MASTER

A decision-support tool for improving Human Thermal Comfort in outdoor environments
Focused on the effect of Urban Green Infrastructure on Human Thermal Comfort

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Award date:
2023

A decision-support tool for improving Human Thermal Comfort in outdoor environments:

Focused on the effect of Urban Green Infrastructure on Human Thermal Comfort

Master Thesis

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MSc Architecture, Building and Planning

MSc Construction Management and Engineering

Eindhoven University of Technology

Built Environment

15-06-2023

Academic year 2022-2023

Colophon

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Thesis

Master Programs	Urban Systems and Real Estate (USRE) Construction Management Engineering (CME)
Department	Built Environment
University	Eindhoven University of Technology
Course Code	7CZ60M0
Study Load	60 ECTS
Academic Year	2022-2023

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Date Final Presentation 19-06-2023

Preface

The built environment is a complex system which creates an environment for individual persons. The environment influences how people behave and experience daily life. It was a pleasure to learn about this complexity and the influence of the built environment during my studies. By understanding the complexity, it will be possible to make better decisions for the people living in the built environment. Being able to contribute to creating better living environments for people is what fascinated me during my studies and writing this thesis.

This thesis marks the end of my master's studies at Eindhoven University of Technology. It makes me proud to be able to complete these studies and to realize the personal development it has brought me. I am curious what the next part of my life will bring.

I would like to thank my supervisors Pauline van den Berg and Peter van der Waerden for their provided feedback during my graduation project. It was very helpful to have their guidance in making choices when I got stuck and it kept me motivated to discuss the complexity of this project with them.

Secondly, I would like to thank Witteveen + Bos, especially Anna Goede and Arie de Niet, for giving me the opportunity to work with and expand the algorithm. Furthermore, I am thankful that they shared their perspectives and insights with me.

At last, a special thanks to my family and friends for their unconditional support whenever I needed it. Furthermore, I would like to thank them for sharing their knowledge with me which gave me new perspectives while conducting this project. I am more than grateful for those that kept me positive and motivated during the hard times of my studies.

I wish you pleasure reading this thesis and hope to provide new insights.

Anouk van Duijven
Eindhoven, June 2023

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Summary

As a consequence of climate change, extreme heat events are occurring more often and intense (Norton, Coutts, Livesley, Harris, Hunter & Williams, 2015). Moreover, urban areas are dealing with the Urban Heat Island (UHI) effect which is caused by a large amount of paved surfaces (e.g. roads, buildings, concrete surfaces). The UHI effect in combination with extreme heat events increases heat stress experienced by people which leads to more mortality and morbidity because people are exposed to higher temperatures for longer periods. Heat stress is experienced as discomfort and affects Human Thermal Comfort (HTC) which expresses "the satisfaction with the thermal environment" (Rupp, Vásquez & Lamberts, 2015). For the well-being of people, it is important to improve HTC to more comfortable conditions.

Urban Green Infrastructure (UGI) is a medium to adapt urban areas as a response to climate change by reducing the temperature with shadow and evapotranspiration. Therefore, UGI can help with improving the thermal comfort of people and is indirectly related to HTC (Huang, Wu, Teng & Lin, 2020). Different decision-support tools have been developed to support urban planners in determining a strategy for the implementation of UGI. Many of these tools are focused on the temperature effect of UGI and not on the broader concept of HTC which could give more meaning to how the environment is experienced by people (Rupp et al., 2015).

Therefore, this study investigates and illustrates how to develop a decision-support tool which supports urban planners by determining a strategy for the implementation of UGI by focusing on improving HTC.

To develop a decision-support tool for improving HTC, HTC needed to be investigated to define the factors that influence HTC and how HTC is measured. From existing literature, it could be concluded that a wide range of factors affect HTC which could be divided into physiological, physical, and psychological factors. Furthermore, it was concluded that the Physiological Equivalent Temperature (PET) index is a suitable measure to calculate HTC. This index includes aspects of the microclimate, urban fabric and UGI.

To strengthen the relationship between HTC and UGI, an existing PET index calculation algorithm has been expanded by including green roofs and green walls in the calculation. From this study, it could be concluded that green roofs and green walls can be included in the PET index calculation by adjusting the vegetation fraction and Bowen ratio calculation. To calculate a realistic effect of green roofs and green walls, the effect is made dependent on the building height of the buildings. Moreover, the PET index gives a good impression of what the effect is of adding more vegetation and where heat stress will be experienced. This study demonstrates a way to calculate HTC which can be incorporated in a newly developed decision-support tool.

By calculating HTC, it is possible to decide where UGI is needed to improve the thermal comfort of people. The second component of the decision-support tool focused on where different types of UGI are possible. Based on existing studies, the different types of greenery are divided into three main categories: Trees, shrubs and low planting located in the public

space or at built structures. For these different types, a list of requirements was defined that need to be fulfilled to be able to implement the types in urban areas. The categories and requirements are incorporated in the newly developed decision-support tool by programming a raster analysis for the different types of UGI in a Geographic Information System (GIS) with Python. The outcome of the raster analysis is a raster layer per UGI type which represents the locations where which UGI type is possible. Based on the effect of the different UGI types on the PET found in the literature, a priority list is defined which represents the order of UGI types that have the most reducing effect on HTC. Based on the self-defined priority list, the raster layers per UGI type are combined into one raster map which presents in a presentable manner which UGI type can be best implemented at certain locations. Therefore, the newly developed decision-support tool adds, in comparison with existing decision-support tools, a wider range of UGI types; a more extensive list of requirements; and the self-defined priority list to define the best suitable UGI type for a certain location. In this way, the newly developed decision-support tool can identify the possibilities for the implementation of Urban Green Infrastructure.

The relationship between HTC and UGI is further incorporated into the newly developed decision-support tool by programming a self-defined analysis for the combination of the outcome of the HTC calculation with the outcome of the UGI analysis in the same GIS Python script as the UGI analysis. Whereas the outcome of the HTC calculation defines where UGI is needed by defining the locations with poor HTC, the requirement analysis defines where UGI is possible. By linking these outcomes, it is possible to define which UGI types are possible at locations with high HTC values. Furthermore, it is demonstrated how these possibilities can be brought back into the HTC calculation algorithm which shows the effect of the UGI types on the HTC values.

Altogether, this study contributes to bringing together the knowledge in the field of UGI and HTC by developing a decision-support tool for determining a strategy for the implementation of UGI for improving HTC. By performing an expanded PET index calculation which includes the relationship with all UGI types and linking the outcome with defined possibilities for types of UGI, it is possible to advise urban planners on a strategy for implementing UGI in urban areas by using the newly developed decision-support tool.

Overall, this study demonstrates that a decision-support tool can be developed for improving HTC by performing an extensive literature review; describing how a decision-support tool can be developed which incorporates the relationship between UGI and HTC; and testing the decision-support tool on the case study of Rotterdam. Although further research will be needed, it will already be possible to improve the thermal comfort of people based on this study which will reduce heat stress, increase productivity and create better health circumstances for the population in urban areas.

Samenvatting

Als gevolg van klimaatverandering komen hittegolven vaker voor en worden steeds intenser (Norton et al., 2015). Bovendien hebben stedelijke gebieden te maken met het stedelijk hitte-eiland effect dat wordt veroorzaakt door een grote hoeveelheid aan verhard oppervlak. Het stedelijk hitte-eiland effect in combinatie met de hittegolven verhoogt de hittestress die wordt ervaren door de bevolking. Hittestress leidt tot meer ziekte en sterfte omdat de bevolking gedurende een langere tijd wordt blootgesteld aan hogere temperaturen. Dit wordt ervaren als ongemak en beïnvloedt het menselijk thermisch comfort, dat "de tevredenheid met de thermische omgeving" uitdrukt (Rupp et al., 2015). Voor het welzijn van de bevolking is het belangrijk om het menselijk thermisch comfort in stedelijke gebieden te verbeteren.

Stedelijk groen is een middel om stedelijke gebieden aan te passen als reactie op klimaatverandering, door de temperatuur te verlagen met schaduw en verdamping. Daarom is stedelijk groen indirect gerelateerd aan het thermisch comfort en kan het helpen met het verbeteren ervan (Huang et al., 2020). Er zijn verschillende beleidsondersteunende systemen ontwikkeld om stedenbouwkundigen te ondersteunen bij het bepalen van een strategie voor het toepassen van stedelijk groen. Veel van de systemen zijn gericht op het temperatuureffect van stedelijk groen maar het menselijk thermisch comfort is een breder concept dat meer betekenis zou kunnen geven aan hoe de stedelijke omgeving door de bevolking wordt ervaren.

Daarom onderzoekt deze studie hoe een beleidsondersteunend systeem kan worden ontwikkeld die stedenbouwkundigen ondersteunt bij het bepalen van een strategie voor het toepassen van stedelijk groen met als focus het menselijk thermisch comfort te verbeteren.

Om een beleidsondersteunend systeem te ontwikkelen voor het verbeteren van menselijk thermisch comfort, moest worden gedefinieerd welke factoren van invloed zijn en hoe het wordt gemeten. Uit de literatuur kon worden geconcludeerd dat fysiologische, fysieke, en psychologische factoren van invloed zijn op het menselijk thermisch comfort. Verder kon worden geconcludeerd dat de PET (gevoelstemperatuur) index een geschikte maatstaf is het te berekenen. De index bevat aspecten van het microklimaat, de fysieke stedelijke omgeving en stedelijk groen.

Om het verband tussen menselijk thermisch comfort en stedelijk groen te versterken, is een bestaande PET index algoritme uitgebreid door groene daken en groene wanden in de berekening op te nemen. Uit deze studie kan worden geconcludeerd dat groene daken en groene wanden kunnen worden meegenomen in de PET index door de berekening van de vegetatiefractie en de Bowen ratio aan te passen. Om een realistisch effect van groene daken en groene wanden te berekenen, is het effect afhankelijk gemaakt van de hoogte van gebouwen. Verder geeft de PET index een goed beeld van wat het effect is van meer vegetatie en waar hittestress wordt ervaren. Deze studie demonstreert een manier om thermisch comfort te berekenen, die kan worden opgenomen in een nieuw beleidsondersteunend systeem.

Door het menselijk thermisch comfort te berekenen, is het mogelijk om te beslissen waar stedelijk groen nodig is. Het tweede deel van het nieuwe beleidsondersteunend systeem

legde het accent op waar verschillende typen stedelijk groen toegepast kunnen worden. Op basis van bestaand onderzoek zijn de verschillende typen ingedeeld in drie hoofdcategorieën: Bomen, struiken en lage beplanting gelegen in de openbare ruimte of op bouwwerken. Voor de verschillende typen is een lijst met eisen gedefinieerd waaraan moet worden voldaan om de typen in stedelijke gebieden te kunnen toepassen. De bevindingen zijn opgenomen in een nieuw beleidsondersteunend systeem door een rasteranalyse voor de verschillende typen te programmeren in een Geografisch Informatiesysteem met Python. Het resultaat is een raster laag per type die representeert waar welk type groen kan worden toegepast. Op basis van de in literatuur gevonden effecten van de typen groen op de PET is een prioriteiten lijst gedefinieerd die de volgorde weergeeft van types die de meeste invloed hebben op thermisch comfort. Op basis van deze lijst zijn de mogelijkheden van de verschillende typen gecombineerd tot één rasterkaart. De kaart toont op een representatieve manier welk type stedelijk groen het beste kan worden toegepast op bepaalde locaties. Het nieuwe beleidsondersteunend systeem voegt meer groen types, eisen en een prioriteitenlijst toe in vergelijking met bestaande systemen. Hierdoor kan het nieuwe beleidsondersteunend systeem de mogelijkheden voor het toepassen van stedelijk groen identificeren.

Het verband tussen menselijk thermisch comfort en stedelijk groen is verder opgenomen in het nieuwe beleidsondersteunend systeem door de uitkomst van de berekening van thermisch comfort te combineren met de uitkomst van de raster analyse. De combinatie is geprogrammeerd in hetzelfde Python script als de raster analyse. De uitkomst van de berekening van thermisch comfort definieert waar stedelijk groen nodig is door de locaties met thermisch discomfort weer te geven en de uitkomst raster analyse definieert waar stedelijk groen mogelijk is. Door de uitkomsten te koppelen is het mogelijk om te definiëren welke typen stedelijk groen toegepast kunnen worden op locaties met thermisch discomfort. Verder wordt gedemonstreerd hoe de mogelijke typen ingevoerd kunnen worden in de berekening van het menselijk thermisch comfort zodat het effect van de typen stedelijk groen op de waarden voor thermisch comfort zichtbaar wordt.

