Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur

Masterthesis

Green Roofs and Green Walls: A Research Weaving Analysis

Bob Daniëls

Scriptie ingediend tot het behalen van de graad van master handelsingenieur, afstudeerrichting technologie in business

PROMOTOR :

Prof. dr. Sebastien LIZIN

BEGELEIDER :

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This master thesis was written during the COVID-19 crisis (2020-2021). This worldwide pandemic has potentially had an impact on the (writing) process, the research activities and the research results that form the foundation of this project.

Acknowledgements

It has been almost seven years since I came to the University of Hasselt for the first time. I was a last-year high school student that wanted to apply for the education programme of Business Engineering. One summer break later, the adventure officially began: my studies at the UHasselt kicked off, on a Monday morning, with a three-hour course of abstract mathematics.

And my education programme comes to an end with this thesis.

Over these seven years, I have met a lot of people, professors and students alike. And every one of them taught me something. Whether it was a new abstract theory of economics, or just a suggestion new place to eat sushi; I valued every single lesson.

There are no personal regrets of these past seven years of education, even if they were supposed to be five years, originally. I'll have to thank my professors for that, making their courses so interesting that I gladly wanted to take them a second time, and a third time… I just couldn't say goodbye to them! All jokes aside; in the process of redoing a few courses, I also learned a very valuable lesson. And that lesson said that I would have to work hard to get good results, but that the hard work really would pay off, in the end. And it did.

I worked myself up the ranks of my student association, eventually becoming president of our provinces' biggest fraternity (Hermes). I also became chairman of the council of student associations. I lead the organisation of a networking event, that completely sold out. And I started working at Voka – Chamber of Commerce fulltime two months ago, which I somehow miraculously managed to combine with my studies, to my own surprise. All thanks to hard work.

Memories exist of all of the experiences I had during the process of writing this thesis. I remember the productive Sunday afternoons, and the disappointingly unproductive Wednesday evenings. I remember the short nights, and the long mornings. I remember all of the highs, and all of the lows.

I am genuinely proud of this paper, because it symbolises the whole seven years I spent studying at the UHasselt. The past lessons I learned all served their purpose during the different steps of the writing process. And I would like to thank everyone that I've met in these seven years for that, and for making me the person I am today.

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And finally, I would like to thank you, reader, for taking the time to read this thesis. May it be insightful, informative, or maybe even useful: I sincerely hope that it serves you well.

Bob Daniëls

4th of June, 2021

Summary

(in Dutch from pgs. 9 to 12)

Chapter 1: the purpose of this research

Today's global warming causes many things: an increase in the yearly average temperature, a rise of the seawater level, and even biodiversity loss. Especially in urbanised regions, the greenhouse gas effect's consequences are noticeable. Examples of these consequences include: health issues due to overheating, a decreased air quality, or floodings.

Urban greening can be a solution to these urbanisation issues. In this paper, research on green roofs and green walls (two urban greening systems, besides parks and street trees) is studied in order to see what the current research field looks like, to see where the research requires more depth, and to see in what ways green roofs and green walls can become an interesting alternative to the inhabitants of urban areas.

Chapter 2: literature research

Green walls and green roofs are surfaces on the building envelope covered with vegetation. This vegetation can be vivid and voluminous (as is the case with "living walls" and "intensive green roofs", their respective terms), or more superficial and smaller (which is the case for extensive green roofs and green façades). Vividly and voluminously covered rooftops and walls can be more aesthetically pleasing and soothing for the user, whereas the more superficially covered surfaces are less aesthetic, for as they are designed just to be eco-performant.

Concerning said eco-performance, green walls and green roofs serve multiple purposes: they capture stormwater (thus mitigating the chance of the streets being flooded after a storm), serve as an insulator (therefore also contributing to energy savings, because there is less temperature loss), and even as a sound barrier (mitigating over 10 dB of noise). The plants of the green roofs and walls contribute to cleaning the air from CO_2 and other pollutants like NO_x or O_3.

However, the literature study points out the lack of demand of green roofs and walls: said products are not yet attractive to investors, for as the production and usage of green roofs and green walls has not reached full sustainability yet (people, planet, profit: green roofs/walls are, as of today, still too expensive and its production too environmentally damaging).

Chapter 3: bibliometric research

In order to see if green walls and green roofs can be optimised, it is important to know what the current state of the research field is.

A bibliometric research is then conducted. This research is a holistic analysis of the total research conducted, useful to create a science map of the field, indicating important clusters that can show the amount of collaboration (which in turn promotes and stimulates innovation), or to identify the different topic clusters to see what parts of the research field have been researched extensively (indicating more knowledge generated on that part), and what parts haven't (indicating that there is more research needed in order to possibly reach the sustainability equilibrium, benefiting people, planet and profit, as was found to be the utopia in chapter two). The bibliometric research conducted is completely based on citation data. However, a bibliometric research does not analyse the contents of an article – it can only point out the state of the research field.

The collaboration clusters (authors, organisations, countries) analyses indicate promising results: on each of the three levels, a considerable amount of collaboration is present. This indicates that the researchers tend to work together with many others, even across organisations, stimulating knowledge spillovers. It is also found that climates do act as a barrier for international collaborative research on green walls/roofs: countries like India and Canada even work together on conducting the research on these greening infrastructures, whilst having very different climates.

The topic clusters analyses indicate the more developed research topics on green roofs and walls, such as stormwater retention (to avoid flooding in the streets), research on the thermal insulation characteristics, and research on the different components of the walls/roofs. Lesser developed research topics are studies on the UHI (urban heat island) effect and other urban heat related issues as well, possibly due to the difficulty of correctly measuring the effects on an urban scale (because without computer-assisted simulations, it is impossible to cover an entire city in green just to measure the temperature changes, for instance).

Whilst taking a closer look at the quantity of assessment studies like LCAs (lifecycle assessments), CBAs (cost-benefit analyses), and MCDAs (multi-criteria decision analyses), it becomes clear that there still is room for in-depth research, because a large amount of analyses is not available yet. This accompanies the findings of chapter 2, saying that there is no significant demand yet, because of the lack of a full sustainability equilibrium (people, planet, profit). The reason why is that a lack of assessment studies (financial and environmental for example) implicates a rather low interest in the green infrastructure. However, nothing certain can be concluded (because only the state of the research field, not the information, could be analysed with a bibliometric research). This is why we take a closer look at these assessments in chapter 4, by conducting a systematic mapping analysis.

Chapter 4: systematic mapping

The systematic mapping takes a closer look at the LCAs, CBAs, MCDAs and other related assessments. It does so by first categorising the articles, which is then followed by an in-depth reading in which all of the conclusions, shortcomings,… are compared to each other and summarised afterwards, in a systematic way.

Profit

From a financial point of view, it is found that the NPV (net present value) of green roofs and green walls is not attractive within the private scope; only when extending the scope to a societal scale, the investment in green infrastructure becomes financially interesting, because of the externalities that are added into the calculation. Still, the installation cost, and maintenance cost, of green roofs/walls is too expensive. This indicates that there still is more research needed that looks into the optimisation of the production process, thereby lowering the investment cost of green roofs/walls.

Planet

Green roofs and walls do seem like more environmentally friendly alternatives, but the production phase of green roofs/walls is found to be the most (and very significantly so) environmentally damaging of all phases during the lifecycle of the product. Also, not much green infrastructure is recycled after its lifespan – most often, materials are landfilled or incinerated.

People

There still is a lack of interest to invest in green roofs/walls, due to a high cost, but also because of a lack of knowing all of the infrastructure's benefits. Governments provide few incentives as well, and just there is a general lack of awareness that green infrastructure can provide for the environmental urbanisation issues. Raising awareness can generate an increase in the interest of buying the infrastructure, because it will affect an important decision factor: the full knowledge of the roofs'/walls' benefits. Furthermore, an increase in urban greening is preferred by the people, for as it benefits psychological wellbeing.

Full sustainability

Only when the investment cost lowers, the environmental damage decreases, and people's awareness of the full spectrum of benefits rises, the investment in green infrastructure on the building envelope unlocks its full potential.

Conclusion

In mitigating the urbanisation environmental issues, green roofs and walls still haven't reached their full potential yet. The literature research in chapter 2 mentioned a lack of buying power and indicated that further research was needed to optimise the products. This was confirmed in chapter 3: some research fields contained less articles compared to other ones. In chapter 4, the sustainability assessments were investigated in order to find economic, societal, and ecological arguments to explain the lack of buying power for green roofs and walls. Only when financial costs and negative externalities decrease (through research and process optimisation, for instance), and when awareness is raised (by government assistance, for example), the full potential of green roofs and walls becomes available.

Samenvatting

Hoofdstuk 1: het doel van dit onderzoek

Klimaatopwarming kent vandaag de dag vele gevolgen: een toename van de gemiddelde jaarlijkse temperatuur, een stijging van de zeespiegel, en zelfs een vermindering van biodiversiteit. Vooral in verstedelijkte gebieden zijn de gevolgen van het broeikaseffect merkbaar. Deze gevolgen zijn bijvoorbeeld gezondheidsproblemen (oververhitting door de toename in temperatuur), maar zelfs ook overstromingen en een verslechterde luchtkwaliteit.

'Stedelijk groen' zou een oplossing kunnen bieden tegen deze bovenvermelde problemen. In deze paper wordt het onderzoek naar groendaken en groenmuren (twee toepassingen van stedelijk groen, naast parken en geboomte langs de straat) onder de loep genomen, om te zien hoe het onderzoeksveld er vandaag uit ziet, om te zien waar er op dit moment meer diepgaand onderzoek nodig is, en om te zien op welke manier groendaken en groenmuren een interessant alternatief kunnen vormen voor de bevolking in stedelijke omgevingen.

Hoofdstuk 2: Literatuuronderzoek

Groendaken en groenmuren zijn, in se, met vegetatie bedekte oppervlakken op de boven- en zijkanten van een gebouw. Deze vegetatie kan erg levendig en volumineus zijn (zoals dit het geval is bij zogenaamde 'levende groene muren' en 'intensieve groendaken'), of net wat oppervlakkiger en kleiner (het geval zijnde bij de zogenaamde 'groengevels' en 'extensieve groendaken'). Levendig en volumineus bedekte daken en muren kunnen esthetisch aangenamer en meer relaxerend zijn voor de gebruiker, terwijl de meer oppervlakkig bedekte daken en muren dit niet zozeer zijn (zij zijn vooral ontworpen om een bepaalde eco-prestatie te leveren).

Betreft deze eco-prestatie: groendaken en groenmuren hebben verschillende functies. Ze vangen het regenwater op (waardoor de straten minder snel blank staan, omdat ze het opgevangen water vertraagd afgeven en dus de rioleringen een kans geven om al het overtollig water sneller te verwerken), ze dienen als isolatiemateriaal (en zorgen daardoor voor besparingen op elektriciteitsverbruik omdat er minder temperatuursverlies is), en ze dienen zelfs als geluidsbarrière voor meer dan 10dB aan geluidsvermindering). De planten zelf van de groendaken en groenmuren hebben ook hun nut: zij zuiveren de lucht van o.a. CO_2 en andere vuilstoffen (NO_x, O_3,…).

Echter, de literatuurstudie vermeldt ook het huidige gebrek aan interesse in groendaken en groenmuren. Ze zijn op dit moment nog niet aantrekkelijk genoeg voor investeerders, omdat de productie- en gebruiksfase nog niet volledig duurzaam is (people-planet-profit: groendaken en groenmuren zijn voorlopig nog te duur, en diens productie is nog steeds erg beschadigend voor het milieu).

Hoofdstuk 3: Bibliometrisch onderzoek

Om te kunnen zien of groendaken en groenmuren nog geoptimaliseerd kunnen worden (hetzij in de productiefase, hetzij in de gebruiksfase; zowel financieel, ecologisch als maatschappelijk bekeken), is het vooral belangrijk om te zien hoe het onderzoeksveld er op dit moment bij ligt.

Een bibliometrisch onderzoek is hiervoor dus uitgevoerd geworden. Deze onderzoeksmethode is een holistische analyse van het onderzoeksveld, waarbij er op basis van citatiedata (referentiedata) een onderzoek gevoerd wordt met behulp van clustervisualisatie om te zien waar er sprake is van o.a. samenwerking tussen de onderzoekers (dit stimuleert namelijk innovatie), of om te zoeken naar onderwerpclusters, om zo te zien welke delen van het onderzoeksveld reeds uitbundig onderzocht zijn (resulterend in reeds veel beschikbare kennis over dat onderwerp), en welke delen nog niet uitbundig onderzocht zijn (wat betekent dat er hier nog eventuele ruimte voor diepgang is, die kan zorgen dat de utopie van het evenwicht tussen people-planet-profit (vermeld in hoofdstuk 2) meer benaderd wordt en dus het niveau van duurzaamheid omhoog kan doen gaan). Echter, een bibliometrisch onderzoek zegt niets over de inhoud van het onderzoek; het dient enkel om via een ‘science map’ weer te geven hoe het onderzoeksveld eruitziet. Niets inhoudelijks kan reeds expliciet geconcludeerd worden.

De analyses van de samenwerkingsclusters (collaboratieclusters) van auteurs, organisaties en landen indiceren veelbelovende resultaten: er is een deugdzame hoeveelheid samenwerking te zien in het onderzoeksveld. De onderzoekers werken dus samen met vele anderen, zowel op persoonlijk als organisatorisch niveau, wat zeer goed is voor kruisbestuiving). Er werd ook gevonden dat er weinig sprake is van klimaatbarrières: ondanks het hebben zeer diverse klimaten werken landen zoals Canada en India samen aan het onderzoek naar groendaken en groenmuren.

De analyse van onderwerpclusters onderscheidt de uitbundig onderzochte topics (opvang van regenwater, isolatiefuncties en onderzoek naar de onderdelen van groendaken en groenmuren) van de minder onderzochte topics (zijnde onderzoek naar stedelijke opwarming en andere problemen op stedelijk niveau, hoogstwaarschijnlijk omdat het zeer moeilijk is om zonder computersimulatie een onderzoek van groendaken en groenmuren te meten op een stedelijke schaal; het is namelijk financieel onmogelijk om elk gebouw te bedekken met groen, enkel om een onderzoek op grotere schaal te voeren).

Als we kijken naar de aanwezigheid van enkele geavanceerde analyses (kosten-batenanalyses (KBA’s), levenscyclusanalyses (LCA’s), multicriteriabeslissingsanalyses (MCBA’s), of andere gerelateerde alternatieven), wordt het duidelijk dat de ideeën van hoofdstuk 2 (het nog niet bereikt hebben van een echte interesse in de producten omdat het people-planet-profitverhaal nog niet geoptimaliseerd is) een juist vermoeden insinueerden: er is nog maar een beperkte aanwezigheid van dit soort analyses in het onderzoeksveld. Hierdoor er ook geïnsinueerd dat er voorlopig nog geen grote interesse is in de groene producten. Om te zien waar het aan kan liggen, worden deze analyses nauwkeuriger onderzocht in hoofdstuk 4.

Hoofdstuk 4: Systematische mapping

De systematische mapping bestudeert de bovenvermelde geavanceerde analyses iets nauwkeuriger in dit hoofdstuk. Een systematische mapping begint met het categoriseren van de verschillende analyses, die daarna nauwkeurig gelezen worden, om zo alle conclusies, tekortkomingen,… met elkaar te kunnen vergelijken en achteraf samenvatten, op een systematische manier.

Profit

Vanuit een financieel perspectief wordt er gevonden dat de NAW (netto actuele waarde) van groendaken en groenmuren niet aantrekkelijk zijn op een private schaal; enkel als de schaal vergroot wordt naar het maatschappelijk niveau, worden de investeringen in groendaken/groenmuren financieel interessant, omdat er een hoop maatschappelijke externaliteiten toegevoegd werden in de berekeningen van de NAW. Echter, de plaatsings- en onderhoudskosten van de groendaken/groenmuren zijn nog steeds te duur. Dit concludeert dat er nog steeds onderzoek nodig is naar het optimaliseren van de productieprocessen van deze daken/muren. Zo kan de investeringskost verminderen.

Planet

Groendaken en -muren lijken op het eerste zicht twee milieuvriendelijke alternatieven van een gewoon 'grijs' alternatief, maar er wordt gevonden dat de productiefase van de producten een significante hoeveelheid schade toebrengt aan het milieu, vergeleken met de andere fases (gebruiksfase en recyclagefase). De recyclagefase, bovendien, is relatief beperkt: niet veel van deze groene infrastructuur wordt op de juiste manier verwerkt na afbraak, integendeel, een groot deel wordt gewoon in de grond gestopt, of verbrand.

People

Er is nog steeds een gebrek aan interesse om te investeren in groendaken en groenmuren: dit wegens een te hoge kost (zie vorige paragraaf 'profit'), maar ook omdat de bevolking eigenlijk geen idee heeft van het hele spectrum aan voordelige eco-prestaties dat een groendak of groenmuur kan bieden. Daarenboven is er ook nog eens weinig steun van de overheid, zowel op financieel vlak als op vlak van sensibilisering. En het is nu net dié sensibilisering die zal zorgen dat de bevolking het hele spectrum aan milieuvoordelen van groendaken en groenmuren te weten komt, en daardoor dus ook sneller zal overwegen om te investeren in groendaken en groenmuren. Bovendien heeft een hoge aanwezigheid van groendaken en groenmuren in een stedelijke omgeving ook positieve effecten op het psychologisch welzijn van de bevolking.

Gehele duurzaamheid

Enkel met een vermindering van de investeringskost, met een daling van de impact op het milieu en met maatschappelijke sensibilisering, zal het investeren in groendaken en groenmuren een populaire en duurzame onderneming worden.

Conclusie

Er zal nog meer onderzoek moeten plaatsvinden over groendaken en groenmuren voordat de impact van de stedelijke milieuveranderingen efficiënt verminderd kunnen worden door deze producten. de literatuur in hoofdstuk 2 vermeldde een gebrek aan koopkracht en de nood aan het optimaliseren van het productieproces. Dit werd bevestigd in hoofdstuk 3: enkele onderzoeksvelden omvatten minder artikels dan anderen. In hoofdstuk 4 werden verschillende geavanceerde analyses onder de loep genomen om argumenten op economisch, ecologisch en maatschappelijk niveau te zoeken, die een verklaring zouden kunnen geven voor het gebrek aan koopkracht vandaag de dag. Enkel wanneer de kosten en negatieve externaliteiten afnemen, en wanneer de bevolking het gehele spectrum aan milieuvoordelen te weten komt, zullen groendaken en groenmuren hun volledige potentieel kunnen laten zien.

Table of contents

1 Introduction and problem statement

"When the well is dry, we will know the worth of water."

– Benjamin Franklin, *Poor Richard's Almanac*

1.1 The urge to 'go green'

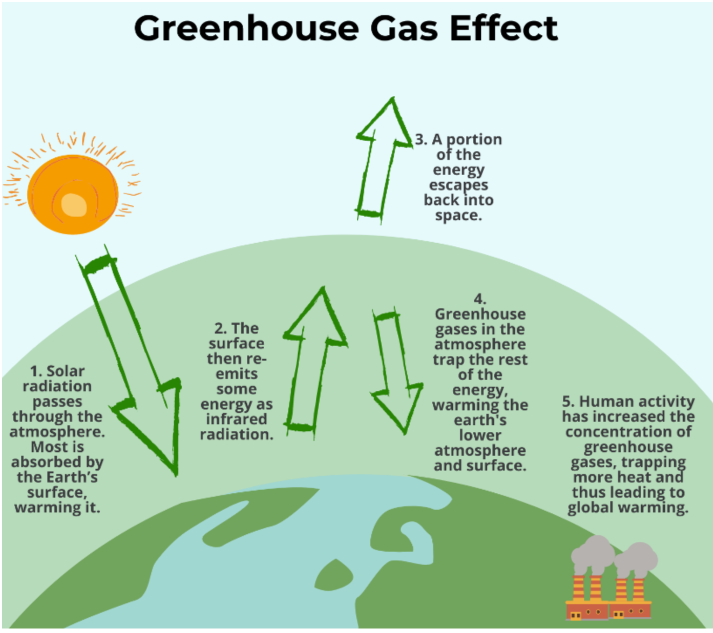

Figure 1: Greenhouse Gas Effect (source: Scotland Climate Assembly)

Today's global warming is a direct consequence of increasing greenhouse gas emissions (Lashof & Ahuja, 1990). Due to their molecular composition, these greenhouse gases form a thick isolating layer in the earth's atmosphere, so to speak. When the sun shines its heat beams on our planet, these beams partially bounce back from the surface. They get trapped, however, between the earth's surface and the greenhouse gas layer, thus making the temperature rise in the environment between these layers. This is shown in Figure 1. And the further this temperature rises, the more our earth's climate will change. Mother Earth's response to climate change is not a positive one: average yearly temperature rises, vegetations and natural habitats disappear, and the seawater level rises (Hughes, 2000). This sometimes further results in extreme weather conditions and disasters all around the globe. Therefore, change is obligatory, and any form of it helps. (Hughes, 2000; Lashof & Ahuja, 1990)

The social urge to 'go green' has been rising over the past few decades (*Flemish Government Research: Environmentally Responsible Consumption*, 2017). Our earth is warming up (due to this greenhouse gas effect), and many nations are teaming up to do something about it (UNFCCC, 2021). This is the case all over the world. Some countries impose emission regulations; others invest in renewables as well, such as Belgium. Photovoltaic systems, windmills, or even hydropower – all of these renewable energy source technologies contribute their part to cooling down Mother Earth. But there are other concepts for reducing global warming as well: minimising one's ecological footprint, creating circular business models, and trying to preserve nature (in the broadest way possible, that is).

However, the latter one, preserving nature, has not always been consistently successful. Today, many cities are built on thousands and thousands of square kilometres of what once were, historically speaking, forested areas. Green had to make room for brown and grey. Plants and trees were replaced by bricks and cement. Nature was replaced by skyscrapers.

1.2 Urbanisation affects the environment

1.2.1 Urbanisation: pros and cons

The urbanisation of the world happened for various reasons. To name a few examples: economic advantages (e.g. company clusters), educational advantages (much easier to find a school in a city than in a rural area), and even social benefits (in the meaning that social events have a positive effect on mental health). Despite all of these privileges, urbanisation does have its downsides. As mentioned above: green is being replaced with brown and grey. The adverse effects of climate change are noticeable in the urban areas, more than they are in rural areas. A rise in temperature, as well as the loss of biodiversity and the unmanageable water floods, are all present in the cities; even more intensely than they are in the rural areas.

The urban heat island effect

Yearly mean temperatures are higher in cities than in rural areas: due to the heat-preserving nature of buildings (or more specific: the heat-preserving nature of building *materials* like asphalt, concrete, or glass), the sun's heat remains 'caught' in cities, much longer than it does in rural areas. This causes an increase in the cities' mean yearly temperatures, compared to the ones in more rural areas. The warming effect of cities is commonly referred to as the Urban Heat Island (UHI) effect.

Unfortunately, the UHI creates many negative consequences, not only for our planet, but for our people as well. These consequences go from health issues like overheating (Buechley, van Bruggen, & Truppi, 1972), to overusing electricity (e.g. for air conditioning: a 17% increase in cooling energy usage was found) (Sun & Augenbroe, 2014).

Loss of biodiversity

A loss of biodiversity logically occurs when building cities: green makes room for brown and grey, as was mentioned above. Many plants and other species aren't able to survive in urban environments (due to a lack of natural resources, for example). Local ecosystems, therefore, start to disappear. This, in turn, creates a chain reaction of various effects, e.g., the air pollution that rises, or the water quality that diminishes. On top of that, an absence of green in the city also causes aesthetical displeasure for the people.

Unmanageable stormwater flow

Due to global warming, the frequency of natural disasters (such as storms or floods) keeps growing. What used to be a 'normal' rain cloud has now become a more extreme rain cloud. And with more natural disasters, more damage is being dealt. When a storm occurs in a city, the sewage draining systems can only drain so much water at a time. When their maximum capacity is reached, the water flows back upwards, to the streets, creating an overflow, which generates massive water damage for the city. (Carson, Eaker, Gibson, & Randall, 2010)

1.2.2 Urban greening could help

These adverse effects that are mentioned above, are just three examples of urbanisation's downside, having enormous consequences for the people. But it can be reverted, in a certain sense. These effects *can* be mitigated. Living in an urban area can be optimised without further intensifying the earth's response to climate change, which has significant consequences for the people in the end. One such solution is the increase of urban green. This concerns street trees, parks, or even vegetated roofs and walls. Various academic reviews have pointed out that the increase of urban green also increases public health (Tzoulas et al., 2007), cools down cities (Bowler, Buyung-Ali, Knight, & Pullin, 2010), and sometimes even manages stormwater runoff (thus avoiding overflooding sewers) (Berndtsson, 2010).

1.3 What this paper could clarify

Urban greening systems exist in various forms: parks, street trees, ground vegetation (e.g. grass), roof vegetation, even green façades. A lot of research had already been conducted on the first three, even ten years ago (Bowler et al., 2010), but not so much on the last two: green roofs and green walls. This brings us to the topic of this thesis: conducting a science mapping analysis of green roofs and green walls. This paper aims to answer the holistic research question 'What do the research fields on green roofs and green walls look like today?', which has been divided into a few subquestions, which will all be discussed later.

The layout of the paper will consist of three major parts. First, a thorough literature research will be conducted on green roofs and green walls, in order to provide the reader with some background knowledge. The concept explanation could also be useful to highlight possibly essential research topics to keep in mind whilst conducting the research in the second and third part. See chapter 2 for this study.

The second part will consist of a bibliometric study of the research field of green roofs and walls. This is useful to create a science map of the research field, indicating important clusters that can show the amount of collaboration, or identify the different topics in the research field, for instance. See chapter 3.

The third and last major part of this study will then choose a relevant and important research topic (which was highlighted in the second part) to further look into. This is a systematic mapping of the research. Different types of research will be distinguished and analysed. See chapter 4.

After each part, the thesis will have a sub-conclusion. These will be briefly summarised again in the final conclusion at the very end of the thesis. See chapter 5.

2 Urban greening systems: roofs and façades

"Dirt is an inert substance that holds up plants. Soil is a system."

– Chad Adams, *Founder, Ground Plan Studio*

2.1 The concept of urban greens

As mentioned in the section above, greening systems can help mitigate the (often disastrous) effects of global warming in urban areas. The more frequently occurring greening systems are parks, which also include ground vegetation, and street trees. These urban greens help to clean the air and regulate the climate, and especially parks because of their huge green-covered surface (Vieira et al., 2018). In doing so, they also cool down the cities, thus reducing the UHI effect (Bowler et al., 2010).

Nonetheless, street trees also do significant similar jobs (Mullaney, Lucke, & Trueman, 2015). But a city only has so much surface to install greening systems on. A few decades ago, the question rose: what if the surfaces of all buildings were also used in order to construct greening systems? What if not only parks or street trees would contribute to urban greening? Ideas were derived from e.g. the hanging gardens of Babylon (one of the seven ancient wonders of the world, which had vegetated roofs and walls), and were modernised in Germany in the 1980s. The contemporary green roofs and green walls were born (Bartfelder & Köhler, 1987; Krüger, 1982).

2.2 Research questions

For this chapter, a literature research was conducted, in order to provide the reader with sufficient background knowledge of green roofs and green walls. In order to do so, some research questions will be answered:

1. What are green walls? What are green roofs?
2. What are the types of green walls and green roofs?

3. What are the components of green walls and green roofs?
4. What are the functions of green walls and green roofs?

The answers to these questions will help to understand all of the information gathered in the next chapter (chapter three), which will focus on a bibliometric analysis of the research field.

2.3 Green walls

A green wall is, concept-wise, exactly the same as a green roof, except for the fact that the vegetation isn't oriented horizontally, but vertically. It is therefore also known as a vertical greening system. It is, however, very important to distinguish the multiple terms that are given to these greenery systems on the walls of buildings. The names of these systems that are used most often in literature, are *green walls* and *vertical greening systems*. The terms *living walls* or *green façades* on the other hand, may be thought of as synonyms as well. But this is confusing: the latter two terms are mere subcategories of vertical greening systems. (Manso & Castro-Gomes, 2015; Medl, Stangl, & Florineth, 2017; Pérez-Urrestarazu, Fernández-Cañero, Franco-Salas, & Egea, 2015; Perez, Rincon, Vila, Gonzalez, & Cabeza, 2011; Perini, Ottele, Fraaij, Haas, & Raiteri, 2011)

To avoid any further confusion in this paper, only the terms *vertical greening systems*, *vertical greenery* or *green walls* will be used to collectively describe the whole concept of vegetated walls, whereas *living walls* or *green façades* (and all of their derivatives) will only refer to a specific type of vertical greenery (see below). Other possibly descriptive terms like *vertical gardens* or *biowalls* will *not be used* in this literature study. They may, however, be used as synonyms to conduct the bibliometric research.

