE REVIEW

Literature describes the change of the roof-lifespan when adding a green roof. The majority of literature on the subject indicates that doing so increases life expectancy. The reasoning behind this can be identified in most papers. This stems from the fact that it serves as a protective layer for the most critical layers and protects them against extreme temperature fluctuations, ultraviolet radiation and accidental damage (Carter and Keeler, 2008). The high temperature and the diurnal temperature fluctuations cause thermal stress in the membranes (Liu and Baskaran, 2004). The expansion and shrinking are affecting the performance in the long term. The ultra-violet radiation from sunlight causes chemical degradation making the material become brittle (Oberndorfer et al., 2007), which lowers the physical and mechanical properties. The layers also serve as a barrier against physical damage from users, but also weather influence such as hail and storms.

The literature on the lifetime of green roofs presents varying values, with most studies focusing on an economic cost-benefit analysis. This economic lifetime is generally estimated to be between 40 and 50 years, which is approximately two times longer than the lifespan of a conventional roof (20 years). It is clear from the literature that green roofs have a longer lifetime compared to traditional roofs. The evidence for this is in mostly all cases based on real-life figures.

D.9.1.1. QUANTIFICATION

A number of papers rely on empirical evidence without proper scientific substantiation. The experience of application on European roofs is used in the substantiation of Carter and Keeler (2008); Peck et al. (1999); Kosareo and Ries (2007); Saiz et al. (2006), and specifically the application in Germany by Porsche and Köhler (2003). The latter four are the substantiation sources of those papers we examined: Claus and Rousseau (2012); Macháč et al. (2016); William et al. (2016); Berto et al. (2018); Alves et al. (2019). The paper of Porsche and Köhler (2003) for example, as used by Claus and Rousseau (2012); Macháč et al. (2016); Berto et al. (2018); Alves et al. (2019), states:

"*35 years of experience with green roofs in Germany demonstrate the value of the roof planting as protection of the waterproofing membrane. A roof which is covered with planting can be expected to outlast a comparable roof without greening by a factor of at least two. Although modern green roof planting systems are not more than 35 years old, many researchers expect that these installations will keep 50 years and more.*" (Porsche and Köhler (2003), p. 462)

The main issue is that any form of source to verify this statement is missing. This makes the scientific value of this statement, and thus all the statements in the subsequent sources questionable.

Table D.6: Longevity of green roof (GR) and conventional roof (CR) as used in literature

Source	Lifetime GR	Lifetime CR	Study period
(Clark et al., 2008)	40	15 and 20	40
(Carter and Keeler, 2008)	40	20	40
(Niu et al., 2010)	40	20	40
(Chang et al., 2011)	50	15-20	50
(Claus and Rousseau, 2012)	50	25	50
(Sproul et al., 2014)	40	20	50
(Macháč et al., 2016)	40	20	50
(McRae, 2016)	40	17	25
(Mahdiyar et al., 2016)	50	20	50
(William et al., 2016)	40	10 and 20	39
(Ulubeyli and Arslan, 2017)	40	20	40
(Berto et al., 2018)	40	20	40
(Alves et al., 2019)	30	-	30

D

In the study of Claus and Rousseau (2012), the final lifespan is based on the planning of the construction and architectural companies associated with the project, which estimate a lifespan of 50-60 years. German companies may also provide guarantees of 30 years for their green roofs, which indicates the technical parity of extensively greened roofs to conventional tile roofs while also offering additional ecological advantages (Köhler et al., 2001).

More concrete substantiated evidence is found in the research of Sproul et al. (2014) which examined 22 case study flat-roofed buildings in the United States. Based on the median value of a green roof, a roof lifespan of 40 years emerges. In general, the statements in the literature in United States match with the data previously found in Europe.

Some papers use less straight forward information to substantiate their numbers. The justification for the choice of a lifespan of 20 years for a conventional roof compared to 40 years for a green roof in Clark et al. (2008) and Niu et al. (2010) is based on Köhler (2006). Who stated that the EGR installation was virtually free of technical problems after 20 years. Clark's paper is subsequently used directly in the literature by Mahdiyar et al. (2016) and Ulubeyli and Arslan (2017), and indirectly by William et al. (2016) and Alves et al. (2019).

According to the literature, a green roof can extend the lifespan of a building. However, it should also be considered that flat roofs often exhibit low spots due to defects in construction or building movement over time. These low spots can become receptacles of water after precipitation events and can persist in a wet state for an extended period. The presence of water in these areas can damage the roofing membrane and affect its chemical stability. Green roofs can exacerbate this issue by slowing the drying process of these areas through reduced airflow and the high humidity of the above the roof membrane. The low spots on a green roof may not be discernible, making it challenging to detect damage until water infiltration transpires. This is particularly germane in wet regions. This counter-argument is only discussed in Liu and Baskaran (2004).

D.9.1.2. VALUATION

The way the studies translate the extended lifetime into a monetary value is the same in all studies, comparing a green roof with a conventional roof. First, a duration is chosen for the economic analysis. In many cases this duration is the same as the lifetime of a green roof, however, there are exceptions to this (see table D.6). The moment within life-span of the study when the green roof or conventional roof has reached its lifetime, a replacement value is taken into account. This value is equal to the initial value for the installation and material. Therefore, for the studies where the life span of the green roof is equal to the duration of the study, this replacement value of the green roof is not included. For the conventional roof, this means that the replacement value is taken into account once or twice. Some of the studies make the comparison of a conventional roof with a green roof. In these studies, the replacement of the conventional roof is therefore not directly taken into account in the calculation as an advantage over a green roof. Only in the final result, when the two are compared, does it emerge that this replacement value can be an advantage. In the other part of the studies, these two roofs are not directly compared, instead the benefits of a green roof compared to a conventional roof are included in the calculation of the green roof, done using an avoided cost.

D.9.1.3. STAKEHOLDERS

In the current literature, the longer lifetime of the roof package is included in the calculations with the aim of avoiding renovation at a later date. This implies avoiding material and labour costs at a later date, which is beneficial for the project owner. This benefit is often considered when a conventional roof approaches its lifespan, usually after about 15-20 years. The benefit is therefore taken into account at this time. The idea is that the longer life of the roof package provides financial benefits by delaying renovation costs.