Al met al draagt het onderzoek bij aan het samenbrengen van de kennis op het gebied van stedelijke groen en menselijk thermisch comfort door het ontwikkelen van een beleidsondersteunend systeem voor het bepalen van een strategie voor het toepassen van stedelijk groen om het menselijk thermisch comfort te verbeteren. Door een uitgebreide PET index berekening uit te voeren waarin het verband met alle stedelijk groen typen is opgenomen en de uitkomst te koppelen met de gedefinieerde toepassingen voor stedelijk groen, is het mogelijk stedenbouwkundigen te adviseren over een strategie voor het toepassen van stedelijk groen in stedelijke gebieden.

In algemene zin toonde deze studie aan dat een beleidsondersteunend systeem kan worden ontwikkeld voor het verbeteren van het menselijk thermisch comfort door een literatuuronderzoek uit te voeren; te beschrijven hoe een beleidsondersteunend systeem kan worden ontwikkeld waarin het verband tussen stedelijke groen en thermisch comfort is opgenomen; en door het testen van het systeem op de case studie van Rotterdam. Ondanks dat verder onderzoek nodig zal zijn, zal het op basis van deze studie nu al mogelijk zijn om het thermisch comfort te verbeteren, waardoor hittestress wordt verminderd, de productiviteit wordt verhoogd en betere gezondheidsomstandigheden worden gecreëerd voor de bevolking in stedelijke gebieden.

Abstract

Urban areas are dealing with the Urban Heat Island (UHI) effect which is caused by a large amount of paved surfaces. The UHI effect in combination with extreme heat events increases heat stress experienced by people. For the well-being of people, it is important to improve Human Thermal Comfort (HTC) in urban areas. Urban Green Infrastructure (UGI) can help with improving the thermal comfort of people by reducing the temperature with shadow and evapotranspiration. Different decision-support tools have been developed to support urban planners in determining a strategy for the implementation of UGI. Many of these tools are focused on the temperature effect of UGI and not on the broader concept of HTC which could give more meaning to how the environment is experienced by people.

This study investigates and illustrates how to develop a decision-support tool which supports urban planners by determining a strategy for the implementation of UGI by focusing on improving HTC. The study demonstrates that by performing an expanded PET index calculation, HTC can be calculated and that based on a raster analysis including an extensive list of requirements, it can be determined where certain types of UGI can be implemented. By linking these outcomes, it is possible to define which UGI types are possible at locations with high HTC values. Furthermore, it is demonstrated how these possibilities can be brought back into the HTC calculation which shows the effect of the UGI types on the HTC values.

As a result, this study contributes to bringing together the knowledge in the field of UGI and HTC by developing a decision-support tool for determining a strategy for the implementation of UGI for improving HTC. Although further research will be needed, it will already be possible to improve the thermal comfort of people based on this study which will reduce heat stress, increase productivity and create better health circumstances for the population in urban areas.

Keywords: Human Thermal Comfort, Physiological Equivalent Temperature, Urban Green Infrastructure, Decision-support tool, Geographic Information System

List of Abbreviations and Terminology

ASV	Actual Sensation Vote
Albedo	The amount of radiation absorbed and reflected by a surface (Pötz, 2016)
BAG	Basis Register Addresses and Buildings
BMPs	Best Management Practices
Clo	Unit of clothing insulation (Rijal, Humphreys & Nicol, 2019)
COMFA	Comfort Formula
CV	Comfort Value
Decision-support tool	Tools that can support stakeholders in their decisions for certain strategies by incorporating, analysing and demonstrating data in a way that it contains useful information for them (Kuller, Bach, Roberts, Browne, Delectic, 2019; Sarabi, Han, De Vries & Romme, 2022; Voskamp & Van de Ven, 2015)
DSM	Digital Surface Model
DTM	Digital Terrain Model
ET*	Effective Temperature
ETF	Conduction-corrected modified effective temperature
ETFe	Enhanced conduction-corrected modified effective temperature
ETU	Universal Effective Temperature
ETV	Enhanced conduction-corrected modified effective temperature
ETVO	Outdoor Enhanced conduction-corrected modified effective temperature
Evapotranspiration	The vaporisation of water from vegetation and earth surfaces (Irmak, 2008)

Foliage	All leaves of a tree (Pötz, 2016)
GIS	Geographical Information System
GOCI	Global Outdoor Comfort Index
HTC	Human Thermal Comfort
Human Thermal Comfort	The satisfaction with the thermal environment (Rupp et al., 2015)
IZA	Index for cities of Arid Zones
K	Wind chill index
Machine learning	The use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data (Oxford University Press, 2023)
MDI	Modified Discomfort Index
MEMI	Munich energy balance model
Microclimate	The climatic conditions at the local scale (Naiman, Décamps & McClain, 2010)
mPET	modified Physiologically Equivalent Temperature
MOCI	Mediterranean Outdoor Comfort Index
MCDA	Multi-Criteria Decision Analysis
NDVI	Normalized Difference Vegetation Index
OUT_SET*	Outdoor Standard Effective Temperature
PET	Physiological Equivalent Temperature
PMV	Predict Mean Votes
PMV-PPD	Predicted Mean Vote-Predicted Percentage Dissatisfied
SET*	Standard Effective Temperature
STI	Subjective Temperature Index

SVF	Sky-View Factor
TEP	Temperature Equivalent Perception
THI	Temperature-Humidity Index
TIFF	Tagged Image File Format
TS	Thermal Sensation
TSP	Thermal Satisfaction Percentage
UGI	Urban Green Infrastructure
UHI	Urban Heat Island
Urban Green Infrastructure	The network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits (Norton et al., 2015)
UTCI	Universal Thermal Climate Index
WSUD	Water-Sensitive Urban Design
WBGT	Wet bulb-globe temperature index

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1. Introduction

As a consequence of the changing climate, extreme heat events are coming more frequent and intense (Norton et al., 2015). Moreover, urban areas are dealing with the Urban Heat Island (UHI) effect which is caused by a large amount of paved surfaces (e.g. roads, buildings, concrete surfaces). Paved surfaces absorb much solar radiation during the day and discharge the heat at night which keeps urban areas warmer than the countryside (Norton et al., 2015). Figure 1 presents the effect by showing that the temperature in the downtown area is much higher during the day than the areas around it which have a smaller density of buildings and more greenery. Furthermore, urban areas have a smaller Sky-View Factor due to the higher density of buildings which means that heat cannot leave the surface that easily at night. As a consequence, urban areas have a sensible increase in temperature, and the energy consumption for cooling in the summer in utility buildings has become higher than for heating in the winter (Pötz, 2016).

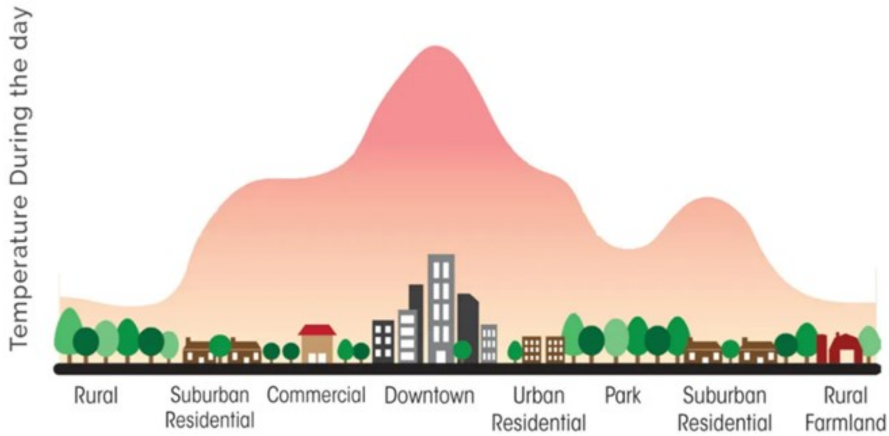


Figure 1: Urban Heat Island effect (Firstgreen Consulting, 2020)

The UHI effect in combination with the extreme heat events increases heat stress experienced by people which means less ability of the body to cool itself (Abdel-Ghany, Al-Helal & Shady, 2013). This leads to more mortality and morbidity because people are exposed to high temperatures during the day and at night which leads to limited recovery from daytime heat stress and this can cause heat-related illness (Norton et al., 2015; Rupp et al., 2015). The illness can have different consequences such as headaches, skin issues, fainting, less concentration, and even death (Pötz, 2016).

Heat stress is experienced by people as discomfort and influences Human Thermal Comfort, which will be further abbreviated as HTC. HTC is defined as “the satisfaction with the thermal environment” (Rupp et al., 2015). HTC is expressed with a certain comfort range which mostly is indicated from too cold to too hot. As a consequence of the extreme heat events and the UHI effect, too-hot circumstances are more often experienced by people (Norton et al., 2015; Rupp et al., 2015; Zhao, Lian & Lai, 2021). For the well-being of people, it is important to bring these circumstances back to more neutral conditions in-between cold and warm.

As mentioned by many researchers, Urban Green Infrastructure (UGI) is a medium to adapt urban areas as a response to climate change because it can contribute to cooling, water management, air quality, and biodiversity. An important benefit is that UGI can affect the UHI effect as stated by Norton et al. (2015). Amongst other measures, implementing green infrastructure can help with getting temperature reductions because of its reducing effect, due to shadow and evapotranspiration, on surface temperatures at locations with high air temperatures and solar radiation. Furthermore, UGI can be implemented to bring HTC back to a more acceptable level because UGI influences the microclimate in urban areas which is related to the thermal comfort of people (Huang et al., 2020). Therefore, UGI can contribute to better urban areas and health circumstances for people.

The benefits of UGI can be categorized under social, economic, and environmental benefits (Carter, Handley, Butlin & Gill, 2017). The different benefits of UGI are a better quality of life, economic prosperity, adaptation to climate change, and a positive influence on energy usage and food shortage (Pötz, 2016; Ramyar, Ackerman & Joston, 2021; Voskamp & Van de Ven, 2015). In response to the positive effect of UGI, different decision-support tools have been developed to support urban planners in determining a strategy for the implementation of UGI. A strategy for the implementation of UGI requires an integrated approach in which all relevant disciplines are included to increase the benefit of UGI (Norton et al., 2015; Pötz, 2016; Ramyar et al., 2021; Voskamp & Van de Ven, 2015). A multi-disciplinary approach is required that covers the following disciplines: engineering and ecology; spatial planning and urban design; and policy and management. To accomplish a multi-disciplinary approach, all aspects of the disciplines need to be analysed. To analyse all aspects, much data is necessary and collaboration with stakeholders is desired (Ramyar et al., 2021; Voskamp & Van de Ven, 2015). Furthermore, a well-developed strategy for the implementation of UGI requires a connection between different spatial scales, such as street, neighbourhood and city. These scales need to be connected by including the different social, economic and environmental processes at these scales (Carter et al., 2017; Ramyar et al., 2021). To decide on a UGI strategy, it is necessary to know the effects of UGI on all the relevant aspects of the disciplines by linking the UGI features with the different processes at different scales. By including all these effects, it is possible to get insight into how to adapt urban areas to climate change (Carter et al., 2017; Ramyar et al., 2021; Voskamp & Van de Ven, 2015). A decision-support tool can assist in determining an urban strategy for implementing UGI because it can provide an integrated approach by being able to merge, analyse and demonstrate different data into a meaningful strategy (Kuller et al., 2019). In this way, it can help to answer questions such as what green infrastructure types have to be implemented and where they can be implemented based on multiple requirements.

Many of the decision-support tools are focused on the temperature effect of UGI but human thermal discomfort is caused by more than just temperature. HTC is influenced by multiple factors, such as the microclimate and clothing (Chen & Ng, 2012; Manan & Nadasiyatus, 2021; Norton et al., 2015; Rahman, Hartmann, Moser-Reischl, von Strachwitz, Paeth, Pretzsch, Pauleit & Rötzer, 2020; Rupp et al., 2015; Zhao et al., 2021). It is of interest to include HTC in urban strategies because by just focusing on temperature alone, no relationship will exist with the perception of people for whom urban areas are developed. HTC will give more meaning to how the environment is experienced by people (Rupp et al., 2015).

