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Enhancing Landscape Connectivity on an Urban Scale

A study on identifying the optimal green corridor

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Enhancing Landscape Connectivity on an Urban Scale

A study on identifying the optimal green corridor

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Summary (English)

Approximately 55% of the world’s population are living in cities. This number continues to rise and is predicted to surpass 70% by 2050 (UNDESA, 2018). The increasing number of citizens has pressured the demand on the housing market which has led to the expansion of the urban environment. This in turn has led to more greenfield developments which threaten green spaces or eliminate them both in and outside of the city. Particularly, the connections established by green corridors or other similar types of green spaces have generally been severed (Hobbs et al., 1993), damaging the landscape and its connectivity.

Green corridors and green spaces contain a significant amount of flora which contributes to the preservation of biodiversity. As more green spaces and connections disappear, habitat fragmentation in the area increases which leaves many green patches isolated. Habitat fragmentation is considered to be one of the major threats to biodiversity (Keller & Largiadèr, 2003). The positive and negative effects of loss in green space in larger patches are still being discussed. However, it is clear that when a green space or ‘habitat’ for the local species is isolated from other green spaces it can result in an increased extinction rate and lead to a loss of species from the regional species pool, which will ultimately lead to a loss of biodiversity (Ryser et al., 2018).

The general loss of green also has an impact on the urban environment and the quality of life of residents. Planted trees and other forms of green infrastructure play an essential role in reducing man-made pollutants and reducing the effects from urban heat islands (Nowak, 2002; Rizwan et al., 2008). Green spaces also have positive effects on mental and physical health. It reduces the feeling of stress and has a higher tendency to invite residents to a more active lifestyle (Hartig et al., 1996; Lee & Maheswaran, 2011). In turn, residents living in these areas tend to self-report fewer health problems and also have a lower risk for cardiovascular diseases (de Vries et al., 2003; Seo et al., 2019).

Despite the loss of green spaces and the ongoing habitat fragmentation, previous studies have been done to find the optimal ways to re-establish the connections between the green spaces. Generally, these studies focused on the natural environments rather than the urban environment (Zhang et al., 2019) and used theoretical values to model the landscape (Kong et al., 2010). The overall methodology for modeling the landscape is by use of graph theory, least-cost analysis, and the gravity model (Kong et al., 2010; Linehan et al., 1995; Zhang et al., 2019). Though their methodology is similar, they each take a different approach on the subject. Linehan et al., (1995) based its landscape model on specific species in the area, Kong et al., (2010) based its landscape model on theoretical values of the local area, and Zhang et al., (2019) utilized vacant land in the urban environment to establish corridors.

In this research, an attempt has been done to improve the current methods in an effort to enhance landscape connectivity by finding the optimal corridors on an urban scale. The previously mentioned studies applied a different approach to the methodology and so will this. One of the major threats to biodiversity is isolation. The isolation is caused by barriers surrounding its habitat which impedes movement and dispersal of species. Impedance for species in the landscape is generally caused by grey infrastructure (Fu et al., 2010). A model has been created based on values from the previous studies but also the infrastructural intensity in the area to identify potential corridors in the urban environment. To find the

optimal corridors, the corridors are then prioritized by the gravity model and the number of residents it affects. A sidestep has also been made to identify which areas in the study area have less access to all the different functional types of green which gives a choice to focus on the overall human population or those which are more isolated from green spaces. This will ensure that both nature and humans can benefit from these corridors.

The results show many potential corridors for the study area which have been prioritized and evaluated. Networks have been created from the more optimal corridors which have been assessed and would show improvements in network connectivity in comparison to the current situation. The model, potential corridors, and networks have also been discussed in an expert evaluation. The model takes the paths of existing corridors but also identifies potential corridors which are aligned with the vision of the local municipality on developing green corridors.

Summary (Dutch)

Ongeveer 55% van de wereldpopulatie woont in stedelijke gebieden. Zolang mensen naar de stad toe trekken zal dit nummer stijgen, het is voorspelt dat tegen 2050 meer dan 70% van de wereldbevolking in steden zal wonen (UNDESA, 2018). De hoeveelheid mensen in een stad zet druk op de huizenmarkt wat leidt tot uitbreiding van het stedelijk gebied en ontwikkeling in groene gebieden. De ontwikkelingen hebben met name de groene corridors aangetast. De verbindingen die waren vastgesteld door deze corridors zijn door de ontwikkelingen voornamelijk verbroken (Hobbs et al., 1993) en heeft geleid tot schade in het landschap.

Groene corridors bevatten een significante hoeveelheid flora wat bijdraagt aan het onderhouden van biodiversiteit. Naarmate er meer groene gebieden en verbindingen verdwijnen zal habitat fragmentatie in de gebieden toenemen. Dit zorgt ervoor dat leefgebieden geïsoleerd raken van elkaar. Habitat fragmentatie wordt ook wel als een van de grootste bedreigingen gezien voor biodiversiteit (Keller & Largiadèr, 2003). De positieve en negatieve effecten van het verlies van groene gebieden wordt nog steeds bediscussieerd. Maar, het is duidelijk dat wanneer de leefgebieden van lokale soorten geïsoleerd raken van elkaar dat dit leidt tot toegenomen uitsterf cijfers. Uiteindelijk kan de soort verdwijnen uit het gebied en zal de biodiversiteit lokaal omlaag gaan (Ryser et al., 2018).

Het verlies van groen in het stedelijk gebied heeft ook invloed op de kwaliteit van leven van de inwoners. Bomen en andere vormen van groen infrastructuur speelt een essentieel rol in het reduceren verontreiniging in het stedelijk gebied en het verminderen van hitte-eilandeffecten (Nowak, 2002; Rizwan et al., 2008). Groene gebieden hebben ook positieve effecten op zowel mentaal als fysieke gezondheid. Deze gebieden kunnen het gevoel van stress verminderen en nodigen inwoners uit tot een meer actieve levensstijl (Hartig et al., 1996; Lee & Maheswaran, 2011). Daarnaast, inwoners die meer in de groene gebieden wonen rapporteren minder gezondheidsklachten en hebben een lager risico voor hart -en vaatziekten (de Vries et al., 2003; Seo et al., 2019).

Ondanks het verlies van groene gebieden en het aanhoudende habitat fragmentatie, zijn er wel onderzoeken gedaan naar het vinden van optimale manieren om de verbindingen tussen de groene gebieden te herstellen. Over het algemeen waren deze studies gericht op de natuurlijke gebieden ten opzichte van de stedelijke gebieden (Zhang et al., 2019). Hierin werd gebruik gemaakt van theoretische waarde om het landschap te modelleren (Kong et al., 2010). De methodologie die wordt gehanteerd voor het modelleren van het landschap bestaat voornamelijk uit grafentheorie, minste-kosten analyse en het zwaartekrachtsmodel (Kong et al., 2010; Linehan et al., 1995; Zhang et al., 2019). Alhoewel de methodologie voornamelijk hetzelfde is, verschilt de benadering. Linehan et al., (1995) baseerde zijn waarde voornamelijk op een specifiek soort in het gebied, terwijl Kong et al., (2010) theoretische waarden gebaseerd op lokale literatuur gebruikte. Zhang et al., (2019) maakte gebruik van leegstaande gebouwen en grond in het stedelijk gebied voor het vaststellen van nieuwe verbindingen.

In dit onderzoek is een poging gedaan om de huidige methodologie enigszins te verbeteren om landschapsconnectiviteit te verbeteren door het vinden van de optimale groene corridors in het stedelijk gebied. De eerder genoemde onderzoeken benaderde het elk telkens vanuit een andere hoek, en zo zal dit onderzoek dat ook doen. Een van de grootste bedreigingen

voor biodiversiteit is isolatie van de leefgebieden. Dit is voornamelijk veroorzaakt door barrières in landschap dat beweging en verspreiding van soorten hindert en wordt voornamelijk veroorzaakt door grijs infrastructuur (Fu et al., 2010). Een model is gecreëerd op basis van de waarde van andere studies maar ook op de intensiteit van infrastructuur in het gebied. Hiermee zullen potentiële mogelijkheden voor groene corridors geïdentificeerd worden. Vervolgens worden deze geprioritizeerd op basis van het zwaartekrachtsmodel en de hoeveelheid inwoners die er baat bij kunnen hebben. Daarnaast is ook een zijstap gemaakt om gebieden te identificeren waarin inwoners wonen welk weinig toegankelijkheid heeft tot de verschillende functionele typen groene gebieden. Dit geeft een mogelijkheid in de keuze om te richten op de inwoners in het algemeen of de inwoners welk minder toegankelijkheid hebben tot de verschillende typen groen in de stad. Zowel mens als natuur wordt erbij betrokken om ervoor te zorgen dat beide partijen er baat bij hebben.

De resultaten laten veel potentiële corridors zien in het gebied welke geprioritiseerd zijn en geëvalueerd. Netwerken zijn gecreëerd bestaande uit de meest optimale corridors. De netwerken zijn vervolgens beoordeeld en laten verbeteringen zien in landschapsconnectiviteit tegenover de huidige situatie. Het model, de potentiële corridors, en netwerken zijn ook bediscussieerd in een evaluatie met experts. Om paden te creëren voor corridors maakt het model gebruik van bestaande corridors, maar vind het ook nieuwe paden welk in lijn staan met de visie van de gemeente op het gebied van ontwikkelen van groene corridors.

Abstract

The increasing number of people moving towards cities pressures the housing market and forces cities to expand, threatening green areas and the overall landscape connectivity. Green areas such as green corridors contain a significant amount of flora and establish connections between habitats which are beneficial to conserve biodiversity. As cities expanded, green corridors and other green areas have disappeared, severing the connections and fragmenting the landscape. Habitat fragmentation is considered to be one of the major threats to biodiversity and its effects have to be mitigated. This research uses GIS for finding the optimal green corridors in the urban area to connect the patches of high value for improvement and conservation of biodiversity. These green corridors have been found by creating an impedance map based on values from previous studies, and a map that indicates the intensity of infrastructure in the area. These maps are combined using the entropy weight method after which a least-cost algorithm finds the potential paths to connect the patches. The potential paths are then prioritized based on the gravity model and the number of residents it can also affect within its range to ensure both man and nature can profit from the green corridor. The results show that the model utilizes the existing green corridors in the study area but also finds new pathways which are in line with the local municipality's vision of developing green corridors.

Keywords: Landscape connectivity, GIS, Gravity model, Biodiversity, Green corridors, Habitat fragmentation

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1. Introduction

Approximately 55% of the world's population are living in cities and this number continues to rise and is predicted to surpass 70% by 2050 (UNDESA, 2018). As population increases so does the demand for housing which in turn leads to a rapid expansion of the urban environment. The expanding urban environment comes at the cost of green spaces and ecosystems in both the inner and outer edges of the area. A case study showed that a big and fast-growing city like Moscow had a significant reduction in green infrastructure as a consequence of an increasing housing market. The demand for housing has led to urban expansion of open areas not protected by any land use planning. The study concluded that if the process continues at the current rate, most of the urban green space losses will be expected to be in the category of urban forests and parks (Klimanova et al., 2018).

Urban green spaces provide a variety of ecosystem services such as reducing air, water, and noise pollution while at the same time regulating the local climate and allowing for recreational opportunities (Bolund & Hunhammar, 1999). Simultaneously green spaces also serve as a habitat for different species of both flora and fauna and are important for maintaining biodiversity (Kong et al., 2010).

Over time urbanization has eliminated ever more green space, particularly the green corridors connecting one green ecosystem to the other (Hobbs et al., 1993). The loss of connectivity between the green ecosystems within a city has led to habitat fragmentation which threatens biodiversity (Adriaensen et al., 2003). Habitat fragmentation is defined as a process in which a large habitat is split and divided into several smaller patches isolated from each other (Hagen et al., 2012). The isolation and eventual loss of habitats are considered to be one of the greatest threats to biodiversity (Wilcove et al., 1998). An example of a high loss of biodiversity as a result of habitat fragmentation can be seen in Munich, Germany. In the city of Munich, more than 180 plant species went locally extinct over a period of 100 years (Niemelä, 1999). Another example would be Singapore where urbanization has encompassed more than half of the total land area which contributed to the local disappearance of roughly three-quarters of its native species (Brook et al., 2003). These and other examples show the importance of protecting green spaces and conserving the connections between the green spaces in the urban environment to prevent local loss of its biodiversity.

Green spaces contain a significant amount of flora which contribute to the biodiversity in the local area by offering important harbours for remnant biodiversity. The fragmentation of the green spaces in the urban environment can have both positive and negative effects on biodiversity. Currently, there is still an ongoing discussion about whether fragmented habitats (when connected) positively or negatively impact biodiversity compared to larger habitats (Fahrig et al., 2019). However, it is clear that when a greenspace or 'habitat' for the local species is isolated from other green spaces it can result in an increased extinction rate and lead to a loss of species from the regional species pool which will ultimately lead to a loss of biodiversity (Ryser et al., 2018).

It is established that urban green spaces provide a variety of positive effects for both flora and fauna in the local area as it serves as a habitat for different species and is important for maintaining biodiversity. It has also been established that urbanization has led to increasing fragmentation and isolation of many green spaces, which affects the wealth and genetic variation of species (Mckinney, 2002). The connection between green spaces play a key role in the general health of its ecosystem and its resilience to change (Thompson & Gonzalez, 2017). To address the problem of green space fragmentation, connections between green spaces can be achieved by linking them through an elaborate network of green corridors which facilitates dispersal and movement of species (Vergnes et al., 2012). A green corridor is defined by a strip of land which establishes a 'bridge' between two habitats and can be placed alongside walking or cycling routes.

Connecting green spaces in practice has its consequences. Land in cities is generally occupied and comes at a premium price. Zhang et al., (2019) looked at using vacant land and empty spaces of shrinking cities, particularly in Detroit. Their research integrated landscape ecology and graph theory, spatial modelling, and landscape design to identify different pathways through the city in which the current green spaces could potentially be connected. As a result of their research, their proposed green corridors were shown to enhance both structural and functional connectivity.

Similarly, Kong et al., (2010) used the integration of landscape metrics, least-cost analysis, gravity model, and graph theory to identify potential corridors in Jinan City, China. In their research, they developed maps of potential green corridors and compared them to the current city's plan showing which green corridors would improve the networks and biodiversity and to what extent they would do so.

Both these studies showed the potential for green corridors to connect green spaces through either vacant and empty land or with the help of a city plan. Other studies also showed that many connectivity studies have focused on broader spatial scales whereas land-use planning decisions are often made on the municipal level (Randolph, 2003). Hence it is important when connecting green spaces to look at the city-level to maintain connectivity. With strategic planning and extensive research, potential routes can be found in a city to connect the urban green spaces. These routes could be found along the city's centre such as walking and cycling lanes or other potential infrastructure to ultimately increase the city's biodiversity and additionally improve the local quality of life for the citizens.

1.1 Problem definition

With habitats becoming increasingly fragmented as urban development expands, many studies have been done concerning the improvement of landscape connectivity (Randolph, 2003) to counteract the increasing fragmentation. Overall, these studies focus on the rural environment (Kong et al., 2010; Linehan et al., 1995; Wu et al., 2017) while there is much potential in trying to establish connections in or through the urban environment. So far, directly related to the urban environment Zhang et al., (2019) looked into using vacant lands in Detroit for the development of corridors to improve the overall landscape connectivity in the urban environment. Besides, despite the potential of green corridors to improve human well-being, the local human population tends to be ignored while assessing the suitability of green corridors.

The values used to simulate the impedance for local species (or biodiversity) are mostly theoretical (Kong et al., 2010) and thus, subjective. Theoretical values can change and might need to be different based on the situation, which can lead to different conclusions if the methods are applied in another situation.

Thus, there are still improvements to be made in finding the optimal corridors by including both humans and nature into the equation. As well as finding a potential way to objectively quantify the impedances for biodiversity to simulate the landscape so that it can be applied to all kinds of urban areas.

1.2 Research question

The following research question and sub-questions have been created based on the current situation and understanding:

"What are the optimal pathways to enhance landscape connectivity on an urban scale?"

To aid answering this question, the following sub-questions have been formulated:

(1) How significant is the role of landscape connectivity in the urban ecosystem?
(2) What are major impedances for biodiversity in an urbanized environment?
(3) What benefits are there to gain for the local population when establishing green connections between the urban green areas?
(4) What are the basic methods and theories to model landscape connectivity?
(5) What is the current state of the study area with regards to its urban green spaces and connectivity?
(6) What are the potential connections which can be made in the study area to connect the urban green spaces?

1.3 Research design

Based on the main research question and sub-questions, the research consists of five stages. The literature review, the connectivity and green space assessment, landscape connectivity modelling, evaluation, and finally the conclusion. The research design model used for this research van be viewed in Figure 1.

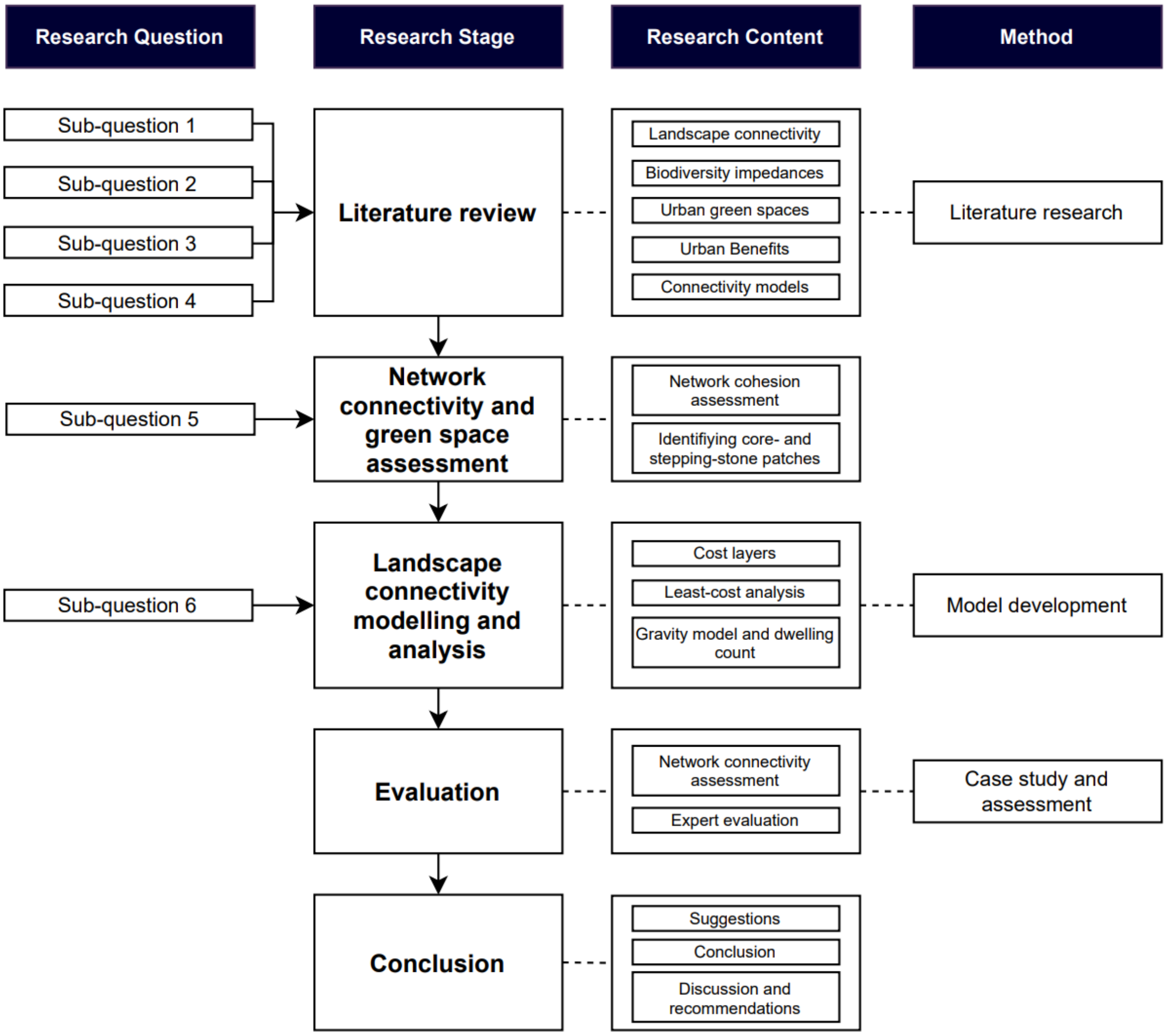

Figure 1 - Research design model

The research starts by reviewing the existing literature. The first subject concerns landscape connectivity, both in an urban and rural setting. The following subject identifies impedances local biodiversity can undergo when moving through the built environment. The next subject is the green spaces in which local species live and thrive within the built environment. Then the benefits for residents living in the urban environment when green spaces or connections are established. Lastly, the current existing theories and methods regarding landscape connectivity modeling will be explored.

Based on the overview gained from reviewing the literature, a brief landscape assessment has been done for the study area to identify its existing conditions and connectivity. Simultaneously, an assessment is done to find the main green areas on which the local biodiversity can live and thrive.

With the existing conditions known, a model has been developed to analyze these conditions further and find potential improvements. The setup for the model consists of creating a cost-layer to be able to deploy the least-cost analysis to find potential improvements in the landscape. These corridors are then prioritized to find the optimal corridors.

In the next stage, the results of the analysis are evaluated, to find out if the identified corridors can improve the landscape connectivity. The standard methods of evaluating the landscape connectivity are applied as well as an expert evaluation.

Lastly, the research is finalized by giving suggestions for the study area as well as answering the main and sub-questions. Lastly, a discussion on the limitations of the research and recommendations for further studies

1.4 Limitations

This study will be limited to the urban environment of the city of Eindhoven. The study will not go as far as understanding the positive effects of increased biodiversity on the surrounding human population and/or environment but look into strengthening the biodiversity by connecting the urban green spaces. The study will also be limited to green spaces without considering the blue areas. Smaller private green spaces have mostly been excluded from the analysis since they are susceptible to change based on the landowner's decision. Due to the high connectivity of tree canopy in the urban area, the research will focus mostly on improving the biodiversity of terrestrial species.

1.5 Scientific importance

As the human population is increasingly moving towards cities the urban environment increases at the expense of green spaces (UNDESA, 2018). Green spaces have positive effects on the quality of life in the urban environment as it helps reduce the effects of urban heat islands and can act as a buffer for flooding and other benefits (Andersson et al., 2017). However, with urbanization, green spaces have become increasingly more fragmented leaving the local ecosystem vulnerable to changes. To keep green spaces healthy and resilient, biodiversity has to be maintained. Though there are discussions about the fragmentation of greenspaces having positive and negative effects on the local biodiversity it is clear that leaving these green spaces isolated from each other results in a limited species pool which is more vulnerable to changes resulting in a decline of the green space (Ryser et al., 2018). Hence it is important to find solutions to connect green spaces allowing the local ecosystems to flourish while not impeding the day-to-day urban life.

1.6 Reading guide

This thesis is organized in the following way. The literature review is covered in chapter 2 which goes over the main subjects for this research. Followed by the methodology in chapter 3, which describes the research methods. Then chapter 4 presents and evaluates the results. Chapter 5 gives suggestions with regards to how the city's landscape can be improved. Finally, chapter 6 concludes this research, and chapter 7 gives the final thoughts on the research, the limitations, and recommendations for future research.

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2. Literature review

This chapter provides a theoretical background for this research and will elaborate on the effects of land development affecting landscape connectivity and biodiversity. It will then provide insight into the effect of green infrastructure on the quality of life in cities. After which landscape model development and approach from other studies are discussed.

To gain an overview of all relevant literature concerning landscape connectivity, biodiversity, its interaction with the urban environment, and modelling of it, papers were sought based on these main terms with mild variances. The papers were then selected by first scanning the titles. Later the relevant papers were identified by reviewing their abstract and conclusion sections. Non-relevant papers were excluded from the research.

The following step was to read the full text of the relevant papers prioritized by their date of publishing. To then gain more information on the subject and its origins, the snowball sampling methodology was applied. This method is a way of finding literature using the previous read relevant papers on the subject to find more information regarding the topic.

To ensure the quality of the literature, only academic databases were utilized and only journal articles were considered to be included in the literature review.

2.1 Landscape connectivity

Landscape connectivity plays an important role in the urban ecosystem and biodiversity conservation. In ecology, it is broadly referred to as "the degree to which the landscape facilitates or impedes the movement among resource patches" (Taylor et al., 1993). Connectivity encompasses structural and functional components. The structural connectivity outlines the physical structure of a landscape which allows for the movement through the area. It also describes the topography, hydrology, vegetative cover and human land use patterns. Functional connectivity outlines how species or populations move through the landscape (Rudnick et al., 2012).

Over time human development has modified a large amount of the earth's landscape leaving many green areas for the millions of species we share this planet with fragmented and isolated (Barnosky et al., 2012). The fragmentation of the green areas, otherwise known as habitat fragmentation is a major threat to biodiversity (Keller & Largiadèr, 2003). Habitat fragmentation is a process consisting of two stages by which large and contiguous habitats are divided into smaller and more isolated patches of habitats (Fahrig, 2019). The first stage of the process is the loss of habitat caused by land development reducing the size of the current habitat. As land development continues and expands the latter process of habitat fragmentation occurs and the habitat becomes a mosaic of green patches (Curcic & Djurdjic, 2013). Land development in form of road construction is one of the main causes of habitat fragmentation. Roads create barriers in the landscape barring the dispersal of wildlife and creating major impedances for local biodiversity, greatly affecting the landscape connectivity of the area (Keller & Largiadèr, 2003).

Though there are some positive effects from habitat fragmentation, it is implied that several linked smaller patches of habitat can have a higher conservation value than a single patch of equivalent size (Fahrig et al., 2019). The main issue with habitat fragmentation is the isolation and disconnect from other habitats. It is clear that when a habitat of the local species is isolated from other green areas it can result in an increased extinction and lead to a loss of species from the regional species pool which will ultimately lead to a loss of biodiversity (Ryser et al., 2018)

2.1.1 Corridors

Improving landscape connectivity is crucial to stop the process of species' population decline and to sustain interaction between species (Opdam & Wascher, 2004). Landscape connectivity can be improved through the implementation of corridors for connectivity between otherwise isolated patches. There are many different definitions for corridors. Perault & Lomolino, (2000) define a corridor as a route that enhances speedy and unselective spread of biota between regions. Another definition would be "avenues along which wide-ranging animals can travel, plants can propagate, genetic interchange can occur, populations can move in response to environmental changes and natural disasters and threatened species can be replenished from other areas" (Walker & Craighead, 1997). The term corridor is used in different ways and none of them are incorrect. This thesis will use the definition given by Hilty et al., (2006) "Corridor is any space, usually linear in shape that improves the ability of organisms to move among patches of their habitat".

In terms of morphology regarding the types of corridors which exist, Curcic & Djurdjic (2013) describe three types of corridors. The types of corridors can be seen in Figure 2. The landscape corridor consists of diverse, uninterrupted landscape elements which offer sufficient cover for a safe journey from one habitat to another. The linear corridors are long, uninterrupted strips of vegetation such as hedges, strips of forest and the vegetation growing on banks of rivers and streams. The stepping-stone corridor is a series of small, non-connected habitats which are used to find shelter, food or rest for different kinds of species.