However, current literature suggests that a longer life of the roof package does not bring direct social benefits. While avoiding renovation costs is beneficial for individual project owners, no significant social benefit is attributed to it.

D.9.2. DISCUSSION

In general, there is consensus in the literature that green roofs have a longer lifespan than conventional roofs. Nevertheless, there is considerable variation in the quality of literary evidence to support this claim. Much literature is still based on old sources with little or no solid evidence, both direct and indirect. This results in weaknesses throughout the research chain. In the literature, there is mostly a generally accepted understanding of extended lifespan however the quality of evidence does not do justice to this. Nevertheless, there is also literary evidence that supports the claim, but even these sources are based on only a few practical examples.

To date, however, little attention has been paid to the potential negative effects it can also bring. It should also be taken into account that the water in the low spots, due to construction defects or movements of the building over time, can damage the roof membrane and affect its chemical stability. The placement of these spots on a green roof may not be noticeable, making it difficult to detect damage until water infiltrates.

D.9.3. RECOMMENDATION

To answer the research question, follow-up research should focus on:

- Gather solid evidence for the lifespan of green roofs:
  Follow-up research should focus on gathering solid evidence to support the claimed lifespan of green roofs. This can be done by conducting detailed studies on existing green roofs, evaluating their performance and durability over time. Through extensive research, reliable data can be collected to support the lifetime claims and provide a more complete picture of the potential limitations and risks of green roofs.
- Researching the risks and potential drawbacks of green roofs:
  In addition to gathering evidence on the longevity of green roofs, it is important to further research the potential risks and drawbacks of green roofs. This should consider factors such as water accumulation and membrane damage. By thoroughly investigating these aspects, potential risks and drawbacks can be identified and a better understanding of the measures needed to mitigate these risks and potential drawbacks can be gained.
- Incorporation of the external cost incorporation
  According to the philosophy of this study, it is important to consider not only the external costs of green roofs, but also the external costs of conventional roofs. These costs are also avoided by installing green roofs. In this way, identifying the external costs of conventional roofs contributes to a more balanced calculation of external costs by placing them within a broader context. This can also be done for the replacement of the conventional roof, but due to the fact that this intervention takes place over roughly 20 years, there is uncertainty about quantification and valuation.

CULTURAL SERVICES

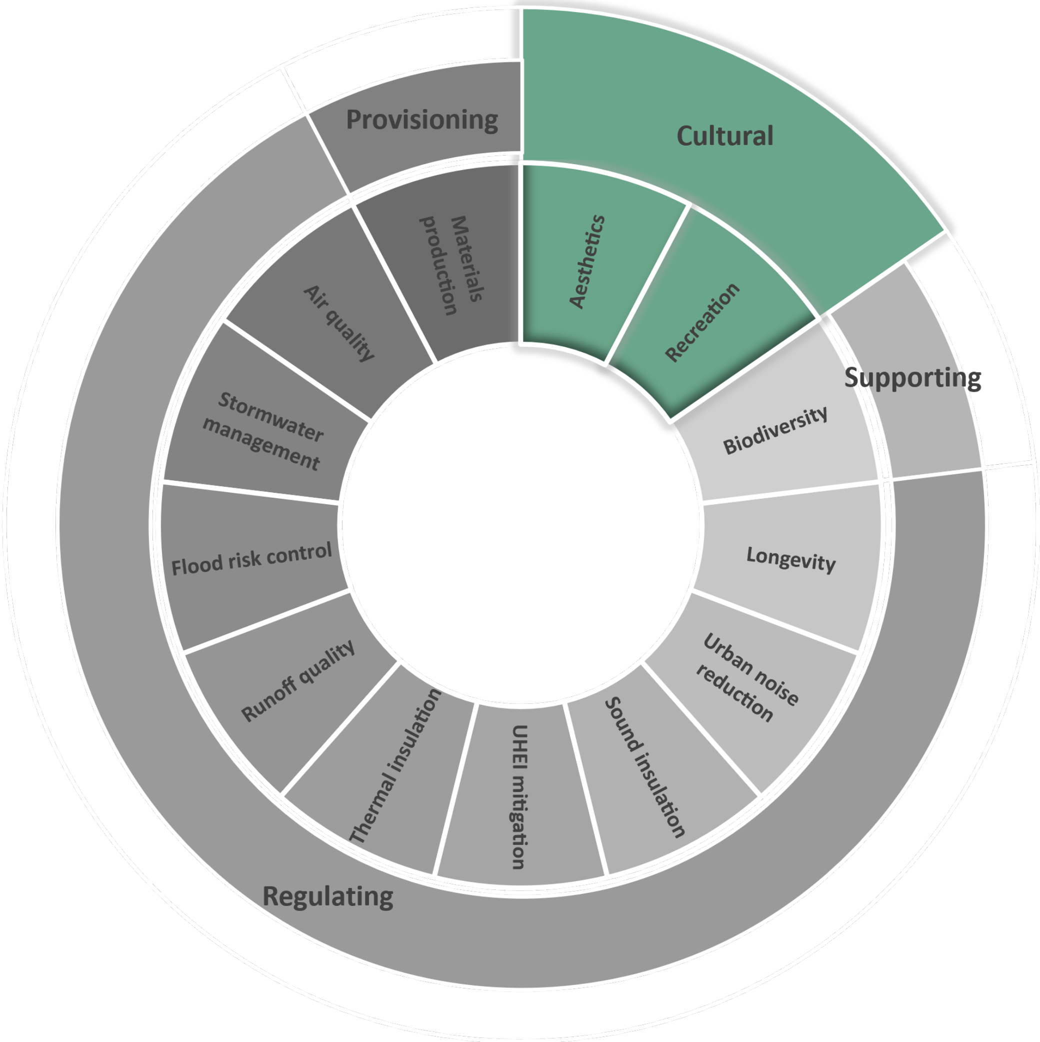

Figure D.14: Cultural services

D.10. AESTHETICS

Aesthetics is closely linked to people's ability to understand and appreciate arrangements that are perceived as pleasing. Thus the aesthetic aspects of a building are very important for the perception of observers and encompasses various aspects related to design elements and designers (Suryasari et al., 2022). The design of our physical environment has a significant impact on our psychological well-being. When assessing the built environment, both cognitive evaluation of building features and emotional responses play a role (Ghomeishi, 2021).