Therefore, a strategy for implementing UGI in urban areas requires a more comprehensive approach. Then, UGI will not only rectify the UHI effect by reducing the temperatures but also improve the well-being of the population by including their perception of the temperature. The existing decision-support tools should be expanded by introducing the factors of HTC to support urban planners by including the perception of temperature. By introducing the factors of HTC in a decision-support tool, it is possible to advise urban planners on a strategy for reducing heat stress experienced by people which contributes to a better quality of life and can play an important role in a well-developed built environment.

1.1 Research questions

This study aims to develop a decision-support tool which can support urban planners in determining a strategy for the implementation of UGI in urban areas by focusing on improving HTC. A strategy for the implementation of UGI requires a more integrated approach, nevertheless, the key objective of this study is to develop a decision-support tool for improving HTC. The decision-support tool should be able to assess the urban area on the need for better HTC. Based on the need, the tool should be able to advise where and what types of UGI can be implemented. Therefore, the main research question will be:

"How to develop a decision-support tool which supports urban planners by determining a strategy for the implementation of Urban Green Infrastructure focusing on improving Human Thermal Comfort?"

Which will be answered by answering the following sub-questions:

1. **How can an existing Human Thermal Comfort index be improved?**
   1a) Which factors affect Human Thermal Comfort?
   1b) How to measure Human Thermal Comfort in the outdoor environment?

2. **How to identify the possibilities for the implementation of Urban Green Infrastructure using a decision-support tool?**
   2a) What types of Urban Green Infrastructure can be implemented in an urban area?
   2b) What is the effect of Urban Green Infrastructure on the temperature?
   2c) What are the requirements for the different types of Urban Green Infrastructure to be implemented?

3. **How can the relationship between Urban Green Infrastructure and Human Thermal Comfort be incorporated into a decision-support tool?**

1.2 Research design

To answer the research questions, the research design as represented in Figure 2 will be executed. The study will consist of a literature review and the development of a decision-support tool in a Geographical Information System (GIS).

First, a literature review will be conducted to determine what factors influence HTC and how to measure HTC in outdoor environments. The second part of the literature review involves determining the different types of UGI, their temperature effects and the requirements to implement UGI in urban areas. The last part consists of reviewing existing decision-support tools. The outcome of the literature review will be used as input for the development of the decision-support tool.

The methodology of developing a decision-support tool will be described to answer the rest of the sub-research questions which consist of three phases. The first phase is about expanding an existing Python algorithm for mapping HTC values with missing UGI types concluded from the literature review and is followed by programming, inspired by existing decision-support tools, a method for analysing the possibilities for the implementation of UGI types in a Geographical Information System (GIS). The last phase is about realizing a decision-support tool that connects the first two phases.

The working of the tool will be illustrated with a case study which will be presented in the results chapter. The outcomes of the literature review, development and results will lead to an answer to the main research question with the corresponding conclusion, discussion, and recommendations.

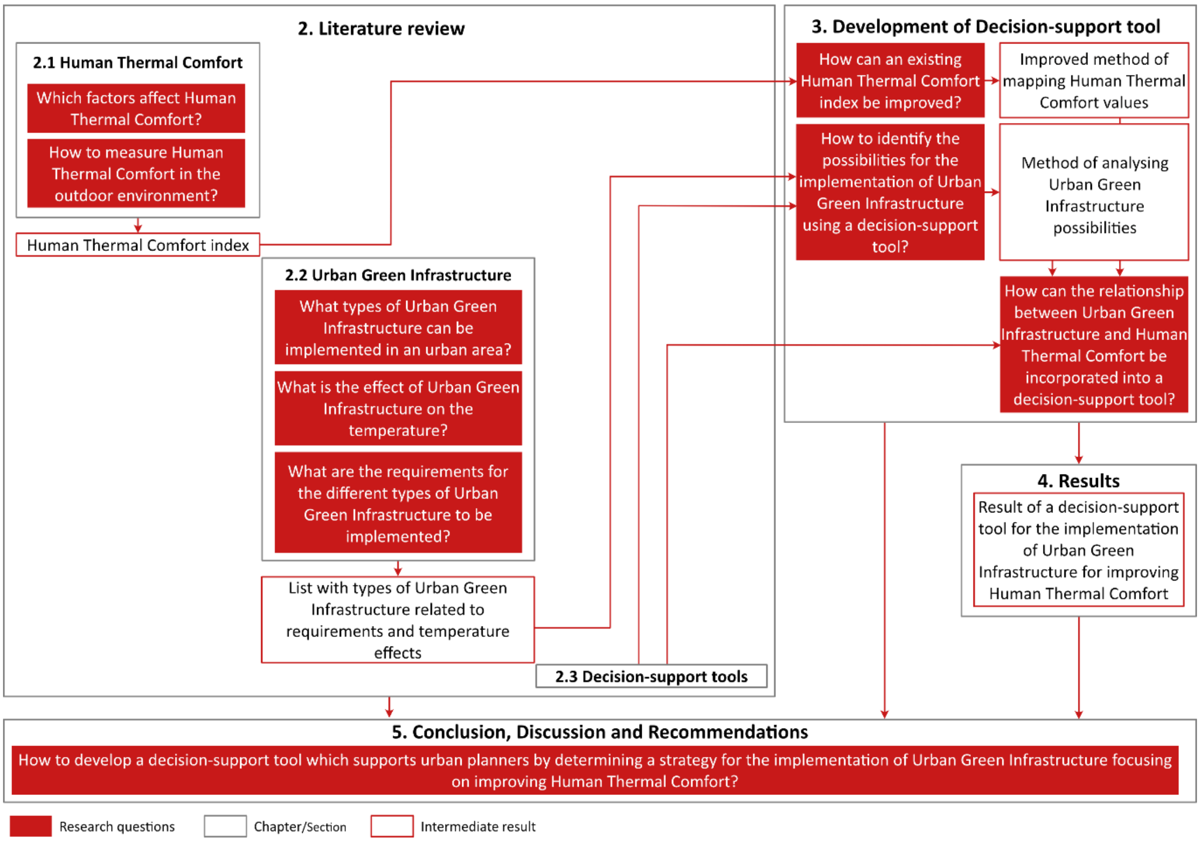


Figure 2: Research design

1.3 Relevance

The relevance of this study can be explained from two sides: scientific and societal relevance.

1.3.1 Scientific relevance

The study will be of scientific relevance because the study will elaborate on a relatively new research field 'Human Thermal Comfort' by putting more focus on how people perceive thermal comfort in the outdoor environment. By elaborating on this topic, it will become understandable how to interpret HTC in outdoor environments and what the important factors are to take into consideration. Furthermore, by developing a decision-support tool based on this topic, new insights will be given into how this topic can be included in determining urban strategies for the implementation of UGI. It will contribute to a better link between the field of 'Human Thermal Comfort' and 'Urban Green Infrastructure'. By being able to link these topics, a new dimension can be given to decision-support tools.

1.3.2 Societal relevance

The extra dimension will be of societal relevance because it will give urban planners insight into how the thermal comfort of the population in outdoor environments can be improved by UGI. The tool will provide urban planners with information on how certain types of UGI will contribute to better thermal conditions which can contribute to a better understanding of certain thermal processes in urban areas. The information can improve the comfort of people which will reduce heat stress perceived by the population, will increase productivity and create better health circumstances for people, especially for the vulnerable population.

1.4 Organization of the thesis

This thesis explains the development of the decision-support tool in five chapters. Chapter two describes the literature review to get more knowledge of HTC in outdoor environments, the different UGI types and decision-support tools. The methodology for developing a decision-support tool will be explained in chapter three. Chapter four will present the results of the development of the decision-support tool by applying the tool to the case study of Rotterdam. The results of the study will be discussed in the final chapter by providing a conclusion, discussion, and recommendations for further research.

2. Literature review

Including Human Thermal Comfort (HTC) in a decision-support tool for the implementation of Urban Green Infrastructure (UGI) in urban areas covers multiple research fields. First of all, it is important to define HTC and the related factors. Furthermore, it needs to be investigated how HTC can be measured in the outdoor environment. A second research field is UGI which includes the different types, the temperature effect and the related requirements to implement UGI. The last research field which needs to be investigated is existing decision-support tools.

2.1 Human thermal comfort

According to a review article by Rupp et al. (2015), which presents papers about HTC from 2005 to 2015, HTC can be defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Within this section, research questions 1a and 1b will be answered by explaining the factors that influence HTC based on existing literature and how HTC is measured by conducting a comparative analysis between different existing methods, for an overview of all indexes see Appendix A. Based on the comparative analysis, it will be decided which HTC index will be used to develop further into the decision-support tool. Figure 3 presents how the research questions are related to the rest of the research design. By answering the research questions, a better understanding of HTC will be accomplished.

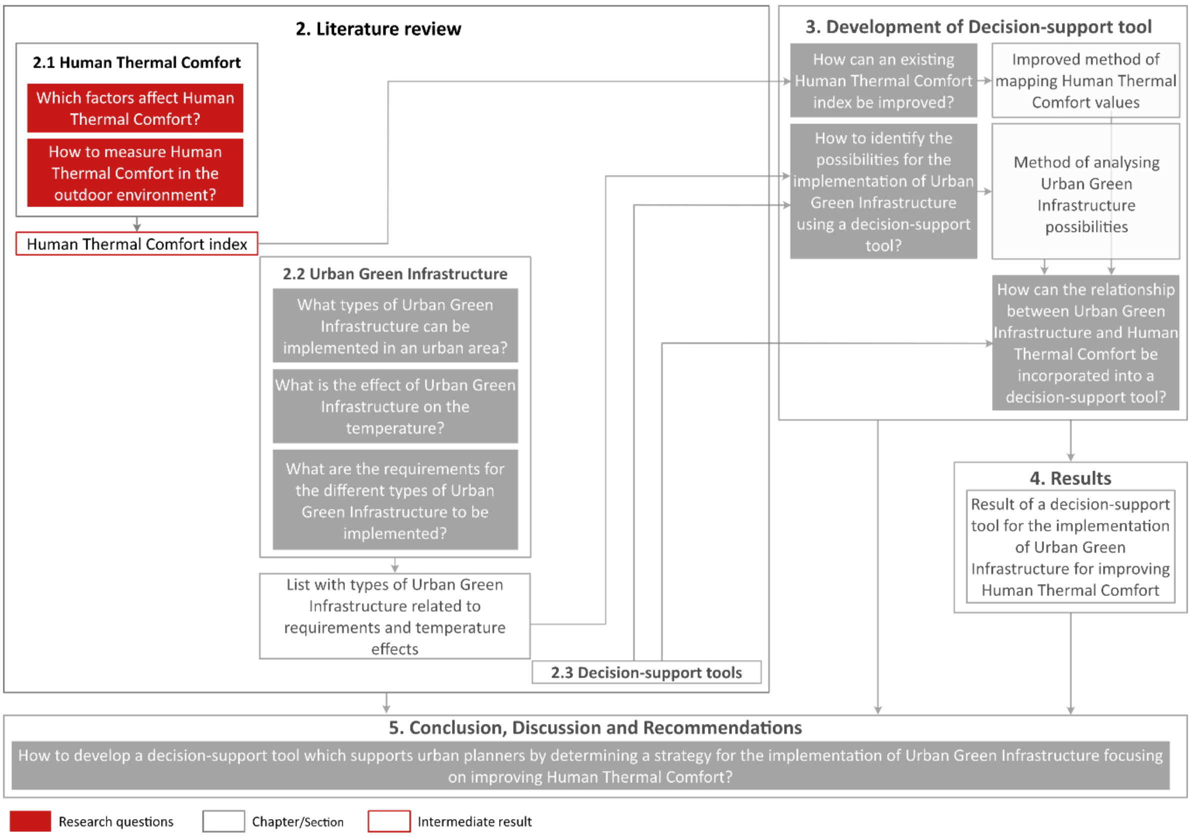


Figure 3: Literature review Human Thermal Comfort within research design

2.1.1 Factors affecting Human Thermal Comfort

According to Huang et al. (2020) and Chen & Ng (2012), the thermal comfort of people depends on thermal adaptation. This adaptation can be divided into psychological, physical and physiological factors. In the outdoor environment, HTC depends mostly on microclimate conditions such as air temperature, solar radiation, shading, wind direction, wind speed and humidity which are seen as physiological factors (Chen & Ng, 2012; Manan & Nadasiyatus, 2021; Rahman et al., 2020; Rupp et al., 2015; Zhao et al., 2021). UGI, which is seen as a physical factor, can change the microclimate and so indirectly influences HTC. For example, a tree blocking solar radiation with its leaves influences thermal comfort due to temperature reduction. The temperature reduction depends on the following aspects of trees: diameter at breast height; the height; the crown spread; and the leaf surface (Rahman et al., 2020). These aspects together are also called the tree canopy cover which is one of the factors influencing HTC. The tree canopy cover can also protect the environment from wind which can be more comfortable during winter times. The research by Rahman et al. (2020) also concluded that different aspects of the urban fabric, such as geometry, building height, density and street orientation, are factors which affect HTC among other things due to wind reduction. It is found, in indoor climates, that some air movement with warmer temperatures is preferred (Rupp et al., 2015). The air temperature and humidity influence HTC because they influence the skin temperature which is related to the thermal comfort and heat stress of people. The factors 'air temperature' and 'humidity' also influence the surface temperatures in urban areas. By reducing the surface temperature, with for example UGI, at locations with high air temperatures and solar radiation, HTC will directly be affected. Additionally, high humidity leads to less productivity and less efficient sweat evaporation of the body which results in a lower ability of the body to cool itself and so to a higher discomfort (Abdel-Ghany et al., 2013; Huang et al., 2020). It can therefore be concluded that UGI has an influence on thermal comfort by controlling humidity, temperature, solar radiation and wind speed. However, air temperature and humidity are difficult to control in outdoor environments and therefore, blocking solar radiation and controlling the wind speed is more effective in improving HTC.