At the end of this section, all information will be summarized in a few tables (tables 1 and 2). These may prove to be useful to return to when reading the rest of this paper, in order to recapitulate this literature research more quickly.

2.3.1 Classification of green walls

Figure 2: Continuous Living Wall in San Francisco, CA, USA (created by Amanda Goldberg)

Figure 3: Indirect Green Façade (from Manso et al., 2015)

2.3.1.1 The types of green walls (research question 2)

Green walls exist in two categories: green façades and living walls (Manso & Castro-Gomes, 2015; Medl et al., 2017; Pérez-Urrestarazu et al., 2015; Perez et al., 2011; Perini et al., 2011; Perini & Rosasco, 2013). The main difference lies in the way the vegetation is attached to the wall: it can either grow alongside the wall (therefore climbing plants are often used) or it can grow in separate growth modules that are attached to the wall. Figures 2 and 3 show examples of a living wall and a green façade, respectively.

Green façades are vertical greening systems which use climbing plants that grow alongside the wall and are (most often) bound to the ground. The connection to the soil is important to distinguish green façades from living walls. The façade plant growth can either be fully autonomously (which is termed a *direct green façade*), or its climb can be assisted by e.g. plastic or steel mesh, which thus acts as a supporting structure. The climb assisted façade is referred to as an *indirect green façade* (Manso & Castro-Gomes, 2015; Ottele, Perini, Fraaij, Haas, & Raiteri, 2011; Perini et al., 2011; Perini & Rosasco, 2013) or a *double-skin green façade* (Medl et al., 2017; Perez et al., 2011), referring to the fact that the wall now exists of two "layers". Both terms (indirect and double-skin green façades) can be used interchangeably. A further subdivision can be made in the category of indirect green façades, e.g. controlling for the various materials used to assist the climbing plants, but this differs a lot amongst the analysed articles. It will therefore not be used as an 'official' classification – however, when the components of green façades are being described further down below, a few examples will be given in order to distinguish the different types of climbing materials used.

Living walls are green walls that aren't connected to the ground, and more importantly, aren't able to climb alongside a wall. Instead, separate modules (for example) are attached to the wall, thus making the growth of the plants fully dependent of the soil in the module itself (whereas green façades were ground-dependent). The direct benefit of living walls is the possibility to grow multiple plants on the same wall – that is, if every plant is to be found in a different module. This way, the wall can contain a more intensive vegetation (compared to the more extensive vegetation on a green façade, similar to the differences between intensive and extensive green roofs). Literature suggests numerous types of living walls: modular living walls, continuous living walls, linear living walls, panelled living walls, or felt-based living walls (Manso & Castro-Gomes, 2015; Medl et al., 2017; Ottele et al., 2011; Perez et al., 2011). Despite the numerous synonyms, two kinds of living walls are always mentioned: the living walls that have free growth, and the living walls that have controlled growth. For the remainder of this paper, the free-growth walls will be referred to as continuous living walls, and the controlled-growth walls will be referred to as modular walls. Other synonyms will not be mentioned, unless necessary.

A table of the above-mentioned green walls and its types is listed here below:

Green walls			
Green façades		***Living walls***	
Direct green façade	*Indirect green façade*	*Continuous living wall*	*Modular living wall*

2.3.1.2 The components of green walls (research question 3)

Components of green façades

Direct green façades grow autonomously. They therefore do not (necessarily) require a support structure: the attachment capability of the climbing plants that are used for the direct green façade is good enough for it to attach themselves to the wall. The plant that is most commonly (although not exclusively) used in a direct green façade is the ivy plant (or as literature refers to it, *Hedera Helix*)(Manso & Castro-Gomes, 2015). The soil of which the plant can grow from is just the terrestrial soil (as was mentioned above – green façades are still connected to the ground). It happens, however, that the building height is greater than the maximum growth height of the climbing plant. This can be solved by placing a soil box mid-height for a new series of ranks to grow from (thus creating an artificial ground surface)(Pérez-Urrestarazu et al., 2015). It is important to note, however, that this structure is still being classified as a direct green façade, for as the plant still attaches itself to the vertical surface.

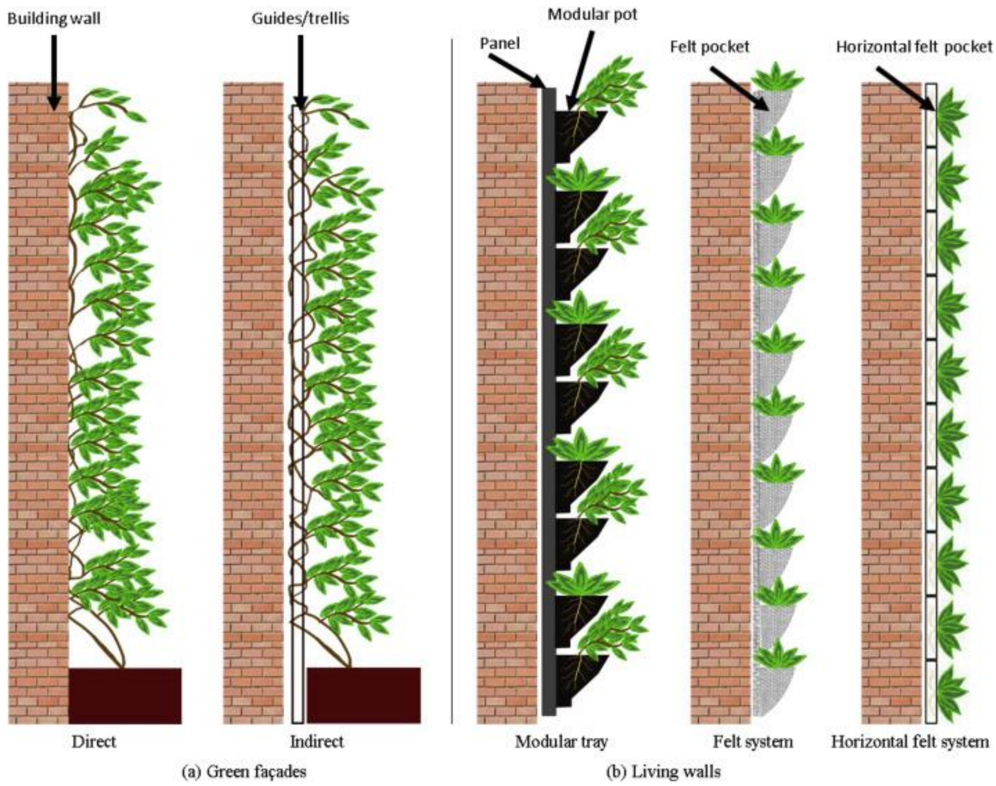

Figure 4: Distinguishing the components of green walls (from: Bustami, Belusko, Ward, and Beecham (2018))

Indirect green façades, on the other hand, *do* have a support structure (namely, a second 'wall') to support their growth. Hence the synonym: double-skin green façade. The assisting wall is often made of (stainless) steel mesh or even steel cables, or wood (Manso & Castro-Gomes, 2015; Medl et al., 2017). Its beneficial purpose is to create a supporting structure that helps to avoid for the vegetation to fall (for instance, during heavy weather conditions). The plants that are being used still are climbing plants, but in a wider variation: twining vines or scrambling plants are also used, instead of just the Hedera Helix (ivy) species (Manso & Castro-Gomes, 2015; Ottele et al., 2011).

Components of living walls

Continuous living walls are designed to mimic a ground surface that is turned 90 degrees upward. They do not possess a growth medium (i.e. a substrate), because the plants are inserted in lightweight screens (e.g. felt) that is waterproof. This, in turn, avoids the forming of humidity between the building and the living wall (Medl et al., 2017). The downside of this lack of a growth medium is that the continuous living wall needs to be permanently provided with water and nutrients in order to grow and develop. The name of this growth system is called a hydroponic system (Manso & Castro-Gomes, 2015; Medl et al., 2017; Pérez-Urrestarazu et al., 2015). Due to no growth boundaries on the wall itself, the plants are free to grow vividly in any way or size they prefer. Seeds, grown plants and cuttings; all can be found on a continuous living wall (Manso & Castro-Gomes, 2015).

Modular living walls, however, *do* have a growth medium. The wall is made up of different modules, each containing their own substrate, and their own respective plant species. Sometimes, a roster is put on the front side of the living wall to prevent plants from falling down (Manso & Castro-Gomes, 2015). Modular living walls can either contain trays, panels, vessels, or planter tiles. Due to this wide variety of substrates, the amount of potential plants to grow on it is quite large as well: even succulents and crops can grow on modular living walls, because due to the modules, they each have their own little ecosystem with its own water and soil supply (Manso & Castro-Gomes, 2015; Pérez-Urrestarazu et al., 2015).

2.3.2 Functions of green walls (research question 4)

In the last subsection, the components of green walls (green façades as well as living walls) were discussed. It came out clear that plant growth, in a vertical fashion, was made possible by the concept and structure of the green walls (living walls even more so than green façades, for as these living walls could even grow crops), but green walls *do serve other purposes*. For instance, the presence of a greening system on the vertical surface of a building can aid with energy saving through insulation and shadowing (Perez et al., 2011). All of the important benefits of a green wall will be briefly discussed down below.

2.3.2.1 Acting as an insulation layer

Green walls can serve as an insulation layer on the building envelope. Pérez et al. (2011) state that the intensity of insulation lies not only in the substrate depth (e.g. for living walls), but in the length of the space between the wall and the wall of the building (for continuous green façades, for example). They also clarify the usefulness of the thickness and density of the foliage: the denser the coverage, the more insulation a green wall offers. The insulation was found to serve better as a cooling layer, than as a heat-preserving layer (mostly due to the lack of soil coverage on green façades and certain types of living walls) (Perez et al., 2011). Furthermore, Perini et al. (2011) found that green walls can also serve as a wind barrier, which indirectly can positively affect energy savings, especially through absorbing colder airflows.

2.3.2.2 Reducing the UHI effect

The concept of evapotranspiration relies on the absorption of the sun's energy in order to make plants evaporate water. This, in turn, reduces the environmental temperature, simply due to the fact that the energy of the sun didn't have a chance to settle in heat-absorbing materials, for as it was used for this evapotranspiration (Givoni, 1991). Green walls therefore serve their purpose in avoiding the warming up of building's vertical surfaces, thus reducing the Urban Heat Island effect (Price, Jones, & Jefferson, 2015).

2.3.2.3 Reducing CO_2 and improving the air quality

Green walls absorb and/or capture CO_2-gases and other air pollutants. Urbanisation has led to so-called 'street canyon environments': these are the gaps between buildings in a city, where streets exist, and where the air pollutant concentration is significantly higher than it would be in an open street, due to many vehicles (cars, buses) passing by. These pollutants, such as NO_x particles, badly affect the people: consequences range from respiratory problems, to even heart diseases (Brunekreef & Holgate, 2002). Research has shown, however, that the air pollution in street canyon environments can be mitigated with green walls. Abhijith et al. (2017) summarised multiple studies into the conclusion that green walls absorb pollutants such as NO2, O3, and CO. One such study included was the one of Jayasooriya et al. (2017), which concluded that green walls only absorb a relatively small amount of pollutants compared to street trees. But in cities with a smaller amount of free space, which constrains the possibility to plant trees, green walls still had significant pollutant-mitigating effects.

2.3.2.4 Biodiversity improvement

Where plants prosper, biodiversity prospers. Madre et al. (2015) have shown that green walls in fact *do* act as ecosystems. Compared to bare walls (which already contain a certain amount of beetles and spiders, green walls contained a larger and more diverse amount of spiders and beetles. Furthermore, they stated that the number of *arthropods* (which is the collective term for the group of living entities with an exoskeleton, a segmented body and paired jointed appendages, such as bugs, beetles, ants and spiders) found vary with the type of green wall (living or façade). Living walls, with its accordingly well-allocated nomenclature, host more arthropods than green façades do. This is due to an increased presence and variety of plants and soil components, as well as a denser foliage. (Madre et al., 2015)

2.3.2.5 Other benefits

Next to the benefits that were discussed above (insulating, mitigating UHI-effect, air-cleansing and biodiversity-improving), green walls do offer extra benefits. They are briefly discussed down below.

Noise reduction

Green walls offer noise reduction (Azkorra et al., 2015). In fact, Azkorra et al. found that green walls can mitigate up to 15dB, measured indoors. This is due to two main mechanisms: the diffraction power of sound waves by the leaves and other surfaces of the plants, and the absorbing power of the thick soil substrate of the green wall (thicker soil absorbs more sound waves). Combining the two mechanisms creates the "passive acoustic insulation system", as they called it.

Aesthetical and psychological improvement

Literature points out that the aesthetic perceptions of a building increases with green walls (or any of its variants) present on at least one side of the building (Medl et al., 2017; Pérez-Urrestarazu et al., 2015). Whether the green walls are built while renovate older buildings, or built on newly-built façades, the perception improvement stays the same. Furthermore, it is proven that natural scenery in an urban environment has psychologically improving benefits – coping with stress-related issues, for instance (Gidlöf-Gunnarsson & Öhrström, 2007). The reason behind it is, besides being aesthetically pleasing, the noise-mitigating capability of urban greenery, discussed above. The passive acoustic insulation works soothing and relaxing (Gidlöf-Gunnarsson & Öhrström, 2007).

2.3.3 Summarising tables: green walls

The two types of green walls

GREEN FAÇADES		**LIVING WALLS**	
Attached to the ground – growth is dependent on ground – attach to the wall		Not connected to the ground – independent growth media (can be multiple modules)	
Decorative and more minimalistic vegetation		Vivid, voluminous vegetation, even vegetables	
Direct GF	**Indirect GF**	**Continuous LW**	**Modular LW**
Autonomous growth	Climb-assisted growth	No growth medium	Growth medium
Plants climb and attach themselves to the wall	Plants are climb-assisted with e.g. steel mesh to grow on	Hydroponic system	Every plant or module has its own growth medium

Table 1: Summary of the types of green walls

The functions of green walls

FUNCTIONS	**DESCRIPTION**
Insulation management	Green walls offer insulation on the building envelope. Factors of influence are: soil thickness, vegetation type and the presence of air between the green wall and the regular wall (like indirect green façades have, for instance).

Reducing the UHI effect	Through evapotranspiration, the sun's rays are absorbed by the vegetation on the wall – this, in combination with regular shading effects, causes the plants to absorb the heat (albeit partially) instead of the building wall.
CO_2-reduction and air purification	Green walls absorb CO_2, but other pollutants as well (NO_x, O_3,…). This, in particular, creates a less polluted urban street canyon, which leads to a decreased chance at respiratory issues.
Biodiversity improvement	Green walls have an increased presence of arthropods, which leads to green walls having their own ecosystem, making up for the loss of biodiversity due to urbanisation.
Other benefits	Green walls offer noise reduction – up to 15dB of indoor noise reduction was found. Furthermore, the green wall is aesthetically and psychologically beneficial.

Table 2: Summary of the functions of green walls

2.4 Green roofs

At the end of this section, all information will be summarized in a few tables (tables 3 and 4). These may prove to be useful to return to when reading the rest of this paper, in order to recapitulate this literature research more quickly.

Figure 5: Extensive green roof (Corda Campus, Hasselt), by Ecoworks

Figure 6: Intensive green roof, Elsene, by Ecoworks

2.4.1 Classification of green roofs

2.4.1.1 Distinguishing the two kinds of green roofs (research question 2)

A green roof is, put simply, a vegetated roof, in the broadest way possible. Literature distinguishes two types of green roofs: intensive and extensive roofs (Castleton, Stovin, Beck, & Davison, 2010; Oberndorfer et al., 2007; Rowe, 2011; Vijayaraghavan, 2016). The practical difference between these two is mostly based on the growth medium (sometimes also referred to as the *substrate* or the *soil layer*) and the degree of maintenance. A visual example of extensive and intensive green roofs is shown in Figures 5 and 6, respectively.

Intensive green roofs are vegetated roofs that are also possibly known as "roof gardens". Before its environmental benefits were researched, intensive green roofs were originally designed to be aesthetically pleasing, and to be a place where people could relax and come to rest. It was therefore used as a soothing place for people to find additional recreation, and thus reducing stress or other anxiety-related problems (Dunnett & Kingsbury, 2008). The major difference with an extensive green roof is the depth of the substrate (the growth medium for the plants). Intensive green roofs have substrate depths of 15-20cm or more – which is significantly deeper than its shallower counterpart (always smaller than 15cm). This results in an increased potential to grow more kinds of plants (because of the ability for their roots to nestle deeper), creating a more vivid 'garden', with sometimes even small trees being able to grow on it (albeit at a substrate depth that needs to be deeper than 1 metre). (Dunnett & Kingsbury, 2008; Oberndorfer et al., 2007; Rowe, 2011; Vijayaraghavan, 2016)

The extensive green roofs have a more 'straightforward' use, compared to the intensive green roofs (Dunnett & Kingsbury, 2008). Recreation is not possible, and these roofs have a purely ecologically 'functional' purpose: insulation, stormwater retention,… These functions will be discussed further down below. The substrate depth maxes out at about 15cm, so only smaller plants are suited for the roof. The upside of it is that it is less costly than an intensive green roof, and due to its smaller sized plants, it also weighs less and demands less maintenance. Having a shallower substrate, however, means that the plants have fewer growth options and need to be less weather-sensitive in order to survive on an extensive green roof. This is why (often) succulents are chosen as the ideal plant to fill an extensive green roof with. More specifically, the Sedum species are preferred. The Sedum species are known for their increased resistance and tolerance to heavy weather conditions and temperature fluctuations, making them ideal to survive even in tougher environments. (Oberndorfer et al., 2007; Rowe, 2011; Vijayaraghavan, 2016)

2.4.1.2 The components of a green roof (research question 3)

Without going into too much detail, it still may be relevant to describe the parts (or components, rather) a green roof exists of. The fact that green roofs can vary a lot between fabricants and producers needs to be accounted for, but the consensus is that it exists of three 'main' layers: the vegetation layer, the substrate layer, and the artificial layer. The latter word, artificial layer, has been arbitrarily chosen as a collective definition to describe every sublayer that is non-biological and pre-produced, going from filter fabrics to insulation layers, to waterproofing membranes. Figure 7 displays the different components of a green roof.

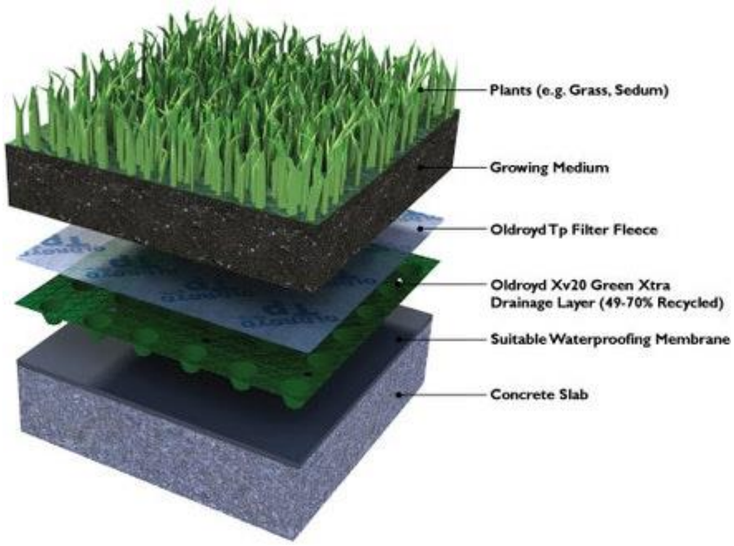

Figure 7: The components of a green roof (from: Safeguard Europe)

(Note: the bottom four layers in this picture are all part of the artificial layer, mentioned down below)

The vegetation layer, of course, is different when placing an intensive green roof than when placing an extensive green roof. The vegetation on an intensive green roof can be, e.g., bushes, trees, or flowers – only being limited by the depth of the substrate they're meant to grow from. The vegetation on extensive green roofs, on the other hand, is quite limited: the shallow soil layer only controls for low-growing plants. It is important to mention, though, that the plant species on extensive green roofs are chosen to withstand harsher environmental circumstances, due to extensive green roofs having this aforementioned more 'straightforward', no-nonsense, purely ecologically functional use. Compared to the intensive green roofs: these still need to provide a certain level of comfort and visual relaxation, whereas extensive roofs need no to provide this as much and can be visually less pleasing in return. As was mentioned before, the Sedum succulent is an ideal plant species for an extensive green roof.

The substrate layer (or *soil layer*, or *growth medium*) is an important layer, for it "directly influences the plant growth", and therefore, the "performance of green roofs" (Vijayaraghavan, 2016). The deeper this growth medium is, the more vegetational variation can be planted on the roof (which creates the difference between intensive and extensive green roofs). The soil thickness is important: it influences the thermal performance of the roof, as well as the water retention rate. These functions will be discussed further down below.

The last layer is the artificial layer. Being a non-official term, this name has been arbitrarily chosen as a collective definition to describe every sublayer that is non-biological and pre-produced; going from filter materials, to insulation layers, to waterproofing membranes. These are all crucial for an optimal performance of a green roof and aid in accentuating the characteristics of a roof like the runoff quality, the insulation performance, and the waterproofness.

2.4.2 Functions of green roofs (research question 4)

In the last subsection, the functionality paradigm of a green roof was mentioned – extensive green roofs were designed to have a more straightforward eco-performance (by sacrificing a bit of its aesthetical value and its recreational accessibility) than intensive green roofs. But what are the 'tasks' of a green roof? What does it have to offer? As it turns out, and as was mentioned in the previous section, green roofs help mitigate the consequences of global warming and climate change in urban areas.

If not explicitly mentioned otherwise, only extensive green roofs and its functions are discussed down below, since most of the research found was conducted on extensive roofs (because they were designed to be more functionally-purposed than intensive green roofs). Castleton also mentions in his research that, of the existing green roofs, 80% was extensive (Castleton et al., 2010). Other reasons as to why the extensive green roofs are observed more commonly than intensive green roofs, are weight restrictions and cost caps (Rowe, 2011).

2.4.2.1 Reducing stormwater runoff

When a storm occurs or when there's heavy rainfall, the sewage system of a city can drain only so much water from the streets per second. If this draining limit is exceeded, the water can't be transported down the sewage systems anymore, causing the water to stay on the streets. Due to the lack of permeability (e.g. like asphalt has), the water cannot seep into the ground. This causes buildings in the urban area to flood as well, potentially creating property damage (Carson et al., 2010). Also, when stormwater doesn't run off via the sewer systems, it can carry a lot of dirt with it – dirt that lies on the streets, for example – causing the water quality to decrease (which then contributes to nature's pollution). All of these effects can occur from snowmelt as well.

But green roofs can help manage the stormwater runoff quantity. Berndtsson (2010) concluded in his review that green roofs can reduce the stormwater quantity by absorbing a part of the water that falls down from the skies. It then evaporates again, never having reached the streets. However, the green roofs can only absorb a certain amount of water; so, during very heavy rainfall, there still is some water left that reaches the ground. But it reaches the ground at a later point in time, thus delaying the peak moment of stormwater runoff, making the draining systems overflow much slower, or even not overflow at all. Certain factors of the green roof play a key role in the quantity of absorbing water, e.g., the soil thickness or the types of plants used to cover the roof. Green roofs can also help to cleanse the stormwater before it reaches the ground, because its vegetation can absorb certain pollutants (such as nitrogen), but there are other sources mentioned in Berndtsson's review that contradict these quality improvements and claim that certain fertilisers in the green roof can cause the runoff water to be even more polluted (Berndtsson, 2010). The research in Rowe's review (2011) also states these findings.

2.4.2.2 Cooling cities down

The concept of an Urban Heat Island was mentioned above – urban areas tend to get warmer than their rural counterparts during the year, due to a much greater presence of heat-preserving building materials (like asphalt, concrete, or glass). The UHI effect has had many consequences over the years, going from health issues, like overheating (Buechley et al., 1972), to energy saving issues, by using about 17% more cooling energy than normal, for instance (Sun & Augenbroe, 2014). A method of cooling these urban areas down (and thus avoiding these consequences) is found through urban greening – including green roofs. Research has shown that urban greens work as a heat-absorbing layer (through either evapotranspiration or simply shading) for the urban surface (Givoni, 1991) and therefore green roofs can also serve for mitigating these heat issues (Bowler et al., 2010).

2.4.2.3 Acting as insulation layer

Green roofs can also serve as an insulation layer on top of the buildings, in the summer and in the winter (Castleton et al., 2010). This isolating effect in the summer is based on the principle of passive cooling (which means as much as 'avoiding heat transfer through the roof' in this context) – the vegetation on top of the roof catches the sun's the heat and reduces it through evapotranspiration and shading, which mitigates the UHI effect, but avoids the insides of buildings from heating up, as well. This way, a lot of the energy costs for cooling are saved (by saving on air conditioning, for example). The insulation effect in the winter, on the contrary, mostly relies on the thermal performance of the green roof's soil. The thicker the soil, for example, the better the insulation effect is in reducing temperature loss: up to 40 percent of energy costs can be saved in the winter through reduction of heat loss (Castleton et al., 2010). The combination of these energy savings is one of the strong economic advantages of green roofs (Castleton et al., 2010; Rowe, 2011; Vijayaraghavan, 2016).

2.4.2.4 Reducing CO_2 and improving the air quality

A fourth aspect of the green roof benefits is the improvement of the air quality, CO_2 in particular. Carbon dioxide is a greenhouse gas, which, as explained in the introduction, contributes to global warming. Therefore, the amount of CO_2 emissions needs to be decreased, *or* the CO_2 emissions can be captured. Plants can help to capture CO_2.

It is commonly known that various kinds of plants (including succulents like the Sedum species, used for extensive green roofs) contribute to cleaning the air. For example: the process of photosynthesis, which plants execute in order to grow, needs CO_2-gases as an input in order to be executed. This is the reasoning behind the roof's plants' ability to capture CO_2-particles in the air, but research has also shown that these plants even capture other pollutants like NO_x or O_3. NO_x, for example, causes respiratory problems, and O_3 is another greenhouse gas. (Rowe, 2011; Vijayaraghavan, 2016).

However, there is an interesting ambiguity concerning this aspect: the same literature reviews that state the potential of air-cleansing green roofs also find that, even though it is ecologically beneficial, green roofs are not an alternative opportunity with mitigating air pollution as its main purpose. In fact, it is actually relatively ecologically disadvantageous to install a green roof just to improve the air quality – the fabrication process of these roofs, namely, is quite CO_2-intensive (Rowe, 2011) and, as a consequence, this results in the net improvement of air quality being much lower than expected, but still positive, in any case. Literature therefore prefers "planting trees in urban areas", as it provides "better benefits in mitigation of air pollution" (Vijayaraghavan, 2016). This is a situation in which the use of *intensive* green roofs could be more beneficial for mitigating air pollution than the use of extensive green roofs would be.

Up until now in this current subsection, only the direct net improvement of air quality has been discussed. But green roofs are much more beneficial when looking at the *indirect* net improvement as well. In the previous subsections, it was mentioned that green roofs save energy usage (for instance, due to their heat insulation effect). If the assumption is made that the required heating energy is generated through the burning of fossil fuels, the saving in energy could be expressed in terms of 'avoided fossil-fuelled gas emissions', which then contributes to 'avoided increase in air pollution'. Rowe (2011) points out in his review that accounting for the indirect net improvement in air quality makes green roofs more ecologically attractive. However, full sustainability for green roofs (in the context of this paper: an equilibrium between social, economic and environmental benefits, also including the opportunity costs of mitigating air pollution) has yet to be optimised to this day (Shafique, Azam, Rafiq, Ateeq, & Luo, 2020).

2.4.2.5 Other benefits

Next to energy saving, cooling cities down, cleaning the air, and reducing stormwater runoff, green roofs offer even more benefits. Three more are briefly discussed in this subsection.