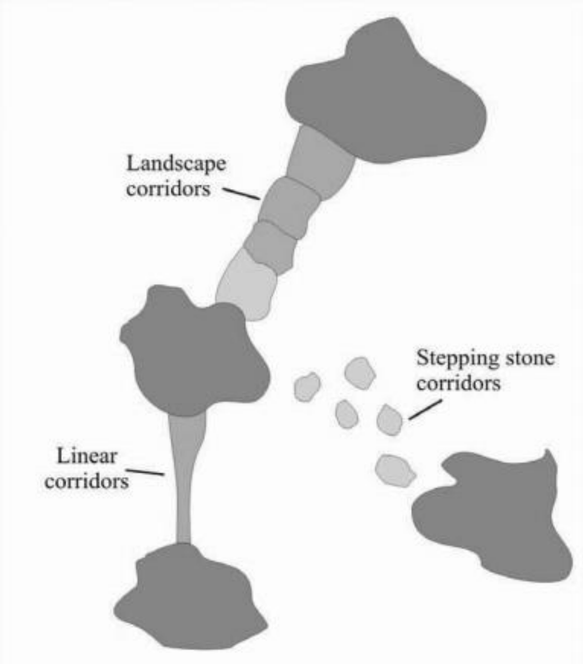

Figure 2 - Morphological types of corridors (Source: Curcic & Djurdjic, 2013).

According to Curcic & Djurdjic (2013), These types of corridors can be used to focus on all levels of biodiversity and at different spatial levels. However, the corridors provide connectivity for species in general but can also create a barrier for other species due to different operational scales and habitat requirements.

2.1.2 Biodiversity improvement resulting from corridors

When corridors are applied in rural and forestry areas to enhance the landscape connectivity they can increase the overall species' persistence as it assists movement between species of otherwise separate populations (Beier & Loe, 1992). The applied corridors are generally linear corridors that effectively connect the existing habitats. However, when corridors are applied it can take years and even decades for extinction rates to go down and changes in biodiversity to happen. In an 18-year experiment conducted by Damschen et al., (2019), 10 experimental landscapes of an equal area which were either unconnected or connected by a corridor were moderated. Within the area, the plant species were censused over 18 years. At the start of the experiment, the species richness in the connected and unconnected areas did not differ. The connected areas had an increased annual colonization rate of 5% and a decreased annual extinction rate of 2% compared to the unconnected area. These annual rates are persistent and over time generate a large increase in species richness in areas connected by corridors. They further conclude that connecting habitats decreases the time required for new species to settle in the area.

2.1.3 Landscape connectivity in the urban environment

In the built environment biodiversity severely suffers from habitat fragmentation. Unlike the rural and forestry areas, green areas in an urbanized environment are not separated by a single road. The green areas are often found few and far between with many grey infrastructural objects along the way. Connecting the habitats in the urban landscape is a daunting task for planning agencies as they face competing priorities and limited resources. Often planners try to enhance landscape connectivity within the urban environment through various forms of green infrastructure (Lechner et al., 2015).

Green infrastructure does not have a widely recognized definition (European Environment Agency, 2011) but is generally known to consist of a network of multifunctional open spaces, waterways, forestry areas, parklands and open countryside within and between cities, towns and villages (Mell, 2008). The main components of green infrastructure encompass connectivity, multifunctionality, and green components. In the urban environment, green infrastructural plans are generally applied in the forms of greenways, green belts and linked park systems. The linked park system is a concept based on connecting urban parks with each other through the use of corridors or greenways. The greenways are usually a shared-use path along a strip of undeveloped land, disused railways, and canals. Greenways can also be considered as linear parks and can also serve as a corridor for biodiversity. Green belts are used on a concept of trying to control urban growth by separating urban and rural areas with a buffer of undeveloped land (Jongman & Pungetti, 2004).

In early network planning practices, habitats were connected to each other for the use of wildlife. The connection between urban green and open spaces were more concerned for people's use and enjoyment of nature (Ersoy, 2016). Developing a network in an already existing urban environment that focuses solely on the conservation of biodiversity is a fallacy. In many cases, it is not feasible to apply such an approach since the interactions between nature and people in the urban environment cannot be ignored. Thus, improving landscape connectivity within the urban environment is best done by transforming already existing infrastructure. An example would be Montreal, Canada where old walking infrastructure had been retrofitted into a 'green pedestrian network' and connects the two largest parks (WWF, n.d.). In Seoul, an old and obsolete highway had been dismantled and transformed into a green corridor, restoring the old river that ran underneath it (DevAsia, 2016). Other means to improve landscape connectivity are to transform vacant buildings or parking lots to create stepping-stone corridors.

2.2 Impedances for biodiversity

In rural areas, the main obstructions for biodiversity are roads that cause habitat fragmentation as has been mentioned. Roads have direct and indirect effects on biodiversity. The direct effect of a road on biodiversity is caused by a higher mortality rate for the species in the areas. The higher mortality rate is caused by vehicle collisions with species trying to cross the road to move from one habitat to another. The indirect effects are caused by the roads separating the habitat leading to isolation of populations or disconnecting resource networks (Bennett, 2017).

Species in an urban environment do not only face the challenges of roads separating their habitats to survive. They are also forced to persist in higher numbers in smaller areas than would be expected. While at the same time the distance between habitats and resource networks are increased as the habitats and resource networks are not separated by a single road but by multiple blocks of infrastructure (Norton et al., 2016)

An example in which loss of biodiversity as a result of urban expansion can be witnessed is Munich, Germany. In the city of Munich, more than 180 plant species went locally extinct over a period of 100 years as a result of the expansion of urban development (Niemelä, 1999). Another example would be Singapore where urbanization has encompassed more than half of the total land area which contributed to the local disappearance of roughly three-quarters of its native species (Brook et al., 2003).

Overall, as the level of urbanization increases, the richness of biodiversity decreases. The increasing urbanization reduces the habitat quality and space affecting the remaining species in the area. There are cases, however, which under some conditions of low to moderate levels of urban development can increase the richness of biodiversity in the area (Elmqvist, Zipperer, et al., 2013; McKinney, 2002). Intermediate levels of human activity, such as the more outlying suburban areas, promote plant diversity through the introduction of new species at the cost of the extinction of a few native species. However, as human activity increases, the extinction of native plant species begins to outpace the introductions of new species. Hence, core areas in cities tend to have lower diversity than surrounding areas (Kowarik, 1995). This can be found in a study done by Robinson et al. (1994) on the plant species of Staten Island, New York. New York had a net gain of several hundred plant species by 1930. However, by 1991 human activity had dramatically increased over the years and most of the gain in biodiversity was erased due to the extinction of hundreds of native plant species.

2.3 Urban greenspaces

Urban green spaces have a common definition which is agreed on by ecologists, economists, social scientists and planners, they define it as “public and private open spaces in urban areas, primarily covered by vegetation, which are directly (e.g. active or passive recreation) or indirectly (e.g. positive influence on the urban environment) available for the user” (Karade et al., 2017). The World Health Organization (2017) defines it as “all urban land covered by vegetation of any kind. This covers vegetation on private and public grounds, irrespective of size and function, and can also include small water bodies such as ponds, lakes or streams”.

Though there is a common definition for urban green spaces it is too broad to cover the different functionalities and/or the impact of the different sizes of green spaces within the urban environment on biodiversity. At the same time, it is very difficult to measure or define the different sizes of green spaces which can help biodiversity in the urban environment to flourish (Aronson et al., 2017). Looking at this from a perspective for humans rather than biodiversity, previous work has already defined different sizes of greenspace areas as can be seen in table 1. These numbers are based on minimum distance and size requirements of the green spaces to which urban residents should have access (Van Herzele & Wiedemann, 2003).

Table 1 - Minimum standards for urban green spaces (Van Herzele & Wiedemann, 2003)

Functional level	Maximum distance from home (m)	Minimum surface (ha)
Residential green	150	
Neighborhood green	400	1
Quarter green	800	10 (park: 5 ha)
District green	1600	30 (park: 10 ha)
City green	3200	60
Urban forest	5000	>200 (smaller towns) >300 (big cities)

For a species' population to thrive, whether it be in an urban or natural environment, it requires a certain size of population and area to live on. Hence, Shaffer (1981) introduced the term 'minimum viable population' size (MVP), meaning 'the smallest isolated population having a 99% chance of remaining extant for 1000 years despite the foreseeable effects of demographic, environmental, and genetic stochasticity, and natural catastrophes'. Shaffer, (1987) then further defined the 'minimum area requirement' (MAR) concept to accommodate the MVP. The MAR can determine whether an area is large enough to sustain the population of a certain species, as species can endure for a considerable amount of time in an area too small for long-term survival. Species in an area too small can thrive for some time but will ultimately go extinct due to extinction debt. This debt occurs because of time delays between impacts on a species, such as the destruction of habitat (Verboom et al., 2014). So far MAR has been applied as a single-species approach. However, Verboom et al. (2014) use MAR for multiple species estimation and biodiversity assessment. They convert the MVP estimates of a multitude of species into area-based estimations and are then able to estimate the MAR for these species.

Having an estimation for the MAR of species in an area can help in defining the size requirements for the green patches in an urban environment. In biodiversity conservation, there is a concept of umbrella species (Hunter, M. L., 1990). The umbrella species are either at the top of the food chain and potentially have the highest area requirement or is a species whose requirements include those of other species (Groom et al., 2006; Ozaki et al., 2006). It can then be argued that by improving the environment for the umbrella species that the species on which they depend on have similar environmental requirements and therefore gain an improved environment as well (Roberge & Angelstam, 2004).

Survival of species in the urban environment relies on the larger green patches in a city also known as 'core green patches'. These patches tend to be more valuable as they can support larger and persistent populations (Bélisle, 2005; Noss, 2004; Rudd et al., 2002). They also refer to more high-quality green areas for different species which remain in the city (Yu et al., 2012). Choosing a minimum size for these core green patches has ultimately been, to a certain extent, hypothetical work. Defining the right size for a core green patch is difficult because you cannot focus on a specific species when trying to improve biodiversity. At the same time, many different species within the area have different area requirements and sometimes are dependent on other species. Thus, for defining the right size of a core urban green patch Kong et al., (2010), Xun et al., (2014) and Zhang et al., (2019) have used 12 ha as a hypothetical minimum requirement.

2.4 Urban benefits

Enhancing landscape connectivity in the urban environment by connecting isolated green spaces through the application of green infrastructure not only improves biodiversity but has several other benefits as well as increasing the overall quality of life.

The heavy activity in the urban area generates local air pollution. Planted trees and other vegetation from green infrastructure play an essential role in reducing man-made pollutants from the air. Trees filter out pollution, absorb CO2, and produce oxygen. Air quality data gathered by Nowak (2002) shows that areas with an abundance of trees have considerably fewer air pollutants. Urban areas also tend to have higher temperatures than undeveloped areas and can lead certain developed areas to become urban heat islands. These urban heat islands, on average, have a higher temperature and require more time to cool down at night. Green spaces in the urban areas help reduce the increased temperatures through shading and evapotranspiration (Rizwan et al., 2008; Zhang et al., 2017).

Most importantly, green infrastructure in urban environments such as parks and corridors not only help by improving the climate of cities (Makhelouf, 2009), they also have positive effects on human well-being. Evidence suggests that being within the proximity or just having visuals of green space has a positive effect on mental health while also reducing the feeling of stress (Hartig et al., 1996). Other studies also show that residents of neighbourhoods with plenty of green space tend to self-report fewer health problems than residents with little to no green space (de Vries et al., 2003)). Besides the positive effects on mental health, green areas tend to be less polluted and more relaxing. This leads to these areas having a higher tendency to invite residents to a more active lifestyle. Green corridors help in this aspect as well by leading people from urban areas to greener areas. In turn, a more active lifestyle improves the overall physical health of people (Lee & Maheswaran, 2011). A study done by Seo et al., (2019) shows that residents living in areas with greater amounts of green space tend to have a lower risk for cardiovascular diseases.

Not only do green spaces provide several health benefits to residents, but it also promotes social cohesion (Jennings & Bamkole, 2019). Social cohesion involves the interpersonal dynamics and sense of connection among people. People living in areas with high levels of social cohesion tend to report more favourable outlooks on their health and a more favourable outlook on their lives in general (Hartig et al., 2014).

Green and social cohesion are related but also linked to having an influence on crime in the area. Having less green in an area tends to lead to less social cohesion. This leaves communities to share fewer common values, residents losing both social control, and social capital which leads to a higher prevalence of crime and violence in the neighbourhood (Kawachi et al., 1999). This can also be backed up by a literature study done by Shepley et al.,

(2019) which reviewed a multitude of quantitative and qualitative papers on crime rates in urban environments. The literature shows that green spaces provide public spaces which support desirable behaviour and inappropriate public spaces provide support for criminal behaviour.

2.5 Landscape modelling to improve landscape connectivity

There have been multiple studies conducted on the subject of identifying corridors to enhance landscape connectivity. This section will mostly discuss the studies done by Kong et al., 2010; Linehan et al., 1995; Z. Zhang et al., 2019 as they serve as exemplary studies on the subject. Overall, studies on this subject follow a similar structure with regards to its applied methodology. It generally starts by applying graph theory which structures the landscape into a network of nodes and links. The links are generated through the least-cost theory after which the generated links are prioritized by the gravity model. Then, with the network of prioritized corridors, further network evaluation is conducted.

This section will mainly discuss the studies mentioned above and compare them to each other to show their similarities and differences and finally show the gaps the studies have left. However, basic information about the subject will first be acquired concerning graph theory, least-cost theory, and the gravity model to give an understanding of the current state of landscape connectivity modelling.

2.5.1 Graph theory

The basis for modelling landscape connectivity is graph theory. Graph theory is applied in geography, information analysis, and computer science and is commonly used to support landscape connectivity measurement (Bunn et al., 2000). A network represents the landscape and consists out of a set of nodes and edges. The nodes are the individual elements (the green patches) and the links (the green corridors) represent the connectivity between the nodes. The links may be binary (connected or not) or contain additional information about the level of connectivity (Minor & Urban, 2008).

2.5.2 Least-cost theory

The link between the two nodes can be generated by the least-cost theory. This theory implies the most cost-efficient route which can be taken through an area from one point to another. In GIS modelling the least-cost analysis consists of two layers. A source layer and a friction layer (also known as a cost layer). The source layer contains the nodes from which the routes can be generated. The cost-layer is a layer consisting of cells in which each cell has a value that represents the resistance (or cost) to move through the area and can be represented by the value of the land cover type attributed. This can be used in different ways to include all kinds of effects (Halpin & Bunn, 2000; Michels et al., 2001). The algorithm then calculates the many ways cells can be connected to reach the target destination and determines the accumulated cost. The resulting least-cost path is determined when all possible paths are evaluated (Chang, 2016).

When applying the least-cost theory with regards to enhancing landscape connectivity, the resistance in the cost-layer represents the unsuitability for species to move from or through an area. This means that species tend to not choose the higher cost paths for their activities (Lechner et al., 2017; Rudnick et al., 2012). The cost-layer can thus also include social, environmental, and economic criteria effects. Ultimately, when the least-cost path(s) have been analyzed and defined they could then be enhanced and transformed into green corridors.

2.5.3 Gravity model

The least-cost analysis can identify potential corridors which have the least impedance from one area to the other areas. However, the least-cost analysis provides less information on the significance of each area and corridor when the connections are developed (Linehan et al., 1995; Sklar & Costanza, 1991). Interactions between nodes can be assessed using the gravity model.

The gravity model is a modification of Newton's equation for gravity to evaluate the interaction between the two nodes (Forman & Godron, 1986; Sklar & Costanza, 1991). The model was created by William J. Reilly in 1931 and tried to predict the interactions that would happen between different cities (nodes). For example, the larger a city is, the bigger its pull factor will be as it will generally provide more services and opportunities. At the same time, the further cities are apart from each other the less they will interact with each other.

The same model can be applied for landscape connectivity. Large green patches generally have a higher habitat quality and can provide more resources and space for the local species. The distance to the other patches is the impedance caused by the landscape for species to move from one patch to another. The intensity of interaction represents the efficiency of corridors and the significance of the areas. Areas with higher habitat quality and lower accumulated impedance have a greater interaction (Linehan et al., 1995; Rudd et al., 2002).

2.5.4 Landscape connectivity studies - similarities, differences, and gaps in the studies

The methodology for finding identifying potential corridors in the landscape has stayed mostly the same. The application of the methodology has subtle differences from study to study dependent on the goals set and the scale on which it has been done. All three studies aim to improve landscape connectivity. However, the approach of all three slightly differ from one another but its focus lies solely in the improvement of the landscape.

To improve biodiversity Linehan et al., (1995) selected two umbrella species in Central Massachusetts which are sensitive to habitat fragmentation. When improving their living conditions, the effects would buffer onto other species in the area. Impedance values related to the umbrella species were used to simulate the behaviour of the species moving from one patch to another. A minimum size for the patches was not set. However, they used the existing protected open spaces as nodes of the network. The minimum area requirement of the flagship species was then used as a weight which would indicate the potential for the species to live in the area.

Kong et al., (2010) focused on the local biodiversity in and around Jinan City. To simulate the behaviour of biodiversity in the landscape they used impedance values based on the locally available literature. To establish the nodes in the network a minimum patch requirement of 12 ha was set to be sufficient.

Zhang et al., (2019) focused on reconnecting habitats by improving the landscape connectivity through using vacant land in the city of Detroit. Based on the analytic hierarchic process (AHP) they assigned weights to factors to produce a suitability map based on existing land use. To represent the nodes in their network they also used 12 ha as a minimum patch requirement. In each study after the nodes were identified and the cost-layer was created, a least-cost analysis generated corridors connecting the nodes. The gravity model was then applied to prioritize which corridors had the most potential. Using the most potent corridors, scenarios were developed and evaluated to suggest possible improvements. Table 2 shows a summary of each studies' similarities and different angles of approach.

Table 2 - Summary of similarities and differences

Related study: **Methodology**	**Linehan et al., (1995)**	**Kong et al., (2010)**	**Z. Zhang et al., (2019)**
Goal	Improve landscape connectivity	Improve landscape connectivity	Improve landscape connectivity
Focus	Flagship species	Overall biodiversity	Vacant land
Scale	Rural	Rural / Urban	Urban
min. patch size	-	12 ha	12 ha
Impedance values	Related to flagship species	Theoretical values	AHP
Prioritizing corridors	Gravity model	Gravity model	Gravity model
Network evaluation	by developed scenarios	by developed scenarios	by developed scenarios

These studies follow the same methodology but each from a different approach on different scales all to improve landscape connectivity to improve and conserve biodiversity. Both Linehan et al., (1995) and Kong et al., (2010) state there is little consensus on whether the designed networks will work as intended. One of the main issues would be that the weighting of habitat suitability and impedance in the least-cost analysis has many subjective factors and has an obvious effect on the identification of potential corridors. Further on, human interaction is not always taken into account while there are many benefits to be gotten from it (Zhang et al., 2019) as the potential of viewing wildlife is a significant attraction for outdoor recreation. The attraction to viewing wildlife can contribute to the protection of green areas. However, designing corridors that both improve biodiversity while providing recreational, esthetic, and other human benefits is no trivial task (Linehan et al., 1995). Lastly, as Zhang et al., (2019) noted, many of the previous studies in conservation ecology paid more attention to the more rural landscapes rather than urban environments.

2.6 Conclusion

Large habitats are becoming increasingly fragmented as a result of urban expansion. This in turn affects the landscape connectivity which facilitates or impedes the movement among resourceful patches. In the urban environment, the connection between these patches are severely damaged by busy roads, creating barriers that impede the movement of species, in combination with multiple blocks of infrastructure increasing the distance between the patches. Restoring the connections between the patches creates more robust networks and a healthier environment for the local biodiversity.

Adding more green to the urban environment through either green spaces or green corridors can improve the quality of life for the residents. Studies showed that green spaces tend to invite people to a more active lifestyle which in turn improves physical health. It has also been reported that residents living in areas with greater amounts of green space tend to have a lower risk for cardiovascular diseases.

Previous studies which looked into implementing green corridors to improve the landscape focused on both rural and urban areas, but mainly the rural area. The methods described in these studies are in their core very similar. Their focus was mainly to increase connectivity in the area to improve or conserve the local biodiversity. The general methodology for finding the corridors used graph theory, least-cost theory, and gravity modelling to identify potential corridors to (re-)establish connections between green patches. In creating the landscape model, theoretical values were mostly applied, and the human population was generally not taken into account. It is important to consider both humans and nature, especially when working within the urban environment.

3. Methodology

This thesis focuses on improving overall landscape connectivity on an urban scale by attempting to find the optimal corridors in the urban environment. In this chapter, the methodology for finding such corridors is discussed. First by identifying the core and stepping-stone patches after which a cost-layer is developed to apply the least-cost analysis and find potential corridors. Then the corridors are prioritized based on their interaction value calculated from the gravity model and the number of dwellings within range of the corridor. Based on these corridors network scenarios are developed and evaluated.

Figure 3 displays the overview of the process which will be described in further detail in this chapter. Most of the work was done in raster format in QGIS 3.18. Overall, the analysis used a pixel size of 2.5 m by 2.5 m to minimize the risk of missing potential corridors.

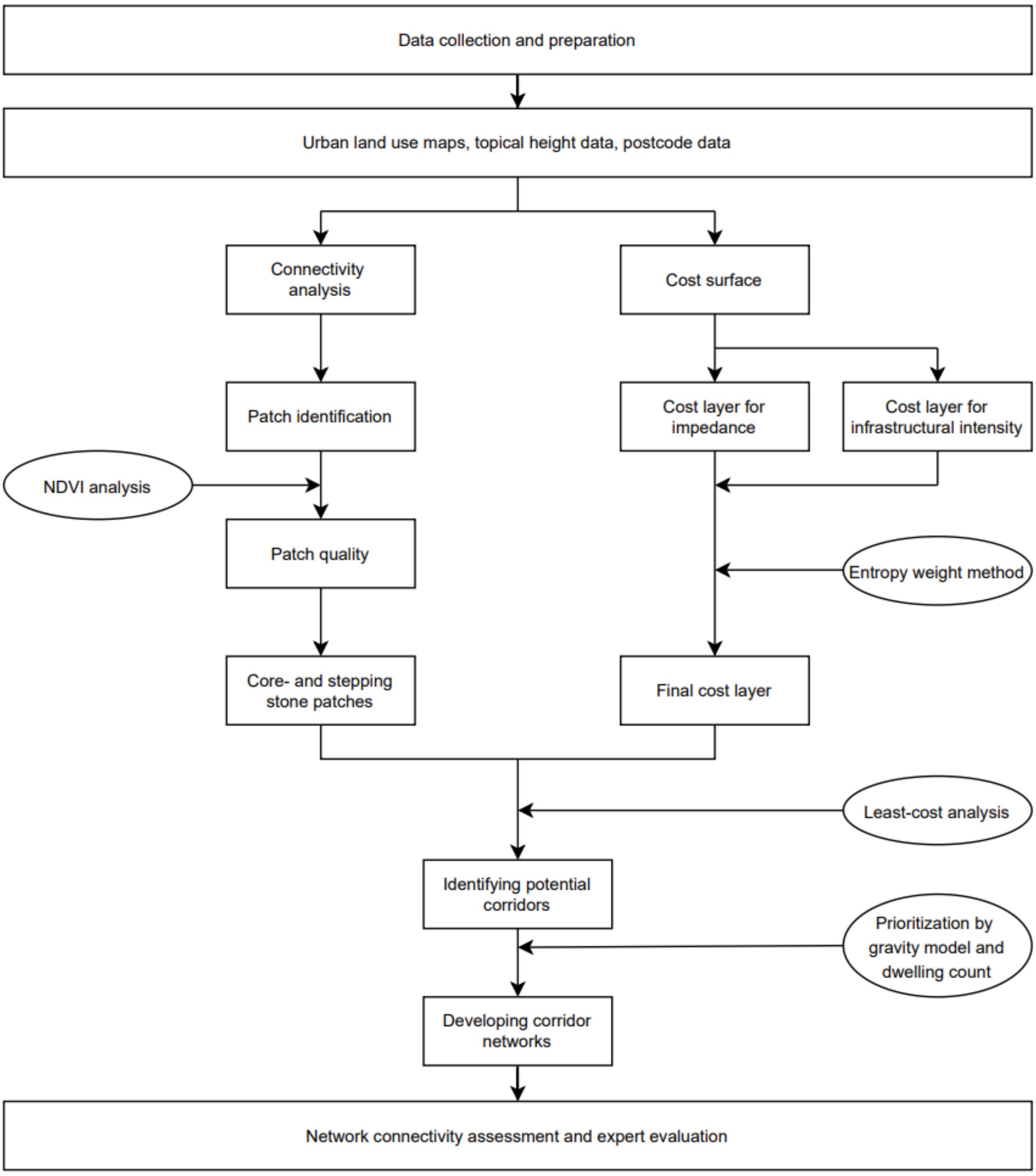

Figure 3 – Process used to identify and prioritize potential corridors

3.1 Connectivity analysis

For species to move and disperse in an area a strong cohesion of the network is required. The cohesion of the network is the result of the dispersal across the landscape and the size of the local populations it links together (Opdam et al., 2003). The current connectivity of the green areas will be calculated by the cohesion index. The index measures the connectedness of the area. Numbers close to zero mean that the area is very fragmented and overall less connected. Higher numbers mean the areas in the layer are more clumped, or rather, more cohesive. The numbers show the cohesion of the areas relative to each other (Schumaker, 1996).

The cohesion index is calculated based on public green data obtained from the study area. To eliminate patch fragmentation from walkways (in i.e. parks) that do not contribute to fragmentation, the layer is buffered by 1.5 m, then dissolved and then shrunk down back to its original size. The layer is then converted from vector to raster format of a pixel size of 2.5 m by 2.5 m.

The area-wide raster data of all the green spaces is then clipped by the boundaries of the neighbourhoods of the study area. This gives an overall view of what areas within the study area are highly connected and which ones are not. The cohesion index is then calculated in QGIS 3.18 using the LecoS plugin which calculates the index per neighbourhood through a batch process.

3.2 Core patches and stepping-stone patches

Core patches are larger green areas that serve as high-quality areas for species to live and thrive on. The patches exist in different scales and their sizes vary from small to large (Fahrig, 2019). In addition, there are also stepping-stone patches. These patches tend to not be fully accounted for in landscape connectivity, but they allow for long-distance dispersal and can provide refuge for species (Saura et al., 2014). This section will cover the identification of core- and stepping-stone patches.

3.2.1 Core patch identification

A large habitat is often regarded as a core patch, it offers space, resources, and its area is generally of higher quality (Forman, 1995). Many studies have used different criteria to select or define what a core patch is, some suggest using the perimeter area ratio index to identify a core area. Other studies would base the criteria for a core patch on an umbrella species and base the criteria for the core patch on its minimum area requirement (MAR) and other such variables (Linehan et al., 1995; Verboom et al., 2014). Firehock & Walker (2015) use a method to incorporate the edge effect of tree lines and the interior area of a site to identify core areas. Kong et al., (2010) and Xun et al., (2014) used a minimum area size of 12 ha as a criterion for identifying core patches.

As this thesis focuses on improving overall biodiversity, finding an umbrella species to focus on and specifying the criteria for core patches based on its MAR is not applicable. The method of Firehock & Walker (2015) has been applied in rural environments and Zhang et al., (2019) tried to incorporate this method in the urban environment but it was not effective. The criteria contained in the method of Firehock & Walker (2015) were hard to apply in the case of an urban environment due to the overall smaller sizes of patches and the overall higher density of grey infrastructure in the city. In their case, only one city park met their criteria. The urban environment is a constrained area and leaves fewer options open for deciding what is to be a core patch. Hence, the criteria for identifying the core patches will be based on the minimum area size of at least 12 ha as suggested by Kong et al., (2010) and Xun et al., (2014) as it is most applicable.

3.2.2 Stepping-stone patch identification

Stepping-stone patches are smaller patches and can facilitate movement between other patches and allow for long-distance dispersal of species. Within the urban environment, these stepping-stone patches also serve as green spaces which provide leisure for residents. There is no clear and concise answer to what size such patches have to be within the urban environment and in relation to the core patches. In the case of this research, a minimum size of at least 5 ha is chosen as a criterion for the stepping-stone patches together with the requirement that they must reside within the inner area of the study area. The requirement of 5 ha is in line with the study of Van Herzele & Wiedemann (2003) which relates the access a person should have based on the size of the patch and the distance to it.