The facade of a building plays a crucial role in reflecting its value and structure. Moreover, the facade can even influence how people perceive the building and how they judge its architectural quality. On a larger scale, it can even influence the image of an entire neighbourhood or city (Suryasari et al., 2022). A well-designed building can make a positive contribution to both the building itself and the environment in which it stands.

D

GREEN ROOFS

The implementation of green roofs adds beauty and natural elements to the built environment, enhancing its visual appeal (Shushunova et al., 2021; Jawad et al., 2022). However, different people will assess the value of using an EGR or IGR differently. Within this context, preferences for vegetation on green roofs may vary, depending on the specific circumstances and individuals involved (Schrieke et al., 2021). Nevertheless, it is evident that aesthetics contribute significantly to the overall value of green roofs. The visual appeal and beauty of green roofs enhances the quality of the built environment and contributes to the connection with nature in urban areas (Jawad et al., 2022).

D.10.1. LITERATURE REVIEW

In the literature, we see limited consideration of property value.

Shazmin et al. (2017) conducted research based on a survey of 103 property valuers experienced in green building valuation. This survey revealed that according to a majority of the respondents (81 respondents), green roofs are a component that increases property values. However, no values indicating the property value are given.

In literature there is an lack of use of actual values that determine the property value increase. Bianchini and Hewage (2012b), as used by Ulubeyli and Arslan (2017) and Teotónio et al. (2018), and mentioned by Mahdiyar et al. (2016), assumes a property value increase due to the provision of green roofs of 2-5% for EGR and 5-8% for IGR. This is however, a conservative derived value originated from the price increase due to provision of trees and greenery in the direct surroundings of a building. Teotonio however uses a value of 10-20% for IGR, given the fact that they provide a higher aesthetic improvement of the buildings and the urban landscape, and in addition they provide recreational area. This recreational aspect, as described in chapter D.11, is however included in this value. The property value increase is established based on green in the direct surrounding. Based on that assumption, Teotonio also makes a statement about the property value increase of the buildings in the local area. For residential buildings an average value of 3,5% and 15% is used. Due to the higher amount of users the value for commercial buildings is equal to the maximum value of 5% and 20%.

The study of Mahdiyar et al. (2016) indicates that use of well maintained green roofs can increase the property value. A similar derivation as in Bianchini is made because of the limited available literature, in which a study about green spaces is used to make a statement about green roofs. The value utilized to estimate the increment in property value is derived from the positive amenity impact of public green space size on house prices in Kuala Lumpur (Noor et al., 2015). A value of 3-6% is assumed for EGR and 6-12% for IGR according to their greater influence on the property value.

Berto et al. (2018) valued based on the stated preference method the willingness to pay for a widespread application of a green roof. Based on questions to individuals a quantification could be made with a value fluctuating between 82-205 euro per property unit. A city wide application was used in which half of the buildings got refurbished with a green roof. Given local conditions where there is a lot of visibility on roofs.

D.10.1.1. STAKEHOLDERS

Despite the fact that only a few sources give an indication of the potential for stakeholders, a clear image is given to whom these benefits occur. The literature translates the aesthetic value into a value for the property owner, or the value of property owners overlooking the roof. This therefore provides both a benefit to the project owner, and a piece of societal benefit. The benefit is in most cares derived from trees and greenery in the direct surroundings of the building. The price increase has been proven both by stated preference methods as well as revealed preference methods. Most of the studies use this relation to derive the impact of green roofs and a property value increase. This relation solely has only been supported by the stated preference method. The benefit of both the private owner as well as the owners of buildings in the direct surroundings occur at the moment after completion, and is a one time benefit.

D.10.2. DISCUSSION

The current literature lacks completeness. The values used are derived from the presence of greenery in the environment, but no solid evidence can be found for a direct correlation between the two. This creates the possibility of important influence factors being overlooked. This is already apparent, for instance, in the presumption that, in terms of recreation, EGR results in a smaller price increase than IGR. The underlying assumption here is that EGR is often not accessible and therefore does not provide the full benefit compared to a park, or an IGR. This relation should be studied in more detail, in order to correctly assess the parameters that are of influence in the height of the property value increase.

The current method relies on assumptions and relations which have not been supported by any research. This process carries the risk not only of overlooking relationships but also of double-counting possible relationships or influential parameters. Although some sources distinguish the influence between EGR and IGR, Teotónio et al. (2018) adds in her calculations that there is a difference in recreational value. Since the current calculation method is based on assumptions, it cannot be said with certainty to what extent this value is already included in the aesthetic value. This could result in double counting the benefit gained from recreational value in the calculation. The 20% property increase described by Teotonio provides significant benefit and has a significant impact on the economic profitability of this investment. However, due to the uncertainty associated with the assumptions, it should be treated with caution.

Berto et al. (2018) uses an alternative approach for translation into monetary values. This research focuses on willingness to pay based on the stated preference method. However, the question arises about the extent to which these values adequately represent true value, given the limitations of the method that often lead to overestimation of actual behaviour.

Moreover, all studies, and Teotónio et al. (2018) explicitly mention the benefit of green roofs applied to the entire building. However, the author places doubts about the scalability of these findings on larger buildings, especially when the ratio of the roof area to the rest of the building's area decreases. Taller buildings will have a smaller roof/building ratio, and in addition the aesthetic view will decrease from the street level as the green roof gets higher. Follow-up research should make a statement on this too, to identify the relationship between the number of floors and the price increase due to the green roof.