The reviews of Rupp et al. (2015) and Zhao et al. (2021) also found that factors such as clothing, age, gender, culture, behavioural aspects, preferences, memories, expectations, metabolic rate and activity influence HTC besides the microclimate factors. The skin temperature of individuals is already influenced by their clothing, age and gender and this influences someone's thermal comfort. Clothing influences HTC because it is the insulation of the human body and helps with regulating the heat exchange between the human body and the environment. However, it is a difficult relationship because the selection of clothes by people is related to the conditions of the outdoor environment and will be adapted when the outdoor conditions change during the different seasons but also per day (Nikolopoulou & Lykoudis, 2006). It is stated that the choice of clothes and the related expectations are based on the weather conditions of the day before. Furthermore, a difference occurs with population groups that are vulnerable to extreme heat. Such population groups are people in socially disadvantaged neighbourhoods; the elderly; young people; people with health issues; and those living alone. These people are more vulnerable based on how they experience temperature (Makido, Hellman & Shandas, 2019; Norton et al., 2015). It is found that children prefer lower temperatures and the elderly prefer higher temperatures, in indoor environments, than the average indexes predict. Furthermore, it is found that women are more sensitive to temperature than men and they are more often dissatisfied in terms of temperature (Rupp et al., 2015). The dissatisfaction is mostly caused by the skin temperature and extremities of women concerning thermal comfort and this relationship does not exist for men. The relationship is found for indoor conditions but is also relevant in non-uniform outdoor environments. In contrast to that, Yin, Zheng, Wu, Tan, Ye & Wang (2012) found that men are more sensitive to higher temperatures than women. Some researchers also concluded that people who are exposed to a smaller range of temperatures also have a smaller thermal comfort range. Culture also plays a role in thermal comfort because cultural differences exist in the attitude toward the sun which influences the time spent outdoors and the related comfort to that. As mentioned by Thorsson, Honjo, Lindberg, Eliasson & Lim (2007), Swedish people like to sunbathe and therefore, their thermal comfort is related to the temperature in the sun but Japanese people do not like to sunbathe and therefore, their thermal comfort more depends on the temperature in the shadow.

The factors preferences, memories and expectations can be categorized under psychological factors and are part of behavioural aspects which influence the thermal perception of people (Chen & Ng, 2012; Nikolopoulou & Lykoudis, 2006). These factors all have to do with naturalness, past experience, perceived control, time of exposure and environmental stimulation. For example, on a hot summer day, people are looking for shaded locations because they expect that it will be a cooler place. After all, that is the memory they have and that influences their behaviour. Looking at it from another sight, Ruiz & Correa (2015b) state that people expect a comfortable environment in the shadow but sometimes this can be disappointing due to the solar radiation from the surrounding. The behaviour is also influenced by the preference for a location in the sun or the shadow but it can be stated that preferences are formed by the combination of memories and expectations. It is therefore stated that memories and expectations have an influence on thermal comfort and play a major role in the satisfaction of people (Yin et al., 2012). Furthermore, expectations are mostly formed by the thermal comfort of the day before but it is also related to seasons (Nikolopoulou & Lykoudis, 2006). For example, in the autumn warmer temperatures are expected due to the higher temperatures in the summer and in the spring colder temperatures are expected due to the lower temperatures in the winter. Another example is that people coming out of airconditioned buildings still seek sunshine outside even when the index exceeds neutral conditions (Chen & Ng, 2012). An important aspect of behaviour concerning comfort is perceived control, when people have the feeling they cannot control the situation then it is more likely that they will be dissatisfied (Nikolopoulou & Lykoudis, 2006). For example, take a square in the full sun, people have no control over where shading by shelters such as parasols will be placed. In public spaces, people cannot interact with the environment to make it more comfortable for themselves. From another point of view, comfort also depends on having the control of leaving a place or not and this kind of control is present in public spaces and outweighs the control over the microclimate.

Lastly, the factor activity influences the behaviour of people based on their preferences (Chen & Ng, 2012). For example, people that sport outside have other preferences in thermal comfort than people that are relaxing outside. Related to activity is the metabolic rate, it is stated that activities with a low metabolic rate, such as resting, can have higher temperatures outside than activities with a high metabolic rate, such as running (Nikolopoulou & Lykoudis, 2006). Activity and metabolic rate can both be categorized as physiological factors. It can therefore be stated that the assessment of outside thermal comfort should include physiological, physical and psychological factors and that one factor alone cannot predict HTC.

2.1.2 Measuring Human Thermal Comfort

To measure HTC, different indexes, which mostly are mathematical functions and algorithms, are developed with an increased interest in the outdoor environment. The calculated HTC must be within an acceptable range because people will then stay longer outdoors than when it is out of range (Huang et al., 2020). The range that expresses HTC is mostly indicated as presented in Figure 4 in which neutral is seen as the best condition. The indexes can help to asses an environment by calculating HTC and evaluating its state.

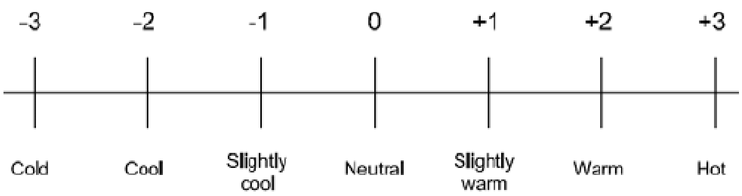


Figure 4: General Human Thermal Comfort index range (Beizaee, Vadodaria & Loveday, 2012)

According to Rupp et al. (2015) and Zhao et al. (2021) who reviewed different HTC indexes, different ways exist to calculate thermal comfort. The most standard thermal comfort indices are ASHRAE 55-2016 and ISO 7730 which are based on Fanger's model. Fanger's model is a mathematical formula with six factors: indoor air temperature, indoor radiation temperature, indoor relative humidity, indoor wind speed, clothing thermal resistance and activity. Based on the formula, the Predict Mean Votes (PMV) model is developed which also includes the theory of the human body. The model is applicable when a linear relationship exists between skin temperature, perspiration rate and human activity intensity. However, these models are all only applicable to steady-state environments and therefore, not usable for outdoor environments. Another model that is widely used is the two-node model which simplifies the human body as a structure with two layers including skin and core. The model is also best applicable to steady-state environments, but the model is further developed in the multi-node model. The multi-node model simplifies the human body into several segments and these segments consist of skin, fat, muscle, bone and other layers. The model includes an active and a passive system and can be applied to non-uniform conditions. These are the classic models and are best applicable to indoor environments because the difference with outdoor environments is large due to solar radiation and wind speed. Next to that, a distinction exists in thermal comfort ranges for indoor and outdoor environments. To overcome these differences, the models are developed further for outdoor environments.

The first index that has been developed further for outdoor environments is the PMV index which has been developed for air-conditioned environments. An improvement of the PMV model is the Klima-Michel-Model (Jendritzky & Nübler, 1981). However, the model only includes the factors 'Metabolic rate', 'Short-wave radiation' and 'Long-wave radiation'. Another improvement of the original PMV index is the Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) index. The outcome is a percentage of people feeling uncomfortable in the environment (Fanger, 1972). It is stated that the index applies to outdoor environments, but it was developed for air-conditioned environments and has strong deviations from thermal votes in outdoor environments (Fanger, 1972; Rupp et al., 2015). Therefore, it can be concluded that the index does not apply to outdoor environments.

Besides the Klima-Michel-Model, multiple other indexes include only a small number of factors. These factors are mostly: air temperature, relative humidity and wind speed. In addition to the small number of factors included, these indexes are mostly location specific and not universally applicable to other locations. For example, the IZA index is only applicable to arid zones and therefore not universally applicable. Therefore, it can be concluded that the following indexes are not worth considering for the new decision-support tool (see Appendix A): ASV, CV, IZA, K, MDI, Vinje's Comfort Index, STI, TEP, THI (also mentioned as DI/DI) TS, TSP and WBGT (Clarke & Bach, 1971; Farajzadeh, Saligheh, Alijani & Matzarakis, 2015; Gaitani, Mihalakakou & Santamouris, 2007; Giles, Balafoutis & Maheras, 1990; Golasi, Salata, De Lieto Vollaro & Coppi, 2018; Johansson, Spangenberg, Gouvêau & Freitas, 2013; Metje, Sterling & Baker, 2008; Monteiro & Alucci, 2009, 2011; Moran, Shapira, Epstein, Matthew & Pandolf, 1998; Nikolopoulou & Lykoudis, 2006; Pötz, 2016; Ruiz & Correa, 2015a, 2015b; Tseliou, Tsiros, Lykoudis & Nikolopoulou, 2010; Wen & Chan, 2015).

Another model that is further developed is the two-node model by combining the model with the human energy balance equation which results in the Munich energy balance model (MEMI) and the model is a physiological-based evaluation. The MEMI model is the base of the PET index and therefore, the PET index is considered as a better-developed index (Höppe, 1999).

The PET index is the most common and widely used index at the moment because the use of PET makes the evaluation result informative and assessable for urban planners and decision-makers. Among other things, this is because the index is expressed in degrees Celsius (°C) instead of the less telling values as shown in Figure 4 (Chen & Ng, 2012). Furthermore, the index is applicable to different climate regions and considers different thermal components of the microclimates which makes it widely suitable (Chen & Ng, 2012; Ruiz & Correa, 2015a). However, the index has some limitations because it does not consider the dynamic elements, such as changing clothing insulation, wind speed and activity, which makes it a static model (Höppe, 1999; Zhao et al., 2021). Moreover, some indexes give better results and include more factors.

According to Ruiz & Correa (2015b), COMFA is a better predictor than the PET index because COMFA better predicts in situations where the focus is on urban strategies for maximizing the liveability of outdoor spaces. These situations fit the purpose of this study, but the COMFA model is individual- and activity-oriented which does not fit the purpose of the new decision-support tool. The decision-support tool should support creating an urban area which is comfortable for different activities and a wide range of population groups and therefore should not be oriented to one activity and person. Furthermore, the model is limited to low wind speeds. The limitations are better represented in an improved COMFA model, COMFA*. The model has improved the clothing insulation and vapour resistance but is still individual- and activity-oriented (Kenny, Warland, Brown & Gillespie, 2009b, 2009a).

According to Golasi et al. (2018), the GOCI (Global Outdoor Comfort Index) and the MOCI (Mediterranean Outdoor Comfort Index) are better predictors than the PET index. It is stated that the GOCI is a widely applicable index because it can take into consideration the differences in climate between regions by including the annual average temperature, the average temperatures of the hottest and coldest month and the latitude. However, the index is only validated in one city (i.e. Rome) and therefore, it is not known whether the index is really applicable to different climates. The MOCI is an index which applies to Mediterranean locations which does not fit the purpose of this study because the index should be wider applicable to be included in the new decision-support tool (Golasi, Salata, De Lieto Vollaro, Coppi & De Lieto Vollaro, 2016).

An improved variant of the PET index is the mPET, the modified physiologically equivalent temperature which according to Chen & Matzarakis (2018) gives a more realistic estimation than the PET index. The improvement of the index is especially in the thermoregulation and clothing insulation model. This means that the body is developed into a multiple-node model instead of a double-node body model (Figure 5). Furthermore, the index makes use of a multi-layer clothing model and an automatically changing clothing insulation value and these improvements lead to a more accurate prediction of HTC.