3.2.3 Patch health

The patch health is also measured. The patch health in this research is defined by the overall vegetation coverage of the patch. A higher amount of vegetation has a significant impact on the biodiversity in the area (Threlfall et al., 2017). The coverage is split into understory vegetation coverage, which ranges from 0.2 m to 2 m, and that of the tree canopy coverage which includes all vegetation above 2 m. The information on the coverage is gained by calculating the Normalized Difference Vegetation Index (NDVI) for the area and combine it with the topical height map (AHN).

3.3 Cost-layer development

Green patches can be connected through corridors by utilizing the least-cost theory. For the application of the least-cost theory, a cost-layer is required over which the least-cost path can be calculated. The cost-layer is based on the degree of impedance local biodiversity can experience when moving from one area to another. When species move over green areas they experience little to no impedance. On the other hand, grey infrastructure such as roads and buildings create barriers in the landscape and leave species exposed when moving over such terrain (Fu et al., 2010).

The developed cost layer in this research consists of two layers. First is the impedance layer, this layer is based on the land use map of the study area and will have assigned theoretical values per land-use type. The second layer will indicate the intensity of the infrastructure in the area by calculating the price to demolish it. A higher demolition price indicates more grey infrastructure which in turn causes more impedance to the movement of species.

3.3.1 Impedance layer

The layer which encompasses the impedance biodiversity experiences through various landscapes in the urban environment is mostly based on the different types of land uses. The types of land uses are taken from the Basisregistratie Grootschalige Topografie (BGT) in addition to the Bestand Bodemgebruik (BBG). When the data is partially incomplete or does not accurately depict the real-life situation, extra data from OpenStreetMap (OSM) will be used to fill in for the missing data. This will help ensure that the developed cost-layer will represent an accurate depiction of the real-life situation.

The impedance values assigned to the different areas and objects are based on previous studies conducted by Fu et al., (2010); Kong et al., (2010); Marulli & Mallarach, (2005); Xun et al., (2014); Zhang et al., (2019) and assumptions based on the literature. The current impedance values used can be viewed in Table 3.

Table 3 - Land use types and their corresponding impedance weights

Type	Impedance value
Green areas	1
Residential areas	40
Commercial areas	60
Public Facility areas	60
Business Park areas	70
Airport area	100
Water	80
Highway, primary and secondary roads	100
Residential roads	40
Cycleway	20
Railway	100
Buildings	100
Other	50

To elaborate on some of the impedance values, it is important to note that overall impedance values differ from species to species. This research focuses on the overall biodiversity of mainly terrestrial species. Roads, buildings, and other general grey infrastructure can significantly impede the movement of these species. On another note, bodies of water do also represent a significant barrier for terrestrial species, but not for aquatic or avian species (Jongman, 2007; Miller et al., 1998). Areas such as residential areas, which often lie around the edge of the city centre, were given a lower impedance value. Studies have shown that lower levels of land development do not impact biodiversity as significantly compared to that of highly developed areas. In certain cases, an increase can potentially be seen in the lower developed areas by the introduction of plant species through the settling human population. However, this generally means the introduction of non-native species and can come at the cost of native species (Elmqvist, Goodness, et al., 2013; McKinney, 2002).

3.3.2 Infrastructural intensity layer

The impedance values that have been assigned in other studies were generally assumed to represent the degree of disturbance or difficulty wildlife can encounter when moving between patches. Overall, these values are theoretical and represent estimates of the resistance to movement per land type (Kong et al., 2010). Impedance experienced by wildlife is mainly caused by grey infrastructure (Fu et al., 2010). As grey infrastructure in the urban environment increases, so does the impedance for wildlife increase. The amount of grey infrastructure in an area can be defined as the intensity of the infrastructure in the area. The intensity can roughly be measured by the amount of infrastructure which has to be demolished. Thus, the price for demolishing grey infrastructure can indicate the intensity of infrastructure and indirectly the impedance it causes for species when moving through the area.

The urban environment is vast and consists of multiple areas, all with different conditions to be accounted for in a calculation of cost, a calculation based on the conditions specific to one area does not apply to the greater scope of the cost analysis. Therefore, to indicate the intensity, the demolition cost will be based on the price of demolition for which an area will be returned to 'zero'. This implies that the infrastructure has been stripped off the land. The demolition price will therefore also not include the costs such as allocating the same function somewhere else in the area or redirecting traffic but purely stripping the infrastructure off the land.

Prices for demolition have been gathered from various sources by price per square meter. The demolition prices of various buildings per land-use type have been obtained from Bouwkostenkompas (n.d.), a website that has a vast amount of data on construction and demolition prices. Prices for demolition of roads and pavement have been obtained from the RROK-C17-01 (Voorschoten et al., 2017) which includes an extended list of reasonable prices per square meter. Prices for railway and airport infrastructure was not available and has been estimated to be the most expensive. Prices per square meter can be found in Table 4 below. The cost-layer will be created based on a pixel size of 2.5 by 2.5 m; hence the price is also given per 6.25 m².

Table 4 - Land-use type and their corresponding demolition price per m² and per 6.25 m²

Type	Price per m²	Price per 6.25 m²
Residential	31.0	194
Commercial	31.0	194
Business Park	25.0	156
Public Facilities	35.0	219
Highway	14.4	90
Primary Roads	11.2	70
Pavement	6.1	38
Airport and Railway (Buildings)	40.0	250
Other	24.1	151

To estimate the intensity of the infrastructure, the prices will be applied as shown in Table 4. Most of the infrastructure can be regarded as 'flat' such as roads and pavement and can thus be directly applied. The demolition price for a building however differs as its total surface area depends on the number of floors. The number of floors is generally related to the height of the building and will be considered in calculating its demolition price. The height of the buildings in the study area is obtained from the topical height map (Algemeen Hoogtebestand Nederland: “AHN”). The price of demolition for buildings will be calculated by the following formula:

$$P_b = \frac{h_i}{e_{avg}} P_a \qquad (1)$$

In which P_b is the total estimated price for demolishing the building per square meter on the map, h_i is the height of the building obtained from the topical height map (Actueel

Hoogtebestand Nederland: AHN), and P_a is the demolition price per square meter. The average elevation height e_{avg} is estimated at 3.0 m based on the minimum elevation requirement of 2.6 m according to the Dutch building decree (Bouwbesluit, 2012) and an estimation of 0.4m for the thickness of the floors.

Green and water areas, and other areas which have no infrastructure, are set to a demolition price of 1.

3.3.3 Final cost-layer

The impedance layer is subjective of nature and its values are theoretical and represent estimates of the impedance. At the same time, it does not consider the amount of infrastructure on the land. The cost-layer which gives an estimate of the intensity of the infrastructure on the land can by that way show the impedance but is not able to take into account the barrier effects caused by roads, water bodies and other such elements. By combining both cost-layers the individual layers can make up for both their weaknesses.

To combine the two individual cost-layers weights will be assigned to them. There are several weighting methods to assign weights to the cost-layers such as the SMART method, mean weighting method, and the various forms of analytic hierarchy process. Due to the subjective nature of the impedance map which serves as part of the base for this research, an objective weighting method is preferred to limit the variations in the results if base values were to change.

For this research, the entropy weight method (EWM) is chosen as the method for weighting the cost layers. EWM captures the distribution of the values which is beneficial to determine how what weight should be assigned to one cost-layer in relation to the other. The method evaluates the values by measuring the degree of differentiation. The higher the degree of differentiation of the index, the more information can be derived and a higher weight is given to the index (Lu et al., 2010; Zhou et al., 2012).

EWM consists of three steps to determine the weights to be assigned. The first step is the standardization of values which can be calculated with the following formula (Amiri et al., 2014; Zhu et al., 2020):

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \qquad (2)$$

In which r_{ij} is the standardized value of the *ith* index in the *jth* sample.

The second step computes the information entropy e_j and is expressed with the following formula:

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} r_{ij} \ln r_{ij}\,, \;\; j = 1, 2, \dots, n, \qquad (3)$$

As e_j becomes smaller, the bigger the effect of the *j* index will be. The entropy weight can then be calculated in the final step with the following formula:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)}, \quad j = 1, 2, \dots, n, \tag{4}$$

In which w_j is the final entropy weight of the *jth* parameter

3.4 Corridors by least-cost analysis

To find potential corridors to connect the core- and stepping-stone patches, the least cost path method is utilized. This method is a process of iteration in which paths are built consisting of cells (pixels) of which the path with the least total cost is chosen (Chang, 2016). For this analysis, the cost layer, developed in the previous section, will be utilized as the cost layer for the application of the least-cost path algorithm between the identified patches.

The least-cost path algorithm will be executed for three different situations to find potential corridors. The first situation will apply the least-cost algorithm from stepping-stone patch to core patch. The second situation applies the algorithm between the stepping-stone patches within the inner area of the study area. The third and last situation applies the algorithm from core patch to core patch.

- situation 1: stepping-stone patch to core patch;
- situation 2: stepping-stone patch to stepping-stone patch;
- situation 3: core patch to core patch.

The reason for splitting them up into three situations is to ensure fair comparisons are made as the situations operate on different scales.

3.5 Application of the gravity model

The corridors found using the least-cost analysis do not provide information about the relative significance between them. The gravity model can help identify what corridors to develop. The model calculates the interaction between the nodes and a higher interaction value is given to corridors between patches of high quality and low impedance between them. Previous studies by Kong et al. (2010); Linehan et al. (1995); Rudd et al. (2002); Zhang et al. (2019) calculated the interaction between the patches and used that as an index to evaluate the corridors. A high interaction value means that the corridor provides a more significant link between the two patches. The interaction value can be calculated with the formula expressed below (Linehan et al., 1995; Rudd et al., 2002):

$$G_{ab} = \frac{N_a N_b}{{D_{ab}}^2} \tag{5}$$

In which G_{ab} is the interaction value of the path between the two patches. D_{ab} is the value of resistance between patches a and b and, N_a and N_b are the node weights for patches a and b.

$$D_{ab} = \frac{L_{ab}}{L_{max}} \tag{6}$$

L_{ab} is the accumulation of the resistance value between patches a and b, and L_{max} is the maximum total of the resistance values of all corridors.

The node weight N_a is calculated by the formula below:

$$N_a = \frac{C_{t,a}+C_{v,a}}{S_a} \cdot \ln(S_a) \qquad (7)$$

In which $C_{t,a}$ is the tree canopy coverage of patch a in square meters, $C_{v,a}$ is the understory vegetation coverage of patch a in square meters, and S_a is the total area of patch a in square meters. The formula for the node weight is different from Linehan et al. (1995); Rudd et al. (2002). The current node weight considers the 'effective mass' of a patch, meaning that patches with more overall vegetation add more value than patches consisting of only grass. Area of the 'mass' is also considered but less so due to the normalization as a minimum size for patches had been a requirement all along.

3.6 Green corridors and accessibility

Finding the optimal corridor in the urban environment not only includes enhancing the landscape for improvement and conservation of biodiversity but also accessibility for citizens to green areas. Green areas improve the overall quality of life in the urban environment and have positive effects on both the physical and mental health of residents (de Vries et al., 2003). To include the residents of the study area, postcode data has been obtained of residential areas from the Basisregistratie Adressen en Gebouwen (BAG). The postcode data shows all individual dwellings in the study area and can give an estimation of the number of residents by counting the number of dwellings within the range of a potential corridor. The corridor can then be prioritized by the number of dwellings, and thus the residents, it affects.

There will be two versions for assessing the accessibility of residents to the found potential corridors. The first version will include all dwellings in the study area. The second version will only include the dwellings which are located in areas that are considered to have low access to green spaces. By doing so, priorities can be set whether one wants to focus on all residents regardless of their accessibility to green spaces or focus on residents located in areas with low access to these spaces.

3.6.1 Overall dwelling count

The effective range of a corridor in this research is defined by the maximum distance for a resident to reach residential green according to the study of Van Herzele & Wiedemann (2003). According to them the maximum distance for a resident to reach residential green should be no more than 150 m. To consider this, a buffer of 150 m will be created around each potential corridor. The number of dwellings within this buffer zone will be counted and the corridors can then be prioritized by the number of dwellings.

3.6.2 Dwellings in areas with low accessibility to green

Not all dwellings are located equally within range of all the different functional types of green spaces. In an optimal situation, each dwelling should have access to the different functional types of green spaces based on their maximum distance to reach them (Van Herzele & Wiedemann, 2003). Values for these maximum distances have been shown in Table 1. The next step is to figure which dwellings have low access to the different functional types of green spaces.

A map will be developed to show the areas in which dwellings have low access to the different functional types of green spaces. The green spaces of the study area will be split into these functional types based on their size and then buffered according to the minimum required distance. The values for the development of this map can be viewed in Table 5 and are based on the values shown in Table 1.

Table 5 - Type of green by functional level with the buffer distances and minimum surface requirement

Functional level	Buffer distance	Minimum surface (ha)
Residential green	150	<1
Neighbourhood green	400	>1 and <10
Quarter green	800	>5 and <12
District green	1600	>12

The accessibility of an area will be based on a scale ranging from 0 to 4. The accessibility number represents the number of overlaps from the buffers of the different functional types of green. An accessibility number of 0 means that the area is not within range of any functional type of green space. Whereas an accessibility number of 4 means that the area has access to all the different functional types of green. In this research, the threshold for 'low access' is set at 2.

The dwellings located in areas with an accessibility of 2 or lower will then be counted the same way as described in section 3.6.1. Dwellings in areas with higher accessibility will be excluded from this count.

3.7 Corridor prioritization, network scenario development, and evaluation

The least-cost analysis generates many potential corridors within the study area. Not every corridor can be developed at once. It is important to select the corridors which will enhance landscape connectivity most efficiently and is beneficial to the quality of life of the residents. By prioritizing corridors, networks of corridors can be developed consisting of the more optimal corridors which can then be evaluated to what extent they improve the study area.

3.7.1 Prioritizing corridors

The corridors are prioritized based on the final combined score of its interaction value between the patches and the number of residents. This final score is obtained by multiplying the interaction value with the number of dwellings within the range of the corridor. This will ensure that outlying corridors which have a high interaction value and low dwelling count and vice versa will have a lower priority. It must be noted that there will be two versions of the final score. The first final score is based on the overall dwelling count according to section 3.6.1. The second final score is based on the number of dwellings counted in the areas which have lower accessibility to different functional types of green as per section 3.6.2.

The corridors are then sorted based on their score per situation which is described in section 3.4. For clarification, the three situations will be stated here again.

- situation 1: stepping-stone patch to core patch;
- situation 2: stepping-stone patch to stepping-stone patch;
- situation 3: core patch to core patch.

The reason to split the corridors into three situations is to ensure a fair comparison between the corridors when prioritizing them by the gravity model. The gravity model relies on the relative significance between the corridors and the three situations operate on different scales.

For network development and evaluation, the corridors which score at or above the 75th percentile for each situation will be considered. The 75th percentile amounts to the upper quartile of potential for the corridors of each situation. Using the 75th percentile as a threshold will ensure that there will be plenty of corridors that are above average to use for the development of different network scenarios within the study area.

3.7.2 Network scenario development

Several scenarios of networks have been developed. The first scenario portrays the already existing network in the study area (network A). Three more network scenarios are then developed (network B, C, and D) which portray a new scenario for the area to evaluate potential improvements to the currently existing network. The developed networks (network B, C, and D) consist of potential corridors identified by the least-cost analysis. The corridors have been handpicked by using the corridors which score at or above the 75th percentile from each situation to form the networks. Because space in the urban environment is limited, the new scenarios will be based on branching networks. These tend to offer the least cost to builder in comparison to circuit networks (Linehan et al., 1995). Meaning that the network occupies less space which gives these networks a higher potential for actual realization. Three common typologies of branching networks can be viewed in Figure 4. The three network scenarios that are developed are based on these three typologies (Hellmund, 1989).

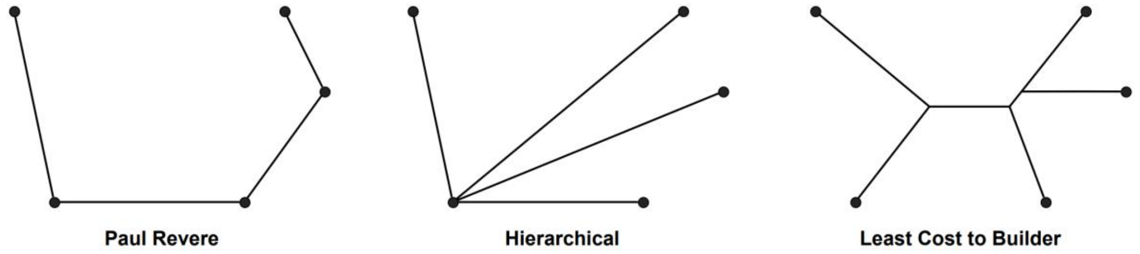

Figure 4 - Common network typologies (Hellmund, 1989)

The Paul Revere network is the simplest network and creates a single route that connects all nodes. Its disadvantage lies in the fact that the return journey must pass through all the nodes again which increases the cost for the user. The hierarchical network has a direct route that originates from a single node, the node of origin must be sufficient to provide for all 'traffic' that can come through. The last network 'Least Cost to Builder' provides the shortest route to connect all the nodes while allowing routes to bypass intervening nodes.

3.7.3 Network evaluation

A network influences the movement and flows in a landscape. The developed networks are evaluated using connectivity indices; statistical measures helpful in calculating network efficiency. The indices selected are the two widely used network indices beta *(ß)* and gamma *(γ)*. Beta *(ß)* represents the node connection and Gamma *(γ)* indicates the network connectivity. Therefore these indices will help understand the movement pattern (Forman, 1995).

$$ß = \frac{l}{v} \tag{8}$$

Beta *(ß)* is equal to the number of links (l) divided by the number of nodes (v). If *ß* < 1 then a dendrogram occurs (diagram which represents a tree structure). When ß = 1 there is a single circuit. When ß > 1 then there are more complex levels of connectivity (Linehan et al., 1995).

$$\gamma = \frac{l}{l_{max}} = \frac{l}{3(v-2)} \tag{9}$$

The Gamma *(γ) index* equals to the number of links (l) divided by the maximum possible number of linkages (l_{max}). The gamma *(γ)* index ranges from 0 which indicates that no links are connected to 1 where every node is linked to the other nodes (Forman & Godron, 1986).

Aside from the network indices, the number of dwellings within the range of the corridors are also compared per network scenario. Both the overall number count of dwellings and the dwellings which are considered located in the low access areas are taken into account.

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4. Results

This chapter will present the study area and its existing situation as well as giving some background information. The overall connectivity of the study area will also be presented which will later be compared to a situation after which potential corridors are implemented. The core- and stepping-stone patches have also been identified and presented on a map together with a summary of their size and vegetation coverage. The best corridors have also been identified and are presented, after which several networks have been developed based on the best corridors and evaluated to observe different network efficiencies in the area. Finally, the corridors have also been discussed in an expert evaluation to obtain feedback on the found corridors.

4.1 Study area

This research focused on the city of Eindhoven. Eindhoven is one of the largest but also one of the greenest cities in the Netherlands with 236.000 residents and still growing with its prognosis set at 248.000 residents in 2040. The city functions as the technological centre of the southern Netherlands, and thus also gathers lots of data on its urban environment. This research identifies opportunities through the use of GIS in which potential can be found for the application of green infrastructure to improve the quality of life and optimize landscape connectivity in this already green city. The abundance of data on the city in combination with a high number of green spaces gives a great opportunity to test the model whether it can identify existing corridors and find potential new corridors. Figure 5 gives an overview of the study area.

Figure 5 - Overview of the key features of Eindhoven's landscape

4.1.1 Brief History of Eindhoven

Eindhoven was founded in 1232 and has for centuries been a small city until Philips established its light bulb factory in 1890. In times of extreme poverty, Philips offered many opportunities for employment, which attracted people from all corners of the country to lift themselves from poverty and create a brighter future. The surge of people caused a rapid expansion which led to Eindhoven merging with the surrounding towns Stratum, Strijp, Woensel, Tongelre and Gestel (Eindhoven, 2016).

In a short span of time, the city grew to 48.000 residents and kept on expanding with the British garden city model in mind. In the 1980s this model was let go but made a comeback not much later with the green policy plan in 2001. The green policy plan continues the idea of the garden city model and protects its green areas. With the policy plans in place, Eindhoven is committed to improving the quality of life, cultural history, and biodiversity to this day (Eindhoven, 2016).

4.1.2 Existing conditions and opportunities

Eindhoven in its current state, due to its green policy plan, is a very green city. The three main green areas are generally referred to as 'de wiggen' (the wedges, Figure 6) of Eindhoven and comprise most of its green areas. These wedges reach into the city and fulfil a green and recreative connection between the residential areas, parks and outer areas of the city. These main green areas also allow for green veining through the city which creates ecological connections, helps in the prevention of flooding from downpours and reduce urban heat islands in the city (Eindhoven, 2016).

Figure 6 - The 'wiggen' (wedges) of Eindhoven (Eindhoven 2016)

And though the green areas of Eindhoven are established, there are plenty of opportunities to improve its current state. The city centre breaks the connection between the three wedges of Eindhoven contributing to habitat fragmentation. Identifying routes through or around the city to connect these areas can lessen habitat fragmentation and improve overall biodiversity.

4.2 Existing conditions and landscape connectivity

The connectivity of Eindhoven has been calculated per neighbourhood by the cohesion index using LecoS. The results from the analysis are graphically shown in Figure 7, for the complete results see Appendix A. A larger cohesion index means that the green areas in the neighbourhood are more connected. The numbers are relative to each other.

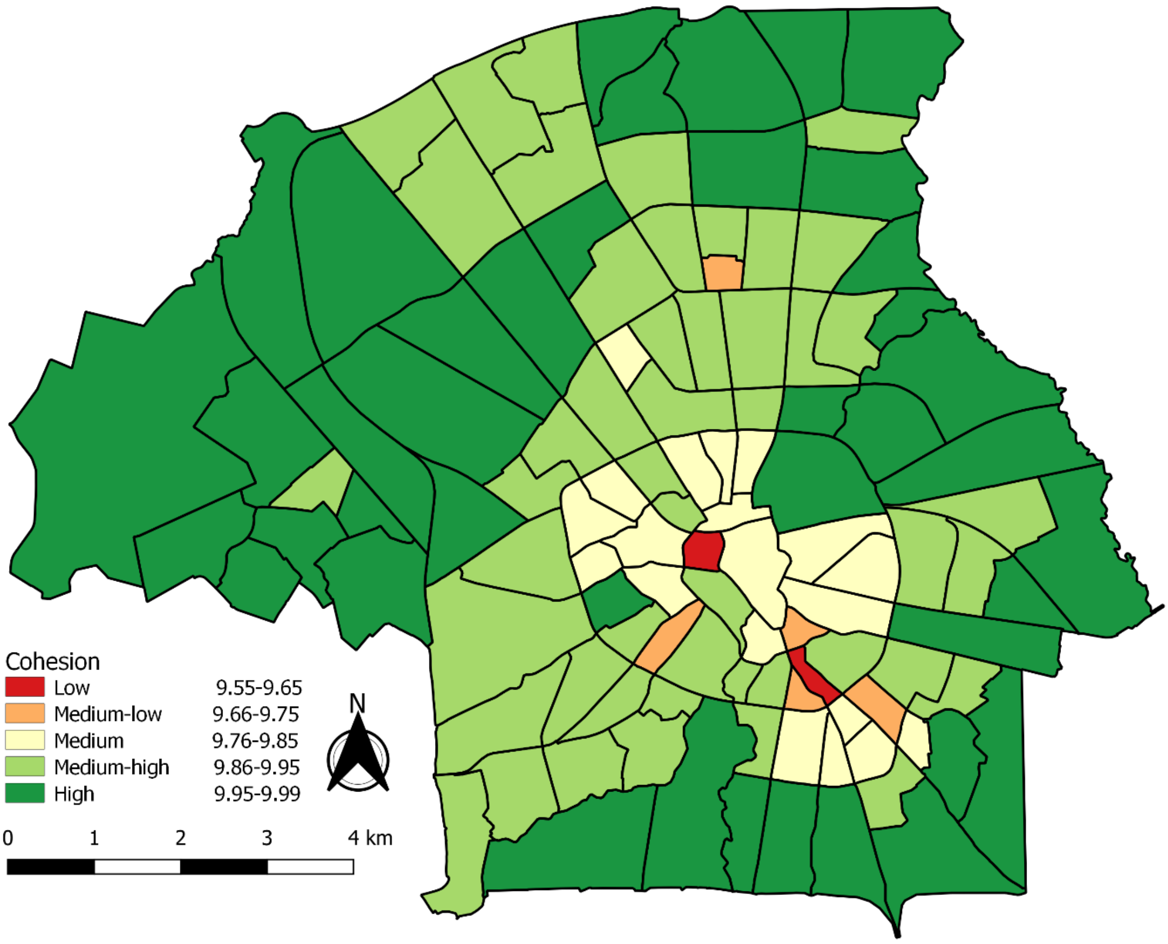

Figure 7 - Cohesion results per neighborhood

The results show that in its current state the outer-lying neighbourhoods of Eindhoven have a relatively higher connectivity. The overall connectivity per neighbourhood decreases near the centre. The main reason for the decrease in connectivity is that the centre of Eindhoven has a higher level of urbanization compared to the outer lying areas. This can be seen in the figure as the cohesion index per neighbourhood is on average far lower within the inner ring of the city. Figure 7 can also be visually compared to Figure 6, the neighbourhoods that lie within or are adjacent to the three wedges have an overall higher cohesion index. To give a visual example of a neighbourhood with a low and high cohesion index, satellite images are compared in Figure 8.