The same consideration applies to buildings in the vicinity of the green roof, which Teotonio says benefit from the price increase. However, it is not realistic to apply one value to the entire value of surrounding buildings. Instead, the surrounding buildings that have direct views of the green roof should be considered. This should take into account not only the vertical part that has views, but also within the horizontal plane which part has views to get a more accurate picture. In Berto et al. (2018), this is underpinned by the fact that there is enough view on all roofs due to local conditions. Macháč et al. (2016) additionally mentions, although not taken into consideration, that owing to the roof pitch the presence of greenery on the rooftop not only enhances the visual appeal from nearby structures but also from the street and the surrounding developments. This increase in aesthetic value exerts a favorable impact on the value of neighboring properties. Both of these bring additional strength to the fact that this correlation must be properly taken into account.

D.10.3. RECOMMENDATION

To answer the research question, follow-up research should focus on:

- Establish the causal relationship between green roofs and the aesthetic value
  It is important to conduct follow-up research aimed at establishing the causal relationship between the presence of green roofs and the increase in property value. The recommended research should aim to gather empirical evidence and statistical analysis to establish a clear causal relationship between green roofs and property value increase. This would contribute to a better understanding of the specific benefits offered by green roofs and their impact on the property market.
  In this, it is important to further investigate the scale at which this price appreciation occurs. Follow-up research can focus on identifying the impact on property value at specific locations within a building

by looking at different building shapes. This can help determine the optimal locations for green roofs and maximise the potential benefits.

- Distinguishing between aesthetic value and recreational value
  It is important to conduct strong follow-up research that clearly distinguishes between the aesthetic value and recreational value of green roofs. This research can help understand the specific benefits associated with each. Current literature may double count the benefits of aesthetic value and recreational value, so it is essential to correctly interpret the aesthetic value of green roofs.
- Explore potential of property appreciation on surrounding buildings
  It is important to investigate whether the presence of green roofs on one building can also have a positive impact on the property value of surrounding buildings. This can contribute to understanding the wider impact of green roofs within urban areas. Follow-up research could focus on analysing property value data and identifying any links between green roofs on one building and the value of neighbouring properties.
- Explore potential of appreciation value
  It is important to investigate whether the presence of green roofs on one building can also have a positive impact on the appreciation value of people on ground level. In addition to the before mentioned benefits, some people will probably value the buildings without directly using them. These values could also be fed back as part of the cultural service.

D.11. Recreation

Recreation refers to activities that individuals undertake in their leisure time. It can be provided by different organisations and includes both indoor and outdoor activities, sometimes offering free services (Tribe, 2020). Outdoor recreation, in particular, plays a crucial role in connecting individuals with the environment and contributing to their overall well-being, holding significant value to people, planet and profit (Morse, 2020).

Participation in recreational activities offers numerous health benefits for individuals. These activities can have a beneficial impact on various aspects of well-being, including overall quality of life, mental health and physical fitness (Morse, 2020; Schafft et al., 2021). In particular, participation in outdoor recreational activities often provides an opportunity for people to come together, which promotes social interactions and can create a sense of community. In addition, recreation plays a vital role in promoting environmental sustainability by bringing people closer to nature and making them aware of the importance of environmental conservation (Morse, 2020). Moreover, recreation also provides economic benefits. It offers opportunities to create jobs and generate income from tourism and related sectors, which can have a positive impact on the local economy (Liu et al., 2021b).

Green roof

The recreational use of green roofs refers to utilising these rooftop spaces for relaxation and leisure activities. Studies have shown that recreation is a primary consideration for individuals when considering the installation of green roofs, even more than aesthetics (Teotónio et al., 2020).

Within the context of urban environments, a close relationship with nature is created through the implementation of green roofs, allowing these roofs to serve as an oasis amidst the urbanised environment and create a sense of serenity and relaxation (Sattler et al., 2020). Moreover, green roofs provide an additional green space suitable for recreational purposes within cities, creating opportunities for social contact, walks and gardening (Köhler and Kaiser, 2021). Given the requirement of accessibility of these roofs, only IGR are suitable for recreational activities.

D.11.1. Literature review

In the literature analyzed, little is said about how green roofs support recreation. Most papers only mention recreation without providing additional information (Carter and Keeler, 2008; McRae, 2016; Macháč et al., 2016; Mahdiyar et al., 2016; Ulubeyli and Arslan, 2017; Berto et al., 2018). Only one publication is available that discusses the recreational value aspects of green roofs.

D.11.1.1. Quantification

While Teotónio et al. (2018) acknowledges the positive contribution of green roofs to property value appreciation, no substantiation or explanation can be found as to how this value addition came about. For this reason, the author decided to consult the original research material on which the paper is based. In which it was found that depending on the degree of accessibility, green roofs can serve as a form of rest and relaxation space for residents. The presence of nature helps increase comfort and quality of life for these residents. Moreover, green roofs provide a safe environment as they are in a private space shielded from the outside world.

Finally, Teotónio et al. (2018) calculation merges the value of recreation with the aesthetic value. A benefit of 2-5% is attributed for extensive green roofs (EGR), while intensive green roofs (IGR) are given a value of 10-20%, as described in Bianchini and Hewage (2012b). This article only cites values that describe the relationship between park or tree value and property value. The assumption herein was made that without restrictions in access, green roofs can provide up to 30-70% of the benefits of public parks. However, the exact methodology used in the article is not defined.

According to Tomalty and Komorowski (2010), research shows that houses directly adjacent to public parks have a value 20% higher than comparable houses further away from a park. From this, 9% is deducted as increase in value due to trees in the immediate vicinity of the house, this is seen as a "view benefit". As a result, the value increase of a green roof is estimated at 11%.

D.11.1.2. Valuation

According to Teotonio, the price of real estate will increase due to the provisioning of a green roof. The 11% increase in value has been applied in calculating the value of the property on which the green roof is installed. Here, the increase in value has been multiplied by the entire value of the property in question. In the case of service buildings, this increase in value has been increased between 11% and 20%, based on the fact that these buildings are publicly accessible and therefore used by more people.

No value increase is expected for extensive green roofs, this is based on the fact that these roofs are often not accessible and therefore cannot enjoy the benefits.