Noise reduction

The insulation effect of green roofs does not only benefit temperature management – it also helps to reduce the noise in an urban area. The research of Van Renterghem & Botteldooren (2008) found that green roofs reduce the sound impact up to 10dB, on the outside, in particular between the 500Hz and 1000Hz frequency spectrum. They further noticed that the ability to reduce the sound increased with substrate thickness for extensive green roofs. However, when measuring the effect for intensive green roofs, there were no additional significant benefits (when increasing the substrate depth even more).

Biodiversity improvement

A green roof in an urban area helps to restore and conserve the biodiversity. Green roofs (especially the intensive green roofs) can aid in offering a new place to be inhabited by wildlife again. This wildlife can vary from insects (like ants or spiders) to even certain bird species (Oberndorfer et al., 2007; Vijayaraghavan, 2016).

Roof membrane longevity improvement

The shading effect and the temperature absorption that green roofs offer, also influence the durability of the roof membrane: the vegetation layer keeps the roof membrane cooled, enough to avoid its materials expanding and contracting too often (due to temperature changes on warm days, for instance). This, in turn, increases the lifespan of the roof, for it suffers less from these fluctuations (Vijayaraghavan, 2016). The vegetation layer also naturally protects the roof membrane against UV light, which is beneficial for the longevity as well (Oberndorfer et al., 2007; Vijayaraghavan, 2016).

2.4.3 Summarising tables: green roofs

The two types of green roofs

EXTENSIVE GREEN ROOFS	INTENSIVE GREEN ROOFS
More straightforward eco-performance	Eco-performant, more aesthetic/recreational
Shallow growth medium	Deep growth medium
Low-growing plants (succulents)	Larger plants (even small trees)
Practical, low-maintenance, less costly	Vivid garden, high maintenance, more costly
Three main layers – Vegetation layer (where species matter) – Substrate layer (where thickness matters) – Artificial layer (where fabrics matter)	

Table 3: Summary of the types of green roofs

The functions of green roofs

FUNCTIONS	DESCRIPTION
Controlling stormwater runoff quantity and quality	Green roofs can delay peak stormwater runoff moments and help mitigate the amount of water that reaches the sewers. They can, however, contribute to water pollution, according to some researchers. But this opinion remains heavily discussed.
Reducing the UHI effect	Through shading and photosynthesis, the vegetation absorbs sunrays and avoids roof membranes to overheat, thus mitigating the temperature in an urban area.
Insulation management	The inside temperature of a building can be managed through green roofs as well: the shading effect and evapotranspiration create a natural insulation, further enhanced by the thickness of the growth medium. This is beneficial in winters and in summers.

CO_2-reduction and air purification	Green roofs help to absorb CO_2 and other polluting gases in an urban area. The effect is greater for intensive green roofs than it is for extensive green roofs.
Other benefits	Green roofs also contribute to noise reduction in urban areas, as well as a better overall roof lifespan and an improvement in preserving and reconstructing biodiversity.

Table 4: Summary of the functions of green roofs

2.5 Conclusion: literature research

Urbanisation has many consequences: the urban heat island (UHI) effect, the loss of biodiversity, stormwater overflows, and even air pollution through street canyons. The solution proposed was an increase in urban greening systems; street trees, parks, green roofs, and green walls all had their advantages. It were the latter two that were taken a closer look on.

In this section, the most important results from the literature research on green roofs and green walls will be concluded. A thorough distinction was made between the types of green roofs (intensive – extensive) and green walls (green façades – living walls), answering this chapter’s research questions 1 and 2. Green roofs and green walls proposed a good solution to increase urban greening, especially when the area (cfr the ‘squared’ measure) of an urban region was limited. For in a limited area, one can only plant so many trees before it becomes necessary to look for alternative urban greening methods. It is, however, important to notice the many similarities between green roofs and green walls. But they are no substitutions of each other, on the contrary: green walls and roofs are complementary.

2.5.1 Similarities

Green roofs and green walls contribute to reducing the UHI effect. Through evapotranspiration and natural shading, not only the inside of a building remains better insulated, but the heat-preserving material on the outside of buildings overheats less quickly. This way, one can save energy costs and experience less heat-stress-based health issues, caused by the UHI effect (Buechley et al., 1972).

Besides being aesthetically pleasing, green roofs and green walls are often designed with more ecological performance purposes in mind (like passive insulation, for example). Both types have their straightforward, no-nonsense, eco-performant variant (being extensive green roofs and green façades), and their more aesthetics and recreation-focused variant (being intensive green roofs and living walls). Extensive green roofs and green façades were considered to be less aesthetic than intensive green roofs or living walls. This is due to the difference in vegetation (extensive green roofs and green facades have less voluminous plants growing than their counterparts do).

Other similarities include the noise reduction and air-cleansing properties of the plants growing on the green roofs and walls. It is the combination of all aspects and functions that makes green roofs and green walls sustainably attractive. As was mentioned above, "sustainability" in the context of this paper is understood as the equilibrium between environment, economy, and society. What was also mentioned, was that green roofs and green walls weren't fully sustainable yet (Ottele et al., 2011; Shafique et al., 2020), mostly due to the high environmental impact by creating the materials used (felt layers, for example). This was found in the answer to research question 3 in this chapter.

2.5.2 Differences

There aren't that many major differences between the functions of green roofs and green walls, based on the literature study conducted in this section. This was found in the answer to this chapter's research question 4. However, one difference is mentioned often: green walls do not regulate stormwater retention as good as green roofs do (Manso & Castro-Gomes, 2015; Medl et al., 2017). This is because of the orientation of the green walls; it is more difficult to retain the amounts of water on a vertical surface than it is on a (slightly tilted) horizontal surface. Green walls, on the other hand, can cover more surface on the building envelope and could be more easily visible to the people. This leads to increased visual enhancement, and thus are the aesthetic purposes of green walls more prominent than they would be on green roofs.

2.5.3 Expectations leading into chapter 3

Due to the many similarities between green walls and green roofs, the expected outcome of the bibliometric research is that many of the subjects will be the same between green walls and green roofs. For example: UHI effect, air pollution, insulation management, energy saving, noise reduction, and more, are expected to pop up in the research field of both roofs and walls. The research on the retention of stormwater, on the other hand, is expected to be more vivid in the research field of green roofs. Also, the psychological effects of urban greening aren't specifically researched on green roofs and green walls specifically, so this is expected to be a rather small research field in the results. Lastly, since full sustainability isn't optimized for green roofs and green walls (yet), there is a high expectation to find many lifecycle analyses etc. conducted on the roofs and walls.

3 The bibliometric research

“No grand idea was ever born in a conference.”

– F. Scott Fitzgerald, American novelist

3.1 Introduction to bibliometrics

The second part of this thesis will focus on the visualisation and analysis of the research field on green roofs and green walls. These two topics (green roofs and green walls) will be discussed separately. This chapter answers to the question “What does the research field on green roofs and green walls look like?”.

A bibliometric study (or bibliometric research) is, in theory, a holistic approach to reveal the structure and development of a research field (Nakagawa et al., 2019). The purpose of this thesis’ bibliometric research is to identify (and optionally, visualise) a certain research field, in a way that certain clusters (be it author clusters, citation networks, or topic clusters) can easily be spotted. This, in turn, benefits future research on these topics – the researchers then have an idea what research areas have developed more, and what areas haven’t, for instance.

A bibliometric study contains several steps (these will be discussed more extensively further down below). The first step is to gather the raw data to be analysed; it’s the most important one. This is followed up (step two) by making the decision which analyses are needed to achieve the desired results, in order to process the data in the applicable software (which is step three). After having processed the data in a desired way (e.g., having filtered every author of the articles in order to look for author clusters), it is time to visualise (step 4) and look for certain clusters. This is not necessary, for as some research questions need not necessarily be answered by a network graph – sometimes, simple statistics do the job as well. The fifth and final step is to discuss the results that have been achieved.

3.2 Research questions

The following 14 research questions are answered in this chapter:

- (GW) How many documents/authors/journals/organisations/countries/… are included in the research field?
- (GW) What is the yearly evolution of the research field (no. of articles)?
- (GW) What does the author network look like? Is it clustered or highly collaborative?
- (GW) Is there inter-organisational cooperation, or do the collaborations happen mostly in the same organisations?
- (GW) Is there international cooperation?
- (GW) What are the most cited and the most trending articles?
- (GW) What are the topic clusters of the research field? Is there a difference in intensity?
- (GR) How many documents/authors/journals/organisations/countries/… are included in the research field?
- (GR) What is the yearly evolution of the research field (no. of articles)?
- (GR) What does the author network look like? Is it clustered or highly collaborative?
- (GR) Is there inter-organisational cooperation, or do the collaborations happen mostly in the same organisations?
- (GR) Is there international cooperation?
- (GR) What are the most cited and the most trending articles?
- (GR) What are the topic clusters of the research field? Is there a difference in intensity?

3.3 The five steps of a bibliometric analysis

Before going into further detail, let's explain the steps of a bibliometric analysis with an illustrative example. I will use the research question 'Green walls: are there author clusters present, thus, do certain groups of authors tend to always publish articles together?' to illustrate these five steps. The first step, gathering all data, is to gather all relevant articles around green walls. The next step is to decide what approaches are needed to answer the research question – in this case, we're looking for an author network. We thus need to extract all authors of the articles (found in the first step), and need to check if they often co-author with the same people. This is called checking for co-author networks (more information below). The third step, analysis of the data with applicable software, happens through BibExcel and OpenRefine (also more information down below), which pleasantly allows us to filter for every author of all articles and create a frequency distribution for co-authorships. This means as much as: if authors x and y published five articles together, their frequency is therefore 5. Step four, network analysis, happens through networking software (such as Gephi), which processes the frequency distribution achieved in step three, and visualises it for us. The higher the co-author frequency is, the 'bigger' the connections between these authors are. The final step, discussing and concluding the results, happens next. In this hypothetical case, let us assume that the visualisation of the frequency distribution tells us that there are indeed author clusters. Co-authorship, therefore, happens often with the same authors, concerning research on green walls. The research question thus has been answered. (Please note that this is a purely hypothetical research question to illustrate the five steps of a bibliometric research. The results of this example remain false until confirmed otherwise in the actual research section down below).

3.3.1 Step one: gathering all data

The gathering of data is essential for any bibliometric research – all resulting conclusions depend on the data gathered. If the data is not gathered accurately, the results will be very unreliable. For a bibliometric research, the data used will be bibliographic metadata. Herein, every relevant article and its information (such as authors, publishing journal, topics, etcetera) is found. To find such citation data, one needs to search a suitable bibliographic database. There are many of such databases: EbscoHost, Google Scholar, and Web of Science, for instance. For this thesis, I chose to use Web of Science's data, which is the most widely used database for bibliometric research (Zupic & Čater, 2015). The Web of Science is an extensive bibliographic database that includes citation data.

To gather relevant data, Web of Science provides the user with search queries with Boolean operators (such as AND, OR, or NOT) to easily filter out irrelevant articles. Once the right search query is used, and the number of relevant articles found is maximised, the data can be downloaded and processed with suitable software. We then can proceed to step two.

3.3.2 Step two: deciding which bibliometric analysis methods to conduct

Bibliometric research can be conducted in various ways. Zupic & Cater (2015) state five different bibliometric methods: citation analysis, co-citation analysis, co-author analysis, co-word analysis, and bibliographic coupling. All analyses can be conducted with multiple units of measure. These can vary from authors or articles being the units of analysis, or even journals and organisations.

Citation analysis

Citation analysis is mostly used as a quick tool to find the most important articles for as the unit of measure is the number of times an article is cited: the more an article is cited, the more influential it is (has been) to the researchers. This, however, bears one flaw: newer publications do not get cited as much as older publications do. Therefore, one may deem citation analysis as biased towards older articles. A way to solve this bias is to simply use the relative citation count: the total amount of times an article has been cited, divided by the total amount of years is has been published. This, however, doesn't tell us anything about the most cited articles, only about the most trending (the fastest growing) ones. The unit of measure for citation analysis does not necessarily have to be an article; authors or journals can be units of measure as well. (Zupic & Čater, 2015)

Co-citation analysis

Co-citation analysis is a bibliometric method that looks at the times that two articles are cited together. The higher this frequency, the more likely it is for the articles' contents to be similar (because they are more often mentioned together across multiple articles). The bias is the same here as with citation analysis: recently published articles have lesser chance to be included in another one's reference list, thus biasing the importance of an article that is more recently published. This can be mitigated, again, by carefully controlling for the time period. Co-citation articles can also be used with authors or journals being the unit of measure, for example. (Zupic & Čater, 2015)

Co-author analysis

The third method is co-author analysis (it is also the one used for the hypothetical example above). Co-author analysis is equal to analysing the frequency with which two authors publish a paper together. This acts as a measure of collaboration and can therefore find author clusters, for instance. If there aren't many clusters present, this could implicate that the collaboration in the research field is highly variable – authors, thus, do not necessarily work with the same partners every single time. However, the appearance of one's name on an article is not necessarily a measure for the amount of work done on an article, but sometimes as an "honorary authorship" (Katz & Martin, 1997). Aside from that, co-author analysis still is a good method to measure the social network of the research field. The same ideas mentioned in this paragraph work for co-organisations analysis (or perhaps even co-countries analysis) as well. (Zupic & Čater, 2015)

Co-word analysis

Co-word analysis focuses on the joint appearances of two words in an article. This can go from a keyword-based level, to the full text-based level. The more two words appear together in an article, the more these words tend to be concept-related (e.g., "greenery" and "garden" often appear together in articles on green walls and green roofs, and one can obviously tell these two words are related). The downside of the co-word method is the possibility of synonyms being used, or the possibility that one word can have completely different meanings. (Zupic & Čater, 2015)

Bibliographic coupling

The fifth and final bibliometric analysis method is called bibliographic coupling. Bibliographic coupling is, in a way, the inverted version of a co-citation analysis: instead of observing the frequency with which two articles are cited together, bibliographic coupling observes the frequency with which two articles share their references. The more shared references, the likely it is for these articles to be content-related. This way, one can identify the possible research topics in a research field (because the content-related documents will tend to cluster together). The major benefit of this bibliometric analysis method is that it doesn't account for the number of times an article is cited; bibliographic coupling directly uses the reference list of an article and compares this to the lists of other ones. This way, it is very useful for the research field to be mapped accordingly. However, it does not calculate which article is more important than the other one, because the number of times an article is cited did not matter in this method. Units of measure for bibliographic coupling are the journal articles, but when conducting the network analysis, the names of these articles can be changed to the authors' names, or the organisations in which the research took place, for example. (Zupic & Čater, 2015)

Dependent on the research question one wishes to answer, a choice of method for a bibliometric analysis can be made to achieve the desired results. The case also exists that just a simple statistic is desired (e.g., 'what are the top five journals that publish the most articles on this topic?'), and that therefore no above-mentioned bibliometric method is needed. But in order to answer more mapping-related questions, one should use bibliometric analysis methods.

3.3.3 Step three: using the correct software

In this thesis, the software Bibexcel will be used to conduct the actual bibliometric research. Bibexcel is a tool that helps the user analyse bibliometric data in all kinds of ways. It is developed by Olle Persson, and is free of charge (Persson, Danell, & Schneider, 2009).

The way Bibexcel is used in this paper, is to analyse the bibliometric data, generated in the first step, using the bibliometric methods described in step two. The software allows me to receive frequency tables from a certain unit of measure (article, journal, or author) and to use them to create networks. This goes from co-author networks to shared reference networks (bibliometric coupling). The generated files from bibexcel can also be processed further with Microsoft Excel, in order to answer statistical research questions, for instance.

Sometimes, the data that Bibexcel has gathered, can be a bit chaotic. For example: the citations could refer to the university of Hasselt in various ways: University Hasselt, Univ Hasselt, Univ Hass,…. The problem created by this, is that Bibexcel doesn't understand that these different names all refer to the same entity. If UHasselt has published, for instance, four articles on green walls, Bibexcel could denote this as University Hasselt(1), Univ Hasselt (2), Univ Hass (1), instead of accumulating these numbers as Univ Hasselt (4). The data could therefore be biased, due to this notation issue. Thankfully, the software OpenRefine (previously: Google Refine) can aid us in clustering likely-named entities together, and changing their names so that only one term exists for the university of Hasselt. This also works for authors (Daniëls B and Bob Daniels becomes Bob Daniëls), journals (London Times and Lndn Times becomes London Times) or any other desired information.

OpenRefine is particularly useful to sort and clean the data, whereas Bibexcel is particularly useful for processing it. Combining these two together, creates an almost perfect data file, ready to be used for network analysis. For the remaining details to be adjusted, Microsoft Excel will fulfil the job (very useful for adding new labels to the units of analysis for the visualisation of the network).

3.3.4 Step four: the network analysis

3.3.4.1 Edges, nodes, and centralities

Visualisation is essential for network analysis. It is, namely, quite hard to spot author clusters in a table with over five hundred articles, for example. Luckily, there's some visualisation software available. I chose Gephi to help visualise the bibliometric networks, for the reason of already having worked with the software myself in the past, and thus already being familiar with it.

Figure 8: Visualisation of edges and nodes

Network analysis is based on two things: nodes (the items, subjects, the units of measure) and edges (the connections between nodes). Let's illustrate it with an example: co-author analysis. If author x (termed 'node x' in network analyses) has a co-authorship with author y ('node y'), this is denoted as an edge.

Edges can be weighted: if author x has collaborated five times with author y, it is said that the edge between node x and node y has a weight of 5 (see figure 8 for a visualisation).

Nodes have 'weights' as well, although these are more often referred to as centralities. The degree centrality is used the most: it is a term for the amount of incoming/outgoing/undirected edges on a node. In weighted networks, the weight of the edges is also incorporated in the degree centrality. Author x and y, in this example, have the same degree centrality (which is 1). Their weighted degree centrality, however, is 5, due to the weight of the edge being 5. Other terms, such as betweenness centrality (the number of times the node included in the shortest path from another node to a third one) and closeness centrality (the mean length of the shortest path of the node to all the other nodes) are also used for network analyses, but are less relevant terms for this thesis. If not mentioned otherwise, the degree centrality will further be referred to as 'degree'.

Using the basic knowledge of network analysis in combination with Gephi, one can achieve visually appealing results quite easily. When a certain desired network structure is generated, step five can begin.

3.3.4.2 Normalisation of bibliometric data: co-author networks

When creating a co-author network, the 'relative' contribution of an author matters. For instance, an article with 20 authors shouldn't have the same impact on the author collaboration network like an article with only two authors does. Because all of the authors of that 20-author article will already have at least a degree of 19. This way, despite publishing only one article, these 20 authors will all *seem* quite important in the research field, because of their connections to other authors, despite the fact that they're all within the same article pool. Whereas an article of two authors only has authors with a degree of 1, seeming less relevant (whatever the potential popularity of their article is) in the collaboration network. Thus, the co-author network becomes biased.

The suggestion to solve this biased collaboration network is to take the *relative frequency* to which the authors have contributed to an article. Assuming the total contribution to an article is 1 for one author, 0.5 for two authors (each), 0.33 for three authors (each), and so on, the relative frequency of the 20-author article is then 0.05 for each author. The 'real' degrees now change from 19 connections to 19 times 0.05 connections (which is 0.95). This is less biased, and more representative.

Of course, the research field doesn't contain two articles, it contains a lot more. The question is, then, how will the co-author network identify the 'real' collaborative authors, since the degree centrality will be biased because of these 20-author articles? The answer proposed to this question in this paper, will be to accumulate the frequencies, not the absolute ones, but the relative ones. This cumulative sum of relative frequencies will be termed 'real degree' for the remainder of this paper. In short: authors with the highest real degree will have the highest sum of individual collaboration contribution to the network. This doesn't mean, however, that these authors are also the most connected ones. But it can be interesting to see if they could be, making them the real 'leading researchers' of the research field.

3.3.4.3 Normalisation of bibliometric data: bibliographic coupling networks

Like co-author networks, bibliographing coupling networks can be biased as well. It is therefore important to distinguish the level of content-relation between two papers *as a percentage* rather than as an absolute number. For instance: document A (100 references) and document B (300 references) share 20 references, and document C (30 references) and document D (20 references) only share 15 references. From an absolute point-of-view, one could tell that documents A and B are more closely content-related, because they share more references. However, when calculating the relative shared number of references, documents C and D seem more closely related (with C sharing 50% of its references, and D even 75%; compared to 15% and 5% to documents A and B, respectively). So to avoid these biases in the coupling network, the technique to calculate the networks with their *relative* connections instead of their *absolute* connections is used from hereon. This way, analyses with more strongly content-related papers can, hence, form more accurately clustered networks, making the analysis better to interpret.

Two assumptions in this thesis will be made in order *to conduct the bibliographic coupling analysis* more accurately: (1) from an absolute perspective, the minimum of shared references needs to be at least 5, and (2) the relative connection between two papers needs to be at least 10% in order to make them trend towards content-relationship. A bibliographic coupling analysis can be done without these assumptions, but in order to make the analysis more effective, it is within my belief that these two assumptions will improve the accuracy of which the documents are coupled, and thus, clusters are formed.

3.3.5 Step five: the discussion of the results

The previous four steps were necessary for this step. The data needed to be accurate, the bibliometric method needed to be right, just as the software for its processing and visualisation.

For a hypothetical instance: let us say that we are to look for a co-author network between authors A, B, C, D, E and F. After having put the data through Bibexcel, OpenRefine and Gephi, we achieve the following visual result (displayed in figure 9):

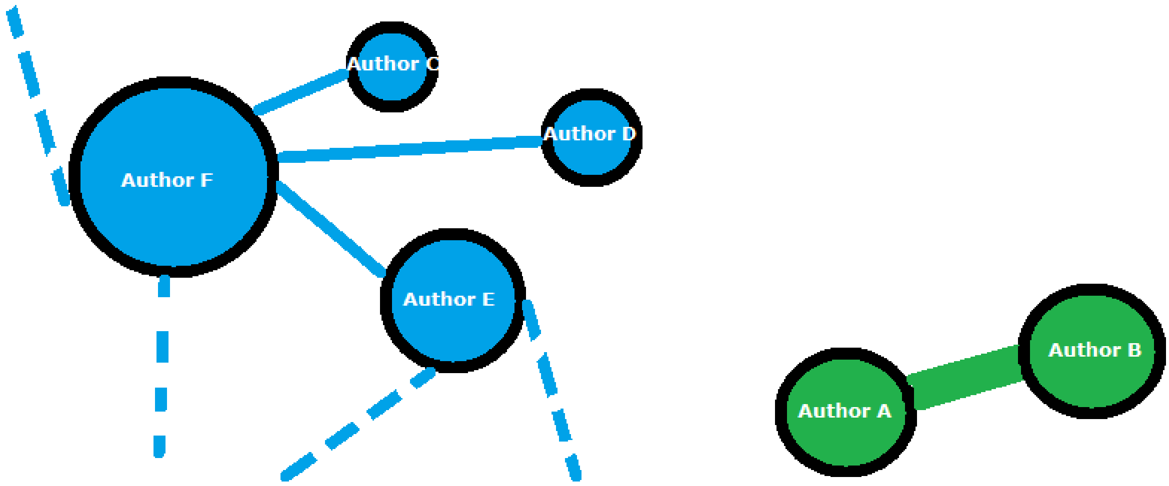

Figure 9: Visualisation of network (with nodes and edges)

The bigger the node, the higher its real degree; the wider the edge, the higher its weight. That's the first thing we look at. But what tells us this about the co-author network? If we look closely, we see two clusters: A-B and C-D-E-F. The degree of F is noticeably higher, which means that F has worked with more authors than C, D or E have, in their cluster. It can be assumed that F is the 'leader' of this research co-author cluster. But the weight of the edge between node A and B is a lot higher – this implies that A has worked with B more times than C, D, E or F have with each other. This points out a more intensive collaborative relationship for the green cluster, compared to the blue cluster.

Many other interpretations are possible with other types of networks.

3.4 Bibliometric research: green walls

In this subsection, a closer look will be taken at the research field on green walls. Executing the five steps of a bibliometric analysis, we try to answer the following research questions (of which the numbering is continued from the four research questions in chapter two):

3.4.1 Research questions

5. How many documents/authors/journals/organisations/countries/… are included in the research field?
6. What is the yearly evolution of the research field (no. of articles)?

7. What does the author network look like? Is it clustered or highly collaborative?
8. Is there inter-organisational cooperation, or do the collaborations happen mostly in the same organisations?
9. Is there international cooperation?
10. What are the most cited and the most trending articles?
11. What are the topic clusters of the research field? Is there a difference in intensity?

3.4.2 Processing the data

Step one: gathering all data

As was mentioned before, data collection is crucial to the outcome of this research. Therefore, much attention was given to finding the right search query in order to gather the most complete collection of documents on green walls.

FINDING THE RIGHT SYNONYMS TO WIDEN THE SEARCH QUERY A green wall is a green wall, but not every researcher uses these terms. As described in the literature research, green walls can also be named living walls, vertical gardens, or green facades. The utopia is to include all of these synonyms in the search query. Down below follows a list with possible synonyms to refer to green walls. The synonyms are found in the various articles used for the literature research, and through kind and useful suggestions from my promotors as well.

Green walls	Green facades	Living walls
Vertical gardens	Planted walls	Planted facades
Vertical greenery	Vertical greening	Vegetated walls
	Wall vegetation	

Now that the synonyms are established, it is time to include these in the search queries. But the search query would be very long if all of these terms were used separately. Luckily, Web of Science provides us with a few shortcuts in order to make the search queries shorter whilst keeping the same search results.

THE $-CHARACTER Web of Science queries are quite character-sensitive, so "green walls" doesn't deliver the same results as "green wall", because titles can contain "Green Wall Analysis", for example, which isn't found with the search term "green walls". The problem encountered here was just a plurality issue, solved quickly at first by including both terms in the search query. This problem can also be solved by using the search term "green wall$", allowing for one extra possible character after the word "wall". This also simplifies the search query, by combining two search terms into one, making it easier to read (for as it can become quite large and complicated, as will be seen later on in this section).

THE *-CHARACTER The possibility to include both the terms "vertical greening" and "vertical greens" can't be solved with the $-character, but with the *-character. Instead of allowing for one extra letter after the word, the asterisk allows for several letters after the term. Thus, "vertical green*" is the right solution to simplify both search terms in the research query.

<u>The Boolean operators</u> Lastly, in order to establish the right search term, the right use of Boolean operators is needed. The NEAR-operator, in particular, is very useful to look for sentences that implicate the research on green walls, but do not explicitly mention the synonyms. An example: the sentence "this research on urban vegetation planted on walls and facades has found that…" cannot be found with the synonyms. The NEAR-operator provides assistance for this problem: the sentence above is found by using the term "vegetation NEAR/3 wall$", which looks for any title or abstract that contains a sentence where the word "vegetation" is located within a three-word range of the word "wall(s)".

Having eliminated the search term problems, it is time to form the search query. The search query used to control for the above-mentioned issues is the following:

(TS = ("green wall$" OR "green façade$" OR "living wall$" OR "vegetated wall$" OR "vertical garden$" OR "vertical green*" OR "wall vegetation" OR "planted wall$" OR "planted façade$" OR "vegetated façade$" OR "façade vegetation")

OR

TS = ("urban green" NEAR/3 wall$)*

OR

TS = ("building envelope" NEAR/3 green)

OR

TS = (greenery NEAR/3 façade)

OR

TS = (greenery NEAR/3 wall)

OR

TS = (vegetation NEAR/3 façade))

However, when looking at the search results, a lot of irrelevant articles were found. A large part of it concerned research on microalgae and the great African Green Wall; even corrosion, technology and videography articles were found. I thus wanted to eliminate these articles by updating the search query with the NOT-operator. The following (and final) search query was created:

(TS = ("green wall$" OR "green façade$" OR "living wall$" OR "vegetated wall$" OR "vertical garden$" OR "vertical green*" OR "wall vegetation" OR "planted wall$" OR "planted façade$" OR "vegetated façade$" OR "façade vegetation")

OR

TS = ("urban green" NEAR/3 wall$)*

OR

TS = ("building envelope" NEAR/3 green)

OR

TS = (greenery NEAR/3 façade)

OR

TS = (greenery NEAR/3 wall)

OR

TS = (vegetation NEAR/3 façade))

NOT

*TS = ("*algae" OR "great green wall" OR "green wall panel$" OR "green bar$" OR "mobile laser scanning" OR stone)*

This generated a modest number of articles. The last steps of pre-cleaning were eliminating irrelevant documents (such as books or newspaper articles) and irrelevant categories (such as politics or women's studies). This was done in Web of Science itself.