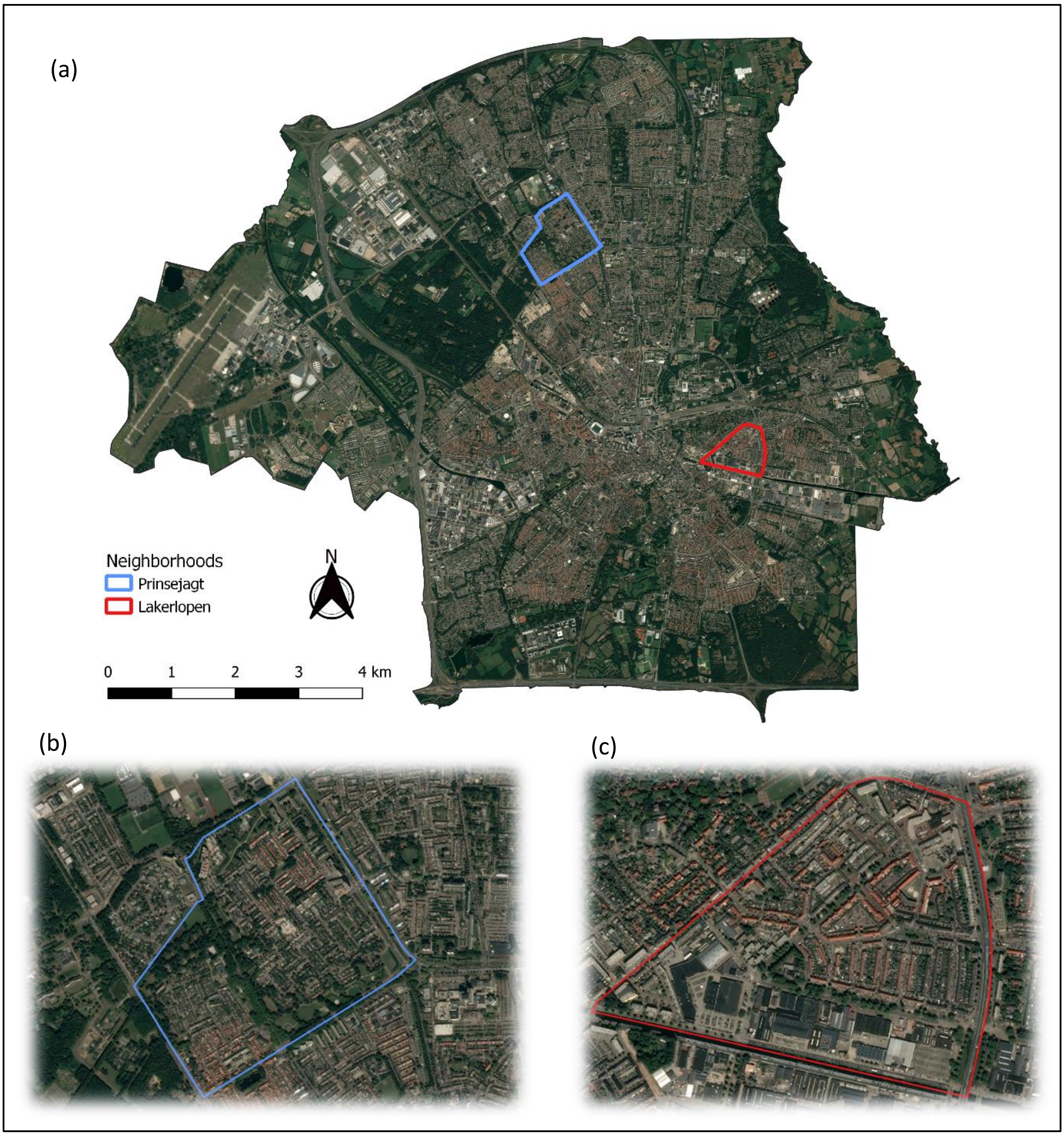

Figure 8 – Overall satellite view of Eindhoven displaying the example neighborhoods (a) and focusing on the neighborhood Prinsejagt in blue (b) and the neighborhood Lakerlopen in red (c)

The neighbourhood Prinsejagt (Figure 8b, blue) has a relatively high cohesion index (9.94) and is located outside of the inner ring. As can be seen in the figure, there is a large stroke of green going right through the middle of the neighbourhood and continues along the border connecting green areas.

Lakerlopen (Figure 8c, red) is a neighbourhood with a relative lower cohesion index (9.75) and is located within the inner ring of the city. This neighbourhood has a single thin stroke of green moving right through the neighbourhood. The rest of the neighbourhood is highly urbanized and has less space for any other green infrastructure. This leaves the few remaining green areas in the neighbourhood mostly scattered and unconnected throughout the area.

4.3 Core- and stepping-stone patch identification

To identify the core- and stepping-stone patches a detailed map of green spaces, obtained from Eindhoven Opendata, has been loaded into QGIS 3.18 to serve as a basis. The map accurately depicts most if not all of the green spaces, and with its accuracy excludes walking and cycling routes from the green areas unlike some maps do. This leaves the map with many small fragmented green patches which are hardly able to reach a size of 12 ha. Walking and cycling routes do not create barrier effects like roads and railways do and thus can partake in the landscape. All the green patches are therefore buffered by 1.5 m and then dissolved to counteract the fragmentation from walking and cycling routes. Afterwards, the map is shrunk back to its original size and for safety measures is intersected with the road and rail network to prevent unintentional merging of green areas disconnected by these networks. This same method was applied for the connectivity analysis and is mentioned in section 3.1.

Larger patches have been identified by their size. Some of the larger patches are separated by a single road but are still connected by the river and its riparian green moving underneath the overpass which serves as a connection between patches of green. Some of the patches persist outside of the borders of the city, for this study, however, the size is restricted to the border. The identified core- and stepping-stone patches can be seen in Figure 9.

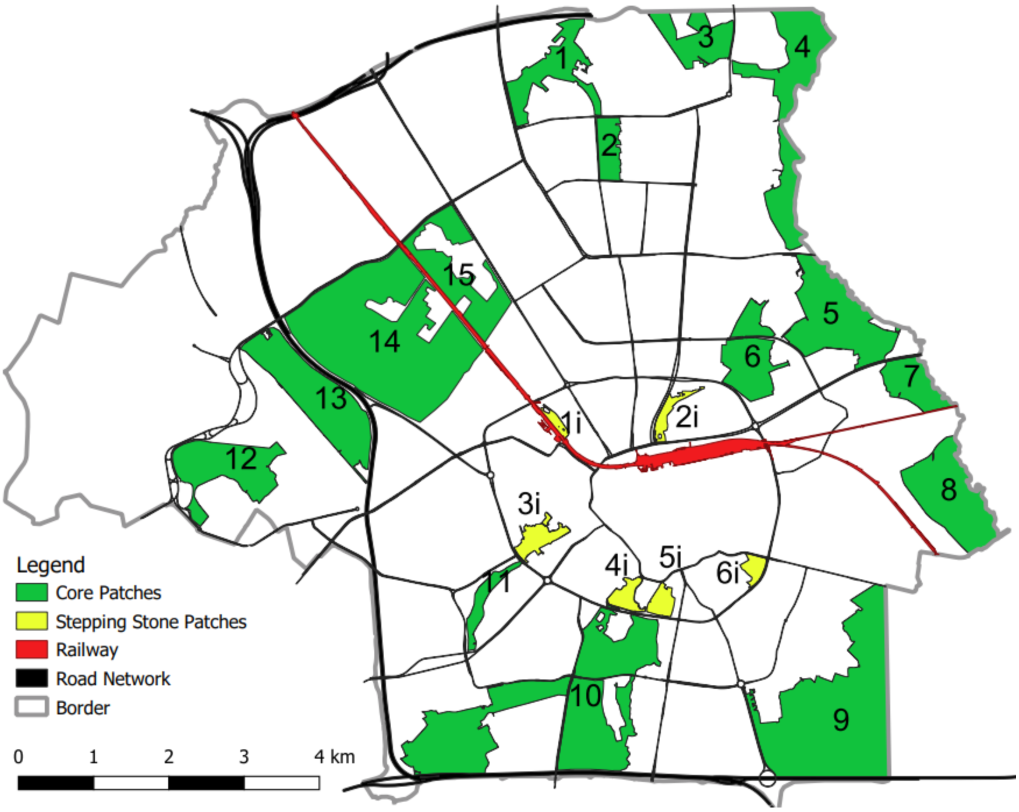

Figure 9 - The identified core- and stepping-stone patches of Eindhoven

The size of each patch has been measured and the overall vegetation coverage per patch is also included. The vegetation coverage has been obtained through a combination of the Actueel Hoogtebestand Nederland (AHN) and the Normalized Difference Vegetation Index (NDVI). The vegetation is split into two categories namely understory vegetation and tree canopy. The presence of understory vegetation improves local biodiversity to a certain extent after which its effect diminishes. The tree canopy from trees on the other hand have a more neutral effect but still serve to provide shelter for certain species (Threlfall et al., 2017).

Table 6 shows the size of each patch, the coverage of the understory vegetation, and the tree canopy. Understorey vegetation is regarded as any vegetation between 0.2 m and 2.0 m. Tree canopy is regarded as any green exceeding 2.0 m. It is possible that some of the understory vegetation can grow taller than 2.0 m, but it is not likely. It also needs to be mentioned that this method is not able to measure the understory vegetation located below the tree canopy due to the limitations of satellite imagery. Hence, there is likely more understory vegetation per patch than is shown in Table 6 but to what extend is unknown. More information with regards to estimating the vegetation per patch can be found in Appendix B.

Table 6 - Summary of the sizes and vegetation coverage of the core- and stepping-stone patches

Core Patches				**Stepping-Stone Patches**			
Patch ID	Area (ha)	Canopy (ha)	Vegetation (ha)	**Patch ID**	Area (ha)	Canopy (ha)	Vegetation (ha)
1	56.7	15.5	8.8	**1i**	5.2	1.0	2.0
2	23.9	10.9	3.8	**2i**	10.4	1.5	5.1
3	47.4	11.2	5.3	**3i**	18.3	2.8	4.4
4	118.8	27.4	24.4	**4i**	11.9	1.7	3.9
5	113.3	49.8	14.7	**5i**	11.1	1.4	3.7
6	63.8	22.0	7.7	**6i**	8.4	1.0	3.5
7	39.9	6.7	6.2				
8	100.9	27.1	14.4				
9	261.6	117.2	25.0				
10	286.0	83.4	36.6				
11	33.5	7.6	6.2				
12	80.8	13.3	11.7				
13	114.3	41.0	19.2				
14	316.3	107.1	29.6				
15	76.0	28.8	5.6				

It also has to be noted that core patches 10 and 11 do reach into the inner ring of the city by the connection of the riparian green alongside the river which flows underneath the overpasses. Thus, stepping-stone patch 3i is part of core patch 11, and stepping-stone patch 4i and 5i are part of core patch 10. For the inner ring analysis, these parts are considered as stepping-stone patches. The overlap of these mentioned core- and stepping-stone patches have no implication for the analysis.

4.4 Final cost-layer and least-cost analysis

As explained in chapter 3.3, two cost-layers are created and then combined using the entropy weight method to create the final cost-layer. The first layer, the impedance layer mimics the impedance species experience moving through certain areas and is based on theoretical values (Kong et al., 2010). The second is the intensity of infrastructure in the area and is based on demolition prices following the logic that when the higher the demolition price is, the more infrastructure there is in the area. When there is a high amount of infrastructure (generally grey infrastructure), species are less likely to move through the area or be able to live and potentially thrive in it (Mckinney, 2002).

The two cost-layers have been created according to the values mentioned in chapter 3.3. The cost-layer which describes the intensity of the infrastructure has been rescaled to the same scale as the impedance layer (1 to 100) for combination. The results can be seen in Figure 10 and Figure 11.

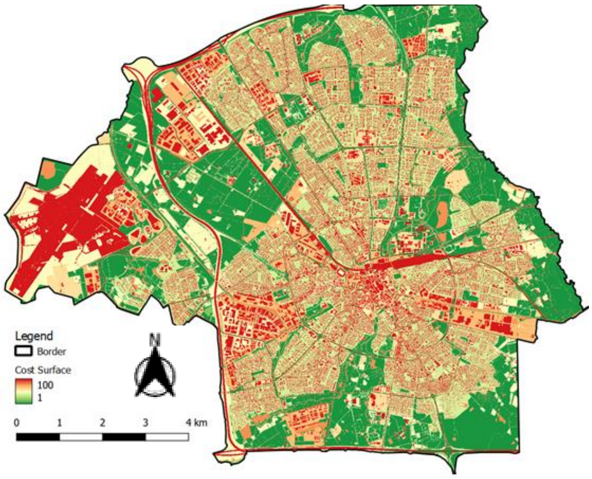

Figure 10 - Impedance layer

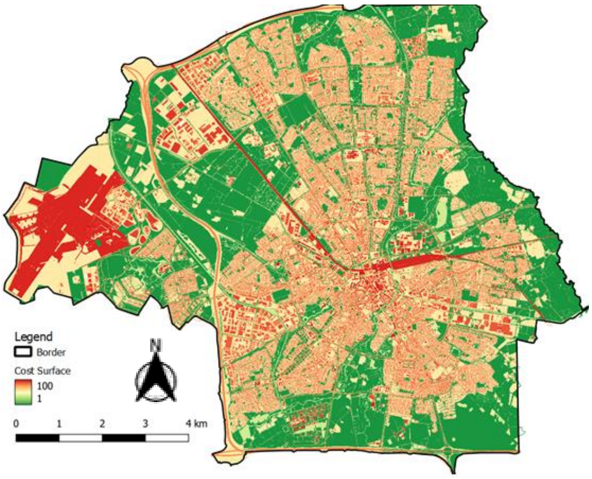

Figure 11 - Layer for indication of infrastructural intensity

The impedance layer (Figure 10) shows a higher value for infrastructure which creates barrier effects such as roads since it is easier to consider these effects in the impedance layer. However, it also shows higher values in the large empty spaces of business terrains due to the value assigned to these land uses. The layer which indicates the intensity of infrastructure (Figure 11) shows lower values for roads as it cannot consider the barrier effect but also for the empty spaces of the business terrains which have potential for greening. Overall, the layer also shows more resistance through the urbanized areas of the city. More information on the individual layers and their differences can be found in Appendix C.

The layers have been combined using the entropy weight method. The weight assigned to the impedance layer, as a result, is 0.25. The weight assigned to the layer for indication of the intensity of infrastructure is 0.75. The calculation for the results of the assigned weights can be found in Appendix D. The result can be seen in Figure 12.

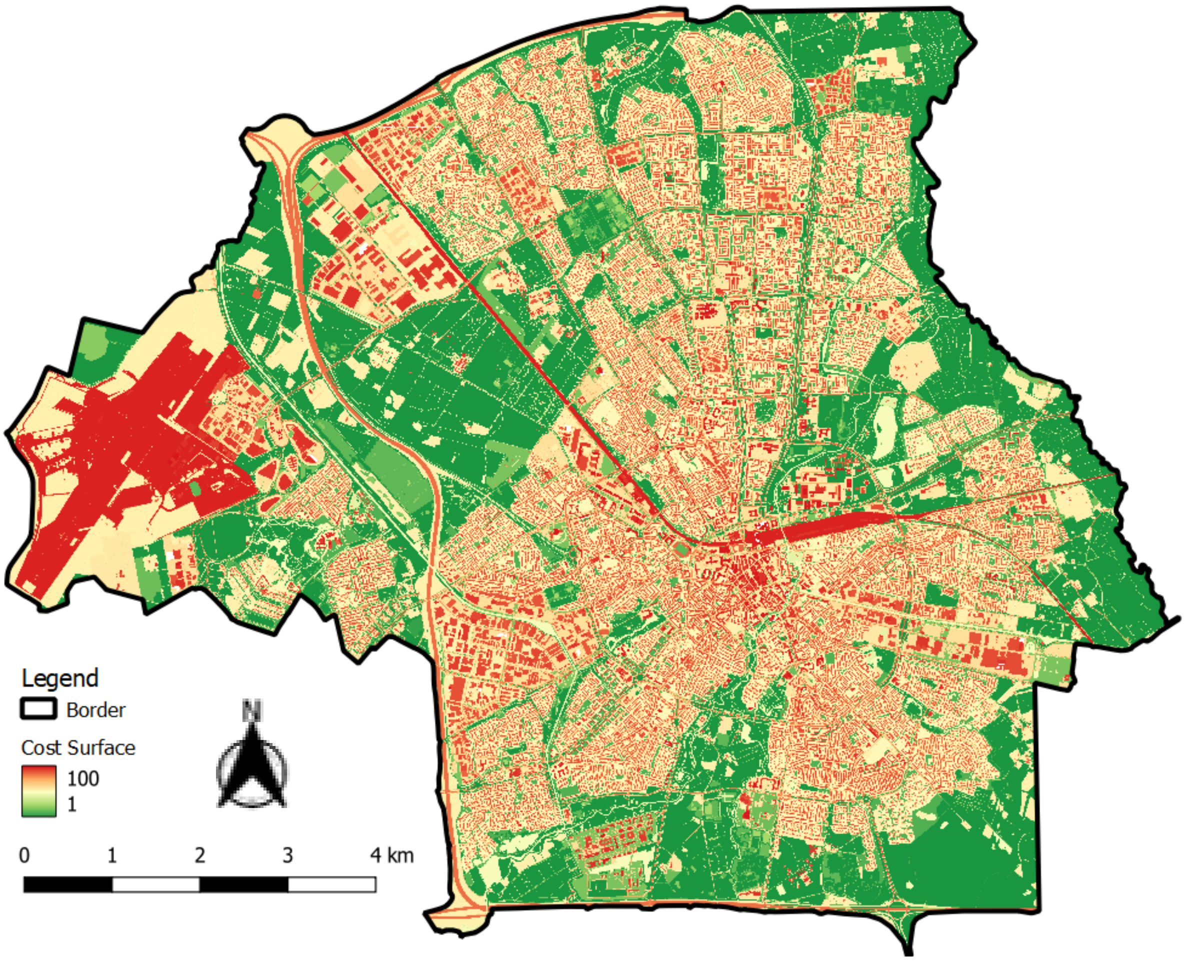

Figure 12 – The final cost-layer as a result of combining the previous cost-layers

The final cost layer has been used for the least-cost analysis to generate potential corridors from each core- and stepping-stone patch to one another.

4.5 Prioritizing corridors by gravity model and human population

The least-cost analysis has been applied for the three situations as described in sections 3.4 and 3.7. A total of 210 potential corridors have been identified, 90 belong to situation 1 (stepping-stone patch to core patch), 15 to situation 2 (stepping-stone patch to stepping-stone patch), and 105 to situation 3 (core patch to core patch).

The gravity model has calculated the interaction value of each potential corridor. The number of dwellings in the range of each potential corridor has been counted as well as per section 3.6.1. A separate count for the number of dwellings located in the areas with low access to different functional types of green has been done as well according to section 3.6.2. The map related to the areas with low accessibility to different functional types of green can be seen in Appendix E as well as further information on it. The final scores have then been generated from these values as per section 3.7.

Figure 13 gives an overview of all found potential corridors by plotting their interaction value against the number of dwellings within its range. The dwelling count in this figure is based on the overall dwelling count (counted according to section 3.6.1).

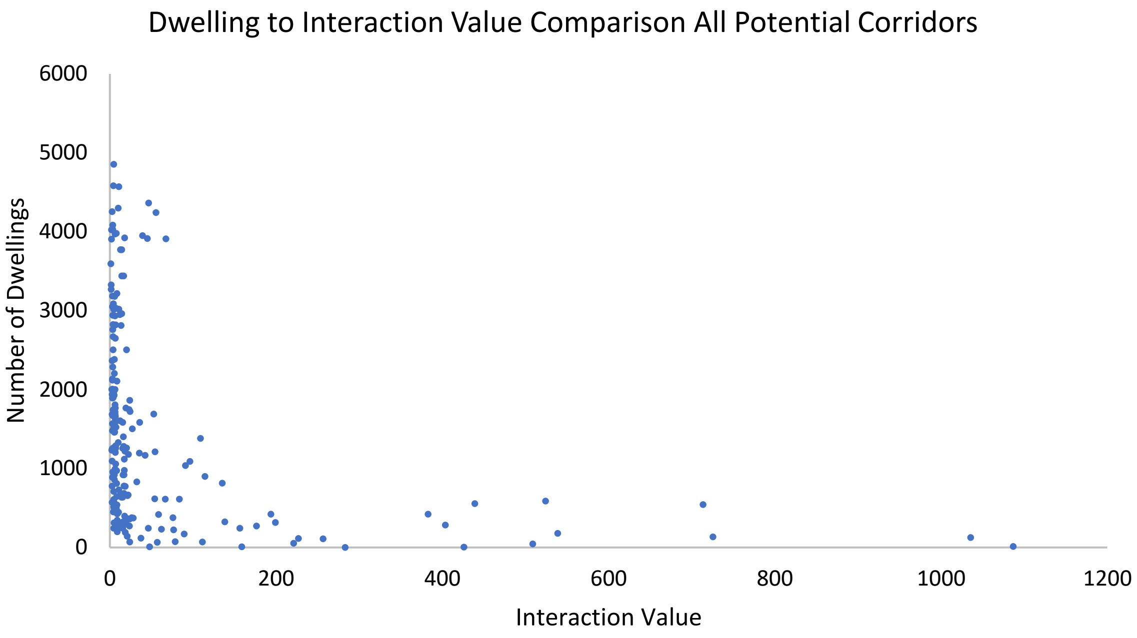

Figure 13 – The number of dwellings in relation to the interaction value of all potential corridors

Overall, the potential corridors with a high interaction value cover a low number of dwellings and vice versa. Corridors with a high interaction value tend to be those which connect the patches close to each other or experience minimal impedance from urban development or both. When a corridor covers a high number of dwellings, it generally means it passes through more urbanized areas that have a higher impedance which in turn affects the interaction value. The more optimal corridors are a combination of both a high interaction value and high coverage of the number of dwellings. The interaction value, final score, dwelling count, and dwelling count for the areas of low accessibility can be found in Appendix F along with a visual overview of all potential corridors per situation.

4.5.1 Prioritizing corridors by interaction value and overall population

The corridors have been sorted and prioritized by their final score based on the overall dwelling count. The corridors which score below the 75th percentile are considered sub-optimal and are left out. An overview is given in Figure 14.

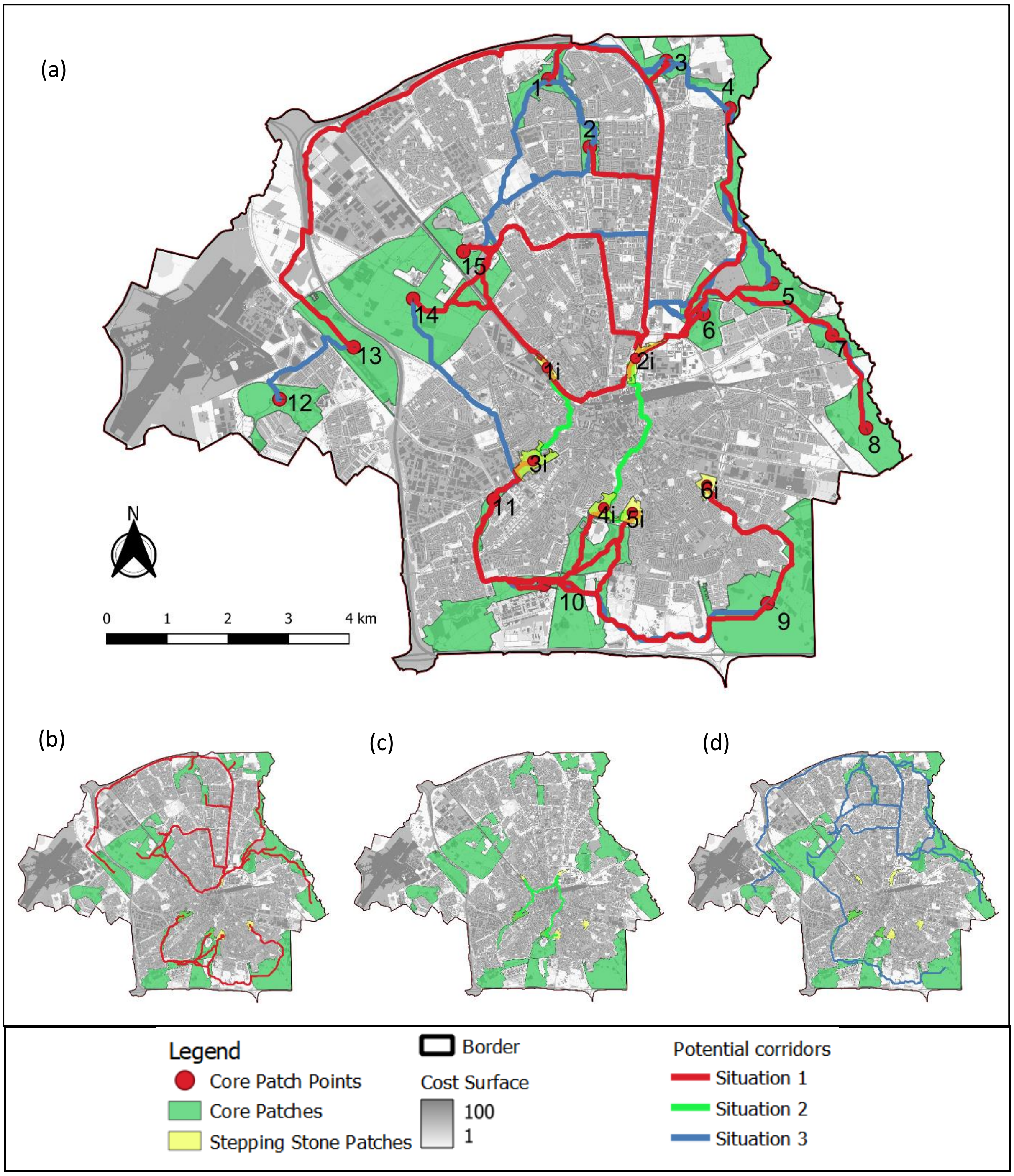

Figure 14 – Overall view (a) of at or above 75th percentile scoring corridors for each situation based on overall population, situation 1 (b) Stepping-stone patch to core patch, situation 2 (c) stepping-stone patch to stepping-stone patch, and situation 3 (d) core patch to core patch

The overview is split into four parts, Figure 14a gives the overall view of all corridors which score at or above the 75th percentile. The remaining parts (Figure 14b, c, and d) show the corridors which score at or above the 75th percentile per situation to give a clearer view due to the overlap of some corridors. Situation 1 (Figure 14b) has some similarities with situation 3 (Figure 14d). The reason for this is because some of the patches are located close to each other, from that point the least-cost path is calculated, and similar paths emerge as there are no better options in the area. The more optimal paths from situations 1 and 3 lie mainly outside of the city centre because these areas are not as highly developed. This allows the paths to retain a high interaction value while still covering a significant number of dwellings. Situation 2 (Figure 14c) mainly shows the usage of the riparian green alongside the river to find a feasible path through the centre of the city. It also tries to utilize as many patches of green as possible to navigate through the highly developed area.

4.5.2 Prioritizing corridors by interaction value and population in 'low access' areas

The corridors have also been sorted and prioritized by their final score based on the dwelling count of dwellings located in areas with low accessibility to the different functional types of green. As in the previous section, the corridors which score below the 75th percentile are considered sub-optimal and are left out. Figure 15 shows an overview of all the corridors above the 75th percentile.