D.11.1.3. STAKEHOLDERS
Based on the current calculation methodology, the building owner could benefit directly from the implementation of a green roof. The construction of the green roof results in an increase in property value, which is realised immediately in the first year on paper.

D.11.2. DISCUSSION
The current methodology relies on a number of assumptions that are not literary, gradually the fact that these values rely on assumptions may get lost. However, it is important to elaborate on green roofs using the right values. In this, there should be a clear distinction between aesthetic and recreational values. Because the current literature counts these values together, the full potential of the roof is not recognised. In addition, it should be acknowledged that using such values as in Teotónio et al. (2018) give significant overestimates. The assumption of a property increase of 20 % is highly questioned by the author. This means that the current literature does not yet offer enough insight.

The recreation value increase due to green roofs is based on the appreciation people experience when using it. In the current calculation, this increase in value is only reflected in the value of the property, but also has an impact on those who use the green roof. A more complete picture of the increase in value could be obtained by taking into account the improvement in comfort and quality of life for users, as described in Tomalty and Komorowski (2010). This would lead to a more balanced assessment that takes into account different stakeholders, in this case users. This creates a fairer assessment that also takes into account the societal interest.

D.11.3. RECOMMENDATION
To answer the research question, follow-up research should focus on:

- Validate the contribution of green roofs recreation value to property value
  Future research should focus on validating the contribution of green roofs to property value. It is essential to establish a causal relationship between green roofs and property value. Comparative studies could be conducted to assess the impact of green roofs on property value in different contexts. This would provide a better understanding of the economic benefits associated with green roofs.
- Assess the cultural value and social benefits of recreation provided by green roofs
  Further research is needed to understand the recreational cultural value and social benefits of green roofs. This research should focus on the improvement of comfort and quality of life for users, taking into account the social value that green roofs can provide. It is important to assess the difficult to monetise aspects of recreation.

SUPPORTING SERVICES

Figure D.15: Supporting services

Supporting services		
Appendix	**Title**	**Page**
D.12	Biodiversity	161

D.12. BIODIVERSITY

Biodiversity indicates a certain degree of variation of flora and fauna. Within biodiversity is the pool of ecosystems, species and genes. Biodiversity is important to keep an area in balance. The wide variation within the ecosystem makes it resistant to survive in different conditions. In doing so, it ensures proper stability and hence health of the ecosystem. This is mainly due to the interrelationship that different species have with each other. Even beyond the food chain, different species depend on each other to survive. In this way, it is important to have the right ratio and variety of species within an ecosystem (Roe et al., 2019).

Ecosystems also develop within cities, with greenery within the city providing habitat and services for this purpose. In cities, these areas are often smaller and more fragmented and isolated. While it is precisely the connection between these systems that is important. In urban environments, habitats exist of a diverse range of native and non-native species, including both intensively maintained and converted areas with managed and unmanaged vegetation, as well as unmanaged or semi-natural areas (Mayrand and Clergeau, 2018). Parks and roadside vegetation provide the location for important urban ecosystems. Their success depends on their number, quality and connectivity (Wooster et al., 2022).

D

Scientific bodies have sounded the alarm over the precarious state of biodiversity worldwide, with about 1 million species threatened with extinction, partly due to the decline of their habitats. Biodiversity loss has substantial implications for aspects such as: the link between climate change and biodiversity, food security, air and water quality, natural resources and goods, pest and disease control, and quality of life (Mommer, 2022). While some biodiversity is unavoidably lost, the current rate is about 1000 times that of natural loss. The majority of this loss is caused by humans, and poses a significant barrier to future growth and development and creates a serious environmental crisis (Roe et al., 2019).

GREEN ROOFS

Green roofs have an important role to play within the urban area when it comes to improving biodiversity. Because a large part of the urban area consists of roofs, there is a lot of margin to be gained here, especially since solutions at ground level are proving difficult. These roofs can thus be part of the stepping stones that can connect separate habitat elements. In order to move towards a situation where green corridors increase biodiversity within the urban landscape (Mayrand and Clergeau, 2018).

Green roofs often consist of actively growing plants, some of which were originally planted but others as a result of spreading by birds and the wind. These plants provide habitat for a variety of insects and a nesting site for birds. In this way, they provide quantitative ecological benefits (Wooster et al., 2022).

D.12.1. LITERATURE REVIEW

In the literature analyzed, little is said about how green roofs support urban biodiversity. Most papers only mention biodiversity without providing additional information (Wong et al., 2003b; Carter and Keeler, 2008; McRae, 2016; William et al., 2016; Ulubeyli and Arslan, 2017; Ziogou et al., 2017; Kim et al., 2018). While some sources mention the potential benefits of increased biodiversity, they also mention the difficulties in quantifying them (Sproul et al., 2014; Alves et al., 2019). Other sources mention them in qualitative terms but do not quantify or monetize these, Claus and Rousseau (2012). However, Teotónio et al. (2018) claimed that, at the time of writing his paper, they are correctly identified in the literature but their translation into monetary values remains complex.

Green roofs provide an opportune habitat for various flora and fauna. The specific taxonomic groupings of plants and animals that seek refuge on green roofs are influenced by several determinants, including the type of green roof, the taxonomic diversity of plant species present, the environmental flora and fauna, and the humidity level of the green roof. Scientific research has provided compelling evidence that insect populations frequently flourish on these roofs, and green roofs also serve as reproductive habitats for native bird communities (Claus and Rousseau, 2012). In addition to the local influence, within an urban and suburban setting, green roofs can also be an integral part of a broader ecological corridor (Claus and Rousseau, 2012; Berto et al., 2018; Teotónio et al., 2018). Evidence of a survey conducted in Hanover, Germany, as highlighted by Macháč et al. (2016). Found that green roof soils were able to support 30 species of springtails, a number comparable to the number of species found in urban soils such as those found in parks and gardens. However, no further steps are taken with that information.