For the relevant documents, only journal articles and reviews were kept in the search results. For the relevant categories, the following were eliminated:

Zoology	Mineralogy	Nutrition Dietetics
Spectroscopy	Philosophy	Criminology penology
Computer science AI	Cardiac Cardiovascular systems	Limnology
Paleontology	Political Sciences	Women's studies
Electrochemistry	Film Radio Television	

This, finally, resulted in 638 relevant documents about research on green walls (cut-off date: 25th of January, 2021). They were globally checked afterwards, and seemed to be accurate. If there would still be irrelevant documents in the data, they would not influence the bibliometric research in a large way, because of either the lack of shared references or irrelevant authors that did not collaborate with other ones (thus not influencing the bigger author clusters, for instance).

Step two: bibliometric analysis methods

The research questions above can be answered using e.g. author networks (when looking for author clusters: research question 7), organisation networks (organisation clusters: research question 8), bibliographic coupling (identifying the similar articles: research question 11), and some simple statistics (to calculate the average yearly trend of an article, for instance: research questions 5 and 6).

Step three: the right software

The data was cleaned up with OpenRefine (especially when conducting the organisation network analyses, by clustering the different denotations of the organisations), processed with Bibexcel, and fine-tuned with Microsoft Excel, ready to be analysed with Gephi (if needed). Statistics were achieved through BibExcel and Microsoft Excel in order to answer research questions 5, 6, and 10, whereas Gephi-formatted files were prepared in order to answer research questions 7 through 9, and 11, processed in step four.

Step four: the network analysis

The network analysis needed to answer research questions 7 through 9 was done using collaborative network analyses (co-author, co-organisation, and co-country), whereas research question 11 was answered through bibliographic coupling. Normalisation was used for the co-author analysis and the bibliographic coupling. The organisation and country networks didn't necessarily need the normalisation techniques, because their respective research questions aimed more at the presence of cooperation, rather than the intensity of it.

Step five: the discussion of the results

This will happen in the next subsection, for as the pre-processing of the data had finished.

3.4.3 Results and discussion

3.4.3.1 Summarising numbers (research question 5)

To start off the research, I made a word cloud in order to answer the research question 5 of the bibliometric research on green walls: how many documents, authors, journals, organisations, countries,… are included in the research field?

Figure 10: Numbers cloud, Green Walls research

The numbers (figure 10) speak for themselves: an article is written with an average of three authors, and nearly twenty thousand unique references were cited in the 45 years of research. Only one third of the world's countries, however, has conducted research on green walls.

The 638 documents altogether have been cited for over 11000 times (also including citations amongst themselves).

3.4.3.2 Yearly publications (research question 6)

The yearly evolution of the research field on green walls is important as well – it could be that the research, despite the relatively low number of articles (compared to green roofs, more in the next section), has already reached its plateau, or perhaps the contrary. Below is a graph (figure 11) that illustrates the yearly (marginal, as well as cumulative) evolution of the research conducted on green walls, expressed in the number of documents published per year.

It is clear that the number of articles published each year (yellow line) is still rising, albeit slowly. The research field hasn't hit its plateau yet, which means there is still much to discover/optimise. Both lines display a clearly rising trend. The year 2021 hasn't been included in this graph, just because it wouldn't be indicative for the evolution lines, for as 2021 isn't finished yet.

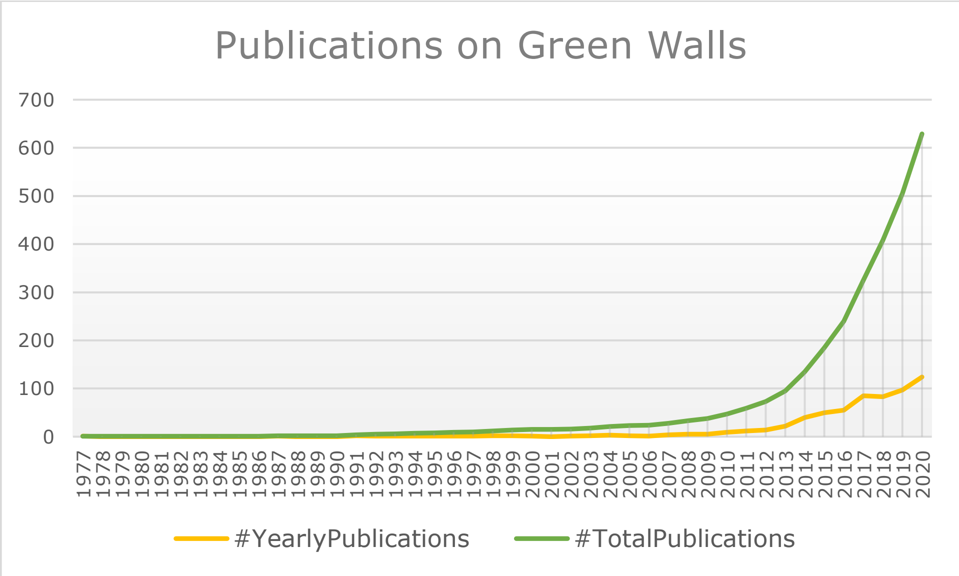

Figure 11: Publications on Green Walls

The turning point on green walls research seems to be 2009, where the marginal increase line (yellow) starts to rise appropriately. Thus, in the 30+ years before, green walls weren't that popular to conduct research of. Since it only started trending for the last ten years or so, the research on green walls could be a result of the increase in the 'social urge to go green' (chapter one).

3.4.3.3 The author network (research question 7)

To answer if the research field is highly volatile on an author-based level, a further look needs to be taken at the co-author network analysis. The purpose of this analysis is to investigate the level of collaboration – because a high level of collaboration promotes innovation (Inoue & Liu, 2015). Also, other research has shown that research teams receive higher amounts of citations than solo-researchers do (Wuchty, Jones, & Uzzi, 2007); in academic worlds, therefore, more collaboration is better as well. For the remainder of this section, author collaboration means 'the number of times two authors have worked together', as well as 'the number of authors one has worked with'. Both meanings have a cooperative nature.

Shown down below is a network graph (the larger version is attached at the end of this paper) that displays the author networks in the research field on green walls. It is important to mention though, that only the top eight author clusters were chosen, and a ninth smaller author cluster (mentioned further in this subsection). The reason behind it is just to maintain a certain level of structural overview in the network analysis. So it is not representative as a graph that displays all of the authors, but it *does* represent the *amount of collaboration* in the research field.

The number of clusters, 8, is the standard number of clusters that Gephi highlights from the data when calculating the different modules (each having its own modularity class), namely, clusters, using the Louvain Method to do so (*I will not go any further into explaining the Louvain method but I have included the reference*) (Blondel, Guillaume, Lambiotte, & Lefebvre, 2008).

The eight (or nine, with the grey cluster included) clusters each have their own colour, and will primarily be referred to via that way. The ninth cluster is that of C.Y. Jim (Univ Hong Kong, named Jim C in the graph); he had the highest amount of individual contribution in the research field (the highest real degree), but didn't collaborate as much with other researchers, thus making his cluster very small (and not one of the top eight). In other words: he wrote most of his papers alone or with one other colleague, which gave him a high real degree; but due to his limited collaboration, he didn't create a big collaboration network. For illustrative purposes, he was nevertheless included in the network graph.

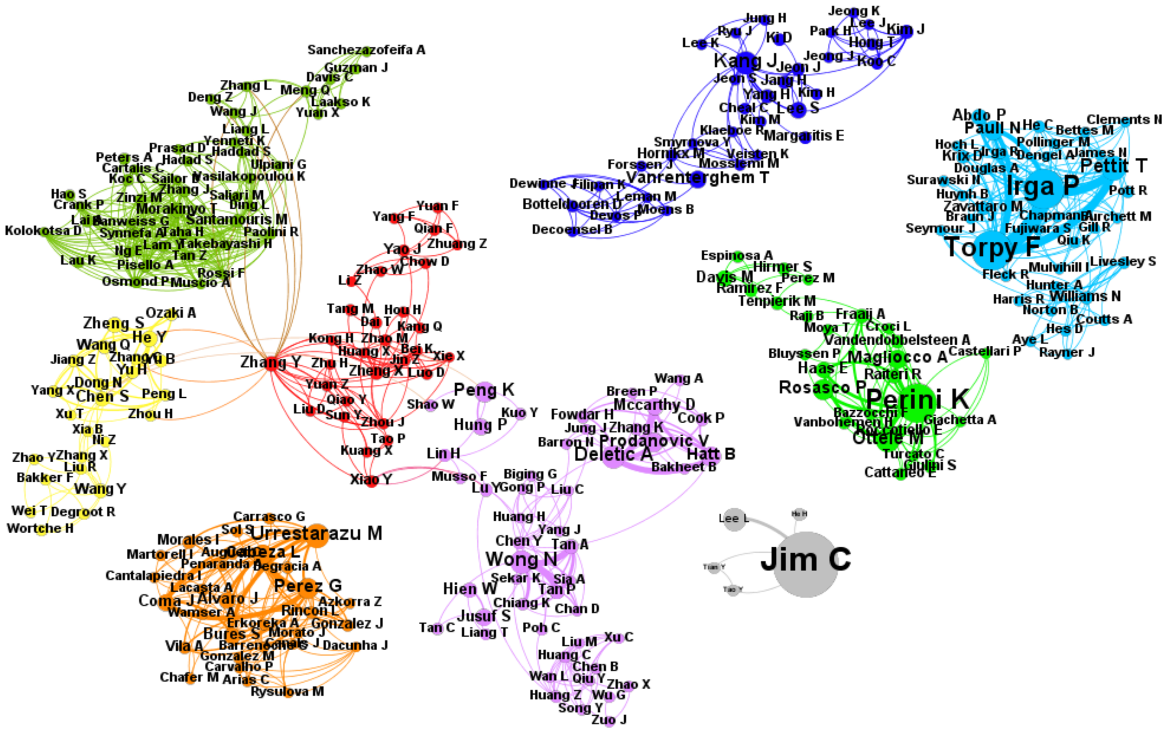

Figure 12: Green walls author network

The nodes have been sized accordingly in relation to their respective real degree, and the edges are merged (thus thicker edges indicate more collaborations between two authors). When taking a first look at the network, it can clearly be seen that the clusters are quite large (often 20-40 authors per cluster). The mean size of an author team is 4 (Wuchty et al., 2007), indicating that multiple documents are written within one cluster. When inspecting the graph more properly, one notices that a lot of nodes have more than four connections. This further contributes to the fact that author collaboration is relatively high compared to the number of analysed documents.

However, there is a relatively small presence of inter-modular (inter-cluster) collaboration – the majority of the eight clusters only collaborate with their own authors (intra-cluster), rather than collaborating with other clusters. This is easily seen by observing the number of intra-cluster and inter-cluster edges. This *could* support the assumption that research on green walls hasn't reached its plateau yet (as was mentioned in the answer on research question 6), for as the author collaboration level has not been optimised yet. This indicates that there still is more innovative potential in the research on green walls (Inoue & Liu, 2015). Also, the clusters seem to have the same lingual origins of names: the yellow, light green and red clusters mainly contain Asian names, and the orange cluster contains mainly Hispanic names. This finding will be discussed more in detail in the answer to research questions 8 and 9.

As for the most contributing authors: the blue cluster clearly displays Fraser Torpy (Univ Tech Sydney) and his colleague Peter J Irga (Univ Tech Sydney) as the main contributors in their cluster. When analysing their papers, the conclusion is made that their main research topic is about the air-quality-improving aspect of green walls. The orange cluster displays Miguel Urrestarazu (Univ Almeria) as its main contributor, and he (and his co-authors, like Gabriel Pérez, Univ Lleida) write(s) about energy savings and acoustics as well. The dark green cluster mentions Katia Perini (Univ Genoa) as its 'commander in chief', so to speak: she writes about all of the research topics on green walls. It seems she is specialised in the research field of green walls from a more global perspective. The grey cluster, the one of C.Y. Jim (Univ Hong Kong), the top contributor, is a smaller one. He conducts research on urban greening, mostly. Despite his current state of collaborations, it would be interesting to see what he could achieve when he started collaborating with the leaders in the other clusters (Peter Irga or Katia Perini, for example).

To conclude: some authors only write about certain topics, others write about green walls as a whole. The clustering is very interesting, for as the clusters are quite large. But the optimal level of collaboration (namely, more presence of inter-modular collaboration), hasn't been reached yet.

3.4.3.4 The organisation network (research question 8)

The author clusters presented a first look of the research collaboration field. It was noticed before that the clusters seemed to speak the same language (when taking a look at the names of the authors, that was). It makes sense, though, for as communication is more effective without language barriers. The question then rises: do organisations of the same language tend to work together more often, than those of a different language? This assumption will also be discussed further in the answer on research question 9.

The interorganisational collaboration, again, is to be promoted, for it contributes to more innovation by enhancing knowledge spillovers (Henderson, 2007), so the utopia in answering this research question lies in finding large organisation networks, with not too many small clusters. Again, like with the author network, the top eight clusters were taken from the analysis. The nodes were sized accordingly with their respective degree size, and the edges were merged again.

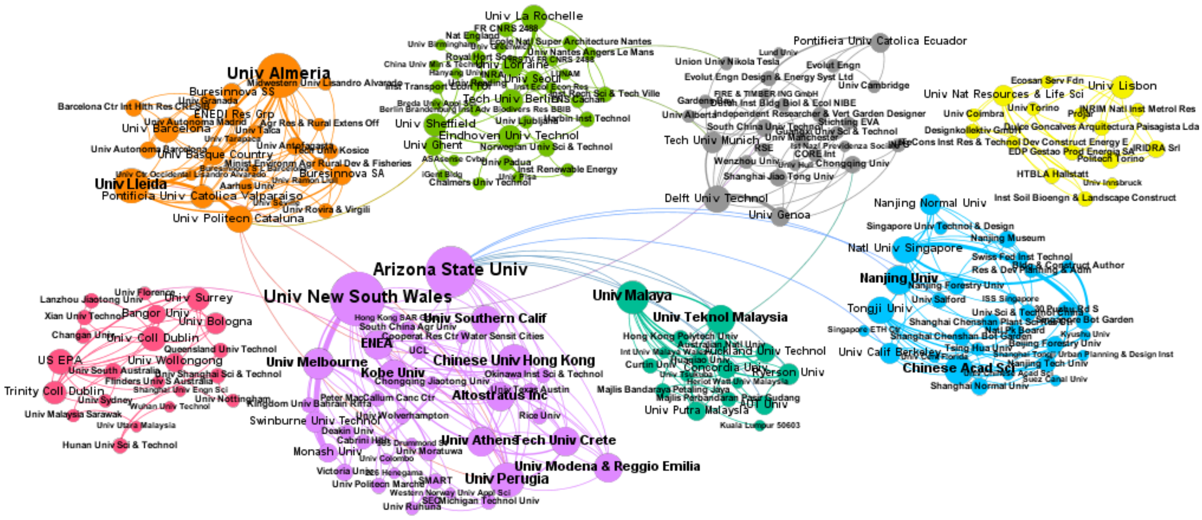

Figure 13: Green walls organisation network

Like before, the larger version of this network is attached at the end of this paper.

The first thing we see, again, is limited clusters. The clusters, still, are very large for an organisational level, but they only show relative cooperation at the first sight. When looking at the clusters in a more detailed way, the blue one mainly displays Asian institutions, mostly Chinese. The same goes for the orange cluster, which consists of mainly Spanish organisations. However, the green cluster displays a true interorganisational collaboration: institutions from Belgium, Netherlands, Germany, France, England, Sweden, Norway and even more, are included in this cluster. It's mainly European, but China and South-Korea are included in it too. The same goes for the grey cluster, and the purple and pink ones as well.

The purple cluster has the institutions with the most connections. It's the UNSW (Univ New South Wales, Sydney, Australia), together with Arizona State University (USA) that have the largest degree. Although UNSW is an Australian institution, it doesn't host the largest Australian contributors, which were Peter Irga and Fraser Torpy. Their university is in the pink cluster (Univ Sydney), and actually relatively small. So although Peter Irga and Fraser Torpy dedicated a lot of work to the research of green walls, they did not collaborate much on an interorganisational level.

The orange cluster, on the other hand, keeps its main contributor as main interorganisational collaborator. It was Miguel Urrestarazu from Univ Almeria who was the main individual contributor in the co-author analysis. It is his institution that leads the cooperation within its respective (orange) cluster. This is an opposite situation, compared to the top collaborator in the purple cluster.

In conclusion: there is a limited inter-cluster collaboration, but a relatively extended amount of interorganisational collaboration. The organisations that collaborate the most extensively are universities, for as other institutions (or even companies) remain in the 'local' cluster. It is important to notice, however, that, per cluster, the main contributing author to green walls research (seen in the answer to research question 7), does not always bring along the most interorganisational collaborations with him (as seen in the difference between the purple and orange clusters).

3.4.3.5 The country network (research question 9)

The main aim of this network analysis is to look for international exchanges, despite the language and climate differences. This network has been created with countries as units of analysis, and has been clustered using the same methods as in the previous two sections. The layout can seem quite intertwined at the first sight, but as was mentioned before: each node with the same colour has stronger connections within its own cluster than it does with other clusters.

The nodes have been sized accordingly, relative to their respective degrees; edges were merged again. Thicker edges indicate more intensive collaborations. A larger version of the graph can be found in the attachments at the end of this paper.

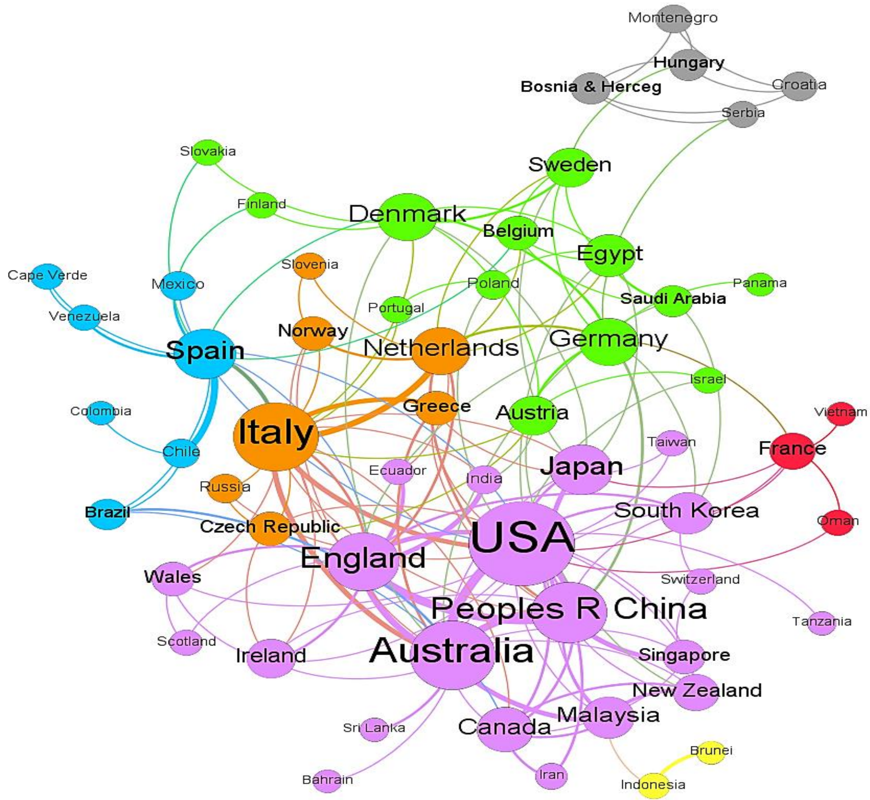

Figure 14: Green walls country network

There definitely is a large degree of international collaboration. The main countries that 'carry' the network are Australia, the USA, China, England, and even Italy. This wasn't seen as clearly when analysing the organisation network. However, the language barriers still play their part: Spanish-speaking countries tend to work closer together with each other than with other countries (light blue cluster). This can also be related to the same 'sunny' climate, though, for as Brazil and Cape Verde don't speak Spanish (they speak Portuguese). Furthermore, there are no links between Portugal and Brazil, which tends to support the 'sunny climate' hypothesis in the light blue cluster, away from the 'same language' assumption.

The grey cluster stands out from the rest: it has the Slavic countries together, with very few ties to other countries. We also see tighter connections between European countries (orange and green clusters), and some other countries that aren't as connected. France, for instance, doesn't have many links to other countries; it may thus prefer to work on a regional level, rather than on an international level. The proof of this can also be seen in the organisation network, in the light green cluster. A potential explanation could be found in the protectionist nature of France, perhaps preferring not to share its knowledge with other countries as much as the USA or Australia do. These are mere speculations, however.

To conclude the answer to this research question: there certainly is a high degree of international collaboration, with the English-speaking countries as the main contributors to the network. Some countries, like France, or the Slavic states, prefer to work on a regional level rather than on an international level. Despite the different climate conditions and language barriers, countries still tend to collaborate extensively.

3.4.3.6 The popular and fast-growing articles (research question 10)

In advance of the network analysis, the most trending and most popular articles were observed. This could indicate the level popularity of certain research topics, which will be observed whilst trying to answer research question 11, calculated by conducting a bibliographic coupling analysis. The following two tables display the top ten articles on green walls (reviews were left out for these tables), both expressed in terms of popularity (total number of citations) and fast-growing (most yearly average citations).

Table 5: Top 10 cited articles (GW)

#	Total citations	Title (year)
1	419	Temperature Decreases In An Urban Canyon Due To Green Walls And Green Roofs In Diverse Climates (2008)
2	383	Simulation Of Surface Urban Heat Islands Under Ideal Conditions At Night .2. Diagnosis Of Causation (1991)
3	314	Planning For Cooler Cities: A Framework To Prioritise Green Infrastructure To Mitigate High Temperatures In Urban Landscapes (2015)
4	272	Effects Of Asymmetry, Galleries, Overhanging Facades And Vegetation On Thermal Comfort In Urban Street Canyons (2007)
5	244	Thermal Evaluation Of Vertical Greenery Systems For Building Walls (2010)
6	205	Comprehensive Concept Planning Of Urban Greening Based On Ecological Principles: A Case Study In Beijing, China (2005)
7	193	Vertical Greening Systems And The Effect On Air Flow And Temperature On The Building Envelope (2011)
8	187	Urban Reconciliation Ecology: The Potential Of Living Roofs And Walls (2011)
9	169	Green Vertical Systems For Buildings As Passive Systems For Energy Savings (2011)
10	135	Quantifying The Deposition Of Particulate Matter On Climber Vegetation On Living Walls (2010)

Not in other top ten: 2,6 and 10

Table 6: Top 10 fastest-growing articles (GW)

#	Avg. Yearly citations (+/-)	Title (year)
1	45/y	Planning For Cooler Cities: A Framework To Prioritise Green Infrastructure To Mitigate High Temperatures In Urban Landscapes (2015)
2	30/y	Temperature Decreases In An Urban Canyon Due To Green Walls And Green Roofs In Diverse Climates (2008)
3	20/y	Thermal Evaluation Of Vertical Greenery Systems For Building Walls (2010)
4	18/y	Effects Of Asymmetry, Galleries, Overhanging Facades And Vegetation On Thermal Comfort In Urban Street Canyons (2007)
5	18/y	Vertical Greening Systems And The Effect On Air Flow And Temperature On The Building Envelope (2011)
6	17/y	Vertical Greenery Systems For Energy Savings In Buildings: A Comparative Study Between Green Walls And Green Facades (2017)
7	17/y	Urban Reconciliation Ecology: The Potential Of Living Roofs And Walls (2011)
8	15/y	Green Vertical Systems For Buildings As Passive Systems For Energy Savings (2011)
9	14/y	Cost-Benefit Analysis For Green Facades And Living Wall Systems (2013)
10	14/y	Green Infrastructure Practices For Improvement Of Urban Air Quality (2017)

Not in other top ten: 6, 9 and 10

No less than seven articles are in both top ten lists (tables 5 and 6) – this can point out that the articles cited the most still seem the most relevant. A lot of them are from the late 2000's and early 2010's, which was the period that the research on green walls was starting to gain interest.

The topics of the articles in these two tables seem to be mostly about the urban heat island temperature problems, energy savings, and cooling capabilities. At both bottom places, the research topic is about the air quality (or the air-cleansing capabilities of green walls). The conclusion of this top ten analysis is the hypothesis that the research field will also look like this top ten – mostly concerning the temperature aspects of green walls, and less about the air-cleansing capabilities, or even the sound isolation discussed in the previous chapter (chapter two). Only the bibliographic coupling network (which answers research question 11) can confirm or deny this hypothesis.

3.4.3.7 The bibliographic coupling network (research question 11)

In this last network, the perspective changes from finding collaboration to finding the different research topics. This is done through a bibliographic coupling analysis, which tries to connect the documents that have a certain number of references in common, in order to distinguish topic-related groups. The purpose of this bibliographic coupling analysis is to achieve a proper holistic view of the research field without having to read every single document.

The choice was made not to label the nodes in this network, because the labels would be too long to read, making the visual observation of the network very confusing and more difficult to interpret. However, I mentioned earlier that every node had its own modularity class, so the label list can be filtered per modularity class (i.e., per cluster, per module), solving for the absence of the labels in the network graph. Again, only the top eight clusters were taken, and sized accordingly to their real degree; edges were merged. Almost all of the eligible documents (after normalisation) are included in the graph: only ten percent isn't included. This raises the generalisability of the results, making the graph very representative.

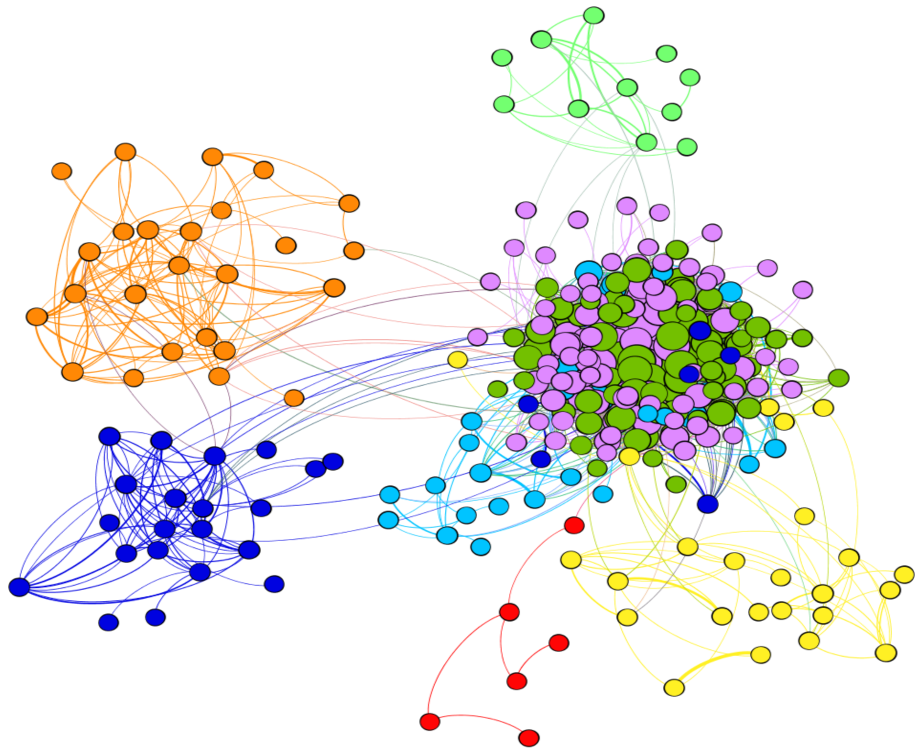

Figure 15: Green walls bibliographic coupling network

When taking a first look at the graph, two clusters seem very intertwined (the dark green and purple clusters). This indicates that the topics of these clusters are very related. Altogether, they seem to form the 'core' cluster of the research field, forming relationships with all other clusters. These other clusters, like the orange or dark blue ones, do not form significant relations with modules other than the core cluster. The hypothesis of purple and green forming the core cluster is further supported by this.

Besides appearing as the core cluster, the purple and dark green modules seem to be the largest (in numbers) as well: a lot of research, thus, has been conducted on the topics in these clusters. the smaller ones, like the red and light green clusters, seem less developed.

Below is a table (table 7) with the colour of each cluster (also doing service as the cluster name) and its respective topics.