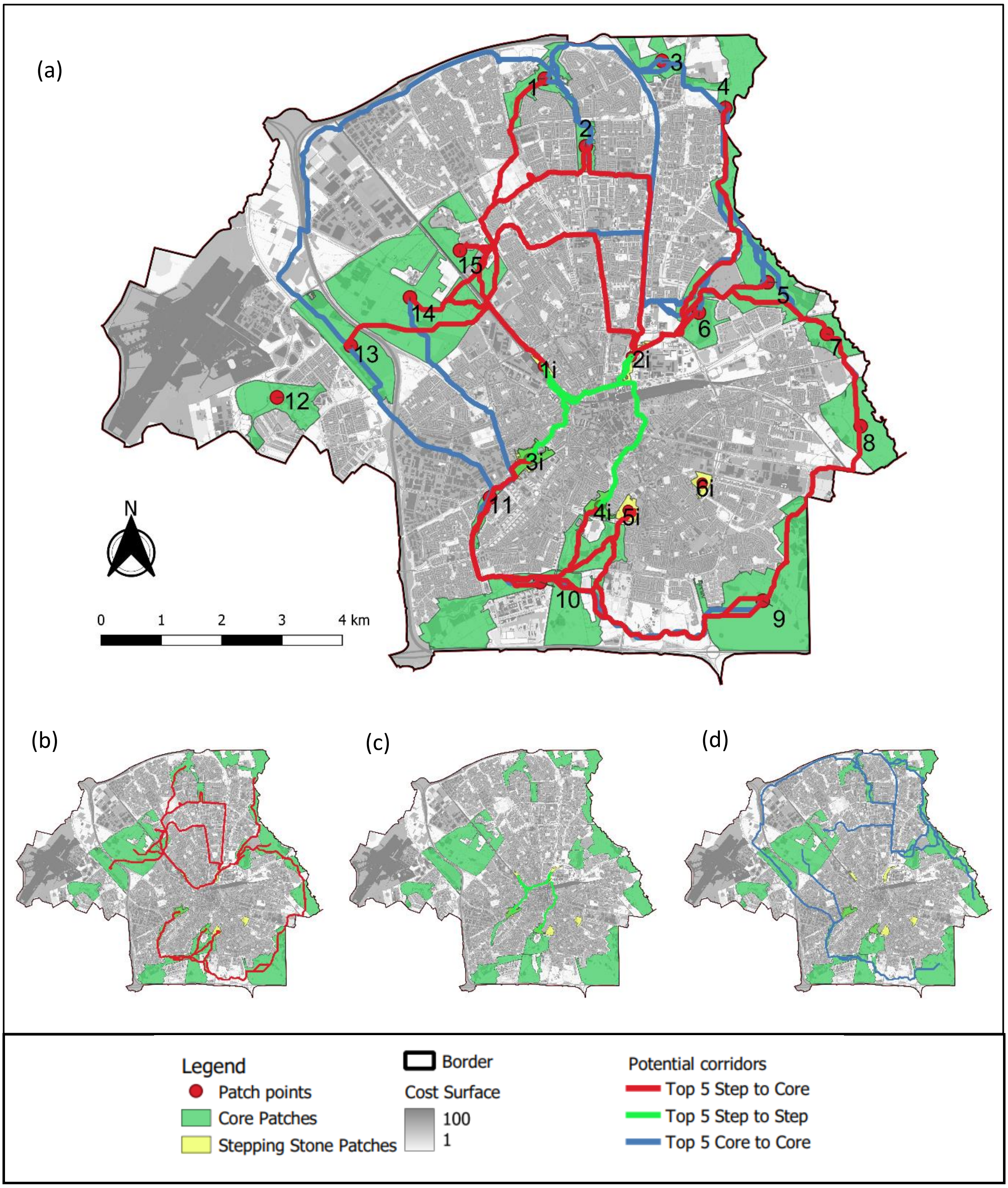

Figure 15 - Overall view (a) of at or above 75th percentile scoring corridors for each situation based on population with low accessibility to different functional types of green, situation 1 (b) Stepping-stone patch to core patch, situation 2 (c) stepping-stone patch to stepping-stone patch, and situation 3 (d) core patch to core patch

The areas which have less access to the different functional types of green spaces generally lie in the more urbanized areas of the city. The results show, in comparison to Figure 14, that there are less similar paths between situation 1 (Figure 15b) and situation 3 (Figure 15d). They still mimic each other's behaviour but are forced to deviate to reach into the residential areas for the dwelling count. Situation 2 (Figure 15c) is mostly identical to Figure 14c as in both cases the corridors have similar interaction values and count the same number of dwellings with low accessibility to the different functional types of green.

4.6 Network evaluation for different scenarios

The network scenarios have been developed and can be viewed in Figure 16a, b, c, and d. Due to limited data, it is not exactly clear which connections in the existing scenario (Figure 16a) are truly established. Therefore, connections between the patches that potentially already exist have been used to portray the scenario of the existing network. The network scenarios which are created to evaluate potential improvements (Figure 16b, c, and d) to the existing network scenario have been created according to section 3.7.2.

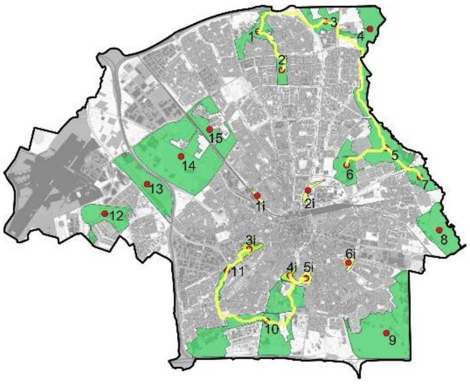

Figure 16a - Current existing situation (Network A)

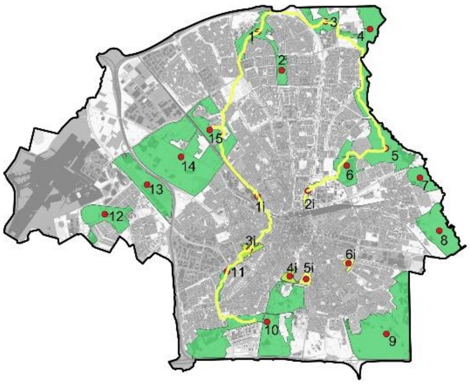

Figure 16b – Paul Revere (Network B)

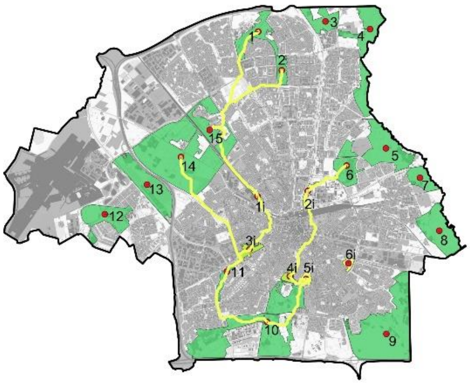

Figure 16c – Hierarchical (Network C)

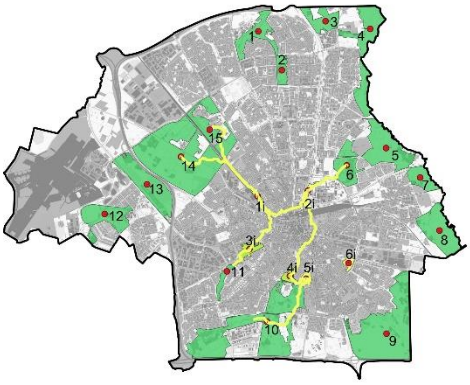

Figure 16d – Least-cost to builder (Network D)

The connectivity indices have been calculated, as per section 3.7.3, for all four network scenarios. To evaluate the potential improvements to the existing network, the developed networks B, C, and D are then individually implemented into the existing scenario (network A). The implementation of the new scenarios into the existing scenarios does consider the links already existing in both networks. The calculated values for each network scenario are shown in Table 7. Aside from the connectivity indices, the human population is also taken into account in form of the number of dwellings within range of the network. This has been done for both the overall dwellings and the dwellings which have low accessibility to the different functional types of green.

Table 7 - Connectivity indices for the four network configurations

Type	Network	Nodes	Links	Beta	Gamma	Dwellings	Dwellings, Low Access
Theoretical max	-	21	210	10.0	1.0	-	-
Existing network	A	21	8	0.38	0.14	3508	1472
Paul Revere	B	21	9	0.43	0.16	7828	4747
Hierarchical	C	21	11	0.52	0.19	12775	5845
Least Cost to Builder	D	21	9	0.43	0.16	9754	7136
Network A+B	E	21	13	0.62	0.23	8924	5246
Network A+C	F	21	17	0.81	0.30	14032	6362
Network A+D	G	21	16	0.76	0.28	12395	8139

The networks B, C, and D show a higher beta and gamma value than the current existing situation (network A). All three new networks (network B, C, and D) show a higher beta and gamma value than the existing network A. This means that these scenarios have an overall higher level of connectivity and patch connection. The network scenarios of networks B, C, and D also target a larger number of dwellings. Of the new network scenarios, network C has the highest beta and gamma value and also targets the largest number of dwellings. Network D has the same beta and gamma value as network B but targets more dwellings in areas that have lower accessibility to the different functional types of green than the other networks.

When the newly developed scenarios (network B, C, and D) are implemented into the existing scenario (network A) the overall connectivity increases. Network A in combination with network C shows the largest increase in both the beta and gamma values and targets the largest number of dwellings for the overall situation. When network D is integrated into network A, it lacks slightly behind network A+C with the beta and gamma values but targets a significantly larger number of dwellings in areas with low accessibility to the different functional types of green. Lastly, network A+B shows only a slight increase in overall network connectivity while also targeting a significantly lower number of dwellings for both situations compared to the other two network combinations.

4.7 Increase of connectivity after implementation of corridors

The connectivity of the neighbourhoods has also been compared by the cohesion index between the current situation and the situation after the implementation of corridors. The width of the corridors is assumed at 15 m as it provides an adequate amount of space for species (Indiana Division of Fish & Wildlife, 2004). Further on, the interaction values attained from the gravity model and the surrounding population are not taken into the evaluation for connectivity. The corridors have been merged into the existing landscape and the cohesion index has been calculated per neighbourhood. Both the current situation and the situation after implementation of the corridors can be seen in Figure 17 and Figure 18 for comparison.

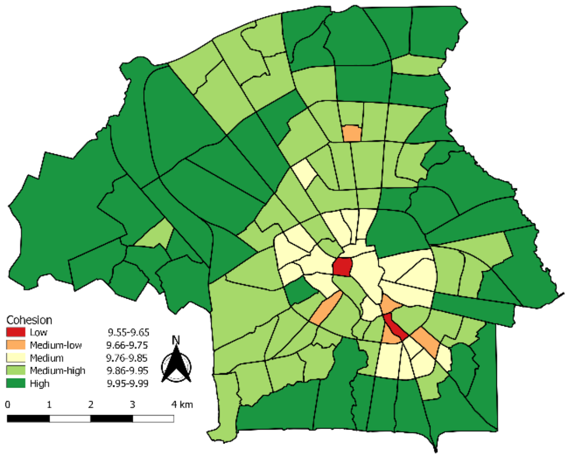

Figure 17 - Cohesion results per neighborhood (current state)

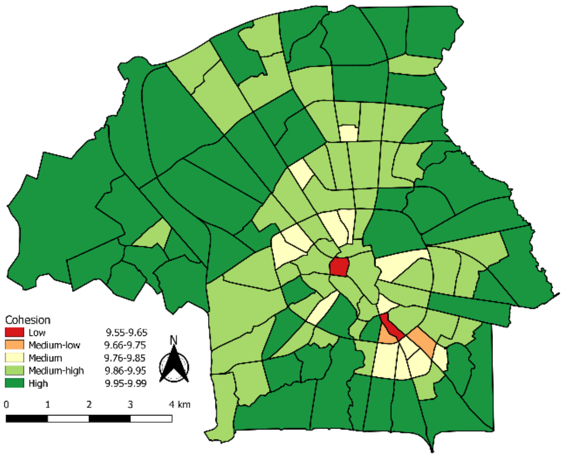

Figure 18 - Cohesion results per neighborhood (After implementation of corridors)

Overall, the connectivity in every neighbourhood increases after the implementation of the corridors. A general summary of the increase in connectivity can be seen in Table 8.

Table 8 - Summary of the cohesion values

	Min	Max	Mean	Median	Variance
Cohesion Index Current Situation	9.561	9.988	9.903	9.933	0.007
Cohesion Index After Implementation	9.636	9.988	9.919	9.944	0.005

It has to be noted however, there are some neighbourhoods that, based on their cohesion index, can experience a decrease in connectivity. This can be explained by the fact that the index is relative to each other. When a certain neighbourhood's connectivity is not affected by the changes while the other neighbourhoods experience an increase in connectivity, then its relative cohesion index experiences a slight decrease due to relativity. The cohesion index per neighbourhood can be found in Appendix A.

4.8 Corridors by expert evaluation

An expert evaluation has been conducted to review the results of the research. The evaluation took place on the 6th of July 2021. The evaluation was done with a project leader and advisor with regards to water and climate adaptation of the municipality of Eindhoven, and a lecturer in urban planning and urban development from the Eindhoven University of Technology. The structure of the evaluation was in form of a presentation in which the results were presented. These were then discussed during and after the presentation.

One of the first points of discussion was the cost-layer which indicates the intensity of infrastructure, which is based on demolition prices. The municipality is interested in a map that can identify whether certain buildings or infrastructure can be demolished to compensate for greenfield projects. The current cost-layer can identify what would be cost-efficient to demolish. However, in its current iteration, due to the scope of the project, it is not able to conform to such interest. It would still require tweaking and more data to increase its accuracy.

The model, according to the experts, generates paths where corridors already exist. It also identifies potential corridors which have not been established yet but are in line with the municipality's vision for developing green corridors. This gives a confirmation that the model can generate useful pathways for developing corridors. However, there is also a demand to identify bottlenecks in corridors. These bottlenecks reduce the effectiveness as it interrupts the connection. An example of an interruption in the corridor would be the riparian green which forms a corridor alongside the river being abruptly interrupted by having no room for land alongside the river under a railway bridge or overpass. The bottlenecks can be identified by manual image search of the corridor path using google maps to identify whether the corridor is interrupted in such places.

Another point of discussion was that the current corridors are selected based on the interaction value in relation to the citizens of the study area. It might be useful to split the selection process based on ecological value and value for the citizens. As the current system could potentially leave out connections that might be crucial for the ecology, leaving out certain links can weaken the system. Maintaining strong ecological links allows for a more robust system for conserving and/or improving biodiversity.

During the evaluation, it was also noted that there is an importance to adding more green infrastructure to business terrains. Some of the corridors generated by the model do move through business terrains which give potential suggestions for paths through the area. However, by the current methodology, it is possible that these are filtered out. The potential corridors generated are prioritized based on a combination of their interaction value and dwelling count within range (section 3.7.1). The business terrains of the study area do not contain any residential dwellings and thus have a high probability of being filtered out in prioritization. If it is of high importance, these paths can be handpicked from the total results and be evaluated.

All in all, based on the input from the expert evaluation, the model in its current iteration generates paths where corridors already exist. This means that the model behaves as it was intended. It also identifies potential corridors in line with the municipality's vision, meaning that the corridors derived from the model do make sense and that there is potential that the model can be used as a tool for identifying potential locations for corridors in the city.

5. Suggestions for potential corridors to focus on

The analysis has brought up many potential corridors. However, not all of them can be developed as space in the urban environment is costly and limited. This chapter is meant to look at some of the results again and consider what potential corridors would be best to focus on. The best scoring corridors have already been discussed, but those are a starting point. The scores are based on the inputs of the model while a city is a complex system in which there are many things to consider, whether it be to improve the quality of life in the city, improve biodiversity, or just making the city more aesthetically pleasing.

5.1 Re-establishing the connection between north and south

The results show that the highly urbanized environment of the inner ring in combination with the railway separating the northern and southern parts of the city's landscape from each other. When looking to re-establish the connection between north and south, there are two main potential connections to be realized. The first connection being the pathway from patch 2i to 4i, see Figure 19. This pathway is mostly already a green corridor but is interrupted by the overpasses of the railway and the Professor Doctor Dorgelolaan. Both overpasses let the river flow through but there is no room for riparian green to establish the connection, at least for terrestrial biodiversity to move. In the expert evaluation, this pathway was discussed and there were plans to create room for riparian green under the railway, but no mentions to establish riparian green under the overpass of the Professor Doctor Dorgelolaan.

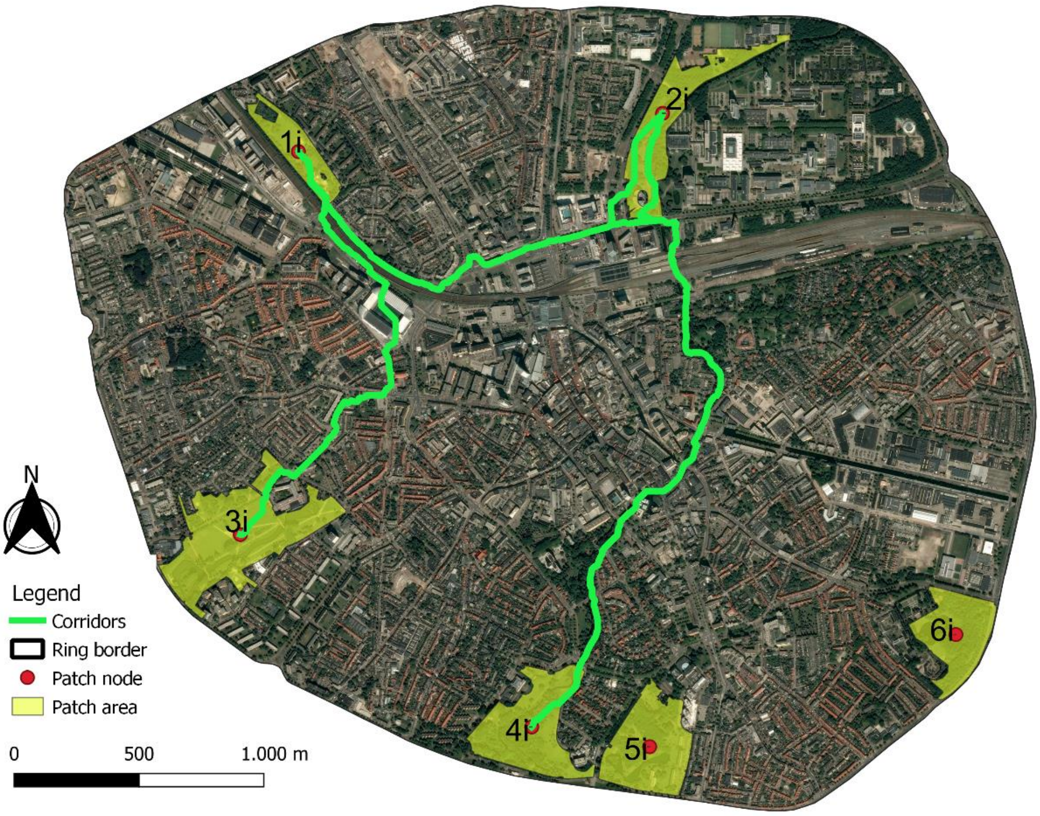

Figure 19 - Suggestions for corridors in the inner ring of the city

Another pathway to re-establish the connection between north and south is the path from patch 1i to 3i (currently, the path moves through the stadium, it defined the football field as a green area). The Jozef Eliasweg from patch 3i is rather wide which leaves many options for green infrastructure. A park could then be created around the stadium connecting to this corridor and from the newly built park utilize the overpass of the railway which is currently used for cars and cyclists to connect it back to patch 1i.

In addition, a corridor could then also be built from patch 1i to patch 2i. It could move along the railway station and give a more pleasing welcome when people enter Eindhoven from the railway station. It would not only be more aesthetically pleasing, but if a robust network is created with the three pathways as seen in Figure 19, it would re-establish the connection not only between north and south but also between the three 'wedges' of Eindhoven. The inner ring of Eindhoven also has the largest population with less access to green, hence it is advisable to focus on building more green infrastructure there.

5.2 Connecting the outer areas

To create a robust network, all the core patches can be connected along the edges of the city according to the Paul revere typology with a twist from the Hierarchical typology, a suggested network can be seen in Figure 20. Many of these connections are to a certain extend already established, but in some cases the railway cuts through the landscape severing the connection between the two patches.

Figure 20 - Suggestion to connect the core patches by the outer edges according to the Paul Revere typology

By ensuring that these connections are established, as well as potential connections with the green areas outside of the border of Eindhoven, it would create a far better environment in which biodiversity can thrive. The connections which are severed by the railway could potentially be solved by implementing fauna passages. The other connections are again, mostly established or can be established by a green corridor. The corridors between the core patches would be suggested to be at least 15 m wide (Indiana Division of Fish & Wildlife, 2004) as it encompasses the core patches.

5.3 Completed network

A more robust green network for the city of Eindhoven could be created by combining both the ‘least-cost to builder’ and ‘Paul Revere’ typology. This would imply a form of a combination of the scenarios described in the previous sections. Figure 21 illustrates the completed network as a combination of both scenarios.

Figure 21 - Suggestion for a completed network for Eindhoven

This network is mostly created from the corridors which score at or above the 75th percentile. However, based on the expert evaluation, some corridors were also taken into this network for their high interaction value for establishing strong ecological links. The presented network would establish the connection between the three 'wedges' of Eindhoven, create a more aesthetically pleasing inner city and a strong connection with the outer green patches of Eindhoven. From the centre of the city, it can also lead people to the larger green areas as they would have to only follow the green corridor. Within the range of this network of corridors, it counts roughly 14000 dwellings of which 6500 are located in areas that have low accessibility to the different functional types of green.

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6. Conclusion

The primary objective of this research is to find the locations for the optimal corridors in the urban environment from which both humans and nature can benefit to enhance landscape connectivity on an urban scale. The main research question with its sub-questions aimed to achieve this objective. In this chapter, the sub-questions will be answered followed by the main research question.

Sub-question 1: **How significant is the role of landscape connectivity in ecosystem health?**

Landscape connectivity determines to which degree the landscape can facilitate or impede the movement of species among the resource patches. As urban development increased and expanded it severely impacted overall landscape connectivity leaving many habitats fragmented. The resulting isolation and disconnect from other resource patches as a consequence of habitat fragmentation have led to increased extinction rates as it is harder for species to breed and move to more resourceful areas which ultimately leads to a large loss in biodiversity.

Sub-question 2: **What are major impedances for biodiversity in an urbanized environment?**

In an urbanized environment habitat fragmentation occurs more severely. Vast road networks and many blocks of grey infrastructure can fill the space between two habitats. For the local species living in the urban environment, it is not easy to traverse this distance which leaves them severed from other patches. Certain species can persist for a while but will ultimately perish due to extinction debt. Thus, as urbanization increases the impedances for biodiversity increase which leads to a reduction in overall biodiversity. There are cases in which low to moderate urbanization can have a positive impact on biodiversity but this is generally through the introduction of new species which can come at the cost of the extinction of native species. When urbanization later increases as a result of demand for expansion, biodiversity will decrease.

Sub-question 3: **What benefits are there to gain for the local population when establishing green connections between the urban green areas?**

Urban areas are condensed with a generally high activity which has negative effects on its local environment, such as air pollution and urban heat islands. Adding more green in these areas through green corridors can help mitigate these effects. In addition to the environmental benefits, Green corridors, given their linear configurations, favour movement, flow and exchange, and connecting landscape elements of different scales. By connecting the green spaces with green corridors, increases the aesthetics of the city, promotes physical activity by leading people to green spaces, and increases mental relaxation.

Sub-question 4: **What are the basic methods and theories to model landscape connectivity?**

The basic method for modelling landscape connectivity comprises of applying several theories such as graph theory and least-cost theory. The standard method consists of identifying the main areas to be connected. After which the cost-surface is created which simulates the impedance of species or 'cost to move' over the area. The least-cost analysis is then applied on the cost-surface which identifies potential paths. The gravity model can then be applied to find the best potential paths as it finds the efficiency between the corridors and the significance of the areas connecting them. With the potential paths, a network can be created which then be compared to the existing network and evaluated using graph theory.

Sub-question 5: **What is the current state of the study area with regards to its urban green spaces and connectivity?**

Eindhoven has a strong green policy plan which has resulted in the city being one of the greenest cities in the Netherlands. This is reflected in its landscape as many large patches provide shelter and resources for local biodiversity, and its green 'wedges' reaching into the city. The cohesion index, which measures landscape connectivity, also shows that per neighbourhood there is an overall high cohesion. However, nearing the city centre, especially within the inner ring, the cohesion decreases as urbanization increases. A lot of the disconnection of green areas in the city is caused by the ring road and the railway separating the city's landscape.

Sub-question 6: **What are the potential connections which can be made in the study area to connect the urban green spaces?**

The least-cost analysis in combination with the gravity model has identified many connections which can be made to connect the urban green spaces and enhance landscape connectivity. All paths the corresponding results from the gravity model can be seen in Appendix F. Overall, the more impactful connections to be made in the city landscape for both improvements of biodiversity and quality of life for residents are the connections made in Figure 16d which represents the least-cost to builder typology. This network connects the northern and southern parts of Eindhoven and moves through the area which, overall, has low access to the many different types of green spaces in the city as seen in Appendix E.

With the sub-questions answered, the main research question can be answered. The main research question which started this research is: **What are the optimal pathways to enhance landscape connectivity on an urban scale?**

The optimal pathways to enhance landscape connectivity on an urban scale should consider both the improvements for nature and its local biodiversity as well as the residents who can gain benefit in quality of life after implementation. This research has integrated various theories and models for building a systematic methodology that can identify pathways that have great potential for the implementation of green infrastructure to enhance connectivity in the city.

The strategy deployed for the cost layer is an alternative that could be applied to cities to identify potential corridors and make decisions based on the local situations whether it be to improve the biodiversity or to add more green infrastructure in areas that are lacking. And though this strategy of considering biodiversity, the residents, and the intensity of infrastructure deviates from the 'standard' landscape connectivity studies, it is a refreshing step into a different direction. There are still things to consider and tweaking to be done, but it opens new opportunities for the integration of various aspects coming with urban planning to enhance landscape connectivity on an urban scale.

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7. Discussion

The results from the initial connectivity analysis show that, in relative numbers, a large number of the neighbourhoods have high connectivity. These neighbourhoods lie mostly in the outer edges of the city which tend to be greener and less developed. The neighbourhoods with lower connectivity generally lie in the more developed city centre. The numbers are relative to each other and the neighbourhoods are cut off by their borders in this analysis. It could be that a neighbourhood has better connectivity due to synergy with green infrastructure from an adjacent neighbourhood.

After the connectivity analysis, core patches were then identified based on a minimum size of 12 ha as suggested by Kong et al. (2010) after figuring that the method suggested by Firehock & Walker (2015) is not effective after Zhang et al. (2019) tried it in an urban environment. As for the minimum size of stepping stone patches, the size for these is rather unclear and varies (Saura et al., 2014). The stepping-stones are mainly the larger parks located within the inner ring of Eindhoven for this study and their main purpose is leisure for residents. Therefore, a minimum size of 5 ha was chosen in accordance with Van Herzele & Wiedemann (2003). A total of 15 core patches and 6 stepping-stone patches have been identified based on these criteria. In the first instances of this study, there were several more core patches. However, some of them have been merged as the river with its riparian passes underneath a separating road connecting the patches. It is not always clear for every river connection of the core patches that the connection is established through riparian green or if the river passing underneath actually functions as a connection, in this research, it is assumed so. If the river connection does not function as an actual connection, it, either way, leaves an opportunity for improvement between the patches. Lastly, satellite imagery data (NDVI) was used to gather information on the 'healthiness' of a patch by calculating the coverage of understory vegetation and the tree canopy of the patch. Understory vegetation can tell whether a patch is healthy as a study by Threlfall et al., (2017) showed that increasing understory volume from 10% to 30% had a significant increase on the local biodiversity after which the effect diminished. Trees on the other hand had a neutral effect. In this study, vegetation coverage is not fully considered for a patch due to a lack of available data with regards to understory vegetation lying underneath the tree canopy. However, applying a coverage percentage when identifying core patches can prove quite useful in sorting out the healthiest patches.

The applied method for identifying potential corridors was similar to Kong et al., (2010); Linehan et al., (1995); Zhang et al., (2019), but the variables and cost-layers used were different. The values for impedance are mostly theoretical based on the available literature. A more objective way was sought and tried for this study. Hence, a cost-layer that indicates the intensity of the built environment was brought to life and combined with the impedance layer by use of the entropy weight method. The two cost-layers were very similar. However, when applying the least-cost analysis on the impedance layer, the algorithm would in some cases utilize every small patch of green and take a long route around to get to the objective. Whereas the cost-layer which indicates the intensity of the built environment would go straight through a zone with little infrastructure as it gave no resistance. The other way around, however, the impedance layer would be more effective in identifying infrastructural objects which serve as a barrier to biodiversity. In the current research, the combined cost-layer has thus intentionally (or unintentionally) worked. A cost-layer based on the intensity of the built environment can therefore work but requires more tuning. Another possible method for using a more objective cost-layer would be to use the NDVI map as a base. The NDVI map, with its value differences, does also look very similar to both the impedance layer and the intensity of the built environment layer and thus could show similar results.

The entropy weight method served its purpose in this research. Though it catches the differences as much as possible and showing the variation, it does have its limitations. The method is prone to distortion when there are too many zero values, in the case of this research this was avoidable. The method being objective of nature is beneficial, but it leaves the outcome to rely on the input of the impedance layer. The impedance layer, in this research, is the only object in the method which required 'manual' input.