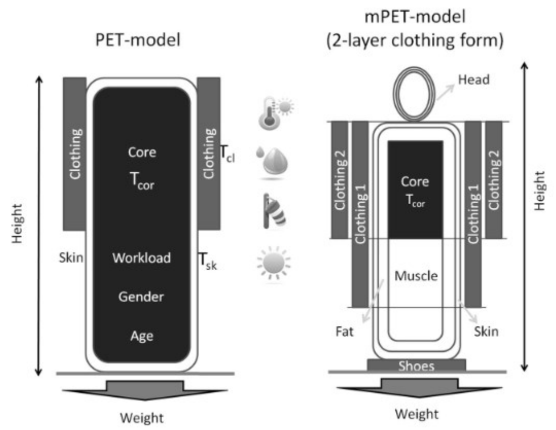


Figure 5: PET versus mPET (Chen & Matzarakis, 2018)

Another predictor is the effective temperature (ET*) which is also able to include solar radiation. However, the index has been developed further in the ETVO which stands for the outdoor modified effective temperature. The ETVO adds to the ET* the possibility to indicate the separate effects of humidity, air temperature, solar radiation and wind speed on thermal perception. Besides, ETVO also can give a universal effect on temperature perception whereas other indexes only can indicate the universal effect (Nagano & Horikoshi, 2011a, 2011b).

Another index is the enhanced conduction-corrected modified effective temperature (ETFe) which is developed from the ETF (conduction-corrected modified effective temperature) for indoor environments. To improve the ETF for outdoor environments, the effects of solar radiation are included in the index (Kurazumi, Fukagawa, Yamato, Tobita, Kondo, Tsuchikawa, Horiskoshi & Matsubara, 2011; Kurazumi, Tsuchikawa, Matsubara, Kondo & Horikoshi, 2011). The ETFe incorporates heat conduction and can indicate the universal and separate effects of the different environmental factors such as the ETVO. However, the ETFe has already been further developed into the ETU (universal effective temperature) which can also be applied to non-uniform conditions (Nagano & Horikoshi, 2011b).

The OUT_SET* index includes elements related to the albedo and temperature of (ground)surfaces (Pickup & De Dear, 2000). Another index is the UTCI (Universal Thermal Climate Index) which according to Golasi et al. (2018) has a worse prediction rate than the PET index. However, according to Blazejczyk, Epstein, Jendritzky, Staiger & Tinz (2012), UTCI is better than the PET index because it incorporates a better clothing model than the PET index (Havenith, Fiala, Blazejczyk, Richards, Bröde, Holmér, Rintamaki, Benshabat & Jendritzky, 2012).

All above-mentioned indexes include mathematical assumptions with certain inputs that generate an output but these are simplified. Therefore, since 2016 machine learning has been introduced in studies of HTC which include mathematical algorithms that improve prediction accuracy. Different algorithms are used since 2016 such as Naïve Bayes, K-Nearest Neighbor, Decision Tree, Support Vector Machine and Random Forest. The Decision Tree algorithm can have an accuracy of more than 90%. Despite the high accuracy of these algorithms, the indexes are developed for indoor air-conditioned environments to be able to adjust the air-conditioning to personal preferences based on an individual's thermal comfort (Ma, Chen, Hu, Perdikaris & Brahama, 2021; Xiong & Yao, 2021; Yang, Li, Liu, Chen, Guo, Wabng & Yan, 2022; Zhou, Xu, Zhang, Niu, Luo, Zhou & Zhang, 2020). Therefore, these machine learning algorithms do not fit the purpose of the study. For a complete overview of all indexes, see Appendix A.

The PET index is the most commonly used index for measuring HTC and chosen as the standard method by the Dutch health organization RIVM to calculate heat stress. Therefore, this index will be used for the new decision-support tool. Multiple applications of the PET index exist but for this study, the application method of the 'Hittekaart Gevoelstemperatuur' at klimaateffectatlas.nl will be used as starting point (Klimaateffectatlas, 2022). This method is used because first of all, it is an already existing HTC calculation which can be applied to a Geographical Information System (GIS) and therefore in line with the approach of this study. Furthermore, the map has a high resolution and includes many factors to determine the value of every raster cell which makes it a deliberate starting point. The map is created by using a different formula for PET in the sun and PET in the shade which together generates the map as presented on klimaateffectatlas.nl. The calculation method behind the map includes the following factors (Figure 6) (Koopmans, Heusinkveld & Steeneveld, 2020):

- Wind speed and direction
- Air temperature
- Global and diffuse radiation
- Relative Humidity
- Solar elevation angle
- Wet-bulb temperature
- Vegetation and trees
- Normalized Difference Vegetation Index (NDVI)
- Water
- Buildings
- Object height
- Sky-View Factor (SVF)

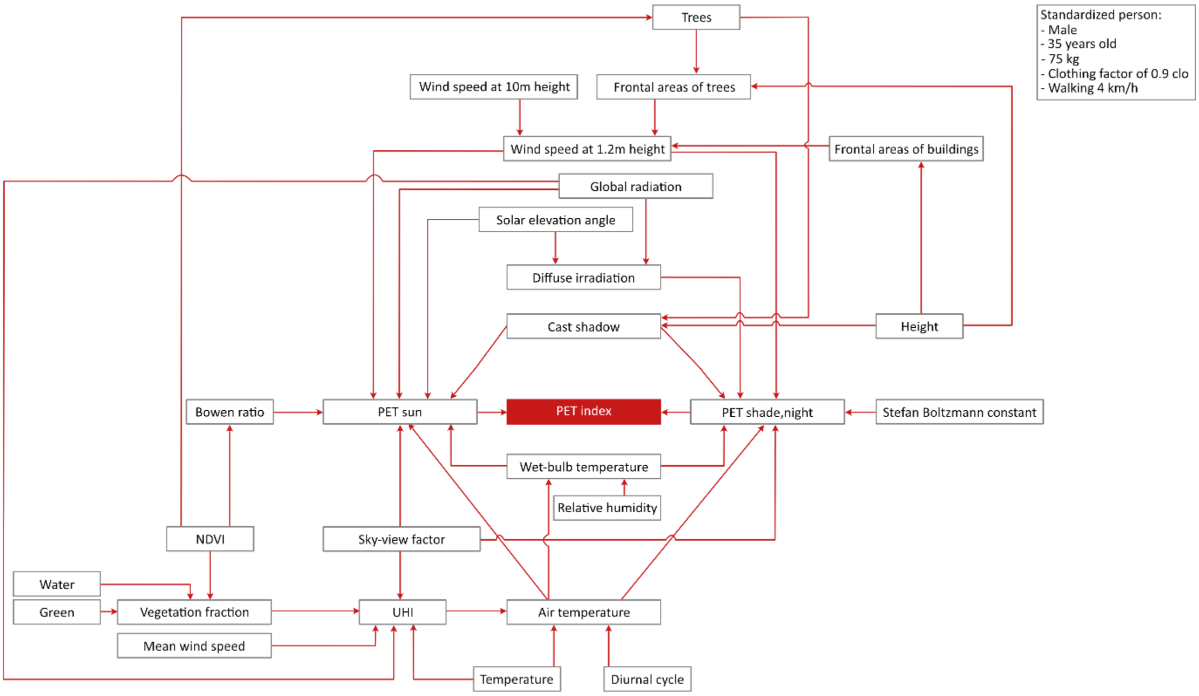


Figure 6: Factors of PET index calculation

The calculation is based on a standardized person who is defined as a male, 35 years old, 1.75m, 75 kg, clothing insulation of 0.9 clo and performing walking with a speed of 4 km/h as metabolic rate. The standardized person determines the different PET index classes and those indicate that moderate heat stress can be experienced with a PET of 29°C or higher, see Figure 7.

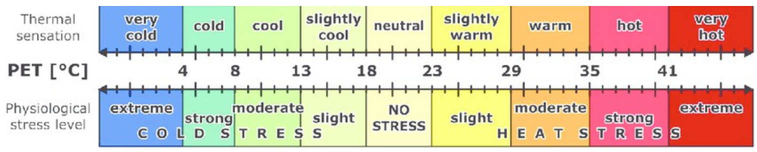


Figure 7: The PET index scale (Kántor, 2016)

The calculation of the PET index has some limitations. First of all, not all UGI types are included such as green roofs and green walls which do also influence HTC (Goede, 2021). Furthermore, due to the standardized person, no difference is made for high-risk groups, such as the elderly and people with health issues, which are more vulnerable to heat stress (Makido et al., 2019; Norton et al., 2015). The use of 0.9 clo as clothing insulation is quite high because that is an outfit with multiple layers which mostly is not worn on a hot summer day, see Figure 8. Another limitation is the uncertainty of the wind speed calculation, especially in the wind reduction calculation around trees and buildings. Furthermore, it would be better if more variation could be created in the wind direction which now is fixed to one direction for the whole country, namely east which was predominantly the wind direction of the day for which the calculation has been made. If the wind direction would have been expressed in degrees more variation could have been included. Moreover, it was not possible to include a calculation of cast shadows under the trees, therefore under trees of 2 meters or higher, the surface is determined as a shadow. It would be better if it can be improved by including the permeability of the tree canopy cover. Another limitation is that the water surfaces are treated as green infrastructure during daytime and as paved surfaces at night because it is difficult to determine the cooling effect for water surfaces. Water surfaces have a high heat capacity such as paved surfaces but also do evaporate which contributes to cooling (Koopmans et al., 2020). It would be better if the effect of water was calculated separately from UGI, but the effect of water surfaces is relatively unknown. The last limitation is that the albedo of the urban fabric is not included in the calculation due to its complexity. Albedo includes the reflectivity of surfaces and therefore, can be relevant to include (Koopmans et al., 2020). These limitations are recommended to improve for more realistic HTC values. Knowledge about the other indexes can help with further developing the PET index.

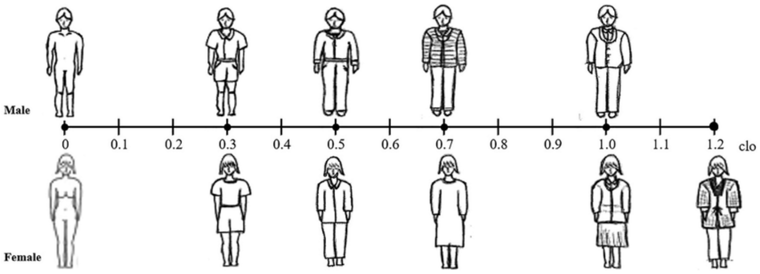


Figure 8: Clothing insulation range (Rijal et al., 2019)

2.2 Urban Green Infrastructure

Urban Green Infrastructure (UGI) is, according to Norton et al. (2015), defined as "the network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits". To determine a strategy for the implementation of UGI, it is important to know its temperature effect and possible implementations connected to their requirements values. By elaborating on these topics, sub-questions 2a, 2b and 2c will be answered and the questions are related to the rest of the research design as presented in Figure 9.