Colour	**Topics (in green walls category)**	**#Articles**
Purple	Thermal performance (outside), UHI, building energy (thermal behaviour)	100
Dark green	Energy saving, cooling effect, thermal performance (inside)	83
Light blue	LCA's, case studies, CBA's, impact studies	28

Dark blue	Air pollution, phytoremediation, air quality	27
Yellow	Sound and acoustics	25
Orange	Particulate matter capture	25
Light green	Greywater	11
Red	Urban Heat Island studies (but not from green wall perspective)	6
Total		305

Table 7: The bibliographic coupling clusters

When topics are allocated to its respective clusters, it is clear that the focus of green wall research lies in optimising the thermal performance of it (to be seen in its core, dark green and purple). This includes isolation capabilities, energy savings, and urban heat island solutions. Almost 50% of the documents are found in these categories.

It seems as if the light blue cluster 'circles around' the core cluster – when looking at the topics in it, this makes sense. Case studies and other assessments can be related to every topic, but it is still a specific kind of research from its own perspective, so that's why they form a separate cluster.

The light green cluster (concerning research about greywater) isn't that developed (yet). This was also assumed in the literature research (the second chapter of this thesis). The yellow cluster, containing studies on acoustics and sound propagation of green walls, is also not heavily developed. The medium-large clusters, being dark blue and orange, focus on the air cleansing aspects of green walls. Although they would seem to have similar topics, there still is visual distinction noticeable on the graph: almost no connections exist between them. The orange cluster mainly focuses on capturing particulate matter in street environments, while the dark blue cluster focuses on air-cleansing aspects on the inside of a building (thus, with green walls on the inside): this is an important difference.

In conclusion: there are very distinguishable research topics, but the core research seems to concern the thermal performances of green walls and the energy savings that come along with it.

3.5 Bibliometric research: green roofs

In this subsection, a closer look will be taken at the research field on green roofs. Executing the five steps of a bibliometric analysis, we try to answer the following research questions (these are the same as the ones on green walls).

3.5.1 Research questions

12. How many documents/authors/journals/organisations/countries/… are included in the research field?

13. What is the yearly evolution of the research field (no. of articles)?
14. What does the author network look like? Is it clustered or highly collaborative?
15. Is there inter-organisational cooperation, or do the collaborations happen mostly in the same organisations?
16. Is there international cooperation?
17. What are the most cited and the most trending articles?
18. What are the topic clusters of the research field? Is there a difference in intensity?

3.5.2 Processing the data

Step one: gathering all data

Like with the bibliometric research on green walls, the data collected from Web of Science needs to be as relevant as possible. The more accurate the data, the better the results are to interpret.

FINDING THE RIGHT SYNONYMS TO WIDEN THE SEARCH QUERY It is of major essence to add the right synonyms in the search query in order to (1) eliminate irrelevant documents and (2) make the collection of documents as relevant as possible: only research about green roofs is allowed in the final selection. Again, with the helpful support of my promotors, and through reading the literature on green roofs, the following selection of synonyms was found:

Green roofs	Roof gardens	Vegetated roofs
Living roofs	Eco-roofs	Rooftop greenery
Roof greenery	Rooftop vegetation	Roof vegetation
Planted roofs	Green-roof vegetation	

The search query was improved using the $-character, the *-character and the Boolean operators, mentioned in the bibliometric research on green walls (the previous subchapter). The following search query was created:

(TS = (“green roof$” OR “roof garden$” OR “vegetated roof$” OR “green-roof vegetation” OR “living roof$” OR “eco-roof$” OR “roof* greenery” OR “roof* vegetation” OR “planted roof$”)*

OR

TS = (“urban green” NEAR/3 roof*)*

OR

TS = (greenery NEAR/3 roof)*

OR

TS = (vegetation NEAR/3 roof))*

When looking at the search results, there don't seem to be any irrelevant documents. The search query therefore seems complete enough in order to continue to the next step of the data gathering: filtering for relevant document types and relevant research areas.

For the relevant documents, only journal articles and reviews were kept in the search results. As for the relevant research areas, the following categories were eliminated:

Mathematics, interdisciplinary applications	Genetics and heredity	Literature, Slavic
Dentistry, oral surgery & medicine	Computer science AI	Spectroscopy
Cardiac cardiovascular systems		

This generated 2187 documents, about thrice the size of the number of documents on green walls research. After taking a quick look through the document list, the papers seemed accurate. If there still would be a presence of irrelevant documents, they would be manually filtered out if they would somehow cause misinterpretations of the data, when stumbled upon. This wasn't the case in the other bibliometric research (green walls), so there is little to no expectation that it will happen in this section.

Step two: bibliometric analysis methods

The same routine (cfr. green walls) was followed: the research questions above can be answered using author networks (when looking for author clusters), organisation networks (organisation clusters), bibliographic coupling (identifying the similar articles), and some simple statistics (to calculate the average yearly trend of an article, for instance).

Step three: the right software

Again, the same routine was followed. OpenRefine, Microsoft Excel, BibExcel and Gephi were used in the process. Questions 12, 13, and 17 can be answered with the use of BibExcel and Microsoft Excel, and 14 through 16, and 18, can be answered using all four software programmes.

Step four: the network analysis

Network analysis was needed to answer research questions 14 through 16, and 18: co-author, co-organisation and co-country analyses were conducted to search for collaboration amongst the authors, organisations, and countries; bibliographic coupling was used to identify the different research topics. The analyses co-authorship and bibliographic coupling both needed normalisation in order to correctly interpret the results.

Step five: the discussion of the results

This will happen in the next subsection, for as the preprocessing of the data had finished.

3.5.3 Results and discussion

3.5.3.1 Summarising numbers (research question 12)

Figure 16: Numbers cloud, Green Roofs research

Like with the bibliometric research on green walls, the most global question was answered first. And again, a word cloud was generated in order to visualise the big numbers.

The research on green roofs has started earlier than the research on green walls (namely, eight years earlier). This may indicate that the research on green roofs has also trended earlier than green walls did (cfr. green walls research started booming about 2009). The rest of the numbers all have increased as well: this is a logical consequence when the number of documents increases. More documents, evidently, means more countries, authors, journals, etcetera.

3.5.3.2 Yearly publications (research question 13)

Before analysing the networks in the research field, it is important to, again, take notice of the yearly evolution of the research field on green roofs. Green walls research didn't reach its plateau, and the expectation for green roofs to not have reached it yet as well is very high. The same two lines return on the graph: the marginal rate of publications (expressed as the number of documents per year) and the cumulative frequency of publications (expressed as total citations up to the respective year). Again, to avoid biased indication, the 2021 data hasn't been included in this graph.

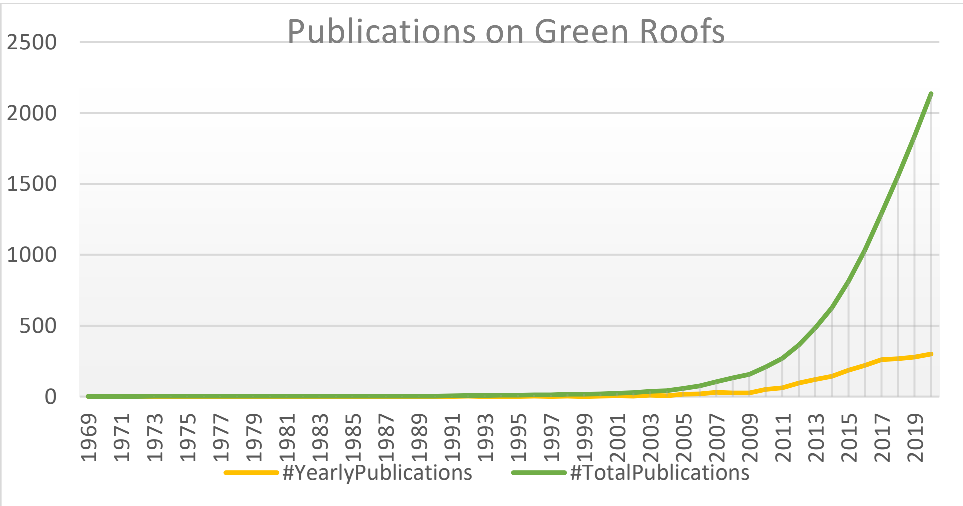

Figure 17: Publications on green roofs

It can be seen that the cumulative curve (the green one) still rises profoundly, while the marginal curve is slightly rising less intensively. These can be indications of a future plateau being approached. However, the curves are both still rising, so the research hasn't reached its full maturity phase yet.

The boom/trending assumption posed in the answer to research question 12 (that green roofs research boomed earlier than green walls research had) is confirmed: the booming begins in the early 2000's, almost a decade earlier than the green walls research started booming.

3.5.3.3 The author network (research question 14)

The green roofs author network is meant to visualise collaboration, and to analyse this collaboration as well. The more edges between the nodes there are, the more collaboration there is, and thus, the more innovation is being boosted (Inoue & Liu, 2015). The amount of intra-cluster cooperation and inter-cluster cooperation is important too: the more different clusters work together, the better. If clusters only work together within their own community, the innovation boost is being slowed down (because of limited knowledge spillovers, for example (Henderson, 2007)).

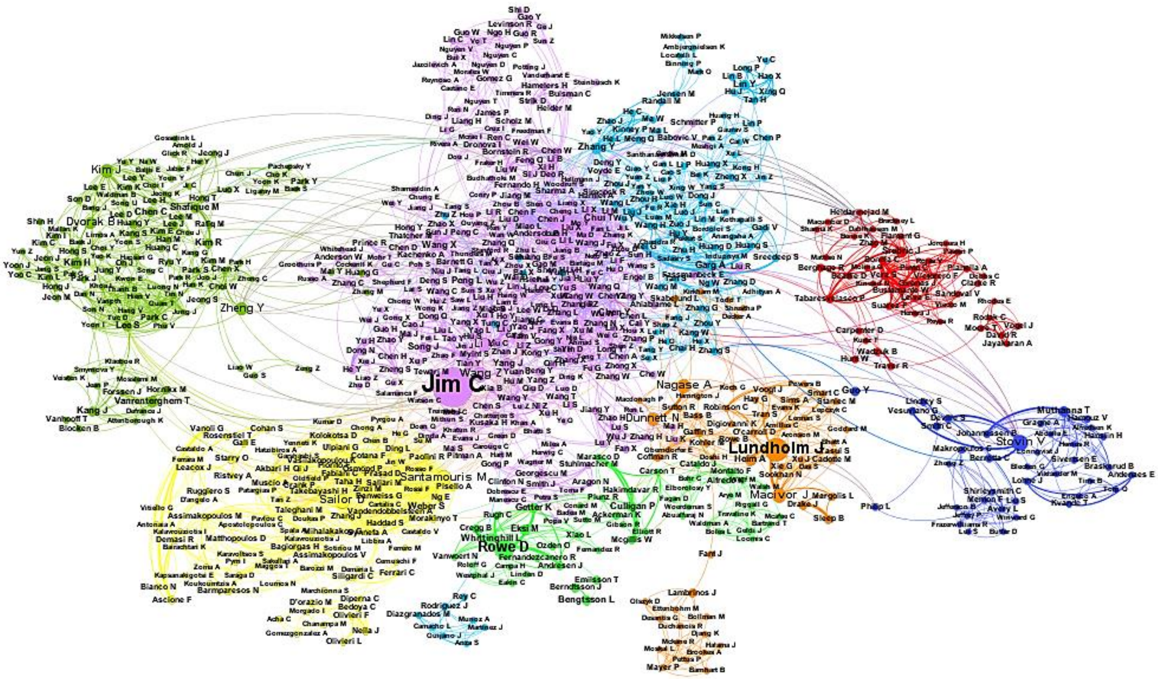

Figure 18: Green roofs author network

Above is an illustration of the author network in the green roofs research field. Like the green walls author network, only the top eight author clusters will be discussed here. Nodes are sized accordingly to their respective real degree, and edges are merged; thicker edges thus symbolise closer collaboration relationships. Only nodes that were connected to a minimum of five other nodes were displayed (in order to decrease the visible number of nodes, making the graph easier to overview). This is just due to the large number of different authors, and will have no other effect on the analysis, because the analysis will be based on the real degree, not the 'standard' degree. The larger version of this graph is attached at the end of this paper (appendix).

At the first glance, the network looks much more complex, because of the increased number of authors (compared to the green walls author network). However, the clusters are still clearly visible; some are bigger than others. The purple cluster is by far the largest one, and also the most central one. Despite its size, all of the purple nodes are quite small (except for CY Jim's node again). This means that the nodes' real degrees are very small, which could indicate that either many of these authors have only collaborated on just a few articles, (and/)or that the articles they authored are written by many authors (e.g. more than 15 authors per article). In either way, their contribution to the research field remains relatively small, despite the size of their network. This may represent the idea of a growing interest in the research – firstly through network introduction by co-authoring only one article, then by supporting more articles (with colleagues new to the network), or even writing some themselves.

The rest of the clusters seem intertwined more than it was the case with the green walls' authors. But it seems that a lot of previous names (i.e., PJ Irga, F Torpy, M Urrestarazu, K Perini) do not reappear in the green roofs top eight clusters author network. After a quick check to see if they were included in the data at all, results only in returning Katia Perini (Univ Genoa) as having a decent real degree, nevertheless not high enough to be included in the top eight. A new name (Jeremy Lundholm, St.Mary's Univ, USA) is seen in the orange cluster with a decent amount of individual contribution. He mostly writes about plant ecology in green roofs research and has co-authored the second most-cited paper: '*Green roofs as urban ecosystems: Ecological structures, functions, and services (2007)*'. The yellow cluster hosts Mat Santamouris (Univ New South Wales) and David Sailor (Univ Arizona State) as their top contributors; both publish articles mainly about the thermal performances of green roofs. D Bradley Rowe (Michigan State Univ, light green cluster) mainly publishes research on green roofs from an ecological point of view, going from carbon sequestration to stormwater retention.

In conclusion: despite an increased amount of inter-cluster collaboration, a lot of authors have small real degrees. Instead of delivering extra individual contribution to the research, they provide in expanding the network. In other words: they prefer working in groups of experts more than 'going solo'. This is beneficial to the promotion of collaboration, and therefore innovation, but, not per se to the *quantity* of the research on green roofs: they choose to publish e.g. 1 article together with 4 authors, instead of 1 article for *each* of the 4 authors.

3.5.3.4 The organisation network (research question 15)

The collaboration network on an organizational level is interesting to interpret. It provides an answer to the question if organisations tend to share their knowledge with many others, or just a select few other organisations. Again, the visualisation happened through Gephi, and the top eight modules were extracted from the data. The organisations in these modules had more connections with each other than with organisations of other modules. So if there still is a decent amount of inter-cluster collaboration, it is safe to say that even the 'tightest' clusters still work together with other organisations, thus improving the knowledge spillovers (Henderson, 2007). This possibility is explored below.

The nodes were sized to their respective degree centrality (again with at least a degree of 5), and the edges were merged again. The things we want to look for are a high presence of inter-cluster edges, stating high interorganisational collaboration, and less intra-cluster edges, indicating that collaboration often happens within the same organisations (thus, not stimulating innovation as much). Nevertheless, a high number of nodes (organisations) within a cluster is also preferrable over a small number of organisations within a single cluster, for the same reason: we want to look for a high amount of interorganisational collaboration. If the nodes within a cluster are all roughly the same size, this indicates a higher amount of collaboration than if there are just two or three bigger nodes in one cluster; it is because all organisations engage in similar collaboration, rather than two or three organisations having to initiate the collaboration.

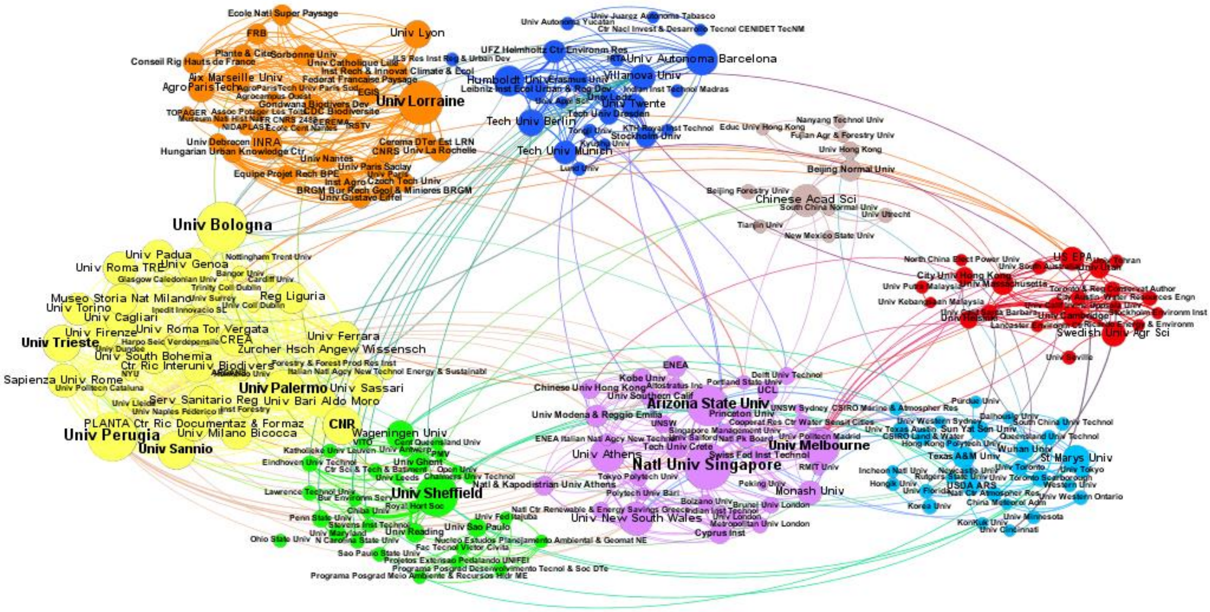

Figure 19: Green roofs organisation network

The clusters have roughly the same number of organisations in it like the green walls organisation clusters did, but, the amount of inter-cluster collaboration has increased. This is benevolent to the sharing of knowledge. The clusters are actually very diverse. The yellow cluster in particular is highly collaborative (all nodes have large sizes, meaning their overall degree is high), and the purple cluster shows (albeit less prominent) similar characteristics. However, the yellow cluster is mainly Italian – this explains the higher degree: it is more likely for organisations within the same country to work together, simply because of a higher convenience of communication (they all speak the same language, namely, Italian). The same goes for the mostly-French orange cluster, and mostly-Chinese beige cluster (although less intensively so).

The big connectors in the other clusters are the University of Arizona (USA), and the universities of Singapore, Melbourne (Australia), and Sheffield (England). The edges between these organisations are somewhat thicker, indicating closer collaboration relationships.

To conclude this subsection: the amount of inter-cluster collaboration has risen, but there also is a higher amount of intra-cluster collaboration (cfr. yellow and orange clusters), mostly on a regional level. This could result in more specific knowledge, due to the intensive collaboration (higher-degree nodes), but perhaps only applicable for those specific climates or regions.

3.5.3.5 The country network (research question 16)

The last collaboration network is the country network. Here, the countries were used as units of analysis to further investigate the amount of international collaboration that was hinted in the previous section (answer to previous research question). The hypothesis is to find clusters that are of the same region, because of (for instance) similar climates, similar research policies, or similar languages. It is beneficial to find a high international degree of collaboration, because research that is globally generalisable is always better than region-specific research.

In the green walls research field, French organisations were formed in one cluster, thus making France remarkably small in the international visualisation because of its internal collaborations. The expectation to find this again is high, because of the French orange cluster in the organisation network. The same goes for Italy.

The nodes and edges have been sized like in the previous section.

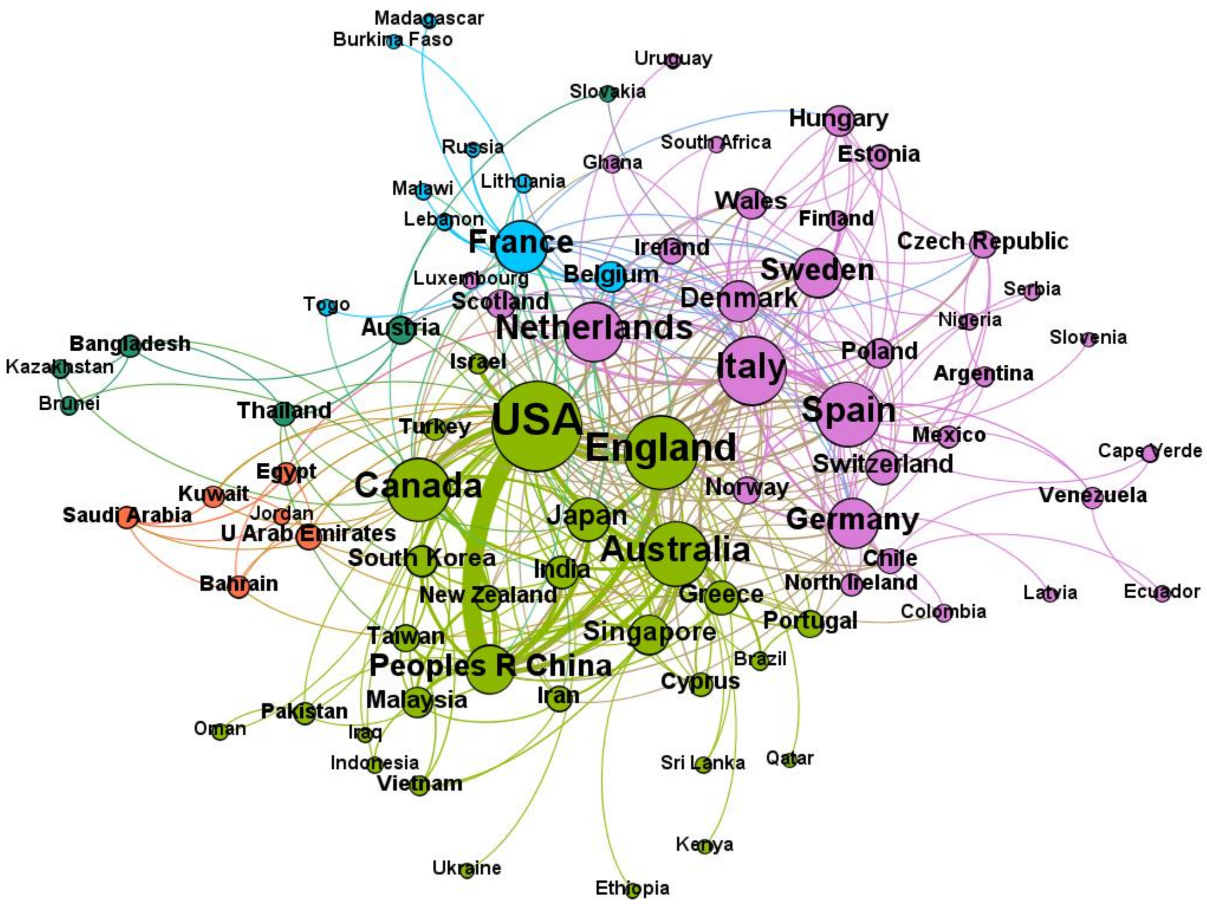

Figure 20: Green roofs country network

It is clear that the countries that collaborated the most in the green walls country network do so again in this network. The USA, England, China, Australia: all of them contribute extensively to the collaboration intensity of the network. A regional cluster is visible: the orange one lists the middle-eastern/Arab countries together. The blue cluster seems to have a few same-language speaking countries (France, Belgium, Lebanon, Burkina Faso, Madagascar).

The assumption of France's and Italy's preferences for intra-cluster collaborations can be discarded: they both show clear signs of international collaborations.

Overall, the network is much more intertwined than it was the case with the green walls collaboration. It seems that green roof research can still be conducted, despite climate differences: even countries of opposing climates such as India and Canada (both in the green cluster) show connected edges. The USA shows the thickest edge between them and China, both very different countries. The purple cluster contains a vast quantity of diverse countries and areas, the green one does so as well. Internationalisation shows off its benefits.

3.5.3.6 The popular and fast-growing articles (research question 17)

Before beginning to conduct the network analyses, it is preferable to obtain some ideas about the direction of the research field: what topics could be the most important ones, or what topics could be the most trending ones? The definite confirmations to these speculations will be discussed in the answer to research question 18, further down below.

The following two tables (tables 8 and 9) display the top ten articles on green walls (reviews were left out for these tables), both expressed in terms of popularity (total number of citations) and trendiness (most yearly average citations).

Table 8: Top 10 cited articles (GR)

#	Total citations	Title (year)
1	1004	Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough' (2014)
2	615	Green roofs as urban ecosystems: Ecological structures, functions, and services (2007)
3	441	Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? (2006)
4	418	Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates (2008)
5	408	Green roofs: building energy savings and the potential for retrofit (2010)
6	364	Analysis of the green roof thermal properties and investigation of its energy performance (2001)
7	348	The role of extensive green roofs in sustainable development (2006)
8	322	A green roof model for building energy simulation programs (2008)
9	320	Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes (2015)
10	312	Green roof stormwater retention: Effects of roof surface, slope, and media depth (2005)

Not in other top ten: 3, 6, 7, 8, and 10

Table 9: Top 10 fastest-growing articles (GR)

#	Avg. Yearly Citations (+/-)	Title (year)
1	143/y	Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough' (2014)
2	53/y	Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes (2015)
3	44/y	Green roofs as urban ecosystems: Ecological structures, functions, and services (2007)
4	39/y	State-of-the-art analysis of the environmental benefits of green roofs (2014)
5	37/y	Green roofs: building energy savings and the potential for retrofit (2010)
6	36/y	The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete (2017)
7	35/y	Climate change: 5^{th} assessment of IPCC: Urban Areas (2014)
8	32/y	Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates (2008)
9	30/y	Positive effects of vegetation: Urban heat island and green roofs (2011)
10	30/y	Biodiversity in the City: Fundamental questions for understanding the ecology of urban green spaces for biodiversity conservation (2017)

Not in other top ten: 4, 6, 7, 9 and 10

The two top tens have five documents in common. What's remarkable is that a lot of popular documents in the 'total' top ten are from the 2000's, rather than from the last decade. It can indicate that the documents mentioned were from a certain revolutionary nature. The documents in the 'average yearly' top then, on the other hand, are more recent. However, this is partially biased due to the older booming date of green roofs research; it is therefore quite logical that older documents, despite being important and relevant, receive less yearly citations on average. This finding clearly illustrates the limitations of a pure citation analysis (mentioned in the 5 different kinds of bibliometric research, see section 3.3.2). Further bibliometric analyses are needed in order to create a thorough and clear view of the research field today.

When looking at the topics of the top tens, similar patterns from green walls research reappear: the temperature effects and other thermal performances of green roof seem to be the most popular. The topic 'stormwater retention' gained some attention over the years, but seems to be less relevant in the last decade. The last decade has a more environmental focus, probably because of the rise in the social urge to go green (chapter 1).

Based on this quick citation analysis, the expectation is for the bibliographic coupling network to find a lot of documents in the thermal performance category, and that the topic of stormwater retention has developed as well. The environmental (and ecological) focus is expected to return, but less extensively.

3.5.3.7 The bibliographic coupling network (research question 18)

The last network of this bibliometric study is going to be a bibliographic coupling network. This type of network connects the documents that share the same references (or at least to a certain extent), in order to cluster them together because of its topics probably being related.

The nodes have not been labelled, in order to accentuate the visual aspect of the different clusters. The top eight clusters have been extracted, but after normalisation, these clusters still represented almost 90% of the documents. This high representation contributes to the accuracy of the interpretation.

The first thing we see is *very* clear cluster groups. Three of them are massively developed (purple, dark green and light blue), and a fourth one almost as well (the yellow one). A lot of connections exist between the three biggest clusters, probably because of their complementary nature (which we will discuss further). The orange cluster floats within, thus relating (topic-wise) to all of the clusters. The dark blue, red, and light green cluster seem not as much developed. This indicates that the topics within have not been researched as extensively as the topics from the big clusters.