The variables used for corridor identification were slightly different from the other studies. The formula used for calculating node weight was more based on an economic approach rather than the standard formulas used by Linehan et al., (1995) and Rudd et al., (2002). The formula used in this study perceives a patch as a city in which the coverage of vegetation can be seen as its population (as vegetation influences biodiversity (Threlfall et al., 2017)(Saura et al., 2014)). Two cities with a vast amount of land and large population will be more likely to interact with each other than a smaller city with a larger city (Wheeler, 2005). Corridor selection by gravity model was slightly different as well as it considers the population the potential corridor would affect. The results from only using the interaction value obtained from the gravity model were correct but obvious, and as the Dutch would call it 'kicking in open doors’. Considering the population by using postcode data when identifying the optimal corridor proved helpful in finding potential corridors which would both benefit the local population and biodiversity. Hence, finding the optimal corridor.

Calculating the final scores had been done by multiplying the interaction value and the number of dwellings within range of the corridor. This was a simple method to find the corridors with a more balanced ratio between the two values. By using a method in which the values were normalized and then added together would still find corridors that would have a high interaction value but zero dwellings in their vicinity. There are potentially other methods, but in this research, it was kept simple as it was effective.

Using corridors that scored at or above the 75th percentile allowed for more freedom in developing scenarios for network evaluation. Of the three new network scenarios, scenario C showed the most potential for improvement to connectivity to the current situation. The current situation, however, is based on the assumption that certain connections are already established, whether this is true requires field research. Overall, any corridor implemented that is not already established by the current situation can and most likely will improve the landscape connectivity.

Eindhoven has been a great study area for this research due to the vast amount of green in the city. This allowed for better testing of the model as it was easier to identify whether the model would work as predicted or take weird turns on the map. Seeing that the model can find potential new connections in an already very green city, in line with the vision of the local municipality, it should have great potential in finding new connections in cities with less green.

7.1 What can be done differently the next time

If the study were to be repeated, several changes would be done. For instance, an attempt at patch identification would have probably been done by using the NDVI data and then compare it to patches identified on the municipality's map of green spaces. More time would also be spent on the gathering and preparation of the data for the creation of the cost layers, as the cost layer is the foundation for the least-cost analysis. Although the creation of the cost layer itself is not that challenging, however, many datasets needed slight adjustments to represent reality (i.e. in one of the datasets a large portion of the water area would be considered as a highway). And another thing to test regarding the cost layers would be the behaviour of the least-cost analysis if the NDVI map was used as a cost-layer due to its similarities to the impedance layer.

A next time, there would also be more involvement with the local municipality. A lot of information can be gained to speed up the process and setting the right direction as they have more knowledge of the area. As well as evaluation of the results could be more beneficial if there was earlier involvement.

7.2 Recommendations for further research

There are still several gaps in knowledge with regards to landscape connectivity in an urbanized environment that would benefit the planning for corridors. A shortlist of subjects that have been encountered during the research but had no definitive answer are compiled here:

1. Previous studies used mostly theoretical values for simulating the impedance for species for the least-cost analysis. This research linked that to demolition prices which indicate the intensity of infrastructure, more infrastructure, more impedance. However, the NDVI maps of areas show very similar results to that of the theoretical values and thus could be tested for use as a cost layer for the least-cost analysis.
2. In-depth research could be done to investigate to what extend the small areas of riparian green crossing underneath an overpass establish a connection between the green areas on either side of the overpass.
3. The width of corridors has been studied in rural areas but so far, there are no tested values for the width of corridors in an urbanized environment. And what optimal widths could be realized in such an environment considering biodiversity, ongoing traffic, and other such factors.
4. It would also be helpful to perhaps develop a better methodology in finding the optimum between the interaction value from the gravity model and the number of the population targeted to find the optimal corridor.

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Appendix A – Cohesion Index

Visual overview of all results for the cohesion index per neighborhood

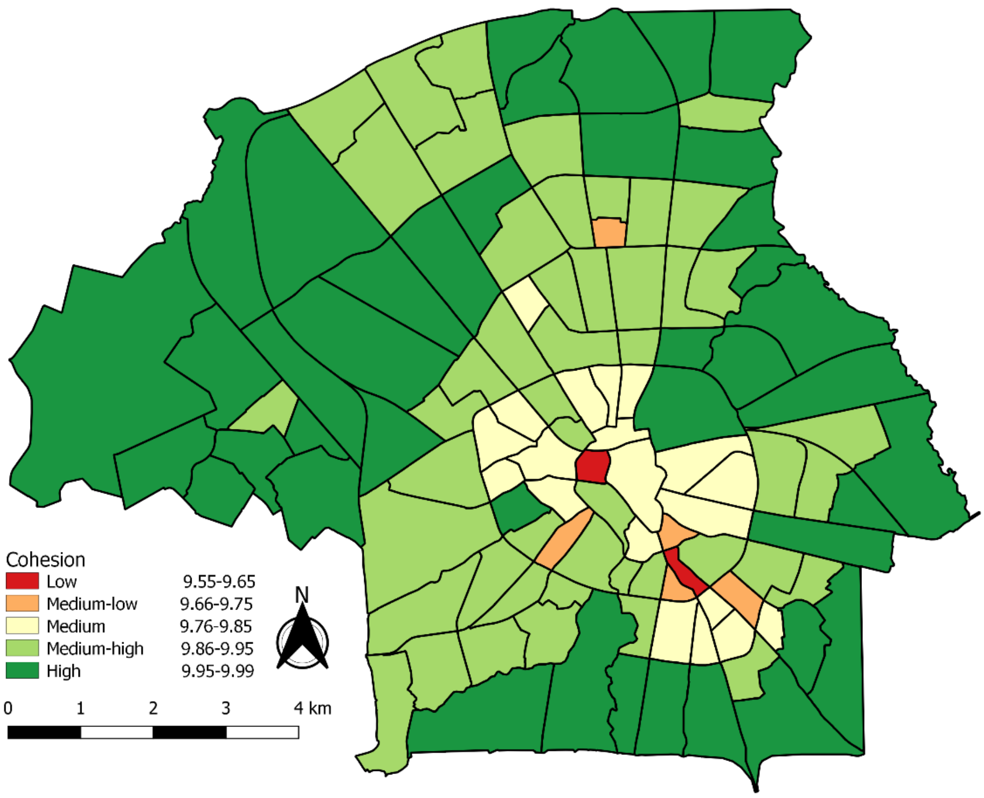

Figure A 1- Cohesion results per neighborhood (current situation)

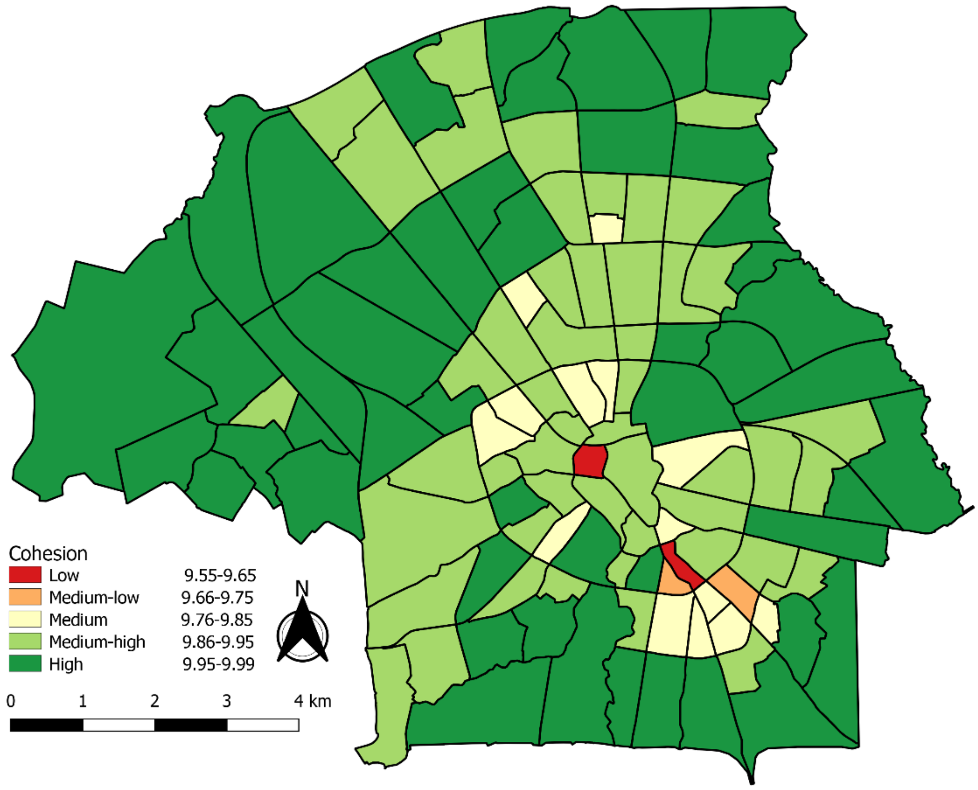

Figure A 2 - Cohesion results per neighborhood (after implementation of corridors)

Overview of all results for the cohesion index per neighborhood

Table A 1 - Summary of the cohesion values

	Min	Max	Mean	Median	Variance
Cohesion Index Current Situation	9.561	9.988	9.903	9.933	0.007
Cohesion Index After Implementation	9.636	9.988	9.919	9.944	0.005

Table A 2 - LecoS cohesion index results from all neighborhoods of Eindhoven, current situation and 'new' situation (after implementation of corridors)

Neighborhood Code	Neighborhood Name	Cohesion Index (Current situation)	Cohesion 2 (New situation)	Difference
111	Binnenstad	9.823	9.925	0.102
112	Bergen	9.872	9.874	0.001
113	Witte Dame	9.642	9.640	-0.002
114	Fellenoord	9.781	9.923	0.142
115	TU-terrein	9.953	9.977	0.024
211	Irisbuurt	9.799	9.865	0.066
212	Rochusbuurt	9.687	9.843	0.156
213	Elzent-Noord	9.841	9.899	0.059
214	Tuindorp	9.938	9.946	0.008
215	Joriskwartier	9.561	9.636	0.074
216	Bloemenplein	9.695	9.695	0.000
217	Looiakkers	9.946	9.953	0.007
218	Elzent-Zuid	9.926	9.937	0.012
221	Kerstroosplein	9.805	9.805	0.000
222	Gerardusplein	9.849	9.849	0.000
223	Genneperzijde	9.944	9.949	0.005
224	Roosten	9.975	9.975	0.000
225	Eikenburg	9.972	9.972	0.000
226	Sportpark Aalsterweg	9.965	9.966	0.001
230	Puttense Dreef	9.933	9.948	0.016
231	Poeijers	9.960	9.970	0.010
232	Burghplan	9.908	9.928	0.020
233	Sintenbuurt	9.654	9.654	0.000
234	Tivoli	9.812	9.812	0.000
235	Gijzenrooi	9.965	9.965	0.000
236	Nieuwe Erven	9.807	9.807	0.000
237	Kruidenbuurt	9.779	9.779	0.000
238	Schuttersbosch	9.907	9.907	0.000
239	Leenderheide	9.985	9.985	0.000
240	Riel	9.983	9.983	0.000
311	Villapark	9.804	9.833	0.029

312	Lakerlopen	9.754	9.892	0.139
321	Doornakkers-West	9.916	9.916	0.000
322	Doornakkers-Oost	9.888	9.888	0.000
328	Tongelresche Akkers	9.964	9.965	0.001
333	Muschberg, Geestenberg	9.927	9.927	0.000
334	Urkhoven	9.986	9.986	0.000
335	't Hofke	9.975	9.978	0.002
336	Karpen	9.964	9.970	0.006
337	Koudenhoven	9.985	9.986	0.001
410	Limbeek-Zuid	9.896	9.921	0.025
411	Limbeek-Noord	9.929	9.936	0.007
412	Hemelrijken	9.815	9.815	0.000
413	Gildebuurt	9.847	9.847	0.000
414	Woenselse Watermolen	9.811	9.871	0.060
421	Woensel-West	9.914	9.921	0.006
422	Kronehoef	9.894	9.895	0.001
423	Barrier	9.813	9.813	0.000
424	Mensfort	9.868	9.868	0.000
425	Rapenland	9.872	9.936	0.064
426	Vredeoord	9.978	9.982	0.004
431	Generalenbuurt	9.919	9.944	0.025
432	Oude Toren	9.917	9.920	0.003
433	Hondsheuvels	9.958	9.967	0.009
434	Oude Gracht-West	9.903	9.933	0.030
435	Oude Gracht-Oost	9.933	9.933	0.001
436	Eckartdal	9.967	9.967	0.001
511	Driehoeksbos	9.969	9.972	0.003
512	Prinsejagt	9.944	9.964	0.020
513	Jagershoef	9.897	9.899	0.003
514	't Hool	9.912	9.914	0.002
515	Winkelcentrum	9.690	9.764	0.074
516	Vlokhoven	9.919	9.938	0.020
520	Kapelbeemd	9.940	9.949	0.009
521	Kerkdorp Acht	9.949	9.949	0.000
522	Achtse Barrier-Gunterslaer	9.925	9.936	0.011
523	Achtse Barrier-Spaaihoef	9.948	9.952	0.004
524	Achtse Barrier-Hoeven	9.944	9.949	0.005
531	Woenselse Heide	9.861	9.880	0.019
532	Tempel	9.960	9.963	0.003
533	Blixembosch-West	9.972	9.973	0.001
534	Blixembosch-Oost	9.971	9.974	0.003
535	CastiliÃ«laan	9.978	9.978	0.000
541	Eckart	9.902	9.917	0.015
542	Luytelaer	9.969	9.969	0.000

543	Vaartbroek	9.958	9.959	0.001
544	Heesterakker	9.919	9.928	0.009
545	Esp	9.979	9.979	0.000
546	Bokt	9.983	9.983	0.000
611	Eliasterrein, Vonderkwartier	9.831	9.890	0.059
612	Philipsdorp	9.783	9.911	0.129
613	Engelsbergen	9.951	9.959	0.007
614	Schouwbroek	9.775	9.866	0.091
615	Schoot	9.791	9.803	0.013
616	Strijp S	9.820	9.820	0.000
621	Hurk	9.892	9.939	0.047
622	Het Ven	9.943	9.946	0.003
623	Lievendaal	9.965	9.965	0.000
624	Drents Dorp	9.944	9.953	0.009
625	Zwaanstraat	9.920	9.929	0.009
626	Wielewaal	9.988	9.988	0.000
627	Herdgang	9.985	9.986	0.000
628	Mispelhoef	9.974	9.980	0.006
631	BeA2	9.986	9.986	0.000
632	Meerbos	9.980	9.981	0.001
633	Grasrijk	9.954	9.955	0.000
634	Zandrijk	9.895	9.899	0.005
635	Waterrijk	9.954	9.954	0.000
636	Park Forum	9.970	9.976	0.006
637	Flight Forum	9.968	9.973	0.005
638	Eindhoven Airport	9.972	9.972	0.000
639	Bosrijk	9.969	9.969	0.000
640	Meerrijk	9.972	9.974	0.002
711	Schrijversbuurt	9.931	9.959	0.028
712	Oude Spoorbaan	9.705	9.817	0.112
713	Hagenkamp	9.922	9.944	0.022
721	Genderdal	9.948	9.951	0.003
722	Blaarthem	9.886	9.886	0.000
723	Rapelenburg	9.874	9.874	0.000
724	Bennekel-Oost	9.943	9.955	0.012
725	Bennekel-West, Gagelbosch	9.949	9.959	0.010
726	Gennep	9.985	9.985	0.000
727	Beemden	9.979	9.979	0.000
731	Genderbeemd	9.945	9.947	0.002
732	Hanevoet	9.943	9.944	0.002
733	Ooievaarsnest	9.948	9.948	0.000

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Appendix B – Estimating vegetation by the NDVI and AHN

Appendix B – Estimating vegetation by the NDVI and AHN

The vegetation coverage is estimated by using the Normalized Difference Vegetation Index (NDVI) in combination with the Actueel Hoogtebestand Nederland (AHN) otherwise known as the topical height map. Based on the study of Threlfall et al., (2017) understory vegetation is limited to a height of 2 m anything above can be interpreted as tree canopy. Low grown grass or generally mown grass is not as beneficial to biodiversity and thus the range for understory vegetation lies between 0.2 m and 2.0 m. Figure B1 gives perspective to height of understory vegetation and tree canopy. These values will be used to estimate the coverage of the patches.

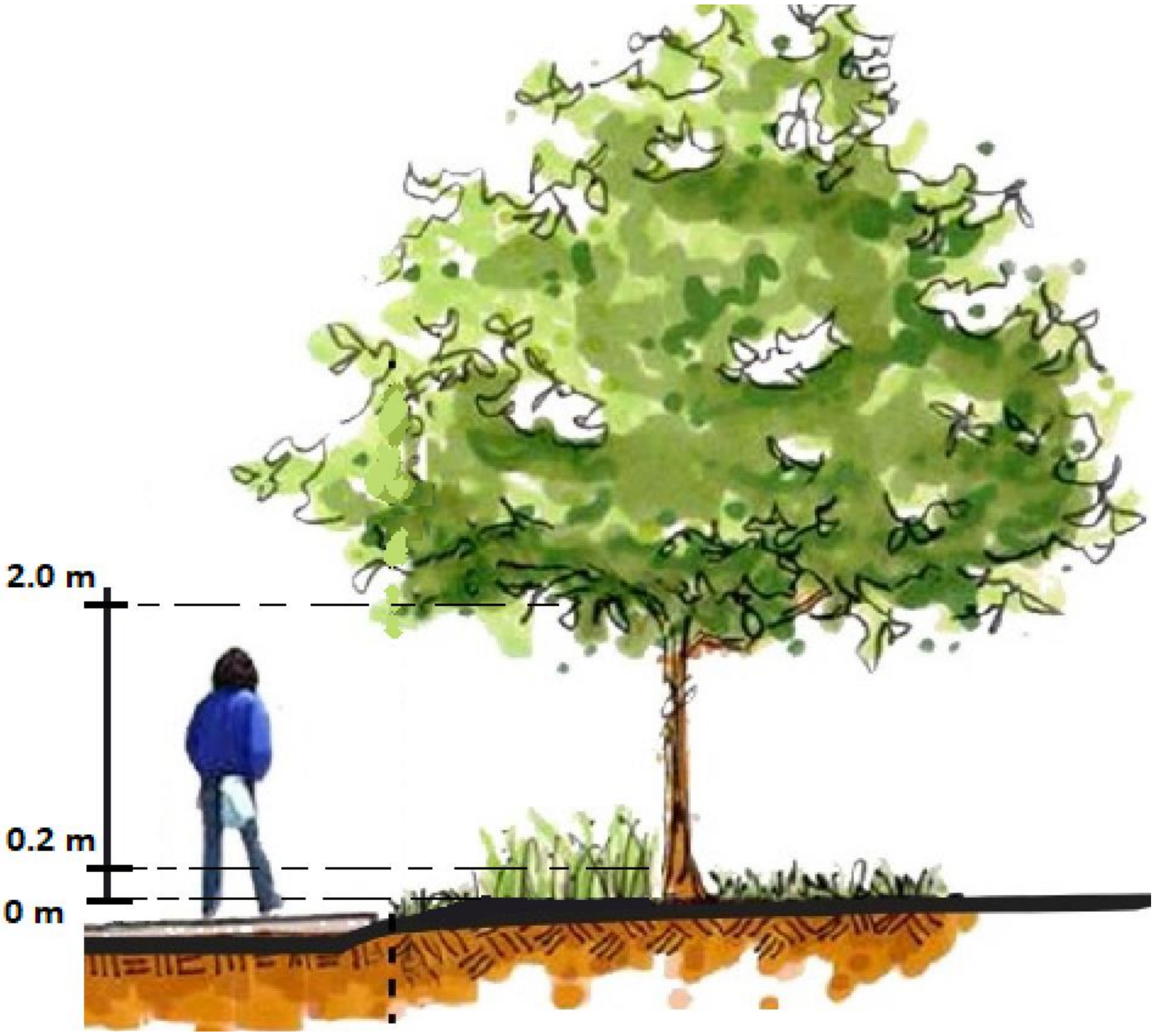

Figure B 1 - Height of understory vegetation and tree canopy

To find the all the vegetation, the NDVI of Eindhoven is used. The NDVI is a measure of the state of plant health based on how light reflects from it at certain frequencies. Chlorophyll resides in plants and absorbs visible light; the cellular structure of the leaves reflects near-infrared light. The Sentinel-2 satellite orbits around the earth and gathers satellite imagery data of these light reflections available for anyone to use. The data can then be used to calculate the NDVI using the following formula:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{B1}$$

In which the NIR stands for reflection in the near-infrared spectrum and RED stands for the reflection in the red range of the spectrum. The index defines values from -1.0 to 1.0. Negative values are mainly clouds, water and snow, values between 0.0 and 0.2 represent areas of rock, sand or overall urban infrastructure. Values above 0.3 are generally plant-life and vegetation.

To calculate the NDVI for Eindhoven, data was taken from the Sentinel-2 satellite. The data was collected on the 5th of August 2020 at around 11:00, this shows Eindhoven in full bloom, which increases certainty of finding all vegetation. Further on, at this time and day there was a cloud coverage of 0%. The datasets of band 4 (RED) and band 8 (NIR) is used. With this data the NDVI for Eindhoven is calculated, the results can be viewed in Figure B2.

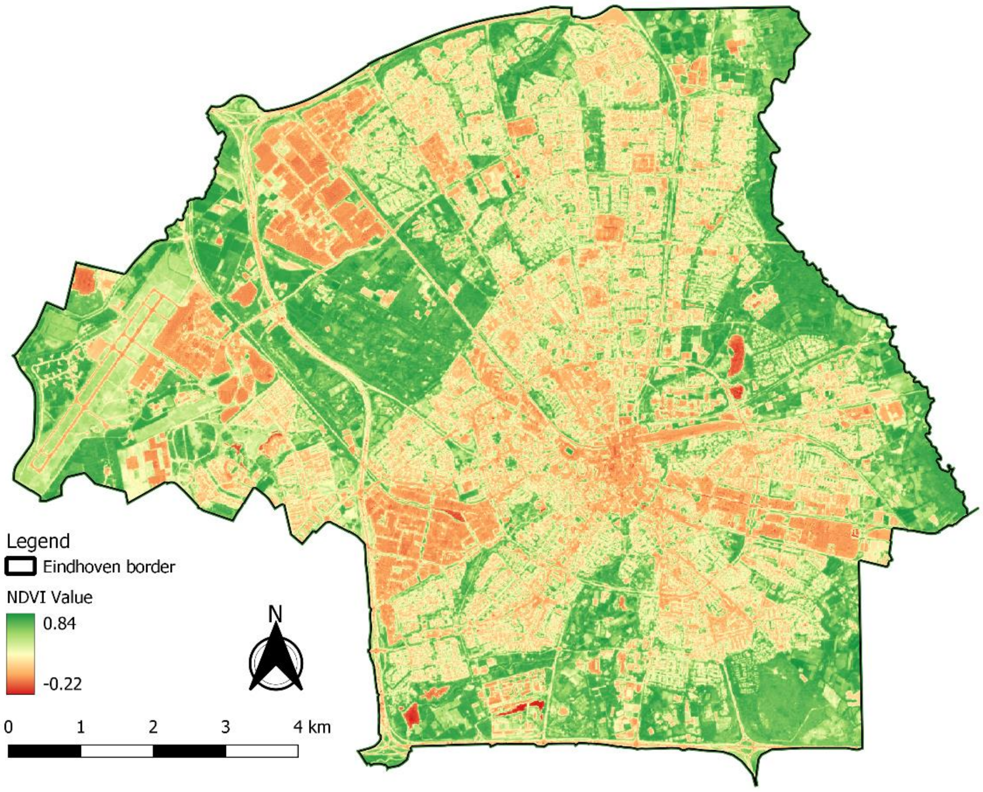

Figure B 2 - The results from the NDVI analysis for Eindhoven

The NDVI values for Eindhoven and its surroundings range from -1.0 to 1.0. The NDVI values for Eindhoven's area specifically range from -0.22 to 0.84.

The results from the NDVI are then combined with the data from the topical height map to separate the understory vegetation from the tree canopy, and to leave out patches of mown grass which hold little to no value. As stated before, the understory vegetation is classified as plant-life which appears between 0.2 and 2.0 m. Tree canopy can be found at elevations above 2.0m. Figure B3 shows that a clear distinction can be made between the understory vegetation and tree canopy.

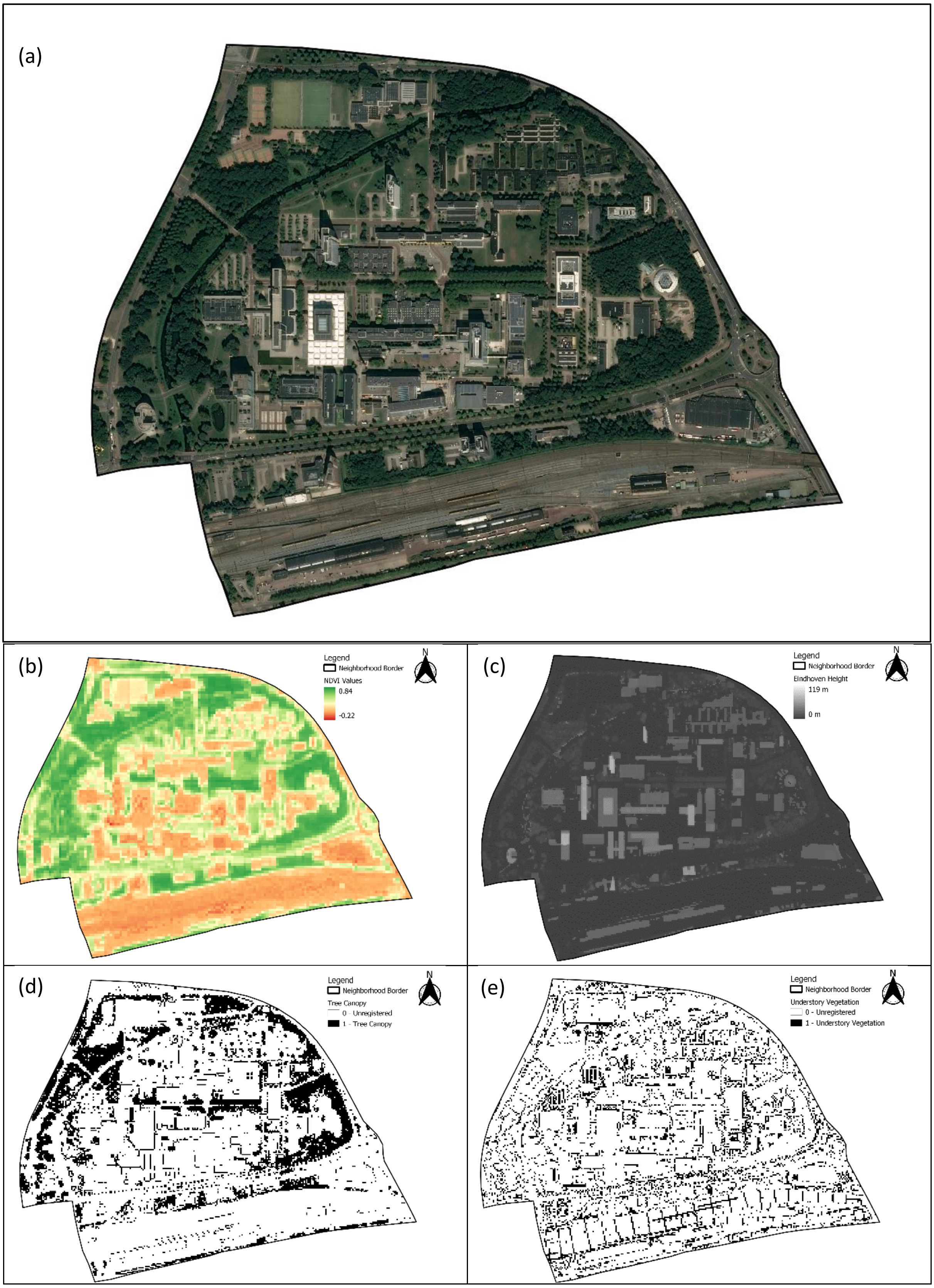
(a)
(b)
Legend
Neighborhood Border
NDVI Values
0.84
-0.22
N
(c)
Legend
Neighborhood Border
Eindhoven Height
119 m
0 m
N
(d)
Legend
Neighborhood Border
Tree Canopy
0 - Unregistered
1 - Tree Canopy
N
(e)
Legend
Neighborhood Border
Understory Vegetation
0 - Unregistered
1 - Understory Vegetation
N

Figure B3a shows an aerial view of the neighborhood ‘TU terrein’, which is the terrain of the Eindhoven University of Technology. Figure B3b shows the results from the NDVI calculations for the area and Figure B3c shows the height of the area obtained from the AHN. All data above a threshold of 0.3 are taken from the NDVI and laid over the topical height map. The Topical height map then splits the NDVI into two layers, one for the tree canopy ($h > 2.0$ m) as seen in Figure B3d and one for the understory vegetation ($0.2 < h < 2.0$ m) as seen in Figure B3e.