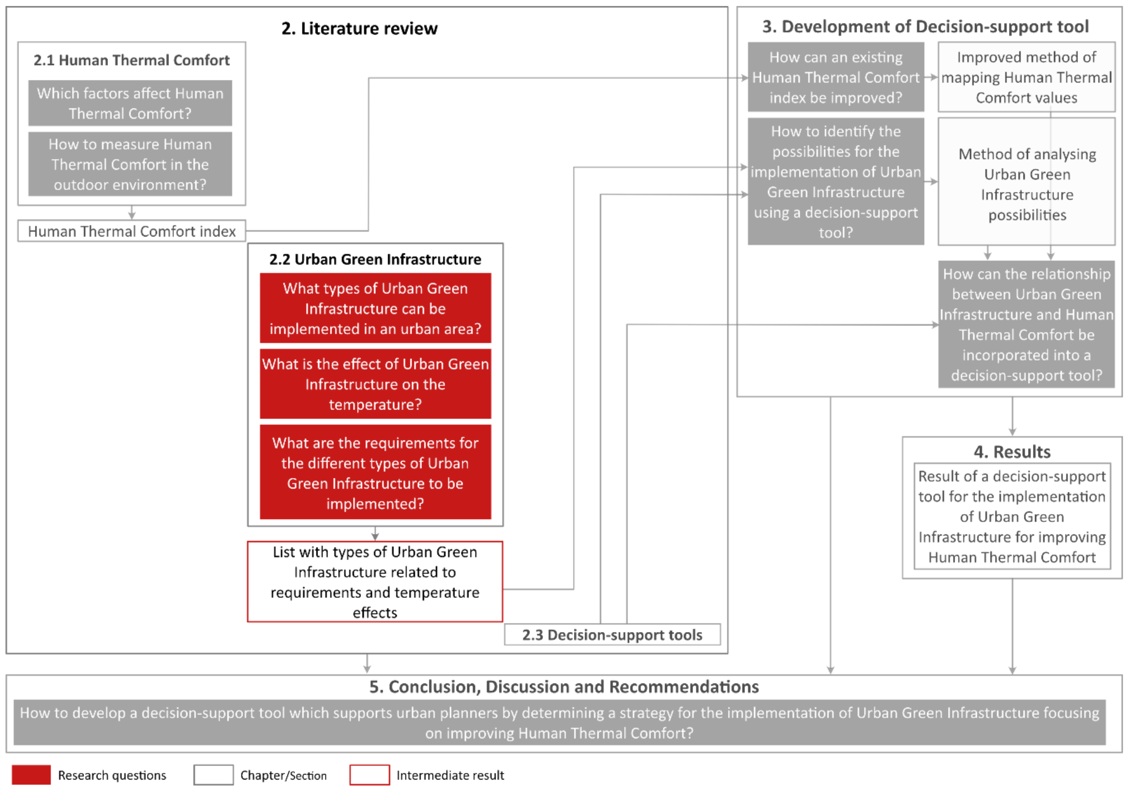


Figure 9: Literature review Urban Green Infrastructure within research design

2.2.1 Types of Urban Green Infrastructure

UGI can be implemented in urban areas on different scales ranging from urban parks to street trees, from public space to private gardens and from green roofs to green walls (Pötz, 2016). An urban open green space, which can be a cool island within an urban area, is an example of a UGI type. It is a cool island because the wind can flow freely at those places (Norton et al., 2015). Next to urban open green spaces, other compositions of vegetation form a type of UGI as well. Examples are street trees, tree avenues, green squares, green playgrounds, parking lots with greenery, city forests, city farms and green ventilation grids (Pötz, 2016). According to the book of Pötz (2016), a small green space will influence the microclimate, defined as the climatic conditions at the local scale. A park of 2.5 ha or more and a network of smaller green spaces will affect the climate of a larger area, such as a neighbourhood (Naiman et al., 2005). The research of Rahman et al. (2020) adds that several small urban parks with a mixture of grass and trees can strengthen the cooling effect of surrounding street trees. The focus of this study will be on the city scale by analysing the microclimate. By presenting the possibilities on the microclimate scale, a network of UGI can be created which will influence the climate in a city.

For walls with exposure to high solar radiation and where the ground-level space is limited and obstacles limit tree growth, green walls can be a solution for cooling the surface. Green walls can also prevent the cooling down of buildings in the winter and autumn. Next to walls also roofs can become one of the hottest surfaces in an urban area and putting vegetation on these roofs can reduce the surface temperatures as well as the temperature within the building. This requires less heating and cooling of buildings which also reduces building energy needs and related greenhouse-gas emissions. Green roofs have a high albedo which makes them even cooler than white roofs. Furthermore, UGI can be added to urban water channels, ditches, ponds, bioswales and seasonal storage which store rainwater. Furthermore, semi-paved options such as grass boulders, grass concrete pavers, woodchips, shells and gravel are better than completely hardened options for paving. These measures will contribute to the green-blue network in urban areas which will prevent thermal discomfort experienced by people (Pötz, 2016).

The focus of this study will be on the UGI types which only include green infrastructure, so no combination with pavement or blue infrastructure. Therefore, types such as bioswales and grass concrete pavers will not be part of the types included. The different UGI types are structured based on the different vegetation categories and their possible alignments instead of basing it on the different possible compositions such as parks and playgrounds which can include different vegetation categories and alignments. By focusing on the different vegetation categories, it is possible to create more flexibility and focus on the microclimate scale instead of using larger fixed compositions. The three main vegetation categories on which will be concentrated are trees, shrubs, and low planting and these main categories are subdivided into sub-categories.

The category 'trees' is subdivided into 24 sub-categories with a distinction between tree avenues, single-line trees, a group of trees and a single street tree (UNaLab, 2019). The sub-categories of trees are subdivided into trees of 1st, 2nd or 3rd size which are trees larger than 15 meters, between 8 and 15 meters and smaller than 8 meters based on their fully grown sizes. The difference is presented in Figures 10, 11 and 12. Furthermore, the trees are subdivided into trees with open or closed foliage (UNaLab, 2019). A foliage is defined as the leaves of the tree and a closed foliage means that the leaves have a high density (Pötz, 2016). This results in 24 different tree categories and Figures 13 to 20 present the tree categories of a tree avenue, single-line trees, group of trees and a single street tree with open or closed foliage.

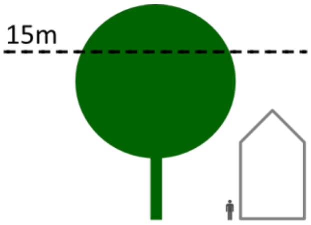


Figure 10: Tree of 1st size - >15m

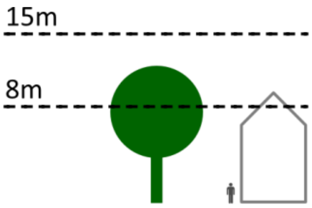


Figure 11: Tree of 2nd size – 8-15m

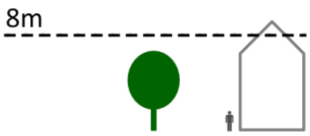


Figure 12: Tree of 3rd size - <8m

Figure 13: Tree avenue with open foliage (Schausi, n.d.)

Figure 14: Tree avenue with closed foliage (123RF, 2022)

Figure 15: Single-line trees with open foliage (Manager of Portland's urban forest, 2022)

Figure 16: Single-line trees with closed foliage (Girish Chandra, n.d.)

Figure 17: Group of trees with open foliage (DeepRoot, 2009)

Figure 18: Group of trees with closed foliage (DeepRoot, 2010)

Figure 19: Street tree with open foliage (FastGrowingTrees.com, 2022)

Figure 20: Street tree with closed foliage (Brinkerink, 2019)

The category 'shrubs' is subdivided into two sub-categories: a single shrub versus a group of shrubs. Figures 21 and 22 present the different shrub categories.

Figure 21: Single shrub (IndiaMART, 2022)

Figure 22: Group of shrubs (Sansone, 2021)

The last category 'low planting' is divided into five sub-categories:

- Grass
- Moss, sedum & herbs
- Bankside plants
- Climbers
- Perennials & annual plants.

Annual plants are just living for one season/year and perennials are plants that bloom more than once and live longer than two years. Both will have the same requirements and therefore are combined into one category. Climbers are plants that climb up against a structure. Bankside plants are plants that live along the water and are resistant to different wet circumstances (Pötz, 2016). Figures 23 to 27 present the different low planting categories.

The vegetation categories are applicable to different types of locations in an urban area, as presented in Table 1 (page 42). The types of locations are divided into public space and built structures. The public space is divided into land and water which is focused on locations along

Figure 23: Grass (Kinwun, 2017)

Figure 24: Moss, sedum & herbs (Sempergreen, 2023)

Figure 25: Bankside plants (Axe, 2020)

Figure 26: Climber (Ambius, 2020)

Figure 27: Perennials & annual plants (Lauren's Garden Service, 2018)

the water. The built structures are subdivided into roof and walls and therefore include every structure with a wall and/or roof, such as buildings, noise barriers and bus shelters. Bankside plants are dependent on wet circumstances and therefore are required to be located near water.

For the built structures, different kinds of green roofs and green walls allow different kinds of vegetation. Based on the possible intensiveness of a green roof, certain vegetation is required. A distinction is made between an extensive roof with grass, moss, sedum and herbs; semi-intensive with grass, moss, sedum, herbs and shrubs; and intensive with grass, perennials, annual plants, shrubs and small trees of the 3rd size (Pötz, 2016; UNaLab, 2019). Figures 28 to 30 present the distinction in intensiveness.

Figure 28: Extensive green roof (Livingroofs.org, 2018)

Figure 29: Semi-intensive green roof (Accredited Green Roof Professional, n.d.)

Figure 30: Intensive green roof (OPTIGRÜN, 2005)

Table 1: Matrix of UGI types and locations

				Public space		Built structures	
				Land	Water	Roof	Walls
Tree	Tree avenue	1st size	open foliage	✓			
			closed foliage	✓			
		2nd size	open foliage	✓			
			closed foliage	✓			
		3rd size	open foliage	✓			
			closed foliage	✓			
	single-line trees	1st size	open foliage	✓			
			closed foliage	✓			
		2nd size	open foliage	✓			
			closed foliage	✓			
		3rd size	open foliage	✓			
			closed foliage	✓			
	Group of trees	1st size	open foliage	✓			
			closed foliage	✓			
		2nd size	open foliage	✓			
			closed foliage	✓			
		3rd size	open foliage	✓		✓	
			closed foliage	✓		✓	
	Street tree	1st size	open foliage	✓			
			closed foliage	✓			
		2nd size	open foliage	✓			
			closed foliage	✓			
		3rd size	open foliage	✓		✓	
			closed foliage	✓		✓	
Shrubs	Single shrub			✓		✓	
	Group of shrubs			✓		✓	
Low planting	Grass			✓		✓	✓
	Moss, sedum & herbs					✓	✓
	Bankside plants				✓		
	Climbers						✓
	Perennials & annual plants			✓		✓	✓

For walls, a distinction is made between ground-based and façade-bound. Ground-based means that climbers are planted in the soil and climb up via a wall. Façade-bound means plants that are attached to a wall and grow from there up or down such as grass, moss, sedum, herbs, perennials and annual plants (Pötz, 2016; UNaLab, 2019). Figures 31 and 32 present this distinction in greening for walls.

Figure 31: Ground-based vertical greenery (Western Pennsylvania Conservancy, 2022)

Figure 32: Façade-bound vertical greenery (Andrews, 2013)

2.2.2 Temperature effects of Urban Green Infrastructure

UGI influences the temperature in urban areas due to different aspects:

- Shadow
- Evapotranspiration
- Wind
- Humidity
- Albedo
- Air quality

First of all, it can be implemented for shading which can modify the microclimates of streets (Norton et al., 2015). Also, Makido et al. (2019) and Carter et al. (2017) emphasize that UGI can provide cooling by shading but also by evapotranspiration. Shading will reduce the physiological temperature as well as the surface temperature of the surface shaded (Pötz, 2016). Evapotranspiration is the vaporisation of water from vegetation and earth surfaces which causes a cooling effect (Irmak, 2008).

The wind effect of UGI also plays a role in the temperature of urban areas. Wind speed is one of the elements affecting the microclimate (Chen & Ng, 2012). UGI can be used to regulate the wind flow in urban areas, for example by putting trees in an open field which reduces the wind flow. But the other way around, by replacing buildings with an urban park, UGI can help with creating more wind flow which is preferred on hot summer days (Manan & Nadasiyatus, 2021; Rahman et al., 2020) Vegetation can regulate the wind flow by breaking, directing, bending and filtering the wind. How UGI regulates the wind flow depends on the composition of vegetation and the kind of vegetation used. It depends on the type, size, leaf density and location of the vegetation and therefore, the selection of vegetation is an important criterion in reducing temperature (Manan & Nadasiyatus, 2021). However, according to Rahman et al. (2020), the effect of UGI on wind speed to reduce temperatures can be outweighed by the effect of evapotranspiration and shading on the temperature because approximately 80% of the cooling effect is caused by shading and the other 20% by evapotranspiration.

It also matters whether an urban area is situated in a humid climate or not because then the influence of UGI is different (Norton et al., 2015). UGI plays a role in controlling the humidity in urban areas because more leaf surface means more moisture due to evapotranspiration which increases the humidity level. A higher level of humidity can create a cooling effect, however, a too-high humidity level will not be perceived as a benefit because it can lead to non-efficient sweat evaporation of the human body especially when people are active (Huang et al., 2020; Manan & Nadasiyatus, 2021) In a humid climate will it, therefore, be more important to create shade instead of having more evapotranspiration. In a non-humid climate, more humidity can lead to cooling, however, too much humidity is not preferred. The humidity level also depends on the amount of greenery and the density of greenery because trees with a wide and dense canopy can stop the vapour from the ground which means that the humidity level under the tree is larger than above it (Manan & Nadasiyatus, 2021).