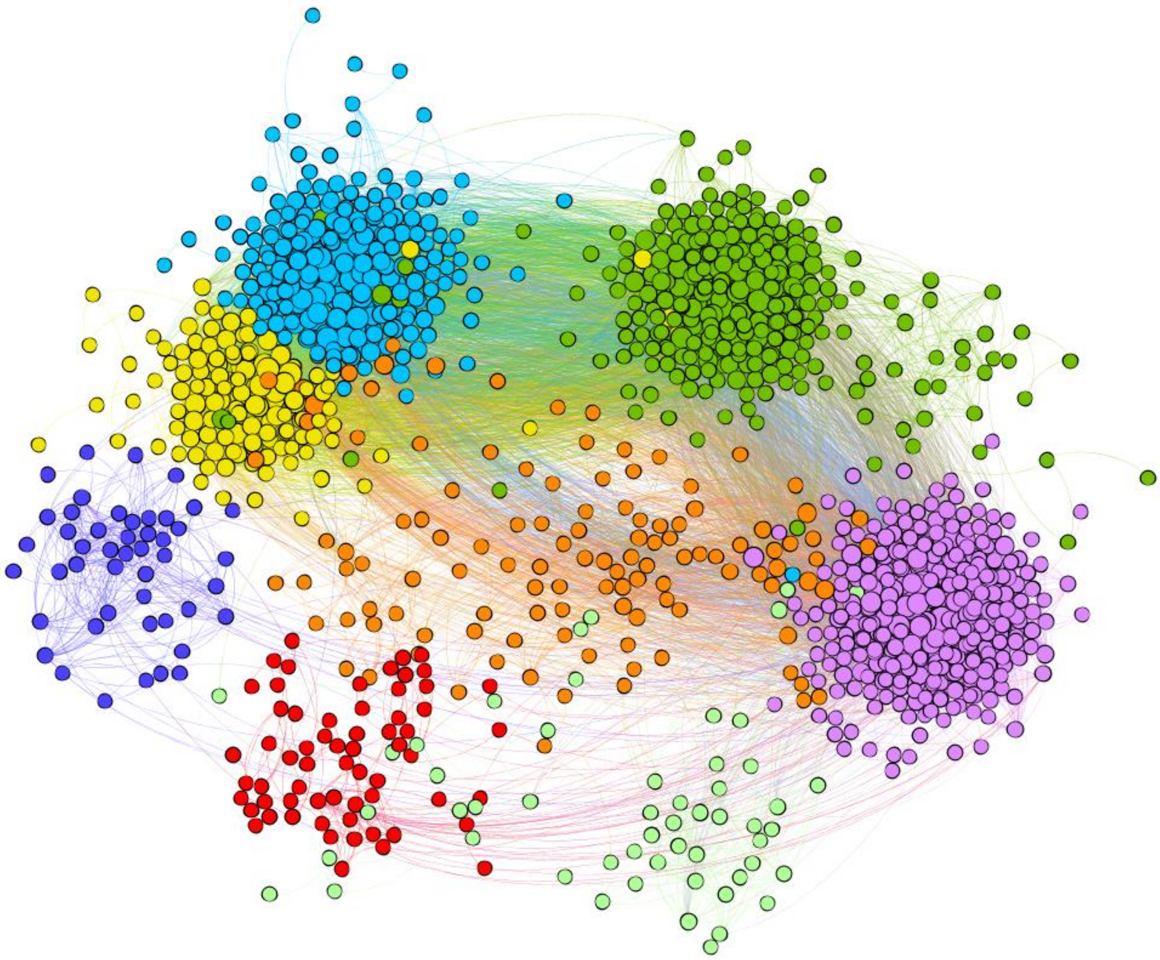

Figure 21: Green roofs bibliographic coupling network

The following topics have been allocated to their respectively coloured clusters:

Colour	**Topics (in green roofs category)**	**#Articles**
Purple	Thermal performance: cooling and energy saving (indoor focus)	315
Dark green	Substrates and other growing media; vegetation	281
Light blue	Stormwater management, water runoff, hydrophony	215
Yellow	Plant-based perspectives: runoff, retention and purification of water; plant nutritions	125
Orange	Case studies, LCAs (LifeCycle Analyses), CBAs (Cost-Benefit Analyses), MCDAs (Multi-Criteria Decision Analyses), and other assessments	118
Red	Urban greening; Urban Heat Island (mitigation)	63
Light green	Street canyon solutions: pollution and heat problems	54
Dark blue	Urban Heat Island (observational studies)	47
Total		1218

Table 10: The bibliographic coupling clusters

The top three clusters (light blue, dark green, purple) display their own topics very clearly. Thermodynamics, substrates, and stormwater runoff: all three topics are essential to green roofs research. The three clusters are still very much connected to each other, and this could indicate that they complement each other's research results – a breakthrough finding of a new substrate could stimulate more stormwater retention research, for instance. The yellow cluster seems like an combination of the light blue cluster and dark green cluster: it includes studies from a plant-based perspective mostly about stormwater runoff.

The orange cluster nodes, as expected, are content-wise related to any topic in the research field. However, the way of conducting research is exclusive for the cluster: LCA's, CBA's, etcetera are included within it.

What's remarkable is that the dark blue and red cluster (concerning UHI studies and solutions) aren't as developed as I expected them to be. Perhaps because of scalability problems: a green roof in an urban environment is much less observable for heat mitigation issues than it is for stormwater retention issues. Water retention as a research method, is representative on a little piece of a roof, which can be scaled to a larger piece (because it's a retention *rate*); urban heat island mitigations on the other hand (1) differ per climate and (2) aren't scalable because the UHI effect needs to be observed as a whole and not be generalised through observing a little heated piece of a roof in a laboratory.

The limited quantity of research of street canyon issues (light green cluster) is easier to explain. A street canyon isn't on the top of a roof; it is in between two buildings. Green *walls* research, therefore, is much more suited to solve street canyon issues than green roofs research would be.

The last thing that can be observed is the absence of air-cleansing characteristics of green roofs as a topic. Perhaps not much research has been conducted for the same reasons as for the red and dark blue clusters, namely scalability problems.

In conclusion: the network is very much divided and clustered, but many inter-cluster connections still exist, meaning that the research probably works complementary (an improvement in topic A boosts new research in topic B).

3.6 Conclusion: bibliometric research

The research field of green walls is less developed than the one of green roofs. The possible explanation is (1) because of the research booming that happened a decade later and (2) because of serving different purposes. We see more interest of green walls researchers in sound mitigation and air pollution mitigation, but more stormwater retention interests are found in studies on green roofs. Both roofs and walls have a respectful amount of assessment studies; but when it comes to mitigating 'big' issues (like urban heat island problems), the research seems less expansive, because of the probable scalability issues.

Concerning collaboration: a lot of international and interorganisational collaboration is present, despite the language barriers and different climates. We do not see the same authors return on both research topics (walls and roofs), and some bigger authors only conduct research on a specific topic instead of green roofs and green walls as a whole.

4 The systematic mapping

"It is a capital mistake to theorize before one has data."

– Sherlock Holmes, "A Study in Scarlett" (by: Sir Arthur Conan Doyle)

This is the final part of the thesis. Its purpose is to gain insights on a subtle, but relevant part of all research analysed in the previous chapter.

The reason behind the choice of articles is to follow up on the findings in chapter 2 (saying that green roofs and walls hadn't reached full sustainability yet, meaning that they didn't reach the equilibrium yet in which they would be beneficial to the people, the planet and the profit).

4.1 Research questions

The following research questions will be answered:

19. What is the current state of sustainability concerning green roofs and walls?
20. What is needed to reach sustainability?

4.2 Preparation: choosing the right papers

For this part, a systematic mapping was done for 56 publications, all of them coming out of the orange and light blue category in the bibliographic coupling analysis on green roofs and green walls, respectively. These two similar categories were probably better known as the categories of various assessments: cost-benefit analyses (CBAs), lifecycle assessments (LCAs), multi-criteria decision analyses (MCDAs), case studies, and other related sustainability and/or long-term viability assessments and/or analyses. The similarities of these assessments are that they all consider the viability of green roofs and walls, be it from an economic perspective (like cost-benefit analyses do) or a mainly ecological point-of-view (like lifecycle assessments do, for instance).

The systematic mapping analysis began with the selection of the right papers. First of all, the green walls and green roofs articles (resp. light blue and orange categories from the bibliographic coupling analyses) were put together in one pool. Of these 146 articles, 127 articles were unique. Of these 127 articles, only 86 articles were relevant to its category (this was evaluated by reading the keywords and abstract of the articles). Of these 86 relevant articles, 57 articles were chosen to be mapped. The other ones (28 articles) were field studies that didn't assess the green roofs or green walls holistically. For this reason, they were not included in the selection. From these final remaining 57 publications, only 1 full text was not found. The final 56 articles were then ready to be analysed.

The approach to this mapping was done in two steps. First, the categories in the final selections were determined. Four categories were formed: CBAs, LCAs, MCDAs and other sustainability- or viability-related articles. Second, these four categories were analysed in depth, each with specific elements. The full tables of analysis will be put in the appendix (chapter 7) for further desired inspection.

4.3 Systematic mapping: yearly evolution and categories

As was mentioned above: four categories were distinguished, in which 56 papers were analysed. All of them were published in the last decade. About one third are CBAs, while about two quarters each contain MCDAs and LCAs.

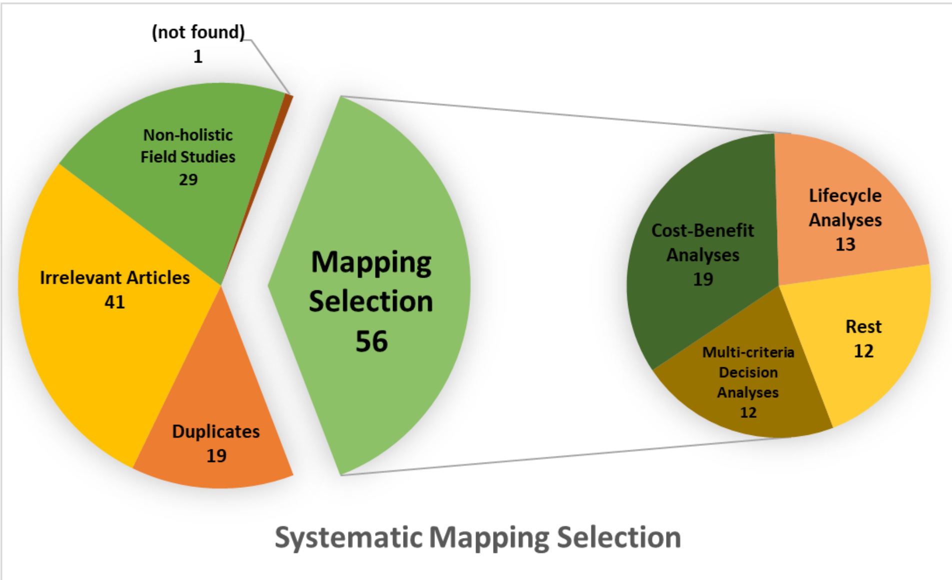

Figure 22: Visualisation of systematic mapping selection

When taking a look at the yearly evolution, it is clear that all MCDAs are quite recently published (only 5 years old at best). The CBAs have grown very steeply since 2017, as did the MCDAs.

After having analysed each category, it should be clear to see what improvements could be made in the research field, and what are already developed items. To clarify this last sentence, a hypothesis will be made: the cost-effectiveness needs to be improved, but the functions of green roofs/walls outperform the functions of regular roofs and walls (for example: green roofs and walls insulate much better than regular alternatives).

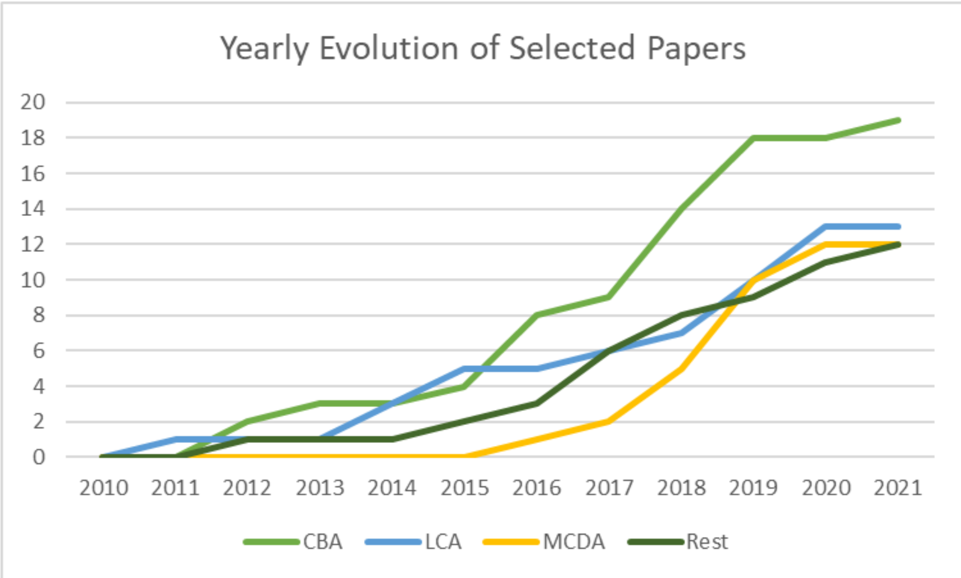

Figure 23: Yearly evolution of systematic mapping selection

The hypothesis will be evaluated at the end of this chapter. Also, it is assumed that the reader already knows how to distinguish CBAs from LCAs and MCDAs. But to summarise it in a nutshell:

- Cost-Benefit Analyses are analyses that focus on the investment of a certain product, weighing the costs against the benefits. The scope of a CBA can vary: sometimes, only private costs and revenues are included; other times, for instance, the scope expands to a societal scale, also including social costs and social revenues. The net present value (NPV) can be used as an indicator to whether the investment has positive long-term returns or not, just like the payback period (PBP) can be another indicator.
- LifeCycle Analyses (or: lifecycle assessments) come from the same nature as CBAs do, but instead of using monetary units to express the results, the focus here lies on the environmental damage done during the lifetime of the product. The scope, again, can vary: some LCAs, for example, focus only on the production phase of the product (so-calles "gate-to-gate" LCAs), other LCAs include the whole life of a product, from resource production to recycling the product (these are called cradle-to-cradle LCAs). Indicators to express the results of an LCA can be damage categories, like 'human health' or 'climate change'. But the categorisation fully depends on the method that is used to perform the analysis (ReCiPe, EcoIndicator,…).
- Multi-Criteria Decision Analyses are assessments that help the investor to make the right decision when intending to buy a product. An MCDA helps to identify the factors that impact the decision-making the most: these can be financial factors (e.g. when a high price is what

keeps investors from investing), environmental factors (e.g. when a product has an ecological footprint that is too big), or even political factors (when for instance there is a lack of subsidies that keeps investors from investing). There can be multiple methods to quantify the decision factors: this ranges from factor analysis methods (EFA: exploratory factor analysis, PCA: principal component analysis) to hierarchy-based classification methods (analytic hierarchical process).

4.4 The cost-benefit analyses

The following paragraphs will be based on the CBA table in the appendix (chapter 7).

In the following paragraphs, no citations of the selected articles will be used, in order to maintain the readability of the paragraphs. This is to avoid unpleasantness when having to read ten citations in one row, just because of the fact that they all concluded the same finding, for instance. The relevant citations, however, will be added in the tables (appendix) and reference list at the end of this paper.

4.4.1 Global findings

For this table of CBAs, only two scenarios were analysed every time: the best and the worst scenario. Scenarios in between were not analysed. This decision was made with the intention to provide a range of CBA values (like an NPV ranging from -1200 euros to 500 euros for 1m² of green roof), rather than evaluating standalone scenarios; this made the comparison of values easier.

When taking a first look at the table, it immediately becomes clear that there are more CBAs on green roofs than green walls, like it was the case with the research in general (see: bibliometric analysis). However, of the green roofs, almost exclusively extensive green roofs have been analysed. This could be linked to its lower installation cost and less intensive maintenance in general, compared to the green intensive roofs (the name 'intensive' implicates this too, of course) (see also: literature research, chapter two).

Almost all of the CBAs of green roofs are calculated on them having a lifespan of at least 40 years or higher, and the main indicator to express the CBA results nearly always was the NPV (net present value), followed up by the PBP (payback period) of the installation. The bigger part of the results provided sensitivity analyses as well, and a couple of sensitivity analyses were done with Monte Carlo calculations.

The NPV on green roofs ranged from -130 euros to 579 euros (expressed in the table as 696 dollars), and the NPV of green walls ranged from -1586 and 8359 euros. Both expressed in euros per square metre. However, the longer the lifespan of the roofs/walls, the higher its NPV seemed to be. This can be explained by the longer-lasting life of green roofs and walls compared to its 'regular' substitutes (as was mentioned in chapter two), because of avoided roof replacement costs after, e.g. 25 years.

Globally, the NPV ranges seemed to be mostly positive: most of them lied between 0 and 300 euros per square metre. Some of the NPVs were negative, this was the case more often for green walls than for green roofs.

The Payback Period (PBP) ranged from 4 to 50+ years, seeming less sensitive to the proposed lifespan of the roofs/walls.

The B/C (benefit/cost) ratio was varying from 0 to nearly 4, but this couldn't be expressed per m², so this B/C carried a small bias.

4.4.2 Most influential costs and benefits

In the table, the most influential costs and benefits on the CBAs were noted. It immediately becomes clear that the most influential costs of green roofs and green walls are either the installation costs or maintenance costs (both fairly equal according to the literature, but not noted in the table). The benefits of green roofs and walls seemed harder to quantify, but energy savings, as well as aesthetics and the increase in property value were the most influential benefits.

4.4.3 Constraints

The biggest constraint was the non-inclusion of social costs and benefits in some articles. The NPV was clearly higher in CBAs where the social perspective was included. However, there still were some negative NPVs, but less extensive ones. The reason behind this was that green roofs and green walls provide much more societal benefits than they provide private benefits. Thus, when calculating these benefits into the CBA, vertical greening systems become much more interesting.

The results seemed not to vary from within Europe to out of Europe that much, neither NPV-wise nor cost/benefit-wise.

4.4.4 CBAs: conclusion

It is clear that the NPV of green roofs/walls still is highly volatile, and mostly due to its scope of costs and benefits included. For instance, the CBAs tend to be more optimistic when accounting for social costs and benefits. However, the lack of private benefits tend to explain the fact that the most influential costs still outweigh the benefits. This could perhaps be changed with governmental incentives, or by decreasing installation costs (either through process optimisation or production upscaling, although the latter one can only exist when enough demand is provided, perhaps by raising awareness).

4.5 The multi-criteria decision analyses

The following paragraphs will be based on the MCDA table in the appendix (chapter 7).

In the following paragraphs, no citations of the selected articles will be used, in order to maintain the readability of the paragraphs. This is to avoid unpleasantness when having to read ten citations in one row, just because of the fact that they all concluded the same finding, for instance. The relevant citations, however, will be added in the tables (appendix) and reference list at the end of this paper.

In short: MCDAs identify the most influential decision factors when considering buying a product. In this case, the product is either a green roof or a green wall.

4.5.1 Global findings

For this table of MCDAs, almost exclusively green roofs were assessed. The top three criteria were taken, as well as the most occurring limitations of the articles. What's worth mentioning is that the MCDA research seems like it is a very 'new' assessment applied to green infrastructure: the MCDAs included in this mapping were published just starting from 2016. The bigger part comes from out of Europe, and mostly seems to use the Fuzzy Delphi Method in order to determine the criteria. The methods of analysis seem to differ a lot, going from AHP (analytic hierarchic process) to even factor analyses (principal components, PCA, and exploratory factors, EFA). The use of different methods does not seem to impact the top three influential criteria.

4.5.2 Most important criteria

The criteria in the table are 'marked' with categories: FIN (financial), FNC (functional), SOC (social), KNO (knowledge) and GOV (governmental) categories. The results vary among the types of green roofs. The key decision factors of extensive green roofs are functional – people need to be guaranteed that extensive green roofs can serve their eco-performant purpose before they consider buying them. For the purchase of intensive green roofs, the functional decision factors seem to be the most important as well, but there is a focus on social results as well – the roofs' physical accessibility, for example, is more important for intensive green roofs (which is in line with the preferred aesthetic benefits it can offer, see chapter two).

Government incentives also seem to be influential, which supports the suggestions made in the conclusion of the CBA analysis (previous paragraphs). The findings in the CBA analysis further suggested an increase of demand by increasing awareness – this apparently is another important decision factor in the MCDAs, that states mostly that the benefits of green infrastructure are unknown to the potential purchasers.

4.5.3 Constraints

There are no real constraints in the decision factors, only the lack of results generalisation, for as most of these MCDAs were conducted in a specific region, having specific policies. Therefore, governmental incentives and other social factors could be less or more important than originally presented in these findings.

4.5.4 MCDAs: conclusion

The biggest decision factor of green infrastructure is its functionality: the ability to outperform traditional systems at e.g. stormwater retention or insulation. The CBA analysis suggested the importance of the cost of green infrastructure, which is supported by the findings of the MCDA results. The total costs matter; the government can aid in mitigating these costs, as was stated by the findings, either through incentives or by raising awareness of the range of benefits these systems can offer.

4.6 The lifecycle assessments

The following paragraphs will be based on the LCA table in the appendix (chapter 7).

In the following paragraphs, no citations of the selected articles will be used, in order to maintain the readability of the paragraphs. This is to avoid unpleasantness when having to read ten citations in one row, just because of the fact that they all concluded the same finding, for instance. The relevant citations, however, will be added in the tables (appendix) and reference list at the end of this paper.

4.6.1 Global findings

When taking a first look at the table of LCAs, it can be noted that nearly half of the articles are reviews on LCAs of green roofs/walls. This is not so beneficial for the results of this analysis, for as the 'number one hotspot' cannot be identified from an LCA review (only if it should really stand out from the rest, that is, but this was not the case).

The results were not very clear to analyse, for as LCAs have many different ways of being conducted. The impact categorisation method is a first barrier to be able to properly compare the results of this mapping. A lot of methods were used, but Recipe seemed to be returning the most. Both European and non-European LCAs were done, but the results did not seem to differ that much.

Concerning waste treatment, landfilling was the most-often used method of disposal. However, some steps were taken in the direction of reuse: a few LCAs opted for composting of the plants or reusing the soil for agricultural purposes. The LCAs that didn't reuse the materials often proposed incineration of the materials (where possible).

The individual LCA conclusions supported the logic of construction quantities: the more materials that are needed to construct the system, the more damaging it is in its life cycle. In other words: extensive green roofs have a more environmentally beneficial lifecycle than intensive green roofs do, and green façades do better as well, compared to living walls.

4.6.2 Top impact categories and hotspots

Despite the less accurate results due to the accentuated presence of reviews, the human health impact category came out as the most important one. The LCA literature suggested high impacts on air quality (which was often included in the Human Health impact category), or temperature (affecting human health through overheating, for instance). These impacts were also explained in chapter two.

The top hotspot was nearly unanimous: materials production was the highest-impacting stage in the life cycle of the green infrastructure. This could be a complementary finding to the high production cost of green infrastructure (found within the CBA analyses): if the environment is damaged a lot during the manufacturing phase, the production of the system could be quite intensive, indicating intensive usage of resources and utilities, which could imply extra support for the fact that the production cost is indeed quite high.

4.6.3 LCAs: conclusion

The LCA-analysis was quite restricted. A lot of information was not found exactly as was desired to be found. This was due to the presence of reviews, containing many varying results. The highest impact category of green infrastructure is that of human health, concerning heat-related health issues and air-related health issues. These problems occurred mostly from the production stage of the systems.

It is ironic, however, that the net environmental benefits of green roofs and walls (mitigating the UHI effect, or improving the air quality) are negatively impacted by its very own production stage.

4.7 'The Rest' of the mapping selection

The following paragraphs will be based on the 'The Rest' table in the appendix (chapter 7).

In the following paragraphs, no citations of the selected articles will be used, in order to maintain the readability of the paragraphs. This is to avoid unpleasantness when having to read ten citations in one row, just because of the fact that they all concluded the same finding, for instance. The relevant citations, however, will be added in the tables (appendix) and reference list at the end of this paper.

4.7.1 Contents

This sub-selection contains the 'rest' of the articles. Although being termed as mere 'residuals', each article serves its purpose in enhancing the findings of this systematic mapping.

The contents are varying. Two articles discuss the willingness to pay (WTP) for green roofs and green walls, other articles research the sustainability of the infrastructure, and there are even 'supporting' articles for the LCAs and CBAs.

4.7.2 Global remarks

Most of the articles suggest the same findings as in the previous paragraphs (CBAs, LCAs, MCDAs). The financial aspect of vertical greening isn't attractive enough on its own to sell the product. The products itself (being green roofs and walls) are, functionality-wise, better than its alternatives (being traditional roofs), but just "aren't there yet", holistically. WTP articles suggest a rather low WTP, due to the lack of information that the customer has about green roofs/walls.

There are two articles in the selection that support the other selections: one for the CBAs, and one for the LCAs. The first one proposes a working scheme in order to conduct the CBA accurately and structurally, while the other one states that the Recipe method is the most useful when evaluating the impact of building technologies (within the scope of an LCA).

Another interesting point is the confirmation that green infrastructure isn't (cost-benefit-wise) interesting when only accounting for a private scope. The scope of analysis needs to include the externalities in order to make the installation of said infrastructure attractive.

Large-scale implementation of green roofs and walls is far from being an existing reality, because there are a number of factors that lower the degree of intention to purchase such infrastructures: e.g. financial (high cost), or social (the production phase still greatly damages the environment) factors.

4.7.3 The Rest: conclusion

Despite being termed 'the rest', this selection contains many useful additions to the findings of the other three selections. This was also the main reason behind the inclusion of these articles in the final selection.

4.8 Conclusion: systematic mapping

The systematic mapping helped to gain useful insights in relevant assessment categories: CBAs, LCAs, MCDAs, WTPs and other supporting articles. All of them identified the manufacturing phase as either the most damaging or most costly phase of the green infrastructure lifespan. The perception of green roofs and walls is quite low, as was pointed out in the MCDAs' conclusion and the rest's conclusion. In other words: people perceive the investment in green roofs and green walls as not very beneficial, due to its high costs, for instance, as well as due to the lack of knowing all of the infrastructure's real benefits. When awareness and the amount of available information about the greening systems would increase, the benefits would become clearer to the people, and to the government as well. This can mitigate the financial impact of the manufacturing phase, either through government incentives, or through an increase in demand (which results in upscaling the production, lowering the production cost per unit). The outcome would be the same: through process optimisation, a lower cost (a financial cost as well as an environmental cost) can be achieved. Together with a decreased environmental impact, the lower cost and raise in awareness contribute to reaching the equilibrium of people, planet, and profit: sustainability.

5 Final conclusion

"It always seems impossible until it's done."

- Nelson Mandela

5.1 Summary of the research questions

All of the 20 research questions were answered in this thesis: it is now clear what green roofs/walls are, what they can provide, what amounts of research are conducted on these infrastructures, that there is a good amount of collaboration amongst the research field (on an author-, organisation-, and country-level) which stimulates innovation, and what the shortcomings of reaching full sustainability are (as of today). For illustrative purposes, the research questions are repeated one more time below, with references to their respective answers as well.

1. What are green walls? What are green roofs? (pgs. 16-30)
2. What are the types of green walls and green roofs? (pgs. 17, 23)
3. What are the components of green walls and green roofs? (pgs. 18-19, 23-24)
4. What are the functions of green walls and green roofs? (pgs. 19-21, 25-27)
5. (GW) How many documents/authors/journals/organisations/countries/… are included in the research field? (pg. 42)
6. (GW) What is the yearly evolution of the research field (no. of articles)? (pgs. 42-43)
7. (GW) What does the author network look like? Is it clustered or highly collaborative? (pgs. 43-45)
8. (GW) Is there inter-organisational cooperation, or do the collaborations happen mostly in the same organisations? (pgs. 45-46)
9. (GW) Is there international cooperation? (pgs. 47-48)
10. (GW) What are the most cited and the most trending articles? (pgs. 48-49)
11. (GW) What are the topic clusters of the research field? Is there a difference in intensity? (pgs. 49-51)
12. (GR) How many documents/authors/journals/organisations/countries/… are included in the research field? (pg. 54)
13. (GR) What is the yearly evolution of the research field (no. of articles)? (pgs. 54-55)
14. (GR) What does the author network look like? Is it clustered or highly collaborative? (pgs. 55-56)

15. (GR) Is there inter-organisational cooperation, or do the collaborations happen mostly in the same organisations? (pgs. 56-57)
16. (GR) Is there international cooperation? (pgs. 58-59)
17. (GR) What are the most cited and the most trending articles? (pgs. 59-60)
18. (GR) What are the topic clusters of the research field? Is there a difference in intensity? (pgs. 61-63)
19. What is the current state of sustainability concerning green roofs and walls? (pgs. 65-73)
20. What is needed to reach sustainability? (pgs. 65-73)

5.2 Final thoughts

This thesis started with a literature research, which indicated the possible critical parts of today's research field of green roofs and green walls. There, it was concluded that green roofs and green walls hadn't reached full sustainability yet. This finding was then further supported in the second research, a bibliometric study, by concluding there was indeed not that much research done on all cost-relevant assessments (CBAs, LCAs, MCDAs and other assessments). Instead, a lot of research was conducted on the benefits of green walls: decreasing the temperature effects, saving energy, retaining stormwater, etcetera. Much less attention was given to the costs of green roofs and walls (them being either private or social costs). These cost assessments were taken a closer look at in the third research of this paper: the systematic mapping, where a more thorough analysis was conducted. In this systematic mapping, the conclusions were clear: the production phase is the most damaging phase in the usage of green roofs/walls. Be it on an environmental or economic level, these production costs are the main setback into considering purchasing green roofs/walls. With enough help of the government, by raising awareness as well as providing incentives, the full potential of green roofs/walls will be unlocked, mitigating the environmental issues of urbanisation, thanks to all of their benefits.