The data from the layers are then intersected with the core and stepping-stone patches. The results have been shown in Table 6 in section 4.2. The limitation to this method, however, is that it is not possible to view what is underneath the tree canopy. Hence, the amount of understory vegetation in the area will most likely be higher than is currently estimated.

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Appendix C – Differences between the cost-layers

Appendix C – Differences between the cost-layers

This appendix will give a short summary of the values used for the creation of the cost-layers. It will not go further into the methodology of creating the cost-layers but will elaborate more on their behavioral differences compared to each other.

C.1 Short summary of the values

Two cost-layers had been created for this research. One of the cost-layers is the impedance map which encompasses the impedance biodiversity experiences through various landscapes in the urban environment is mostly based off the different types of land uses. The types of land uses are taken from the Basisregistratie Grootschalige Topografie (BGT) in addition to the Bestand Bodemgebruik (BBG). The impedance values assigned to the different areas and objects are based off previous studies conducted by Fu et al., (2010); Kong et al., (2010); Marulli & Mallarach, (2005); Xun et al., (2014); Zhang et al., (2019) and assumptions based off the previous mentioned values with the addition to the literature. The current impedance values used can be viewed in Table C1.

Table C 1 - Land use types and their corresponding impedance weights

Type	Impedance value
Green areas	1
Residential areas	40
Commercial areas	60
Public Facility areas	60
Business Park areas	70
Airport area	100
Water	80
Highway, primary and secondary roads	100
Residential roads	40
Cycleway	20
Railway	100
Buildings	100
Other	50

Further on, the second layer indicates the amount of infrastructure in the area based on demolition prices of the objects. These prices have been calculated according to section 3.4.2. Prices for demolition has been gathered from various sources by price per square meter. The demolition prices of various buildings per land use type have been obtained from Bouwkostenkompas (n.d.), a website which has vast amount of data on construction and demolition prices. Prices for roads and pavement have been obtained from the RROK-C17-01 (Voorschoten et al., 2017) which includes an extended list of reasonable prices per square meter. Prices for railway and airport infrastructure was not available and has been estimated to be the most expensive. Prices per square meter can be found in Table C2 below. The cost-layer will be created based on a pixel size of 2.5 by 2.5 m, hence the price is also given per 6.25 m².

Table C 2 - Land use type and their corresponding demolition price per m² and per 6.25 m²

Type	Price per m²	Price per 6.25 m²
Residential	31.0	194
Commercial	31.0	194
Business Park	25.0	156
Public Facilities	35.0	219
Highway	14.4	90
Primary Roads	11.2	70
Pavement	6.1	38
Airport and Railway (Buildings)	40.0	250
Other	24.1	151

C.2The resulting cost-layers

The resulting cost-layers are displayed below, first the impedance layer (Figure C 1) followed up by the layer which indicates infrastructural intensity (Figure C 2).

Figure C 1 - Impedance layer

Figure C 2 - Layer which indicates infrastructural intensity

The higher the value is in the cost-layer, the higher the resistance will be when the least-cost algorithm tries to find the least-cost paths on the map. As can be seen between the two cost-layers is that the layer which represents impedance is much grayer as all objects in a certain land-use zone have the same value. The layer which indicates the amount of infrastructure does not show as much gray. Reason for this is that roads and pavement are relatively cheap to demolish whereas buildings and main traffic infrastructure such as the railway and airport are very expensive to demolish. It also shows that in the center it is grayer due to the increased density of infrastructure (buildings being clumped together etc.). Residential buildings are not very clear in this figure as its relative demolition price compared to the taller buildings in the city is low.

C.3 Differences in behavior

The least-cost analysis has been done for the situation going from core patch to core patch to illustrate the difference in behavior of the algorithm moving over the two cost-layers. The examples will be given with the impedance layer as background as it can illustrate better what is on the map (it is harder to see on the layer for infrastructural intensity). First an overview of the two areas will be given on which will be zoomed in to further illustrate the difference in behavior of the least-cost algorithm on the different cost-layers.

Figure C 3 - Example areas for comparison of the behavior of the least-cost algorithm in the different cost-layers

The first example (Figure C4) example area in the bottom right corner of the map. It illustrates that the least-cost path of the impedance layer (Red) takes the touristic route around the business terrain utilizing every small patch of green it can find along the way. Whereas the least-cost path which looks for infrastructural intensity (Green) finds not much infrastructure on the way and decides to go straight through.

Figure C 4 - Least-cost path differences for the area

Another example (Figure C5), taken from the example area of the top of the map, is that the least-cost path of the impedance layer (Red) here again utilizes all the small green patches alongside the road. It does not cross the road however, as the impedance layer considers the barrier effects of roads. The least-cost path for infrastructural intensity (Green) makes a direct way through the sports area as it has little to no 'real' infrastructure.

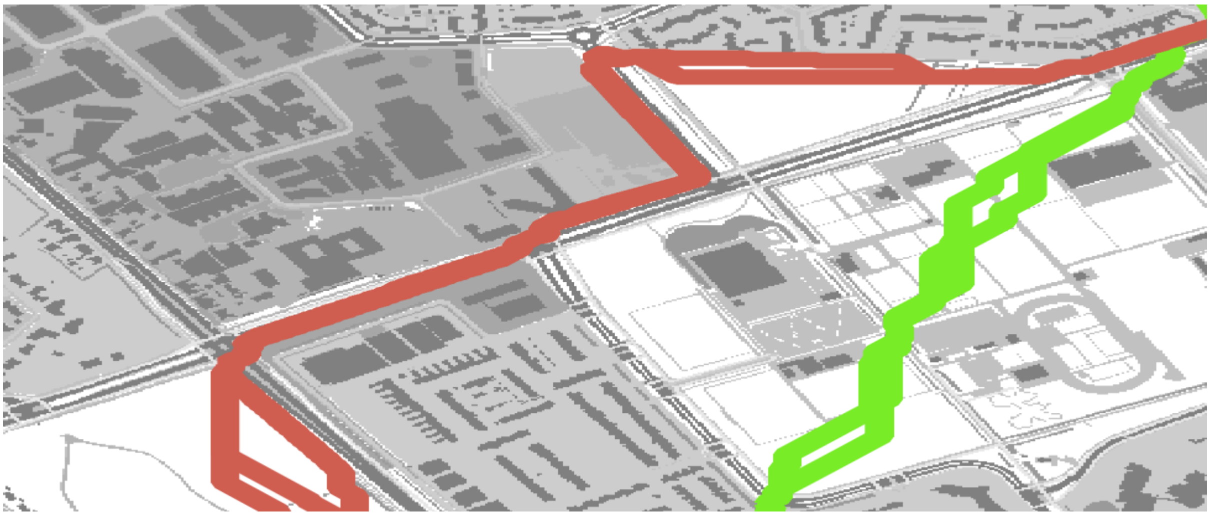

Figure C 5 - Least-cost path differences for the area

Overall, when comparing all paths, the impedance layer tends to move around any infrastructure. Whereas the layer for infrastructural intensity takes more direct routes through the city by taking paths throughout it with least infrastructure as going around the whole city would cost more. All paths are displayed in the following section of this appendix.

C.4 All least-cost paths on the impedance layer

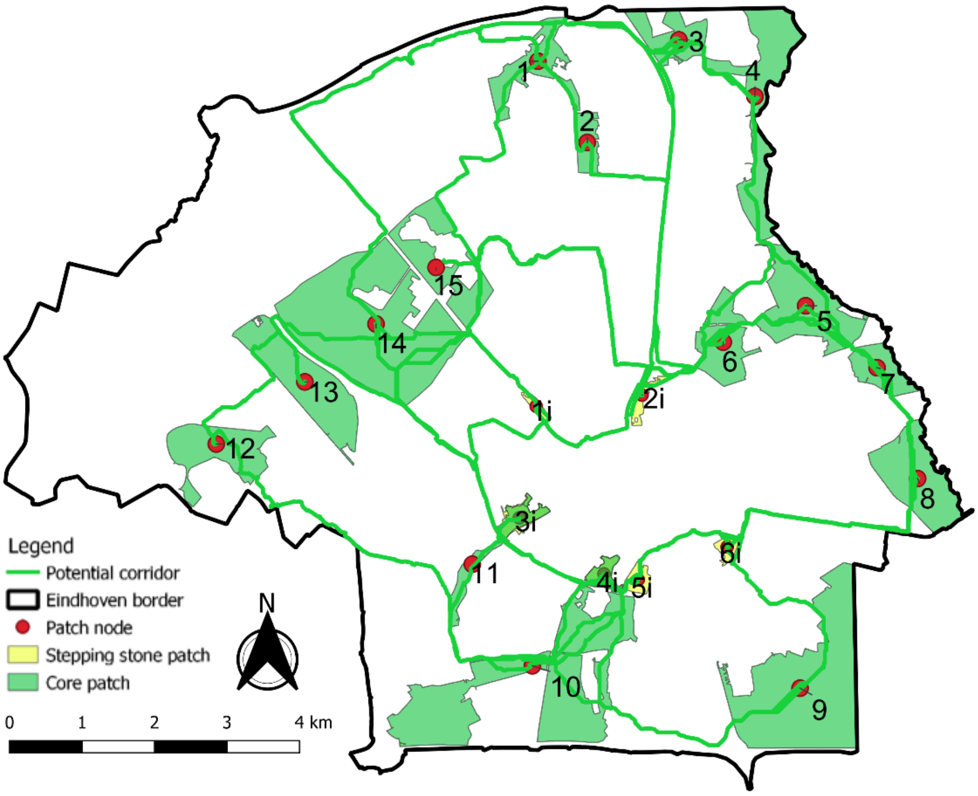

Figure C 6 - Impedance layer, situation 1, stepping-stone patch to core patch, all paths

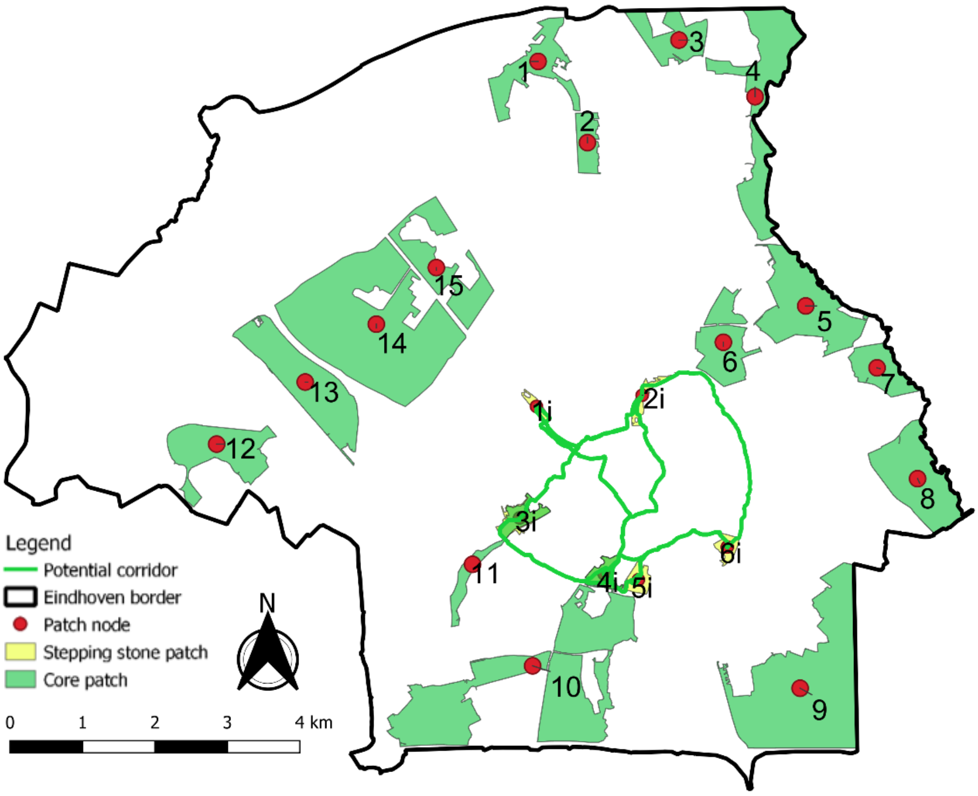

Figure C 7 - Impedance layer, situation 2, stepping-stone patch to stepping-stone patch, all paths

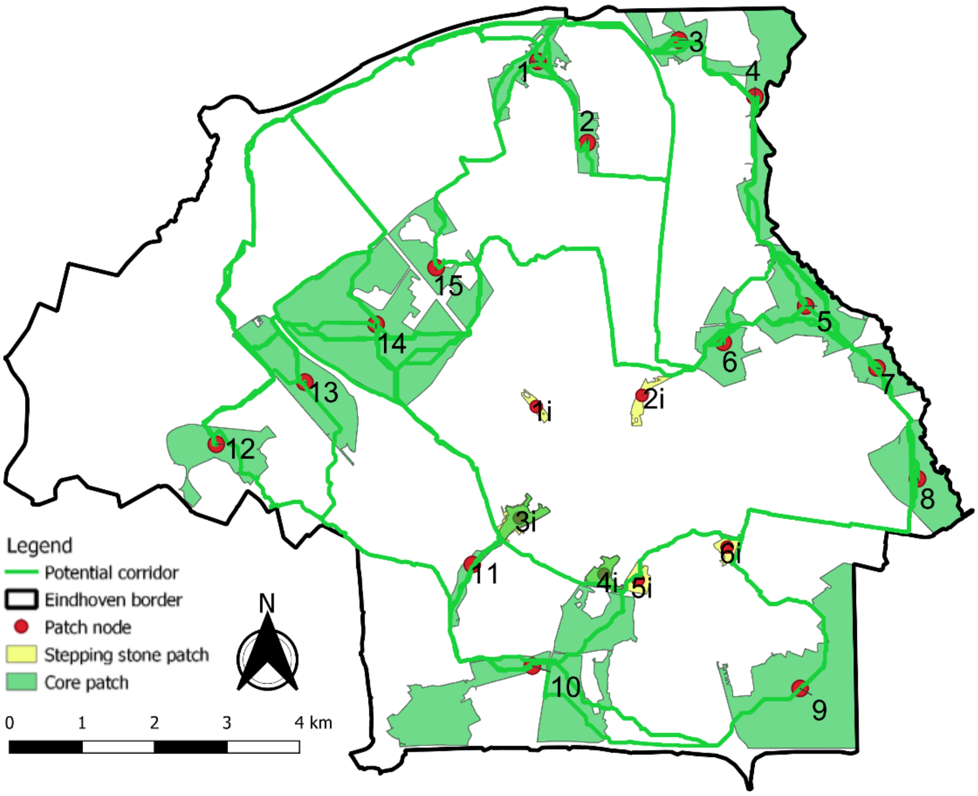

Figure C 8 - Impedance layer, situation 3, core patch to core patch, all paths

C.5 All least-cost paths on the layer for infrastructural intensity

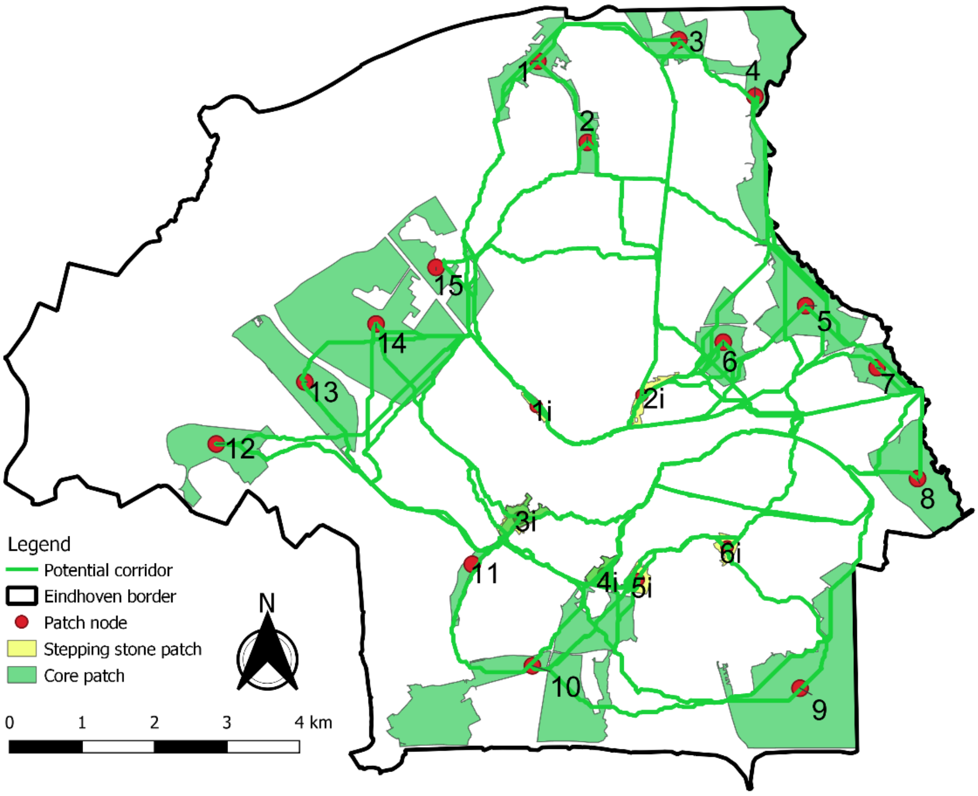

Figure C 9 - Infrastructural intensity layer, situation 1, stepping-stone patch to core patch, all paths

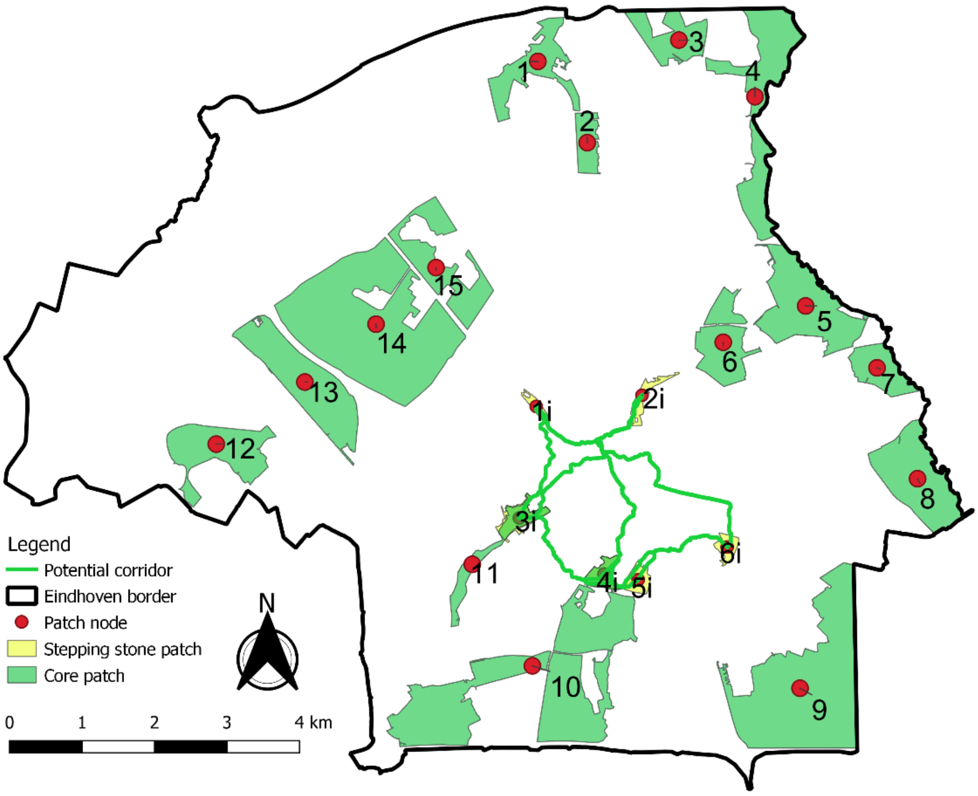

Figure C 10 - Infrastructural intensity layer, situation 2, stepping-stone patch to stepping-stone patch, all paths

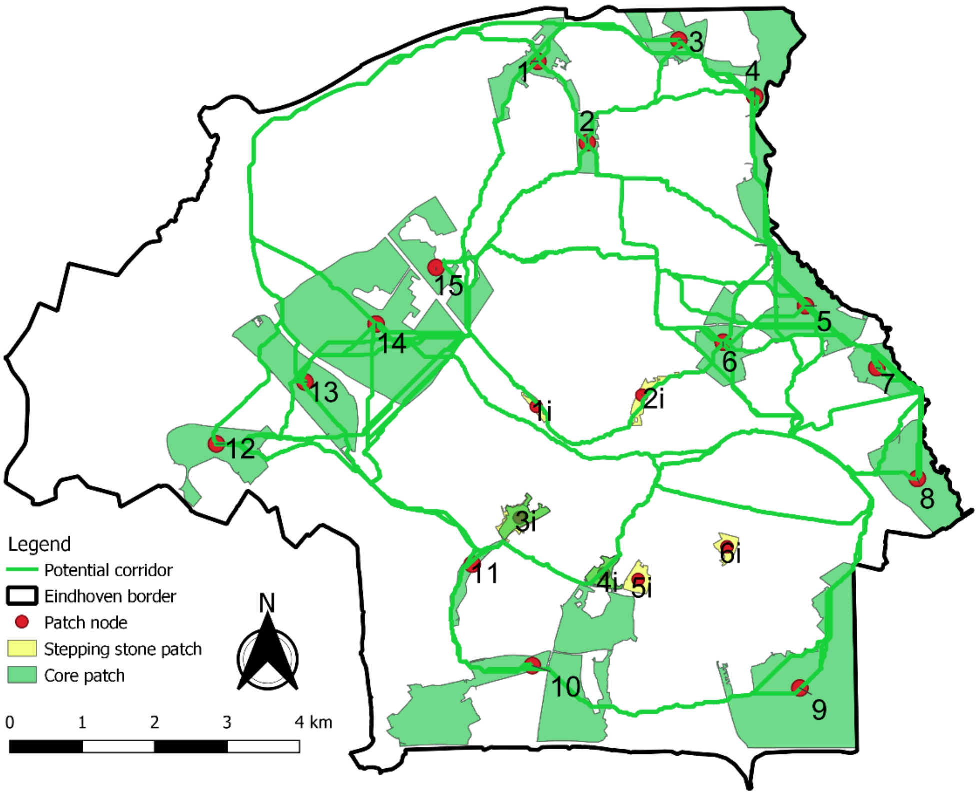

Figure C 11 - Infrastructural intensity layer, situation 3, core patch to core patch, all paths

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Appendix D – The final cost-layer

Appendix D – The final cost-layer

The final cost-layer is the combination of the impedance layer and the layer which indicates the infrastructural intensity as has been shown in Appendix C. The maps have been resized to the same scale (1-100) after which the Entropy Weight Method (EWM) is applied to give each of the layers a weight for combination.

EWM can objectively assign weights to variables and it is based on the degree of dispersion. As the degree of dispersion increases so does the degree of differentiation and more information can be derived, and thus more weight will be given to the variable. The first step in EWM is the standardization of values. Which can be calculated with the following formula (Amiri et al., 2014; Zhu et al., 2020):

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{D1}$$

In which r_{ij} is the standardized value value of the *ith* index in the *jth* sample.

The second step computes the information entropy e_j and is expressed with the following formula:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} r_{ij} \ln r_{ij}\,, \;\; j = 1, 2, \dots, n, \tag{D2}$$

As e_j becomes smaller, the bigger the effect of the *j* index will be. The entropy weight can then be calculated in the final step with the following formula:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)}, \;\; j = 1, 2, \dots, n, \tag{D3}$$

In which w_j is the final entropy weight of the *jth* parameter.

The formulas above have been applied to the values used for the creation of both layers. A full overview of these values with the corresponding calculated numbers from the EWM are listed in Table D1.

Table D 1 - Values used for- and- results from the entropy weight method

			Values			**Entropy values**	
No.	**Category**	**Type**	**Impedance layer**	**Demo layer**		**Impedance layer**	**Infra layer**
1	Areas	Green	1	1.0		-0.005	-0.004
2		Residential	40	38.1		-0.096	-0.075
3		Commercial	60	38.1		-0.128	-0.075
4		Public Facilities	60	38.1		-0.128	-0.075
5		Business Parks	70	38.1		-0.142	-0.075
6		Airport	100	38.1		-0.179	-0.075
7		Other	50	38.1		-0.112	-0.075
8		Water	80	1.0		-0.155	-0.004
9	Roads	Highway	100	90.0		-0.179	-0.139
10		Primary	100	70.0		-0.179	-0.117
11		Secondary	100	70.0		-0.179	-0.117
12		Residential	40	70.0		-0.096	-0.117
13		Railway	100	250.0		-0.179	-0.259
14		Cycleway	20	70.0		-0.057	-0.117
15	Buildings	Residential	100	193.8		-0.179	-0.225
16		Commercial	100	193.8		-0.179	-0.225
17		Business Parks	100	156.3		-0.179	-0.198
18		Public Facilities	100	218.8		-0.179	-0.241
19		Airport and Railway	100	250.0		-0.179	-0.259
20		Other	100	151.3		-0.179	-0.194
		Sum:	1521	2014.6		-2.886	-2.666
m=	20				**ej =**	0.963	0.890
					W_j=	0.250	0.750

The values assigned to each type are based on the values as stated in Table 2 and Table 3 in section 3.4. The results from EWM are that the impedance layer is given a weight of 0.25 and the layer which indicates infrastructural intensity is weighted at 0.75.

Since the layers are based on the same scale, they can be multiplied by their assigned weight and then added together to create the final cost-layer for the least-cost analysis. The final cost-layer can be viewed in Figure D1.