Another important aspect introduced is the albedo of surfaces (Pötz, 2016) By implementing surfaces with a higher albedo such as greenery and green roofs, the surface temperature will also be reduced because these surfaces absorb less and reflect more radiation. In contrast to greenery, paved surfaces mostly have a smaller albedo which means that it reflects less and absorbs more solar radiation which leads to higher surface temperatures. The heat is released at night which contributes to the heating of urban areas and UGI can lead to releasing less heat from surfaces which also lowers the air temperature at night.

The last aspect is that green infrastructure has an improving effect on air quality in urban areas which can contribute to cooling because a higher amount of greenhouse gas emissions makes it more difficult for the warm air to leave urban areas (Pötz, 2016). The greenhouse gasses create a layer above an urban area which blocks the air from moving upwards which keeps the warm air in the urban area (see Figure 33). UGI can reduce the amount of greenhouse gasses which makes it easier for the heat to leave the urban area.

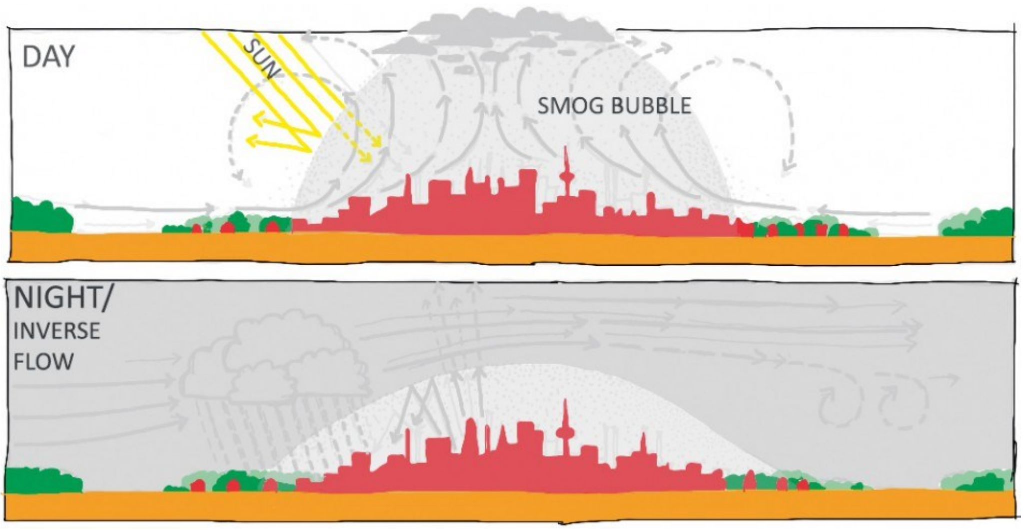


Figure 33: The effect of air pollution (Pötz, 2016)

All these aspects play a role in the influence of UGI on the temperature. Furthermore, it is important to know the quantitative effect of UGI on the air temperature and the Physiological Equivalent Temperature (PET). According to Pötz (2016), neighbourhoods with much green infrastructure can be 10°C cooler than neighbourhoods with many paved surfaces and almost no greenery which is a large difference. Bartesaghi-Koc, Osmond & Peters (2019) studied the differences between different infrastructure types in the city of Sydney. It can be concluded from this study that the temperature difference is different for the time of the year and day and the largest temperature difference is during the day and in the summer. The hottest spots in an urban area are areas with a high density and only low albedo surfaces and the coldest spots are the areas with much green and blue infrastructure. These areas can have a difference of 12°C during the day in the summer. Furthermore, it is noticed that spots surrounded by grass are cooler than those surrounded by buildings and pavement. A similar study was done in Berlin in July by Kottmeier, Biegert & Corsmeier (2007) who concluded that the highest surface temperature is found for traffic areas with a temperature of 41°C which is followed up by the 37°C of streets due to the shading of buildings. The lowest surface temperature is found for water surfaces at 26°C which is followed up by 33°C for parks and greenery in July. The highest contrast is measured around 15 o'clock and the surfaces are cooled down around 18 o'clock except for water surfaces. These studies give a general view into the effect of different infrastructure types on the temperature but a more specific influence of the different UGI types on the temperature and PET should be known to be able to choose the right implementation of UGI.

Different studies have investigated the effect of trees on the temperature in different kinds of situations. Pötz (2016) said that the evapotranspiration of trees can lead to a temperature reduction of 5°C but as stated by Rhee, Park & Lu (2014), the effect on the temperature depends also on the leaf surface. Larger leaf surface leads to lower temperatures under trees. Trees reduce the permeability of short-wave radiation to the ground level, and this can differ between 60 and 90% depending on the tree canopy (Rahman et al., 2020).

Rahman et al. (2020) compared two different tree species and their effect on temperature. One tree, the Tilia cordata, has four times more transpiration which leads to a temperature reduction of 2.8°C in air temperature and an increase in humidity of 2.6 g/m^3 in comparison with 1.9°C and 1.9 g/m^3 for the other tree, the Robinia pseudoacacia. Both trees are trees from the 1st size, however, the Tilia cordata has a closed foliage and the Robinia pseudoacacia has a (semi-)open foliage. The reduction of 2.8 and 1.9°C in air temperature can lead to a maximum reduction of the PET of 11 and 4°C which depends on the surroundings and composition of the trees. The research shows that a difference exists between plant species and open & closed foliage.

Besides the effect of open & closed foliage, it is found that the connection between trees is important for a reduction in temperature (Rhee et al., 2014). From the research done by Huang et al. (2020), it can be concluded that streets with trees can be between 3.3 and 13.9°C cooler than streets without tree coverage depending on the amount of tree coverage. They compared three situations, a tree avenue, single-line trees and a group of trees located in Wuhan. From the study could be concluded that a tree avenue has a larger impact on the air temperature than single-line trees and a group of trees. A group of trees has a slightly larger impact on air temperature than single-line trees. In addition, Morakinyo & Lam (2016) compared the effect of single-line trees, a tree avenue and no tree coverage with each other. The study presented that a tree avenue can have a reduction in the PET up to 3°C and a single-line tree up to 2.5°C. Moreover, Sanusi, Johnstone, May & Livesley (2015) compared a street with almost no tree coverage with a street with a much tree coverage due to a tree avenue with trees of the 2nd size in Melbourne. From the results could be concluded that the influence of a tree avenue on the PET can be up to 4.6°C.

Armson, Rahman & Ennos (2013) compared five different tree species and their effect on the temperature. Four of the street trees were of the 3rd size and one of the 2nd size, and all trees had a (semi-)open foliage. All trees had a reduction in air temperature of less than 1°C. When comparing this size with trees of 1st size in the study of Rahman et al. (2020), it can be stated that a difference in size also means a difference in influence on air temperature. Based on the findings from the different studies, it is assumed that the different types of vegetation will approximately lead to the PET reductions as presented in Table 2 (page 48) depending on the circumstances.

Furthermore, different studies have investigated the effect of shrubs on air temperature and PET. For example, Li, Zheng, Ouyang, Chen & Bedra (2021) investigated the effect of shrubs on HTC at street level in Singapore on a day in January and April. The study concludes that shrubs can reduce wind speed and increase humidity, but it does not influence the air temperature. Due to the increased humidity and decreased wind speed, the effect on the PET is an increase with a maximum of 0.6°C. Another study also found an increasing effect, Karimi, Sanaieian, Farhadi & Norouzian-Maleki (2020) investigated the effect of albedo, trees and shrubs on the PET on a hot summer day. The research was done with the shrub specie 'Buxus' and concluded that the Buxus increases the PET.

Previously, Zheng, Zhao & Li (2016) studied the effect on a hot summer day by comparing the effect of trees, shrubs and a lawn with grass with each other. The conclusion was that shrubs have a little decreasing effect on the air temperature of 0.2°C but the effect of a lawn and trees is larger. Shrubs do have a larger effect on the surface temperature than trees, but in general, the effect of shrubs on the PET is lower than for trees and a lawn. Moreover, the temperature effect depends on the type of environment and the number of shrubs. The study of Zheng et al. (2016) concluded the largest difference of 3°C was measured in an open space in comparison with no greenery. More recently, Yang, Zhou, Wang, Ma, Chen, Xu & Zhu (2019) compared the effect of shrubs with trees and ground-covering plants on the PET by using different greenery ratios. The reducing effect of shrubs was ranging between 0.8 and 2°C.

All studies investigated the effect of a large group of shrubs in different contexts and did not include the effect of one single shrub. Stating that the effect of a group of shrubs is minimal, it can be concluded that the effect of a single shrub is negligible. Despite the studies that concluded an increase in the PET, it is assumed that a group of shrubs decrease the PET by approximately 1°C so comparable to a small tree with open foliage (see Table 2, page 48).

The effect of low planting on PET is a less investigated theme that got limited attention in the literature but some studies are done related to this theme. Bartesaghi-Koc et al. (2019) concluded from a study in Sydney that spots surrounded by grass are cooler than those surrounded by buildings and pavement. It was concluded that surfaces are influenced by the heat of surrounding materials which means that grass and other low planting have an influence as well.

The effect of grass is investigated by Lee, Mayer & Chen (2016) who did a study in which they compared the effect of street trees and grasslands on the air temperature and

PET in Freiburg. They concluded that a tree can lead to a reduction in air temperature of 2.7°C as it is situated on grassland and grassland without trees can lead to a reduction of 3.4°C. However, trees on grassland can lead to a reduction of 17.4°C on the PET while grassland leads to a maximum reduction of 4.9°C on the PET. The large difference in reduction on the PET is caused by the fact that trees create shadow and grass does not. From the study of Zheng et al. (2016) could be concluded that a lawn with grass has a larger effect on the PET and air temperature than shrubs. Furthermore, Aboelata (2020) also concluded that small pieces of grass along a road can lead to a reduction of approximately 1°C on the PET which is smaller than when a large surface is covered with grass.

Another low planting is investigated by Yang et al. (2019) who studied the effect of ground-covering plants on the PET. This study is done with annuals and perennials and it could be concluded that the reducing effect is approximately between 0.1 and 0.7°C depending on the greenery ratio. However, more research is required on the effect of low planting to draw a conclusion about the effect. For this study, it is assumed that the reducing effect of grass is larger than the effect of other low planting. It is assumed that the effect of bankside plants is smaller than other low plantings because these are situated along the water and water has already a reducing effect on the PET. The assumptions are presented in Table 2.

The effect of green roofs on the PET has been investigated where little difference is made between the different intensiveness of the roofs. For example, the study of Knaus & Haase (2020) investigated the effect of a green roof on the PET. It was concluded that a green roof has a reducing effect of 9°C on the PET. However, it was just investigated for one type of roof and at the roof level and not at the street level. Zhang, He, Zhu & Dewancker (2019) did investigate the effect of different green roofs on the temperature in Hangzhou by including different types of roofs and measuring the effect at the street level. The reducing effect of green roofs on air temperature differs between 0.1 and 0.8°C depending on different parameters. A larger coverage ratio and higher vegetation lead to a larger reduction of the temperature, while a higher building leads to a smaller reduction of the air temperature. The wind direction influences the location where the reduction is observable. Previously, Peng & Jim (2013) also did similar research and concluded that an extensive roof has a reducing effect of 0 to 0.7°C on the air temperature and an intensive roof between 0 and 1.7°C. The reduction has an impact on the PET of up to 1 and 5°C. Based on these studies, it is assumed that the effect of the different types of vegetation will be between 0 and 5°C as presented in Table 2.

For green walls, the same applies as for green roofs. The effect has been investigated, but limited attention has been paid to the effect of the different types of vegetation on walls. The general effect concluded by Pötz (2016) is that the surface temperature of walls in the shadow can already be up to 20°C cooler than walls in the sun and vegetation increases the reducing effect. More specifically, Lin, Ni, Xiao & Zhu (2023) investigated the effect of green walls on the PET and concluded that the reducing effect is between 0.3 and 3.2°C depending on the location of the building. The study did not consider different vegetation possibilities. A previous study by Lin, Xiao, Musso & Lu (2019) investigated different forms of green walls and concluded that the average effect of green walls on the PET is a reduction of 2.5°C in the summer. Furthermore, it concluded that a full coverage system has a larger impact than climbers that just grow without control and will not always cover the whole wall. It is therefore assumed that climbers have the smallest effect on the PET and this effect will increase by using larger plants for the façade-bound green wall. The concluded assumptions for the effects on the PET are presented in Table 2.