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7 Appendix

7.1 Green walls: bibliometric research tables

Author clusters: tables

CLUSTER	***NO. OF AUTHORS***	***SHARE***
light blue	37	2.25%
orange	30	1.82%
yellow	24	1.46%
dark blue	35	2.13%
dark green	26	1.58%
purple	48	2.91%
light green	43	2.61%
red	30	1.82%
grey	5	0.30%
TOTAL	278	16.88%

Table 11: The author clusters

Organisation clusters: tables

CLUSTER	***NO. OF ORGANISATIONS***	***SHARE***
grey	26	3.82%
orange	26	3.82%
pink	22	3.23%
dark green	17	2.50%
yellow	16	2.35%
light green	42	6.17%
blue	30	4.41%
purple	38	5.58%
	210	30.84%

Table 13: The organisation clusters

NAME	***CLUSTER***	***REAL DEGREE***
Jim C	grey	8.833
Irga P	Light Blue	4.82
Torpy F	Light Blue	4.82
Perini K	dark green	4.666
Pettit T	Light Blue	2.428
Urrestarazu M	orange	2.351
Ottele M	dark green	2.266
deletic A	purple	2.133
wong n	purple	2.133
Kang J	dark blue	2.116

Table 12: Top ten contributing authors

ORGANISATION	***CLUSTER***	***DEGREE***
Univ New South Wales	purple	23
Arizona State Univ	purple	21
Univ Almeria	orange	18
Univ Lleida	orange	13
Univ Perugia	purple	13
Chinese Univ Hong Kong	purple	13
Univ Malaya	dark green	12
Univ Melbourne	purple	11
Univ Teknol Malaysia	dark green	10
Chinese Acad Sci	blue	10

Table 14: Top ten organisations

Country clusters: tables

CLUSTER	***NO. OF COUNTRIES***	***SHARE***
blue	7	10.29%
purple	21	30.88%
orange	7	10.29%
yellow	2	2.94%
green	13	19.12%
grey	5	7.35%
pink	3	4.41%
TOTAL	58	85.29%

Table 15: The country clusters

COUNTRY	***CLUSTER***	***DEGREE***
USA	purple	24
Australia	purple	18
Italy	orange	18
Peoples R China	purple	15
England	purple	14
Spain	blue	11
Japan	purple	11
Netherlands	orange	10
Germany	green	10
Denmark	green	10

Table 16: Top ten countries

7.2 Green roofs: bibliometric research tables

Author clusters: tables

cluster	no. of authors	share
orange	108	2.17%
light green	191	3.83%
red	83	1.67%
purple	479	9.62%
dark green	79	1.59%
yellow	176	3.53%
dark blue	129	2.59%
light blue	120	2.41%
total	1405	28.21%

Table 17: The author clusters

name	cluster	real degree
Jim C	purple	25.250
Lundholm J	orange	13.215
Rowe D	dark green	10.148
Stovin V	dark blue	7.589
Wang Z	purple	6.619
Santamouris M	yellow	6.534
Macivor J	orange	6.240
Sailor D	yellow	6.167
Nagase A	orange	5.916
Li y	purple	5.565

Table 18: Top ten authors

Organisation clusters: tables

Modularity class	No of organisations	share
green	31	0.017475
red	22	0.012401
dark blue	23	0.012965
purple	38	0.021421
yellow	45	0.025366
orange	39	0.021984
light blue	30	0.016911
beige	11	0.006201
total	239	0.134724

Table 19: The organisation clusters

Organisation	degree	cluster
Univ Bologna	51	yellow
Univ Perugia	45	yellow
Natl Univ Singapore	43	purple
Arizona State Univ	43	purple
Univ Sheffield	40	green
CNR	40	yellow
Univ Lorraine	38	orange
Univ Palermo	37	yellow
Univ Melbourne	36	purple
Chinese Acad Sci	33	beige

Table 20: Top ten organisations

Country clusters: tables

MODULARITY CLASS	***NO. OF COUNTRIES***	***SHARE***
light green	29	32.95%
purple	32	36.36%
blue	9	10.23%
dark green	6	6.82%
orange	6	6.82%
total	82	93.18%

Table 21: The country clusters

COUNTRY	***CLUSTER***	***DEGREE***
USA	light green	43
England	light green	34
Italy	purple	31
Australia	light green	29
Spain	purple	29
Canada	light green	28
Netherlands	purple	26
France	blue	22
Germany	purple	21
Peoples R China	light green	20

Table 22: Top ten countries

7.3 Green walls: bibliometric research graphs

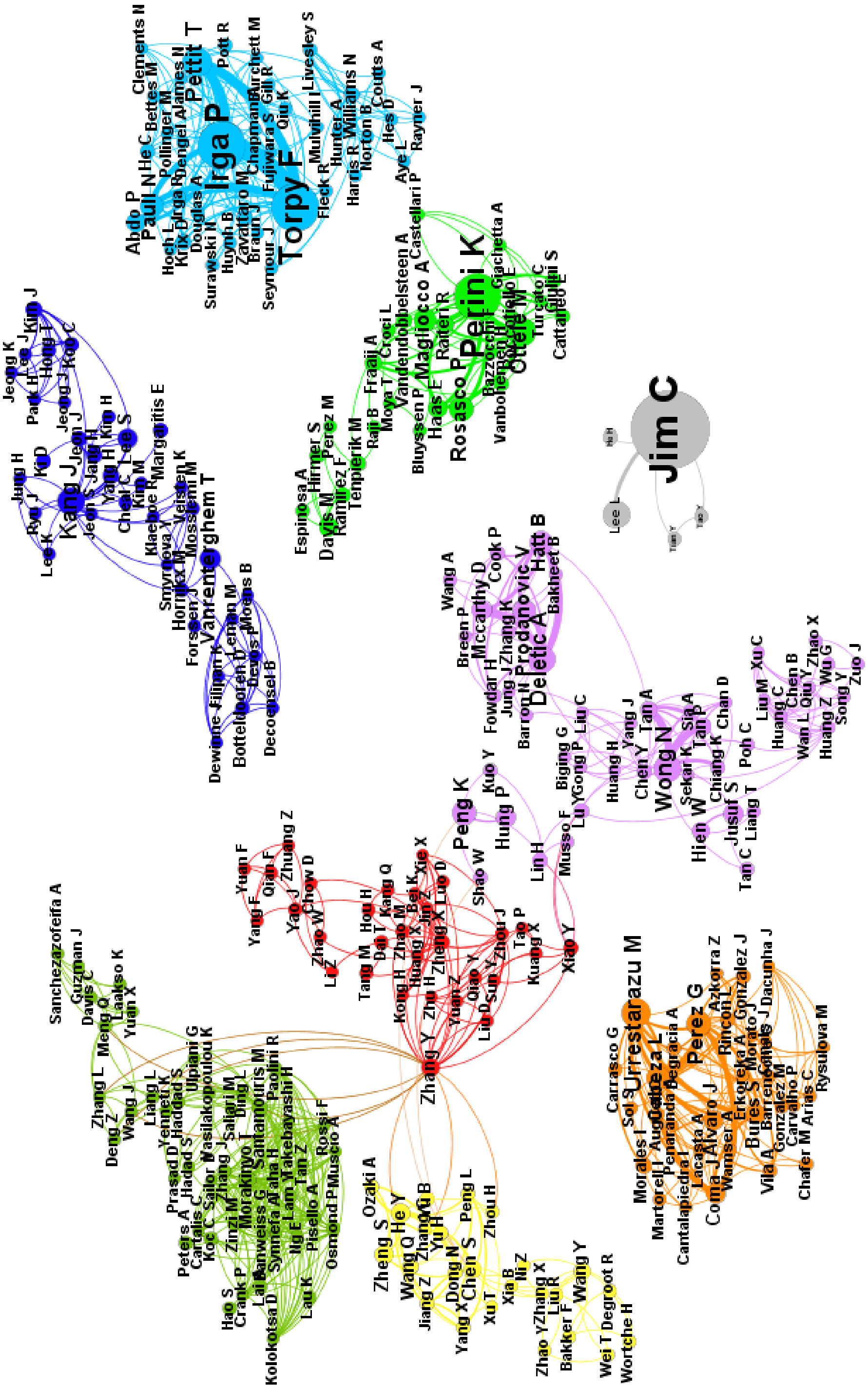

Figure 24: GW Author cluster network (large)

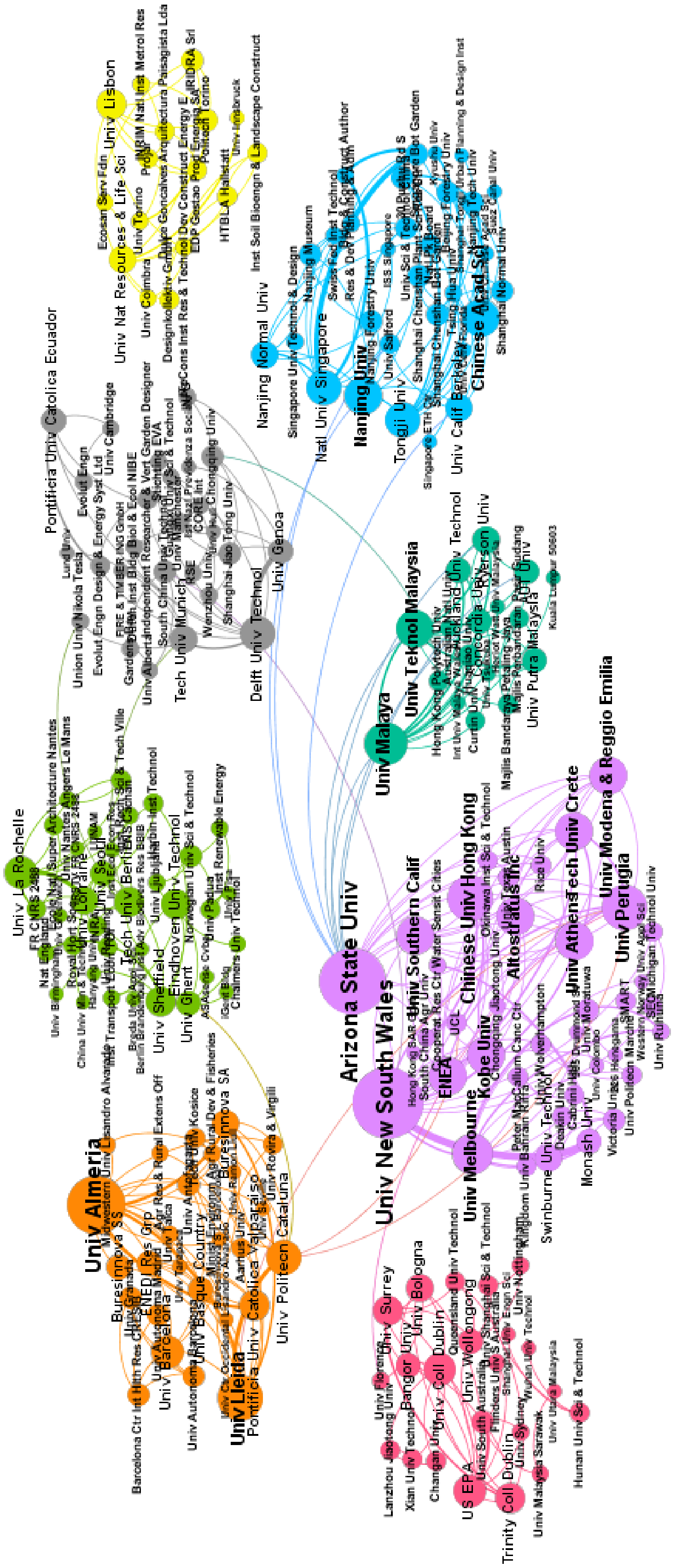

Figure 25: GW Organisation cluster network (large)

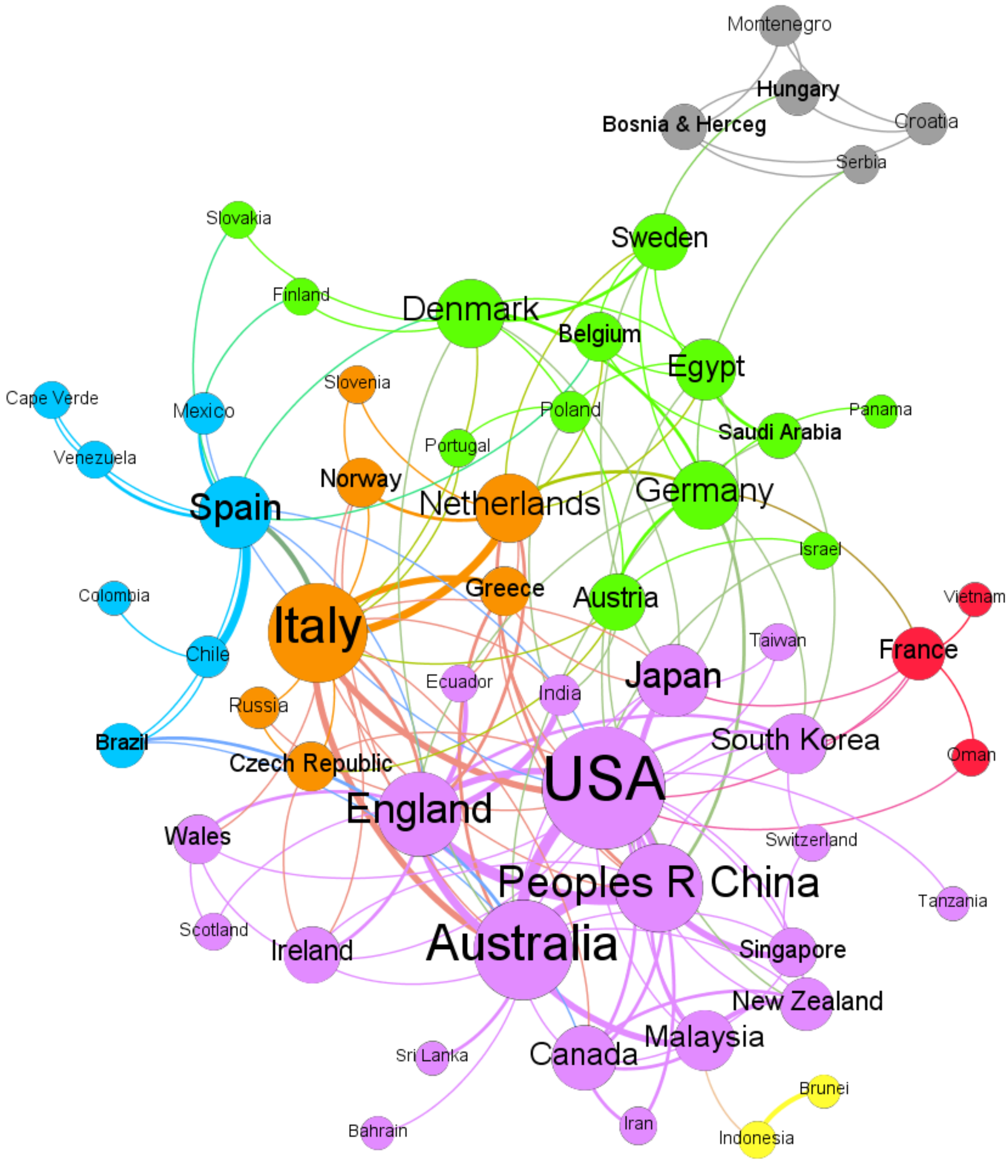

Figure 26: GW Country cluster network (large)

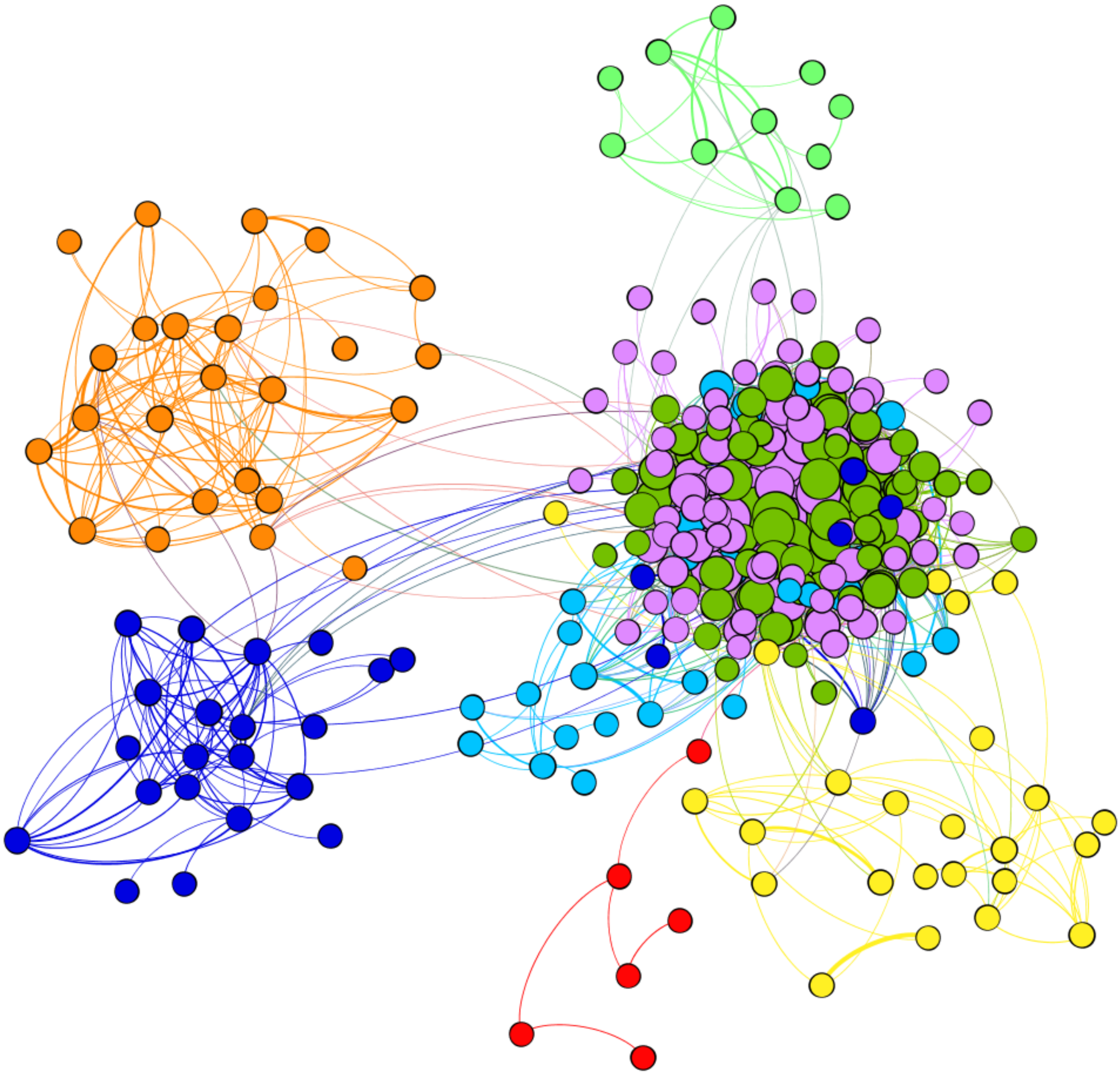

Figure 27: GW Bibliographic coupling network (large)

7.4 Green roofs: bibliometric research graphs

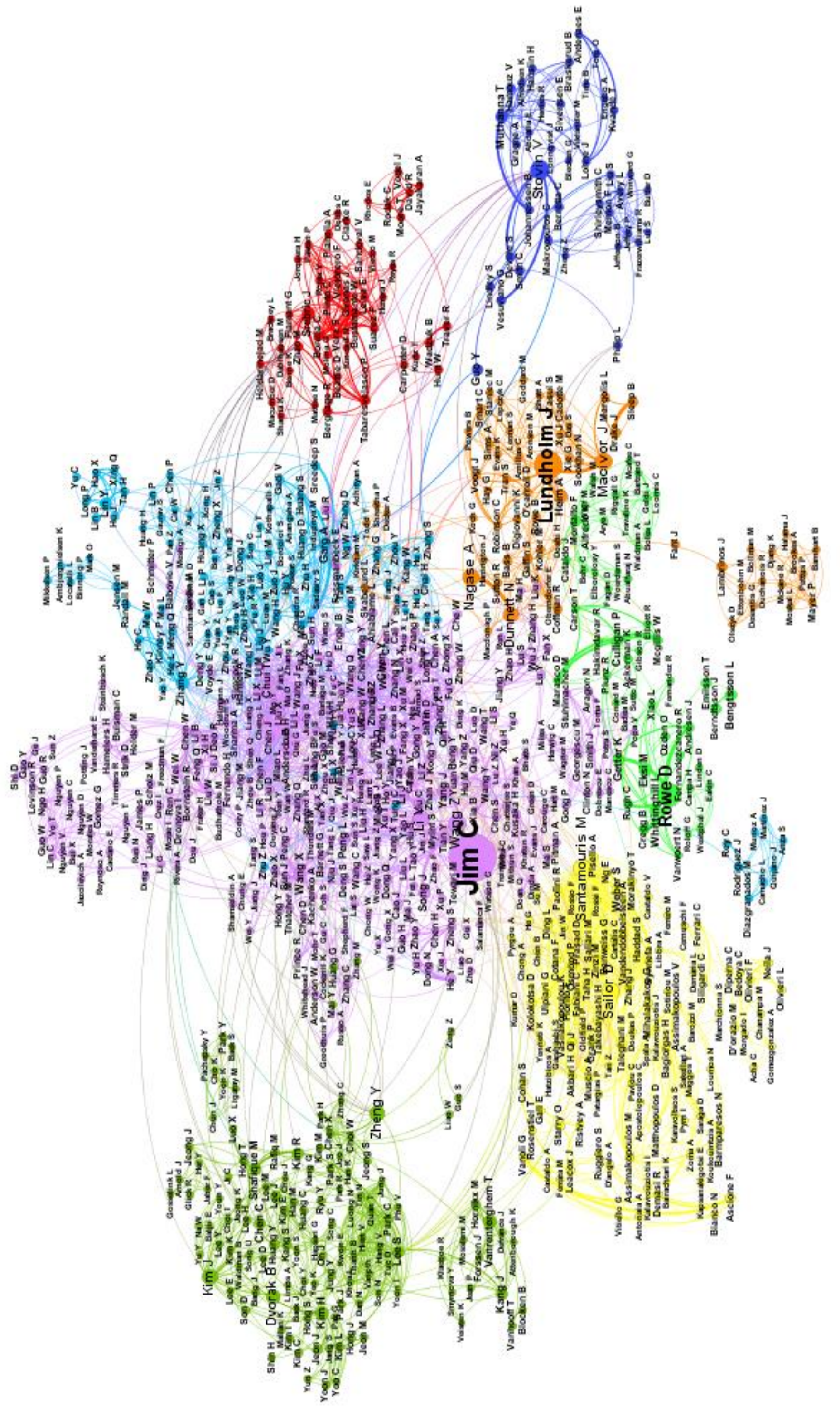

Figure 28: GR Author cluster network (large)

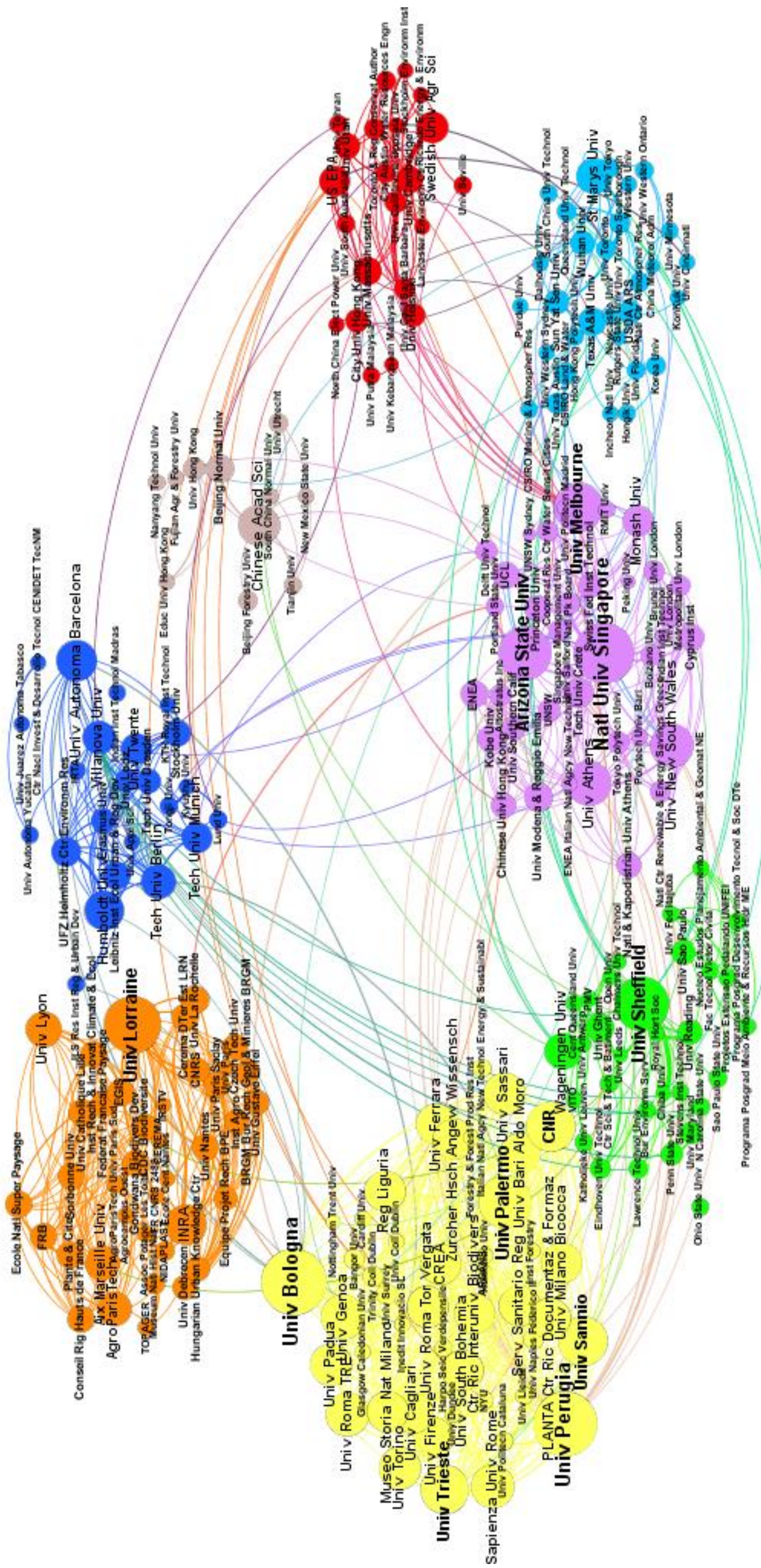

Figure 29: GR Organisation cluster network (large)