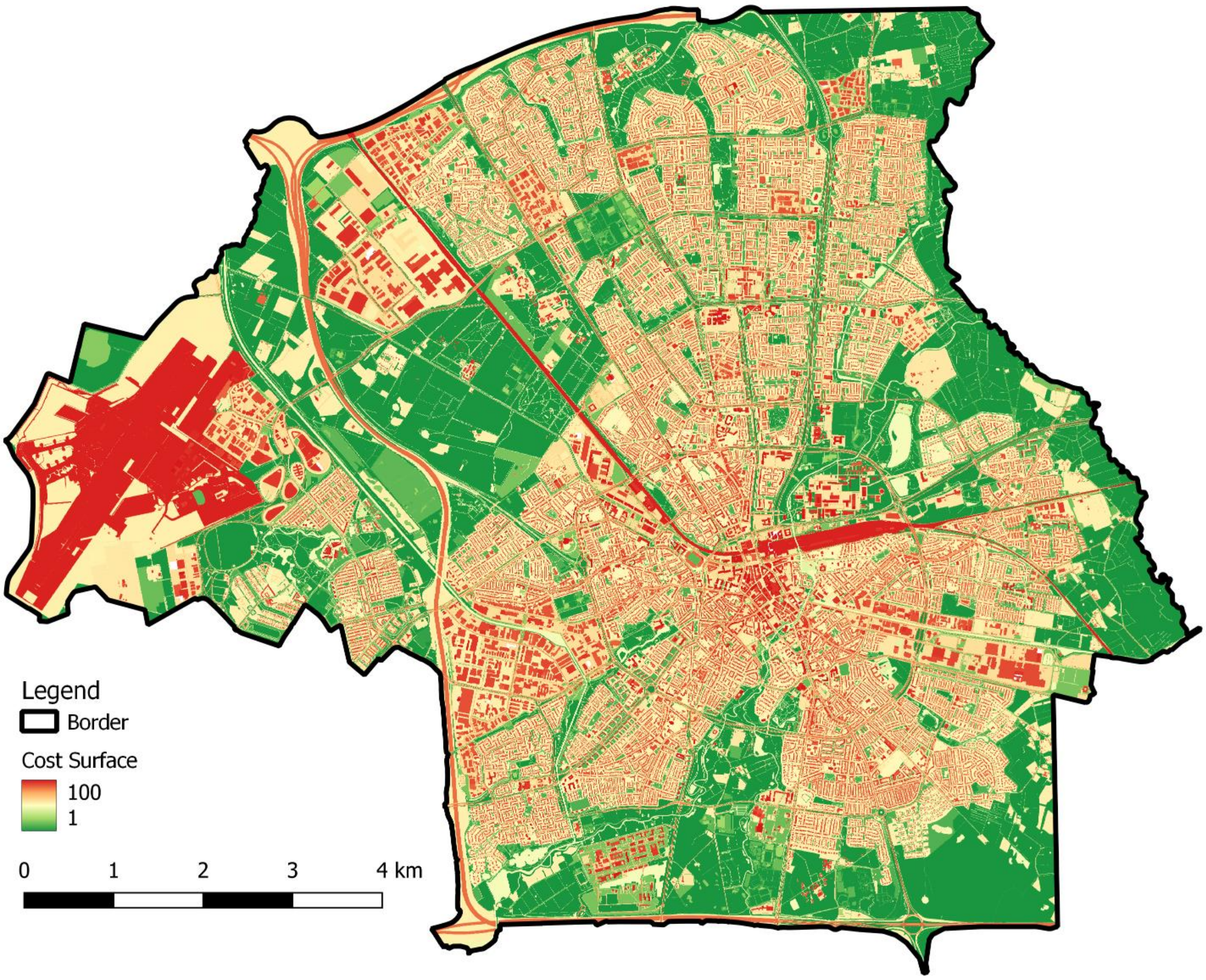

Figure D 1 - The final cost-layer as a result from the entropy weighing method

The final cost layer has been used for the least-cost analysis to generate potential corridors from each core- and stepping-stone patch to one another.

Appendix E – Areas with low accessibility to green

Appendix E – Areas with low accessibility to green

This appendix covers the results from identifying the areas with lower access to the different functional types of green. The development of the map showing the areas has been done as per section 3.6. Figure E 1 below shows the results of all the areas and their accessibility.

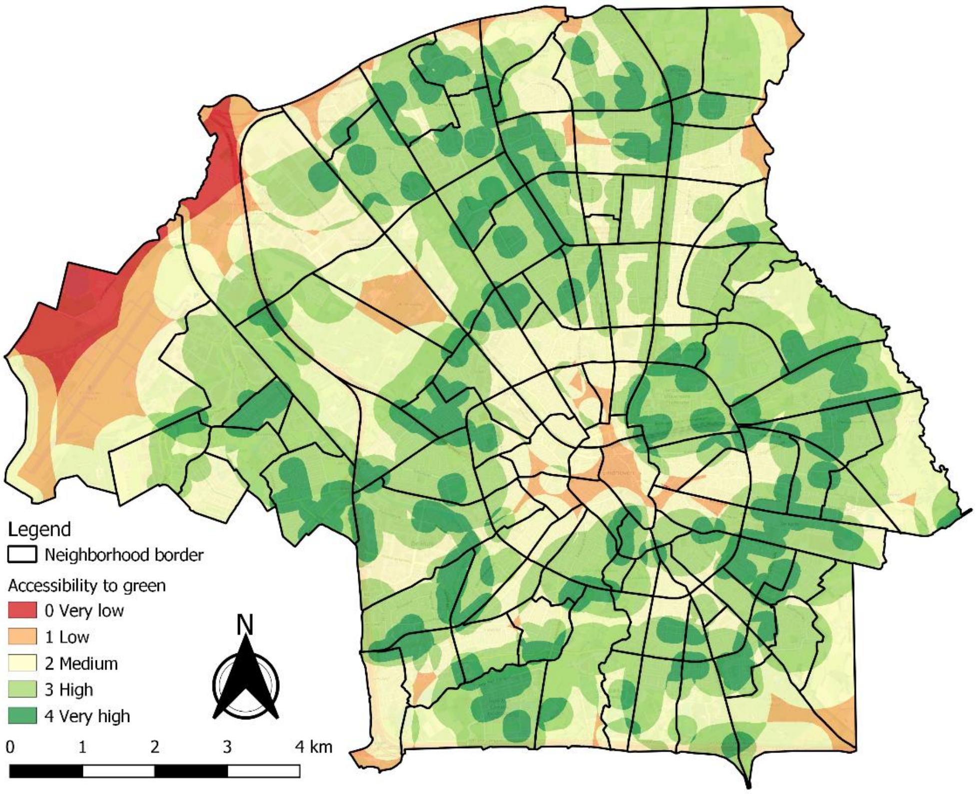

Figure E 1 – Areas by access to the different functional types of green ranging from 0 (very low) to 4 (very high)

Overall, many areas do have a moderate access. The city center however, in which most of the citizens reside, are in the low access zones (0 to 2). These areas can be considered to be in need of green, green corridors can help increase the amount of green in the area as well as be a guide to the other green areas of the city.

Figure E 2 shows all the areas which have low and high accessibility. However, it is not in an instant clear what exactly the low areas are. In figure … the areas with low accessibility to the different functional types of green are filtered out. As mentioned before in section 3.6, the areas with an access 'level' of 2 or lower are considered areas with low accessibility.

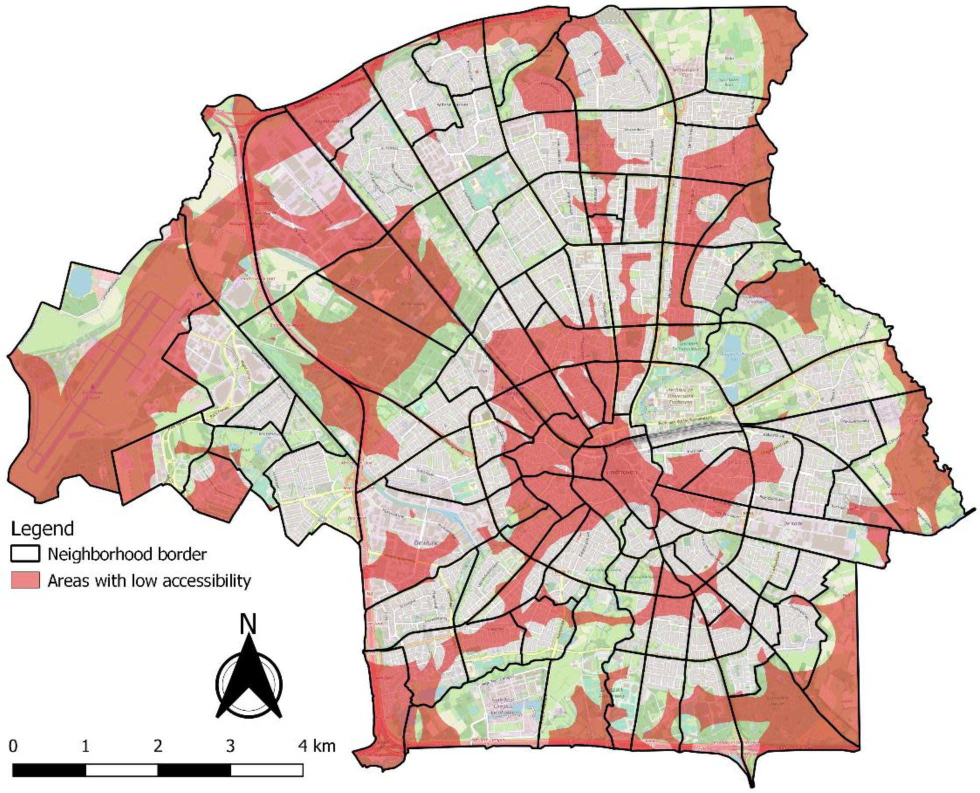

Figure E 2 – The areas with the low accessibility to the different functional types of green

The low accessibility areas identified are true specifically for the center part of the city. Around the outer edges of the city, some of the low access areas are the large green areas which can, in this instance, be ignored. Some other areas are located near or in green areas, but that specific patch(es) of green is the only functional type of green within its vicinity. Giving more options to other areas is highly appreciated. It is however important to consider what areas to prioritize.

Counting the number of dwellings

To count the number of dwellings in these areas or count the overall number of dwellings within range of a potential corridor, the corridors are buffered by 150 m. Figure E 3 shows an example of this. The postcode data shows a dot for each dwelling, all the dots within the buffer area are counted towards the corridor.

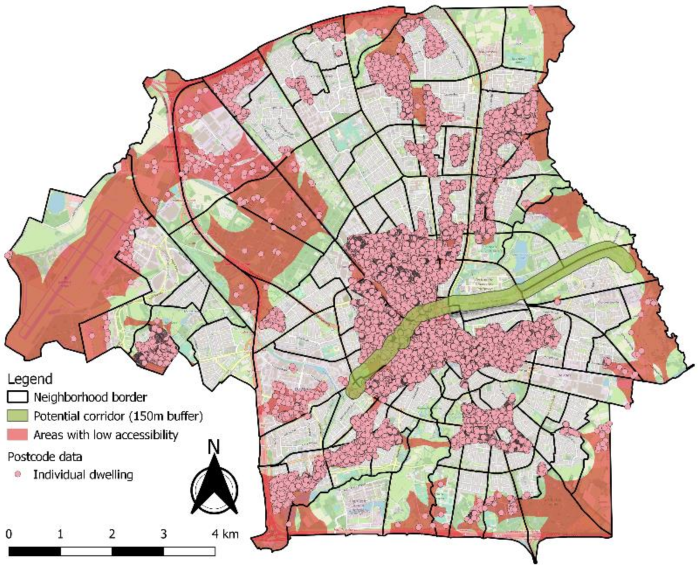

Figure E 3 – Example of the dwelling count, the dwellings that appear within the green buffer (which represents the corridor) are counted

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Appendix F – Least-cost analysis and gravity model

Appendix F – Least-cost analysis and gravity model

This appendix will give an overview of all the results from the least-cost analysis and the applied gravity model. Aside of the interaction value between the patches obtained from the gravity model, it will also state the amount of population the potential corridor affects. For both the overall population and the population with a lower access to green spaces.

The results will be posted per situation to give a clearer overview. The situations as stated in the research were the following:

- Situation 1: Stepping-stone patch to core patch;
- Situation 2: Stepping-stone patch to stepping-stone patch;
- Situation 3: Core patch to core patch.

Of the total 210 potential corridors found by the least-cost analysis 90 belong to situation 1 (Figure F 1), 15 belong to situation 2 (Figure F 2), and 105 belong the situation 3 (Figure F 3).

Figure F 1 - Situation 1 with its 90 potential corridors

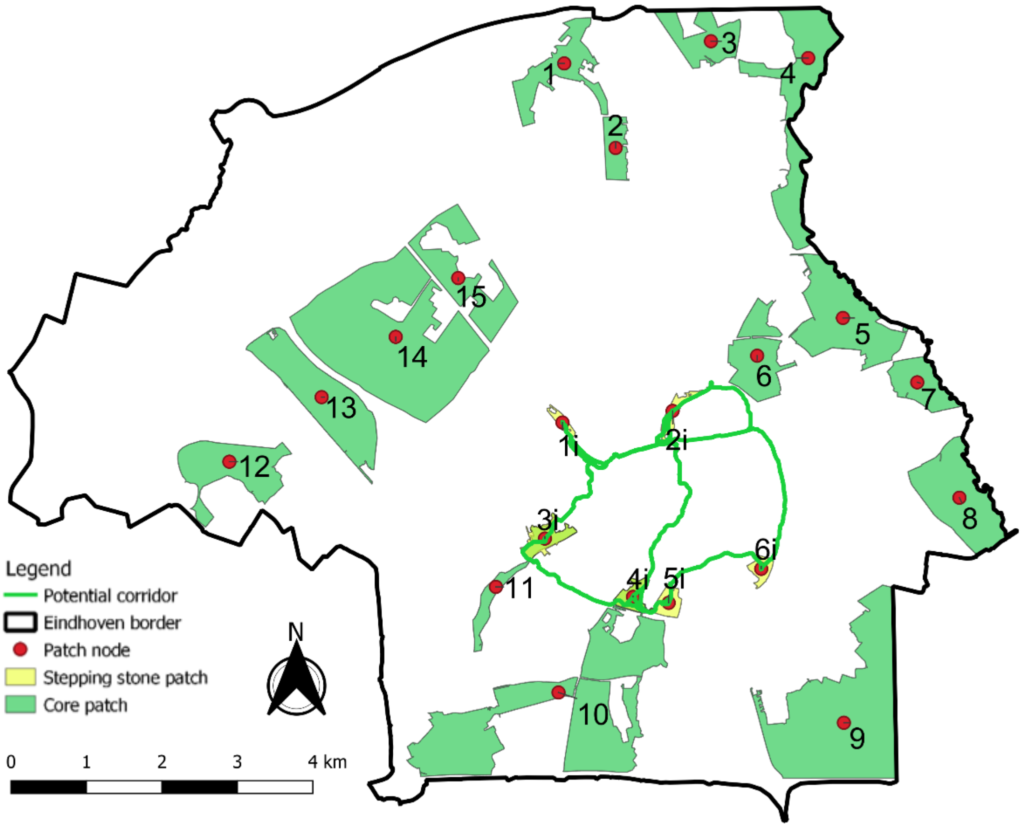

Figure F 2 - Situation 2 with its 15 potential corridors

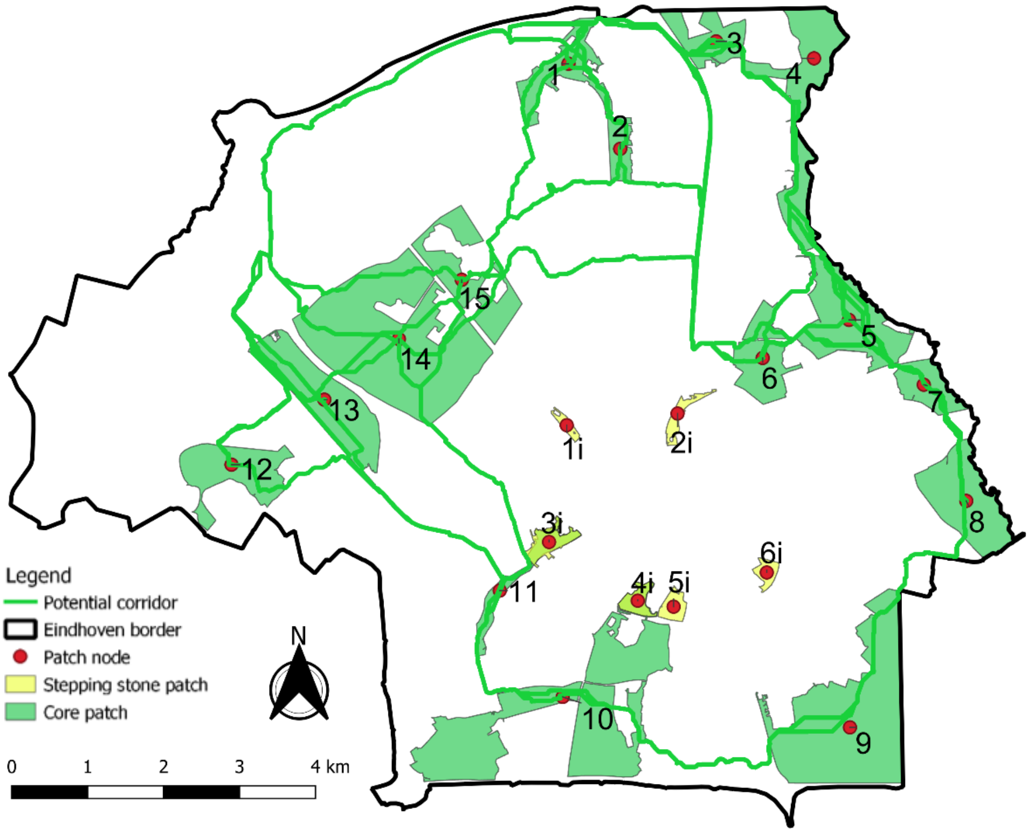

Figure F 3 - Situation 3 with its 105 potential corridors

The tables with all the values of the gravity model and population related to the least-cost analysis can be found here (Table F1, 2, and 3).

Table F 1 – Situation 1, Stepping-stone patch to core patch

Situation 1 - Stepping-stone patch to core patch						
Start Node	**End Node**	**Interaction Value**	**N Postcodes (Overall)**	**N Postcodes (Low Access)**	**Final Score (Overall Population)**	**Final Score (Low Access)**
1i	15	35.2	1197	975	42176	34354
1i	14	42.4	1171	975	49618	41313
1i	13	17.8	1223	977	21822	17433
1i	6	11.8	2950	2088	34891	24695
1i	5	14.1	2963	2088	41656	29354
1i	1	8.5	2109	1007	17861	8528
1i	12	5.7	1464	978	8346	5576
1i	4	8.5	3220	2165	27342	18383
1i	7	4.6	3017	2088	13944	9650
1i	3	5.0	2384	1027	12033	5184
1i	2	7.2	3033	1033	21842	7439
1i	8	5.7	3024	2095	17375	12037
1i	11	3.2	2763	1192	8959	3865
1i	10	3.4	4031	1591	13731	5420
1i	9	4.0	3090	2101	12365	8407
2i	6	713.4	546	0	389523	0
2i	5	438.9	559	0	245347	0
2i	4	134.9	816	77	110080	10387
2i	7	66.5	613	0	40735	0
2i	3	67.3	3911	64	263340	4309
2i	1	55.1	4244	133	234024	7334
2i	8	53.9	620	7	33399	377
2i	2	46.3	4366	450	202045	20825
2i	15	16.3	3443	773	56036	12581
2i	14	13.9	3442	776	47992	10820
2i	9	16.9	686	13	11619	220
2i	13	10.4	4574	313	47673	3262
2i	10	7.7	813	70	6290	542
2i	12	4.3	4856	314	20985	1357
2i	11	3.1	2286	556	7135	1735
3i	11	382.6	424	332	162232	127030
3i	10	52.8	1692	731	89276	38570
3i	9	23.6	1867	757	43988	17836
3i	14	16.2	1284	23	20796	373
3i	13	12.5	670	337	8404	4227
3i	15	6.9	1292	25	8974	174
3i	12	4.6	1268	342	5821	1570

3i	8	4.8	1933	763	9371	3699
3i	7	2.5	1940	770	4892	1941
3i	1	3.2	2129	56	6750	178
3i	5	4.7	1984	770	9405	3650
3i	3	2.2	2002	304	4430	673
3i	2	3.0	3053	82	9294	250
3i	6	3.0	2007	770	5952	2284
3i	4	3.0	2139	304	6464	919
4i	10	256.4	113	0	28971	0
4i	9	89.1	173	28	15422	2496
4i	11	26.7	1504	486	40106	12960
4i	8	9.5	239	34	2263	322
4i	7	4.6	246	41	1135	189
4i	5	8.2	290	41	2372	335
4i	13	7.1	1524	400	10779	2829
4i	6	4.9	313	41	1540	202
4i	14	6.1	2936	616	18030	3783
4i	4	4.8	505	115	2432	554
4i	12	2.8	2122	405	6047	1154
4i	3	2.7	575	115	1543	309
4i	1	2.9	891	191	2604	558
4i	15	3.3	2944	618	9639	2023
4i	2	2.8	1483	554	4186	1564
5i	10	199.0	317	137	63079	27261
5i	9	75.5	378	165	28547	12461
5i	11	22.8	1749	623	39834	14189
5i	8	8.5	444	171	3776	1454
5i	7	4.2	451	178	1877	741
5i	5	7.4	495	178	3670	1320
5i	13	6.4	1769	537	11296	3429
5i	6	4.5	518	178	2317	796
5i	14	5.6	3181	753	17680	4185
5i	4	4.4	710	252	3112	1105
5i	12	2.6	2367	542	6121	1402
5i	3	2.4	780	252	1909	617
5i	1	2.7	1096	328	2927	876
5i	15	3.0	3189	755	9506	2251
5i	2	2.6	1688	691	4363	1786
6i	9	95.9	1094	33	104946	3166
6i	8	23.4	274	3	6409	70
6i	10	22.1	1180	87	26073	1922
6i	7	9.9	281	10	2791	99
6i	5	15.8	325	10	5126	158
6i	6	8.8	348	10	3078	88

6i	11	6.5	2653	573	17116	3697
6i	4	8.4	540	84	4523	704
6i	3	4.5	610	84	2715	374
6i	1	4.6	926	160	4270	738
6i	2	4.3	1518	523	6485	2234
6i	13	3.5	2673	487	9415	1715
6i	15	2.6	4255	460	10894	1178
6i	14	3.2	4085	703	12976	2233
6i	12	1.5	3271	492	5030	757

Table F 2 - Situation 2, stepping-stone patch to stepping-stone patch

Situation 2 - Stepping-stone patch to stepping-stone patch						
Start Node	**End Node**	**Interaction Value**	**N Postcodes (Overall)**	**N Postcodes (Low Access)**	**Final Score (Overall Population)**	**Final Score (Low Access)**
1i	2i	20.0	2506	2088	50046	41699
1i	3i	3.8	2827	2761	10848	10594
1i	4i	1.9	3910	2931	7393	5542
1i	5i	1.6	4025	2931	6555	4774
1i	6i	1.1	3595	2862	3826	3046
2i	4i	5.9	1811	843	10775	5015
2i	5i	5.0	1926	843	9543	4177
2i	3i	3.6	2506	2135	8976	7647
2i	6i	3.0	1895	774	5671	2316
3i	4i	6.2	1646	651	10266	4060
3i	5i	5.1	1761	651	8996	3326
3i	6i	1.5	3329	716	4973	1070
4i	5i	1035.4	126	0	130456	0
4i	6i	6.0	1694	65	10226	392
5i	6i	6.5	1626	65	10579	423

Table F 3 - Situation 3, core patch to core patch

Situation 3 - Core patch to core patch						
Start Node	**End Node**	**Interaction Value**	**N Postcodes (Overall)**	**N Postcodes (Low Access)**	**Final Score (Overall Population)**	**Final Score (Low Access)**
1	2	524.2	591	362	309783	189749
1	3	403.6	286	53	115442	21393
1	4	193.6	423	53	81905	10262
1	5	83.5	614	156	51292	13032
1	6	44.8	3917	302	175426	13525
1	7	20.8	660	156	13752	3251
1	8	21.9	667	163	14630	3575
1	9	10.6	733	169	7744	1785

1	10	5.3	860	226	4551	1196
1	11	3.2	960	296	3105	957
1	12	7.8	648	204	5072	1597
1	13	21.2	366	203	7747	4297
1	14	23.8	364	202	8651	4801
1	15	32.1	833	38	26729	1219
2	3	114.3	901	420	103015	48020
2	4	90.5	1038	420	93985	38029
2	5	54.2	1213	507	65701	27461
2	6	38.9	3952	597	153907	23250
2	7	15.3	1259	507	19262	7757
2	8	17.4	1266	514	21965	8918
2	9	9.7	1332	520	12971	5064
2	10	5.1	1459	577	7404	2928
2	11	3.1	1572	661	4839	2035
2	12	6.8	1260	569	8512	3844
2	13	17.3	978	568	16938	9837
2	14	19.2	1768	55	33889	1054
2	15	24.0	1725	52	41435	1249
3	4	725.4	137	0	99374	0
3	5	138.1	328	103	45300	14225
3	6	58.4	421	121	24596	7069
3	7	27.8	374	103	10382	2859
3	8	26.1	381	110	9941	2870
3	9	10.3	447	116	4584	1190
3	10	4.9	574	173	2814	848
3	11	2.3	1234	342	2803	777
3	12	5.2	922	250	4780	1296
3	13	13.6	640	249	8686	3379
3	14	15.1	638	248	9614	3737
3	15	17.0	1122	79	19047	1341
4	5	538.7	181	102	97502	54946
4	6	176.4	274	120	48324	21164
4	7	76.4	227	102	17342	7792
4	8	61.9	234	109	14476	6743
4	9	19.4	300	115	5826	2233
4	10	8.9	427	172	3787	1526
4	11	3.6	1900	658	6797	2354
4	12	6.6	1061	250	7025	1655
4	13	16.7	779	249	13029	4165
4	14	18.3	777	248	14258	4551
4	15	19.8	1261	79	24941	1563
5	6	1086.8	16	0	17389	0
5	7	508.4	46	0	23389	0

5	8	220.8	53	7	11705	1546
5	9	37.1	119	13	4410	482
5	10	15.3	246	70	3769	1073
5	11	5.8	1719	556	10027	3243
5	12	6.4	1206	324	7773	2088
5	13	15.6	924	323	14379	5026
5	14	16.8	922	322	15509	5417
5	15	17.5	3923	450	68716	7882
6	7	111.1	70	0	7774	0
6	8	78.3	77	7	6026	548
6	9	20.6	143	13	2945	268
6	10	9.1	270	70	2460	638
6	11	3.6	1743	556	6285	2005
6	12	4.2	4585	523	19303	2202
6	13	10.0	4303	522	43136	5233
6	14	12.6	3775	398	47617	5020
6	15	14.2	3776	395	53743	5622
7	8	425.7	7	7	2980	2980
7	9	23.7	73	13	1730	308
7	10	8.8	200	70	1758	615
7	11	3.2	1673	556	5282	1755
7	12	2.3	1250	324	2921	757
7	13	5.5	968	323	5314	1773
7	14	5.9	966	322	5682	1894
7	15	6.0	3974	450	23804	2695
8	9	57.0	66	6	3759	342
8	10	18.4	193	63	3556	1161
8	11	6.2	1666	549	10310	3397
8	12	3.2	1257	331	3967	1045
8	13	7.3	975	330	7078	2395
8	14	7.7	973	329	7518	2542
8	15	7.7	3981	457	30542	3506
9	10	226.5	115	57	26048	12911
9	11	35.7	1588	543	56616	19359
9	12	5.1	2206	462	11192	2344
9	13	12.3	1608	457	19740	5610
9	14	10.8	3020	673	32582	7261
9	15	5.9	3028	675	17951	4002
10	11	108.7	1384	486	150495	52847
10	12	6.1	2002	405	12214	2471
10	13	15.9	1404	400	22264	6343
10	14	13.5	2816	616	37923	8296
10	15	6.8	2824	618	19210	4204
11	12	6.1	996	101	6033	612

11	13	17.5	398	96	6973	1682
11	14	15.4	1585	221	24427	3406
11	15	6.8	1593	223	10766	1507
12	13	156.4	244	1	38150	156
12	14	46.1	246	3	11329	138
12	15	13.9	283	13	3933	181
13	14	283.1	2	2	566	566
13	15	47.7	11	5	525	238
14	15	158.4	10	4	1584	634