Only two papers try to address a monetary value to the ecosystem services. The valuation in Teotónio et al. (2018) is based on the preservation and in Berto et al. (2018) on preservation, protection, restoration and enhancement of land as natural habitat. Both sources take an existing public annual budget into account. However the provided ecosystem services are not seen as equal as those proposed for the original budget. That is why both sources partially address the budget to the benefits of ecosystem services. For extensive green roofs the benefits are lower than for intensive green roofs. A reduction value of 0.2 is used for EGR in (Berto et al., 2018), but lacks substantiation. A value of 0.4 is attached to the benefits of EGR, and a value of 0.8 (Teotónio et al., 2018) for intensive green roofs, based on unspecified expert valuation.

D.12.1.1. STAKEHOLDERS

In the literature, no benefits have been found for the project owner. Benefits to society come mainly from the method of avoided mitigation costs. The savings realised on the annual public budget for biodiversity. This also implies that the benefits will flow to this stakeholder, namely the municipality in the case of Teotónio et al. (2018) and the region in Berto et al. (2018).

D

D.12.2. DISCUSSION

Current literature shows that there has been an understanding for more than 20 years that green roofs contribute to improving biodiversity, however, since that time there have only been two sources that have attempted to express biodiversity in cost-benefit analysis. The lack of data has since been debunked by Teotónio et al. (2018), but instead, the problem was attributed to the translation method to a monetary value. To make an attempt anyway, the current methodology looks at the avoided mitigation costs. The discussion of this has previously been described and is therefore disregarded for now.

However, the methodology used uses a causal connection which has not yet been demonstrated. The method relies on a reduction value that has not yet been substantiated by literature, therefore the validity of this link can be questioned.

D.12.3. RECOMMENDATION

To answer the research question, follow-up research should focus on:

- Improving quantification of green roof biodiversity
  Follow-up research is needed to better quantify the effects of green roofs on biodiversity. While current literature indicates that green roofs have a positive effect on biodiversity at the building level and when creating a wildlife corridor, concrete values are lacking. It is important to develop specific measurement methods and indicators to accurately assess the effects of green roofs on biodiversity. By gathering more empirical evidence, reliable and comparable data can be obtained, contributing to understanding and communicating the value of green roofs for biodiversity.
- Research on the causal relationship between quantification and valuation
  While green roof valuation currently looks at the avoided costs of implementing biodiversity plans, the causal relationship between quantification of impacts and valuation is not yet scientifically proven. Follow-up research should focus on exploring and validating this causal relationship. It is important to understand how the quantification of impacts translates into economic valuation and how this valuation can be applied in decision-making regarding green roofs and biodiversity conservation.

E
(ENVIRONMENTAL) LIFE CYCLE ASSESSMENT

This chapter serves as a substantiation in determining the use of LCA for this study. This chapter provides a brief introduction to the methodology around making an LCA. In it, there is an overview of the structure and stages in making an LCA, and an overview of the different assumptions of the scope of the LCA.

E.1. LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a methodology that focuses on the systematic treatment of all environmental aspects and potential environmental impacts of a product. In the mid-1960s, it was recognised that it is necessary to consider the entire life cycle of a product, and to consider not only the energy used in production, but also the resources used and waste produced (Zuo et al., 2017). The LCA was borne to address the protection of the environment (Toniolo et al., 2020). The calculation structure is formed by the systems approach, where all input and output flows of the entire system are thoroughly analysed, as shown in figure E.1. In terms of input components, these include materials, energy and means of transport. In contrast, the output components include products and services, emissions to the atmosphere, water and soil, by-products and recyclables, including the supply of raw materials for power plants, and finally wastes destined for landfills, incineration and other forms of waste treatment (Vogtlander, 2023).

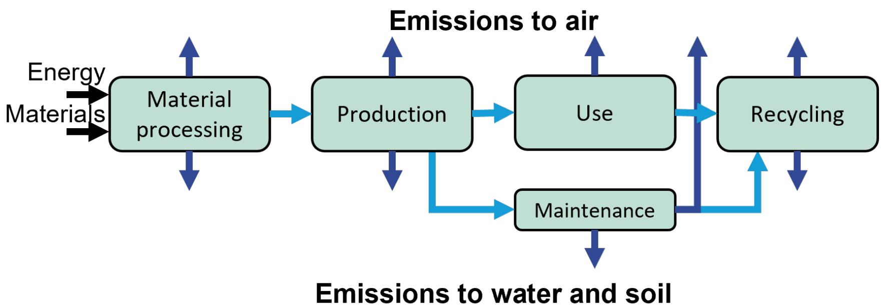

Figure E.1: The basic calculation system of LCA. Adjusted from Vogtlander (2023)

E.1.1. LIFE CYCLE ASSESSMENT FRAMEWORK

The international standard for making a LCA is developed by the International Organization for Standardization in the shape of ISO 14040 "LCA - Principles and Framework" and ISO 14044 "LCA - Requirements and Guidelines". This contributed as an important step in consolidate procedures and methods of LCA. ISO 14040 serves as a framework for making an LCA and offers guidance in this regard. ISO 14044 contains all the technical properties and guidance for this. More specifically it provides a method for uniform measurement of sustainability of construction works in the EN 15804 (Sustainability of construction works - Environmental product declarations) and the EN 15978 (Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method) and a method for the assessment of products in the ISO 14025 (Environmental labels and declarations) (Durão et al., 2020; Jonkers, 2021). The following principles were added: the LCA should include the full life cycle of a product, the focus of the LCA should be on the environmental aspect and its impact, the LCA should be relative based on a functional unit, the approach should be iterative, transparent, comprehensive and priority should be given to relying on natural science (Finkbeiner et al., 2006; Jonkers, 2021).

In order to represent the environment comprehensively, it includes all stages from cradle to grave of a product, from production and subsequent transport to installation, use and even the end-of-life stages. The LCA then systematically maps the impact of all phases. Because the outcome of the LCA must be verifiable against other outcomes, it is important to proceed step by step, for which the following steps have been developed, see figure E.2. The steps have been elaborated based on information from Standardization (2006) and (Jonkers, 2021).