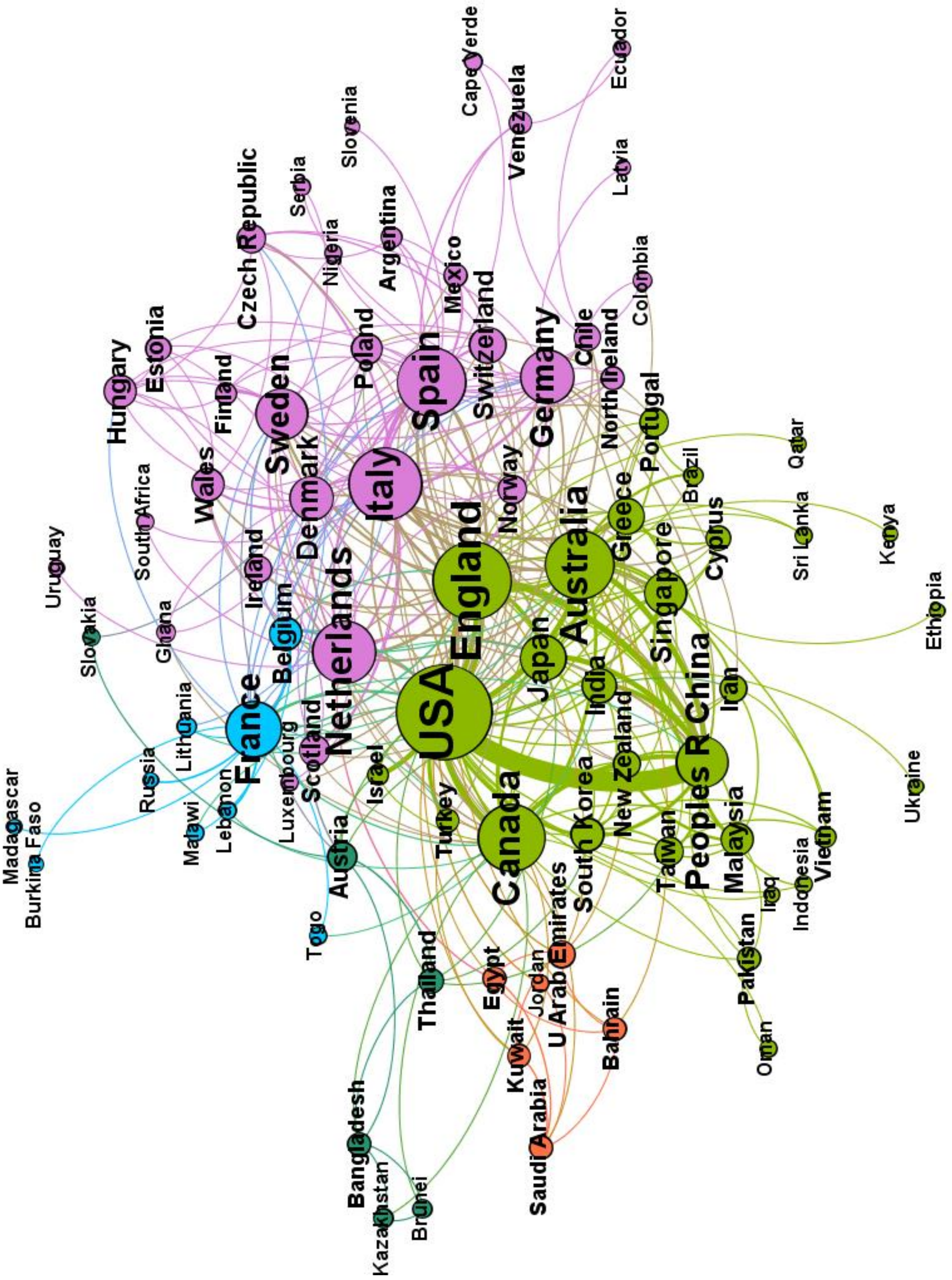

Figure 30: GR Country cluster network (large)

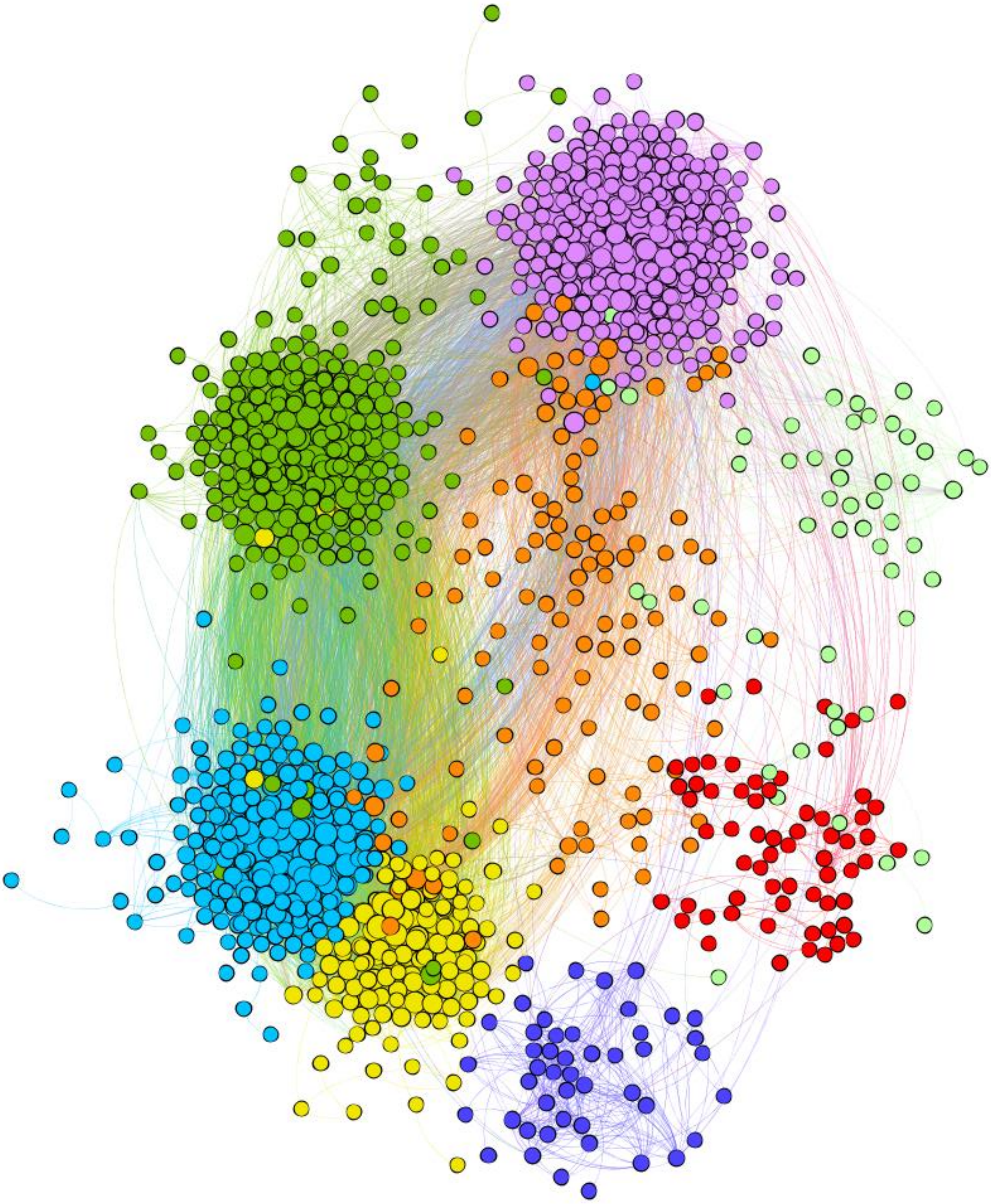

Figure 31: GR Bibliographic coupling network (large)

7.5 Summarising tables: systematic mapping

On the next pages, the summarising tables of the four systematic mapping selection groups are found, in the following order:

1. MCDAs
2. CBAs (part 1 and 2)
3. LCAs
4. The Rest

ID	Title	Region	Roof/Wall	Type	Scenario's	Sens. Analysis?	Lifespan (yrs)	Analysis remarks
1	Socioeconomic feasibility of green roofs and walls in public buildings: The case study of primary schools in Portugal (Almeida, Teotonio, Silva, & Cruz, 2021)	EU	Both	E and F+L	2	Yes	40-50	Lifecycle costing
2	Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach (Mahdiyar et al., 2016)	Non-EU	Roof	E to I	2	Yes	50	Monte Carlo
3	Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical greening systems and green roofs (Perini & Rosasco, 2016)	EU	Both	F+E to L+I	2	Yes	50	
4	Cost-benefit analysis for green facades and living wall systems (Perini & Rosasco, 2013)	EU	Wall	F+L	2	Yes	50	Accounted for inflation
5	Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach (Bianchini & Hewage, 2012)	Non-EU	Roof	E to I	2	Yes	40-55	Monte Carlo
6	GIS-Based Social Cost-Benefit Analysis on Integrated Urban Water Management in China: A Case Study of Sponge City in Harbin (Fan & Matsumoto, 2019)	Non-EU	Roof	E	2	No	40	
7	Benefit-Cost Analysis of Green Roof Initiative Projects: The Case of Jung-gu, Seoul (Shin & Kim, 2019)	Non-EU	Roof	E	2	No	20	Contingent Valuation used for social bnfts
8	The socioeconomic feasibility of greening rail stations: a case study in Lisbon (Silva, Serro, Ferreira, & Teotonio, 2019)	EU	Both	E; F+L	2	Yes	40-50	
9	Eco-solutions for urban environments regeneration: The economic value of green roofs (Teotonio, Silva, & Cruz, 2018)	EU	Roof	E to I	2	Yes	40	
10	A comprehensive study on green roof performance for retrofitting existing buildings (Cascone, Catania, Gagliano, & Sciuto, 2018)	EU	Roof	E	2	No	20	Substrate CBA
11	Case study: A conservative approach to green roof benefit quantification and valuation for public buildings (McRae, 2016)	Non-EU	Roof	E	1	No	25	Lifecycle costing
12	Valuation of Green Walls and Green Roofs as Soundscape Measures: Including Monetised Amenity Values Together with Noise-attenuation Values in a Cost-benefit Analysis of a Green Wall Affecting Courtyards (Veisten et al., 2012)	EU	Wall	L	2	Yes	40	Monte Carlo
13	Enhancing the environmental performance of industrial settlements: An economic evaluation of extensive green roof competitiveness (Berto, Stival, & Rosato, 2018)	EU	Roof	E	2	Yes	40	Monte Carlo
14	Analysing Green Roof Effects in an Urban Environment: A Case of Bangbae-dong, Seoul (Shin & Kim, 2015)	Non-EU	Roof	E	2	No	20	Stormwater Mgmt Analysis
15	Are Neighborhood-level SUDS Worth it? An Assessment of the Economic Value of Sustainable Urban Drainage System Scenarios Using Cost-Benefit Analyses (Johnson & Geisendorf, 2019)	EU	Both	E+F	2	Yes	50	Stormwater Mgmt Analysis
16	Benefit-cost analysis of stormwater green infrastructure practices for Grand Rapids, Michigan, USA (Nordman, Isely, Isely, & Denning, 2018)	Non-EU	Roof	E	1	Yes	50	Stormwater Mgmt Analysis
17	The climatic dependencies of urban ecosystem services from green roofs: Threshold effects and non-linearity (Foudi, Spadaro, Chiabai, Polanco-Martinez, & Neumann, 2017)	EU	Roof	E	2	Yes	79	
18	Green Roof Cost-Benefit Analysis: Special Emphasis on Scenic Benefits (Nurmi, Votsis, Perrels, & Lehvavirta, 2016)	EU	Roof	E	2	Yes	40	
19	Evaluating the economic sustainability of a vertical greening system: A Cost-Benefit Analysis of a pilot project in mediterranean area (Rosasco & Perini, 2018)	EU	Wall	L	2	Yes	25-50	

Abbreviations used

F = Façade L = Living Wall

E = Extensive GR I = Intensive GR

<u>Mapping Table: CBAs (Part 1)</u>

ID	Scenario	#1 Indicator	Monet. unit	#2 Indicator	Best scenario	Most infl. Cost	Most infl. Benefit	Remarks
1	Green Roof			B/C (8.04 to 10.43)	Inconclusive	Maintenance	Property value	Only with social scope it's feasible
	Green wall			B/C (3.01 to 34.99)				
2	Construct and use	NPV (173 to 213/m²)	DOLLAR	PBP (4 to 6)	Construct and use	Installation	Energy Saving	No social cost, no government
	Construct and sell	NPV (-16 to -41/m²)		PBP (not calc.)				
3	GR subsidy	NPV (30 to 60/m²)	EURO	PBP (15 to 20)	GR/GW subsidy	Installation	Subsidy	No social cost
	GR/GW subsidy	NPV (85 to 100/m²)		PBP (7 to 8)				
4	Direct green façade	NPV (44 to 140/m²)	EURO	PBP (16 to 24)	Direct green façade	Maintenance	Energy Saving	Social cost included, IRR calculated
	Living wall	NPV (-541 to -284/m²)		PBP (50+)				
5	Private CBA	NPV (291 to 611/m²)	DOLLAR	PBP (5 to 6)	Private and Social CBA	Installation	Property value	Social cost included
	Private and Social CBA	NPV (400 to 696/m²)		PBP (4 to 6)				
6	Private CBA	NPV (unknown)	RMB	B/C (unknown)	Private and Social CBA	Installation	Property value	Social cost included, No private NPV or B/C
	Private and Social CBA	NPV (70.5/m²)		B/C (1.13)				
7	100% roof coverage	NPV (19/m²)	DOLLAR	B/C (1.174)	100% roof coverage	Maintenance	Rooftop lifespan increase	
	Coverage on public and big private roofs	NPV (-32/m²)		B/C (0.900)				
8	Green roof	NPV (-130 to 442/m²)	EURO		GR	Maintenance	Perceived value (aesthetics etc)	Social cost included
	Green wall	NPV (-1586 to 8359/m²)			Façade i.s.o. LW			
9	Best extensive	NPV (-100 to 163/m²)	EURO		Intensive roof	Maintenance	Property value	Social cost included
	Best intensive	NPV (-218 to 446/m²)						
10	Sedum plant, perlite drainage	NPV (6.72/m²)	EURO	PBP (14.5)	Sedum pl., Perlite dr.	Installation	Energy Saving	No social cost
	Salvia plant, rubber drainage	NPV (0.13/m²)		PBP (19.9)				
11	Green roof vs conventional	NPV (0.58/m²)	DOLLAR	B/C (1.005)	Green roof	Installation	Energy Saving	No social cost
12	High Aesthetic revenu	NPV (243 to 244/m²)	EURO	B/C (3.97 to 3.99)	High aesthetic revenue	Installation	Aesthetics	No discounting used
	Low Aesthetic revenu	NPV (3 to 24/m²)		B/C (1.04 to 1.30)				
13	Private CBA	NPV (-38/m²)	EURO		Private and Social CBA	Installation	Aesthetics	
	Private and Social CBA	NPV (19/m²)						
14	50% of area GR	NPV (7/m²)	EURO	B/C (1.06)	100 of area GR	Maintenance	Air quality	
	100% of area GR	NPV (14/m²)		B/C (1.135)				
15	Low GR GW	NPV (pos/m²)	EURO	B/C (1.33)	Low GR GW	Installation	Property value	Other alternatives of UG are better for stormwater
	High GR GW	NPV (neg/m²)		B/C (0.71)				
16	Green vs conventional	NPV (-3 to 0/m²)	DOLLAR		Green roof is better	Installation	Water quality	Other alternatives of UG are better for stormwater
17	Goodvsbad environment			B/C (0 to 2)	High benefits, low costs	Installation	Energy Saving	GR not really useful in good environments (bcs social benefit is lower)
18	Private CBA			B/C (0.4 to 0.8)	Social CBA	Installation	Aesthetics	
	Private and Social CBA			B/C (0.9 to 2.5)				
19	25 years lifespan	IRR (2 to 13%)		PBP (8 to 21)	25 years Lifespan	Installation	Tax Reduction	
	50 years lifespan	IRR (4 to 11%)		PBP (9 to 23)				

Abbreviations used

NPV = Net present value
PBP = Payback Period
IRR = Internal Rate of Return
B/C = Benefit-cost ratio

Mapping Table: CBAs (Part 2)

Title	**Region**	**Roof/Wall**	**Method Determination**	**Method Analysis**	**Type**	**#1 Criterium**	**#2 Criterium**	**#3 Criterium**	**Limitations**
The Hindrances to Green Roof Adoption in a Semi-Arid Climate Condition (Zakeri & Mahdiyar, 2020)	Non-EU	Roof (I+E)	FDM	FANP	I	FIN - Maintenance Cost	FIN - Construction Cost	SOC - Lifecycle Cost	Results Generalisation - Climate
					E	SOC - Lifecycle Cost	FIN - Construction Cost	KNO - Benefits Unknown	
Barriers to green roof installation: An integrated fuzzy-based MCDM approach (Mahdiyar, Mohandes, Durdyev, Tabatabaee, & Ismail, 2020)	Non-EU	Roof (I+E)	FDM	FBWM	I	FIN - Construction Cost	KNO - Benefits Unknown	KNO - No interest	Results Generalisation
					E	KNO - Benefits Unknown	KNO - No interest	GOV - Lack of Policies	
An assessment model of benefits, opportunities, costs, and risks of green roof installation: A multi criteria decision making approach (Tabatabaee, Mahdiyar, Durdyev, Mohandes, & Ismail, 2019)	Non-EU		FDM (Enhanced)	DEMATEL (Fuzzy)		FIN - Construction Cost	FNC - Insulation	FNC - Stormwater Retention	/
A prototype decision support system for green roof type selection: A cybernetic fuzzy ANP method (Mahdiyar et al., 2019)	Non-EU	Roof (I+E)	FDM	FANP (Cybernetic)	I	SOC - Recreational Space	SOC - Accessability	FNC - Stormwater Retention	Results Generalisation - Climate
					E	FIN - Construction Cost	FNC - Structural Possibilities (Weight)	FIN - Maintenance Cost	
Prospects of green roofs in urban Thailand - A multi-criteria decision analysis (Sangkakool, Techato, Zaman, & Brudermann, 2018)	Non-EU	Roof (I+E)	SWOT	AHP		GOV - Lack of subsidies	FNC - UHI Effect	KNO - Benefits Unknown	/
Identifying and assessing the critical criteria affecting decision-making for green roof type selection (Mahdiyar, Tabatabaee, Abdullah, & Marto, 2018)	Non-EU	Roof (I+E)	FDM (Enhanced)	DEMATEL		FNC - Insulation	FIN - Maintenance Cost	FIN - Payback Period	
Green roofs in temperate climate cities in Europe - An analysis of key decision factors (Brudermann & Sangkakool, 2017)	EU	Roof (I+E)	SWOT	AHP		FNC - Stormwater Retention	FNC - UHI Effect/Air Quality	SOC - Aesthetics/Life quality	No distinguishment IGR and EGR --- Results Generalisation
Selection of (Green) Roof Systems: A Sustainability-Based Multi-Criteria Analysis (Rosasco & Perini, 2019)	EU	Roof (E)	Focus Group	AHP	E	FNC - Insulation	FNC - Roof Protection	FNC - Structural Possibilities (Weight)	Only extensive green roofs
Sustainable roof selection: Environmental and contextual factors to be considered in choosing a vegetated roof or rooftop solar photovoltaic system (Dimond & Webb, 2017)	Non-EU	Roof (E)	Review	/	E				No ranking of benefits
Decision support system for green roofs investments in residential buildings (Teotonio, Cabral, Cruz, & Silva, 2020)	EU	Roof (I+E)	MACBETH	FPV					
Perception and Barriers to Implementation of Intensive and Extensive Green Roofs in Dhaka, Bangladesh (Hossain, Shams, Amin, Reza, & Chowdhury, 2019)	Non-EU	Roof (E)	Questionnaire (100)	RII	E	GOV - Lack of subsidies	FIN - Maintenance Cost	KNO - No interest	Results Generalisation
Public perceptions and attitudes toward green infrastructure on buildings: The case of the metropolitan area of Athens, Greece (Tsantopoulos, Varras, Chiotelli, Fotia, & Batou, 2018)	EU	Both	Questionnaire (400)	PCA/EFA		FNC - Insulation	SOC - Accessability	SOC - Aesthetics/Life quality	

Abbreviations used

FDM = Fuzzy Delphi Method

FANP = Fuzzy Analytic Network Process

FBWM = Fuzzy Best-Worst Method

AHP = Analytic Hierarchical Process

FPV = Fundamental Value Point

RII = Relative Importance Index

DEMATEL = Decision Making Trial and Evaluation Laboratory

MACBETH = Measuring Attractiveness by a Categorical-Based Evaluation Technique

I = Intensive

E = Extensive

Mapping Table: MCDAs

Title	Region	Review	Type	Scope	Waste management	Method IA	Top impact categories	Hotspots phases	Remarks/Conclusions
Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle-based environmental indicators (Lamnatou & Chemisana, 2015)	EU	No	Roofs (E+I)	Cradle-to-grave	Composting (plants), agriculture (soil), landfill (rest)	Recipe	Human Health, Resources	(unknown)	Intensive GR bigger impact than extensive
Photovoltaic-green roofs: a life cycle assessment approach with emphasis on warm months of Mediterranean climate (Lamnatou & Chemisana, 2014)	EU	No	Roofs (E+I)	Cradle-to-grave	Composting (plants), agriculture (soil), landfill (rest)	EI99; IMPACT2002+	HH+RES (EI99), HH+CC (IMPACT)	Material Production	Intensive GR bigger impact than extensive
An overview of life cycle assessment of green roofs (Shafique et al., 2020)	Non-EU	Yes	Roofs	(multiple)	(unknown)	(multiple)	(multiple)	(unknown)	
Environmental performances and energy efficiencies of various urban green infrastructures: A life-cycle assessment (Wang et al., 2020)	Non-EU	No	Roofs (S-I)	Cradle-to-grave	Incineration (plants), landfill (rest)	(unknown)	GWP?	(unknown)	Other UGI alternatives are better
Modeling the substitution of natural materials with industrial byproducts in green roofs using life cycle assessments (Pushkar, 2019)	Non-EU	No	Roofs (E)	Cradle-to-grave	Landfill	Recipe	(unknown)	Material Production	Natural materials as substrate and drainage layer are better than perlite-based
Progress on environmental and economic evaluation of low-impact development type of best management practices through a life cycle perspective (Xu, Jia, Xu, Long, & Jia, 2019)	Non-EU	Yes	Roofs (E+I)	(multiple)	(unknown)	(multiple)	(unknown)	Material Production	
Carbon sequestration potential for mitigating the carbon footprint of green stormwater infrastructure (Kavehei, Jenkins, Adame, & Lemckert, 2018)	Non-EU	Yes	Roofs (E+I)	Cradle-to-grave	(unknown)	(multiple)	(unknown)	Material Production	Other UGI alternatives are better
Mitigation measures to contain the environmental impact of urban areas: a bibliographic review moving from the life cycle approach (Belussi & Barozzi, 2015)	EU	Yes	Roofs/Walls	(multiple)	(unknown)	(multiple)	(unknown)	(unknown)	
Heat island effects in urban life cycle assessment: Novel insights to include the effects of the urban heat island and UHI-mitigation measures in LCA for effective policy making (Susca & Pomponi, 2020)	EU	Yes	Roofs/Walls	Cradle-to-grave	(unknown)	(unknown)	Human Health	(unknown)	
Biodiversity impact assessment of building's roofs based on Life Cycle Assessment methods (Brachet, Schiopu, & Clergeau, 2019)	EU	No	Roofs (E+I)	Cradle-to-grave	Incineration (plants), recycling+landfill (rest)	Recipe	Ecosystems used only	(Layer-only) concrete layer and substrate	Intensive GR bigger impact than extensive
Life-cycle study on semi intensive green roofs (Vacek, Struhala, & Matejka, 2017)	EU	No	Roofs (S-I)	Cradle-to-grave	Landfill	CML2001	Global Warming Potential, Acidification Potential	Material Production	Extra insulation or substrate alternatives are more damaging to environment
Life cycle assessment (LCA) of green facades and living wall systems (Ottele, Perini, & Haas, 2014)	EU	No	Walls (F+L)	Cradle-to-grave	No reuse	Environmental Profile	GWP	Material Production	Facades are less damaging than living walls
Comparative life cycle analysis for green facades and living wall systems (Ottele et al., 2011)	EU	No	Walls (F+L)	Cradle-to-grave	No reuse	Environmental Profile	GWP	Material Production	Facades are less damaging than living walls

Abbreviations used

F = Façade　L = Living wall　IA = Impact Assessment
E = Extensive GR　I = Intensive GR　S-I = Semi-intensive GR

Mapping Table: LCAs

Title	Region	Roofs/Walls?	Subject of research	Hotspots	Conclusions
Implementation of green roof technology in residential buildings and neighborhoods of Cyprus (Ziogou, Michopoulos, Voulgari, & Zachariadis, 2018)	EU	Roofs (E)	Energy and environment analysis	Installation cost high; energy savings high	Green roofs are better than grey alternatives, but cost needs to decrease in order to make them attractive
Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region (Ziogou, Michopoulos, Voulgari, & Zachariadis, 2017)	EU	Roofs (E+I)	Energy and environment analysis	Installation cost high; energy savings high	Not cost-effective, but savings are quite high
Green roof and green wall benefits and costs: A review of the quantitative evidence (Manso, Teotonio, Silva, & Cruz, 2021)	EU	Roofs (E+I)	Review and quantification of costs/benefits GR	Comparable to hotspots LCA and CBA	Very different results altogether
Investing in Sustainable Built Environments: The Willingness to Pay for Green Roofs and Green Walls (Teotonio, Cruz, Silva, & Morais, 2020)	EU	Both	Willingness to pay (with stated preference)	Accessibility, financial	Lack of awareness that GR and GW exist, lack of information leads to low WTP
A system dynamics analysis of the alternative roofing market and its potential impacts on urban environmental problems: A case study in Orlando, Florida (Kelly, Sen, & Tatari, 2020)	Non-EU	Roofs (E+I)	Market analysis	Energy, UHI, Stormwater	Alternative roofs are better, green roofs 'not there yet'
An Insight into the Commercial Viability of Green Roofs in Australia (Tassicker, Rahnamayiezekavat, & Sutrisna, 2016)	Non-EU	Roofs (E+I)	Commercial viability	Policies, Construction	Green roofs have potential to evolve but needs to be supported by government and financials
Media and social impact valuation of a living wall: The case study of the Sagrado Corazon hospital in Seville (Spain) (Perez-Urrestarazu, Blasco-Romero, & Fernandez-Canero, 2017)	EU	Walls (L)	Willingness to pay	Psychological benefit	Other alternatives can have same benefits as well; WTP lies between 100-1000 euros
Vertical greening systems, a process tree for green facades and living walls (Perini, Ottele, Haas, & Raiteri, 2013)	EU	Walls (F+L)	Process Tree	Energy Saving	Economic benefits only appear useful on urban scale, not private
Project GENESIS: An All-inclusive Model to Perform Cost-Benefit Analysis of Green Roofs and Walls (Silva, Cruz, & Teotonio, 2019)	EU	Both	Project GENESIS - A tool and model to perform CBA	Has four tasks to be completed (review - CBA with sensitivity (concept) - case application - outputs)	Enables decision makers to evaluate more accurately and easier
Improving Acceptance of More Sustainable Technologies: Exploratory Study in Brazil (da Rocha & Sattler, 2017)	Non-EU	Both	Finding reasons to adopt GR/GW	Aesthetics are biggest adoption factor; maintenance is biggest non-adoption factor	Findings are in line with other articles, though generalisation is limitation
Green Roof Evaluation: A Holistic 'Long Life, Loose Fit, Low Energy' Approach (Langston, 2015)	Non-EU	Roofs (E+I)	Sustainability analysis (social, environmental, economical)	Economic - higher cost	Only when accounting for all three P's, the real benefits of GR become interesting
ECO-INDICATOR 99, ReCiPe AND ANOVA FOR EVALUATING BUILDING TECHNOLOGIES UNDER LCA UNCERTAINTIES (Verbitsky & Pushkar, 2018)	Non-EU	(unknown)	Comparison of LCIA methods (EcoIndicator99 vs ReCiPe)	(unknown)	ReCiPe is the best evaluation method for building technologies

Abbreviations used

F = Façade   L = Living wall
E = Extensive GR   I = Intensive GR

Mapping Table: The Rest