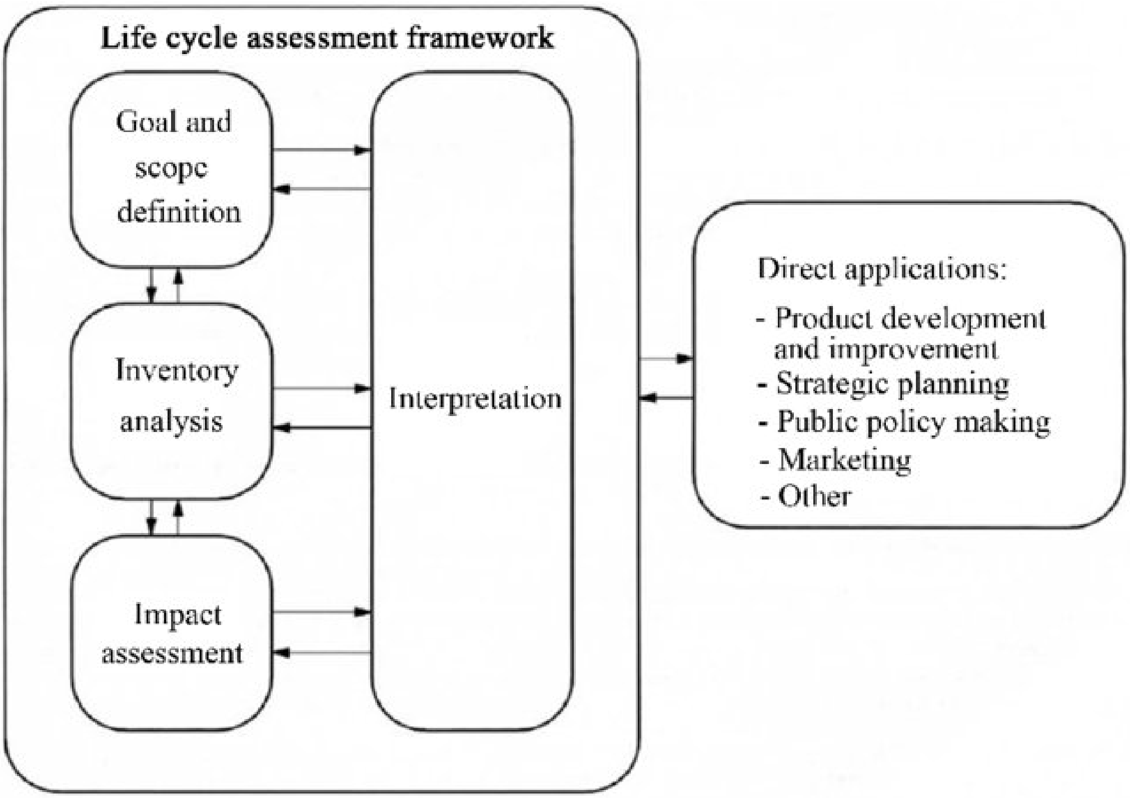

Figure E.2: Life-Cycle-Assessment-Framework-ISO-14040. From Standardization (2006)

- **The goal and scope definition phase**
  Within the framework of research, it is of significant importance to carefully align the research design with its ultimate intended purpose. A meticulous alignment between the research design and the desired goal is crucial to ensure an optimal contribution of the research results in achieving the stated objectives. In this context, it is essential to systematically consider and clearly identify a number of essential aspects regarding the research goal.

  – Intended application
  – Rationale for conducting the LCA
  – Description of the audience

  Delineating the right scope of the study is important when conducting a LCA. The system boundaries and level of detailed information should be carefully determined, appropriate to the subject and intended use of the study. After all, the scope of an LCA can vary greatly depending on the specific objectives of the analysis. It is therefore important to determine which aspects of the product or process life cycle should be mapped in accordance with the goal of the study. The degree of thoroughness and the width of an LCA can vary considerably, as a result. Which is why it is important to proceed carefully here and make the right choices. In this context, it is essential to systematically consider and clearly identify a number of essential aspects regarding the research goal.

- Definition of the functional unit
- System boundaries
- Followed LCA methodology
- The type and sources of the product life cycle stages used
- The level of quality of the data used
- Establishment of the need and quality of the review of the analysis

- **The life cycle inventory analysis phase**
  During the life cycle inventory (LCI) analysis phase, a comprehensive inventory is made out of the input and output data of the system under investigation. In which, it is crucial to collect reliable and accurate data to perform an accurate and complete analysis. A great amount of attention is therefore paid to collecting high-quality data during this phase, this data can be visually represented within a process tree.

- **The life cycle impact assessment phase**
  During the life cycle impact assessment (LCIA) phase, a standardised methodology is used to translate the data from the LCI into ecological effects and impact categories. Additional information is collection and needed to assess the results of the LCI and to gain a better understanding of the impact of the product system on the environment.

- **Life cycle interpretation phase**
  During the life cycle interpretation phase the data obtained is interpreted and evaluated to get a more complete picture of the system's impact on the environment. Based on the goal of the LCA, it can help to compare different product systems and to identify the main environmental impacts resulting from their life cycle. Through this information, strategies can be developed to improve system sustainability and reduce environmental impacts. Therefore, it is an important stage in the LCA process because it provides the information needed to make informed decisions regarding the sustainability of a product within the scope of the study.

E.1.2. THE GOAL DEFINITION PHASE

The results of an LCA can be used to inform decision-makers in business, government, or non-governmental organizations during a (complex) decision-making process (Toniolo et al., 2020). Depending on the study scope and its intended application, such as internal versus external communication, the level of detail of a LCA can vary. However the defined goal and scope should be consistent with the study's intended use (Soukka et al., 2020). In practice, LCAs can be categorised according to their level of description, ranging from a brief screening to a thorough, in-depth assessment. Thus, LCAs can be designed internally as tools to promote environmental awareness within an organisation, focusing on evaluating the environmental impact of products, identifying environmental reduction opportunities in the value chain and gathering environmental information to support eco-design. With regard to external communication, comprehensive LCAs can be of value for an organisation to communicate its environmental impacts and present environmental statements and claims related to its products. This distinction is further elaborated based on information of Ecomatters (2023):

- **LCA screening studies**
  These studies are done at a high level with little or no information at a detailed level. The result from the studies shows from the different life-cycle stages insight and overview of the main impacts of a product. As a result, the main drivers of high environmental impact can be identified and understood. This information can give rise to follow-up research that zooms in on these aspects on a deeper scale.

- **In-depth LCA studies**
  In-depth LCAs are important especially in communicating externally. The comprehensive and complete analysis makes it possible to communicate externally about the product's environmental statement, and its impact on the environment. For this, it is important for the LCA to have been properly

produced. For this, the elaboration is often in accordance with ISO 14040/44 standards. To further guarantee and verify quality, there is usually a third party review. The equal design of all the different studies also means that these studies can be compared with each other, in order to compare products with a similar function.

- **Comparative LCA studies**
  When an LCA study aims to compare two competing products, ISO standards require that a comparative LCA be made. This required approach aims to make a fair comparison. Therefore, there are additional requirements to be met, such as a critical review by an external panel.

For our research it is important to show the potential of implementing the external costs. That is why it is preferred to use analysis methods that allow for comparison, however, at this stage of bridging the gap between the LCA and the cost benefit analysis it is important focus on that aspect instead of the potential for comparison.

E.1.2.1. System boundaries

As part of the study scope, it is of substantial importance to carefully decide which specific phases to include. This decision should be made with careful consideration, as results may vary significantly depending on the deliberate inclusion or exclusion of certain phases. This is particularly due to the fact that input and output parameters depend directly on the respective life stages of the product in question.

The inclusion and differentiation of various life stages can also provide additional insights regarding the research findings. This allows specific analysis of at which stage the impact is greatest or smallest. From a

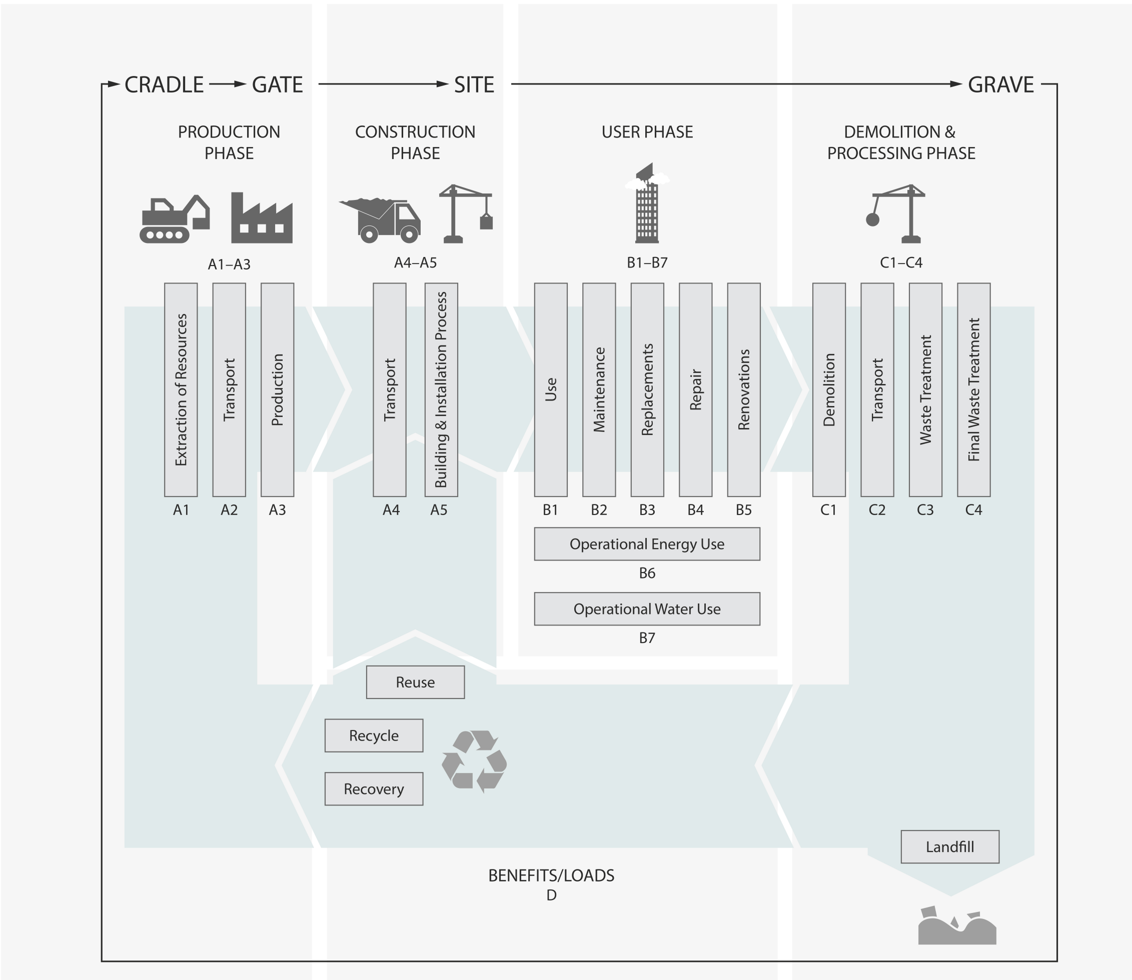

Figure E.3: Life cycle stages of a building, including life cycle phases, represented by A1-D, according to EN-15804. From Lankhorst et al. (2019)

sustainability perspective, this information can be used to develop targeted solutions to reduce emissions (Scolaro and Ghisi, 2022).

The collection of raw materials from the environment, their processing and transportation, their production of the product, their distribution to customers, their use, re-use, maintenance, and disposal, at which point the materials are no longer useful, are all typically taken into account when an LCA is conducted (Soukka et al., 2020). The method, which takes into account every stage of life, is known as a cradle-to-grave assessment, see also figure E.3. However, only 35% of GRs studies followed the cradle to grave boundary approach according to Shafique et al. (2020). In contrary to this statement, Scolaro and Ghisi (2022) mentions that most studies do follow a cradle to grave approach.

Nevertheless, for our research the aim is to gain information regarding a full life cycle approach. This way the full potential could be shown, however a lack of information does not diminish the value of the research.