Table 2: Effects of the vegetation categories on the PET based on the literature

				PET reduction (°C)			
				Public space		Built structures	
				Land	Water	Roof	Walls
Tree	Tree avenue	1st size	open foliage	3.5 - 6			
			closed foliage	10 - 14			
		2nd size	open foliage	3 - 5			
			closed foliage	6 - 8			
		3rd size	open foliage	2 - 4			
			closed foliage	5 - 7			
	single-line trees	1st size	open foliage	2.5 - 4			
			closed foliage	8 - 10			
		2nd size	open foliage	1.5 - 2.5			
			closed foliage	4 - 6			
		3rd size	open foliage	1 - 2			
			closed foliage	3.5 - 5.5			
	Group of trees	1st size	open foliage	3 - 4.5			
			closed foliage	8.5 - 10.5			
		2nd size	open foliage	2 - 3			
			closed foliage	4.5 - 6.5			
		3rd size	open foliage	1.5 - 2.5		1 -2	
			closed foliage	4 - 6		3 - 5	
	Street tree	1st size	open foliage	2 - 3			
			closed foliage	4 - 6			
		2nd size	open foliage	1.5 - 2.5			
			closed foliage	3.5 - 4.5			
		3rd size	open foliage	1 - 2		0.4 - 1.4	
			closed foliage	3 - 4		2 - 4	
Shrubs	Single shrub			0		0	
	Group of shrubs			0.3- 1.3		0.2 - 1.2	
Low planting	Grass			0.5 - 4.5		0 - 0.7	0.5 - 2
	Moss, sedum & herbs					0 - 0.7	0.5 - 2
	Bankside plants				0.1 - 0.3		
	Climbers						0.2 - 1
	Perennials & annual plants			0.1 - 0.7		0.1 - 0.9	1 - 2.5

2.2.3 Requirements of Urban Green Infrastructure types

To implement UGI in urban areas, different requirements regarding vegetation are applicable and the requirements have different values per vegetation category. Table 3 gives an overview of the different kinds of requirements categorized by type of location because the location determines the required conditions (Landscape Development and Landscaping Research Society e.V., 2018; Mentens, Raes & Hermy, 2006; Naing, Nitivattanon & Shipin, 2017; Norton et al., 2015; Patnaik, Seshadri, Mathewos & Gebreyesus, 2018; Pötz, 2016; Sarabi et al., 2022; UNaLab, 2019). Some overlap is existing between the different types of locations, among other things the type of space in the built environment. The type of space represents the distinction between public and private space. The target group for the decision-support tool are urban planners who only can steer by determining a strategy for the public space. The type of space should therefore be public which applies to all types of locations. Furthermore, the soil is an important requirement for vegetation. For vegetation, the best condition is to grow in natural soils as stated by the United States Environmental Protection Agency (2011). However, as presented by PDOK (n.d.), urban areas are categorized as built-up areas and not presented in the type of soil map because urban areas are not part of the natural soil system anymore (Van den Berg, Ricetti & Pixley, 2021). UGI can help with bringing urban areas back to the natural soil system but the requirement of natural soils is not possible to take into consideration. For now, it is important, when a location for vegetation is determined, to look into the soil quality and based on that choose the best-suiting plant species.

Table 3: List of requirement types

Public space		Built structures	
Land	Water	Roof	Walls
Amount of street traffic	Land availability	Building age	Building age
Hydrology	Land use	Building heights	Building heights
Land availability	Presence of underground utilities	Building rooftop	Land availability
Land use	Soil	Land use	Land use
Presence of overhead obstacles	Type of space	Slope of roof	Presence of underground utilities
Presence of underground utilities	Width of paths and roads	Type of space	Soil
Proximity to structures			Type of space
Slope			
Soil			
Tree protection zone			
Type of space			
Width of paths and roads			

Another general requirement is the mandatory width for walkways, bicycle lanes and roads. According to Dutch standards, a walkway should have a minimum width of 1.5 meters which should be obstacle-free. A one-way bicycle lane should have a minimum width of 2 meters and a two-way lane should have a minimum width of 2.5 meters. A one-way road should have a minimum width of 3 meters and a two-way road should have a minimum width of 4.5 meters (Gemeente Leiden, 2013). This requirement is relevant because by knowing the minimum width of these elements in the built environment, it is possible to recognize where is space for UGI.

Another important requirement to decide whether enough space is available for UGI is the amount of land that should be available for the different vegetation categories. The minimal space required for a tree depends on the space the roots need to grow well into a mature tree. For a tree of 1st size, a space of more than 12.5 m^2, for the 2nd size more than 10 m^2 and for the 3rd size more than 7.5 m^2 is required (UNaLab, 2019). For a tree avenue and single-line trees, multiple spots of these sizes in a row should be available. For a tree avenue on both sides of a linear element and for a single-line tree on one side of a linear element. By defining that a group of trees consist of at least 3 trees, a spot of at least 3 times the sizes should be available. For a shrub, a minimal space is required of 0.5 x 0.5 meters to grow well and between two shrubs should at least be a distance of 0.5 meters. Therefore, a group of shrubs consisting of at least 3 shrubs should have a minimal space of 3 m^2 (Richards, 2021; Velt, 2023). The same minimal space of 0.5 x 0.5 meters is required for perennials & annual plants and bankside plants. Grass consists of standard fragments of 1 m^2 and therefore, the minimal space for grass is set to 1 m^2 (Tuin en Gras, 2022). For vertical greenery, a space of 0.5 meters should be available next to the vertical element because for climbers, a space of 30 cm is required between the vertical element and the plant and then the plant itself makes it approximately 0.5 meters. For the façade-bound category with grass, moss, sedum, herbs, perennials and/or annual plants, a package of approximately 0.5 meters in thickness will be placed on the wall (Ambius, 2020; Gids Duurzame Gebouwen, n.d.; Jackson's Nurseries, 2023). An overview of these requirements is presented in Table 4 (page 52).

Besides the land that should be available, underground and overhead should also be obstacle-free. For trees, the same surface should be free of utilities as land should be available and a depth of 2, 1.5 and 1 meters should be obstacle-free for the roots of a tree of 1st, 2nd and 3rd size. Around existing trees also the same space should be free of possible new vegetation, also called the tree protection zone. The roots of a tree are not allowed to touch the groundwater and therefore, the groundwater level should at least be 2.1, 1.6 and 1.1 meters below the surface level which is depending on the required depth of the different tree sizes and a bit of extra space so it does not touch the groundwater. Furthermore, trees should be at least 7.5, 4 and 1.5 meters away from structures such as buildings, because the crown should be able to grow to mature sizes (UNaLab, 2019). For shrubs, perennials & annual plants and bankside plants, a depth of 0.5 meters should be obstacle-free underground together with a surface of 0.5 x 0.5 meters (Richards, 2021; Velt, 2023). Shrubs should at least be 1 meter away from structures such as buildings to have enough space to grow (Richards, 2021). Also, climbers should be 0.5 meters free of obstacles in depth together with 0.5 meters from the vertical element (Gids Duurzame Gebouwen, n.d.; Jackson's Nurseries, 2023). Grass does not require much underground space because it just grows to 0.2 meters in depth (Bosque, 2023). Most vegetation is quite low but trees and shrubs require some obstacle-free space overhead. A tree of 3rd size is approximately 5 meters in height and therefore, the minimal overhead space should be 5 meters. For a tree of 2nd size, the overhead space should be more than 8 meters and for a tree of 1st size more than 15 meters is required. For a shrub, the overhead space should have a minimum of 3 meters (The Editors of Encyclopaedia Britannica, 2019).

Furthermore, vegetation cannot be planted on every slope because it requires enough support to be able to stand. Therefore, trees cannot be planted on a slope of more than 10 degrees. For shrubs, the slope should not be steeper than 20 degrees (First In Architecture, n.d.). Also, green roofs have a maximum slope at which the vegetation can support itself and the rainwater can keep the vegetation wet because when the slope is too steep the rainwater will drain too quickly to water the vegetation. The slope of a roof should be more than one degree because then redundant rainwater can be drained to the sides of the roof. Furthermore, an extensive roof with grass, moss, sedum and/or herbs should have a maximum slope of 30 degrees, a semi-intensive roof with perennials, annual plants and/or shrubs should have a maximum of 10 degrees and an intensive roof with the possibilities for small trees should have a maximum of 5 degrees (Department of Environment and Primary Industries - State of Victoria, 2014; Landscape Development and Landscaping Research Society e.V., 2018; Pötz, 2016; UNaLab, 2019).

For all categories, not all land uses are suitable as a location for vegetation. Trees, shrubs and low planting cannot be planted at locations of buildings, existing trees/greenery and water. Only bankside plants require locations along the water, such as banks. Tree avenues and single-line trees should be located along linear elements such as roads and bicycle paths. The vegetation for the location types 'Roof' and 'Walls' should be located at existing buildings and structures with a roof or vertical elements. Furthermore, a tree should have open or closed foliage based on the amount of traffic that is passing by at a location because a closed foliage will keep the heat of exhaust gasses under the trees. To define the amount of traffic, the types of roads will be distinguished. Trees along a motorway, highway, regional road and local road should have open foliage because much traffic is passing by and with open foliage, the heat can leave easier. Along other streets and at other locations, both closed and open foliage are possible (Pötz, 2016).

For the vegetation on roofs and walls, the buildings should comply with certain requirements. For roofs with perennials, annual plants, shrubs and small trees, a building more than 60 meters high does not affect the temperature on the street level anymore. For a roof with grass, moss, sedum and/or herbs, the building should not be higher than 20 meters because the greenery will have no cooling effect on the street level (Aboelata, 2021; G. Zhang et al., 2019). The effect on street level is taken as a guideline because the PET index is calculated for street level. For climbers, a maximum of 30 meters in building height applies because climbing plants do not grow higher than 30 meters (Gids Duurzame Gebouwen, n.d.). Vegetation on roofs adds an extra layer to the existing roof and a roof should be able to hold this extra layer. Grass, moss, sedum and herbs add a layer of more than 5 cm and more than 60 kg/m^2; perennials, annual plants and shrubs of more than 12 cm and 120 kg/m^2; and small trees of more than 15 cm and 180 kg/m^2 (Fernandez-Cañero, Emilsson, Fernandez-Barba & Herrera Machuca, 2013). The load that is added to the building cannot be generalized for all buildings because it is construction dependent on whether the roof is able to carry the load. To estimate which buildings can carry the load, the load will be related to the building age of buildings. Based on the versions of NEN 6702, NEN-EN 1991 and Bouwbesluit, the assumptions are made that buildings should not be older than the year 1991 for roofs with grass, moss, sedum and herbs and 2012 for roofs with perennials, annual plants, shrubs and small trees (BRIS, 2012; NEN, 2002, 2007). Ground-based climbers add less than 50 kg/m^2 to the wall and grass, moss, sedum, herbs, perennials and/or annual plants attached to a wall add more than 80 kg/m^2. Therefore, it is assumed that buildings should be newer than 1972 for climbers and newer than 2012 for grass, moss, sedum, herbs, perennials and/or annual plants (BRIS, 2012; NEN, 2002, 2007). The building age gives a direction of which buildings are suitable, however, it should always be checked whether the construction can carry the load by checking the construction type and quality per building. A complete overview of the requirements is presented in Table 4.

Table 4: List of requirements

		Built environment aspect	Requirement
Public space	Land	Amount of street traffic	Trees with closed foliage: No motorway, highway, regional road or local road
		Hydrology	Tree 1st size: More than 2.1 meters to groundwater level Tree 2nd size: More than 1.6 meters to groundwater level Tree 3rd size: More than 1.1 meters to groundwater level
		Land availability	Single tree 1st size: More than 12.5 m^2 Single tree 2nd size: More than 10 m^2 Single tree 3rd size: More than 7.5 m^2 Group of trees: A location of more than 3x 12.5, 10 or 7.5m^2 space Tree avenues: Both sides of a linear element, a row of multiple 1st, 2nd or 3rd size possibilities Single line tree: One side of a linear element, a row of multiple 1st, 2nd or 3rd size possibilities Single shrub: Minimal 0.5 x 0.5 m Group of shrubs: Minimal 3 m^2 Bankside plants: Minimal 0.5 x 0.5 meter Perennials & annual plants: Minimal 0.5 x 0.5 meter Grass: Minimal 1 m^2
		Land use	No buildings and water Trees: No existing trees Shrubs and low planting: No existing greenery Single-line trees and tree avenues: Linear elements (roads, bicycle paths etc.)
		Presence of overhead obstacles	Tree 1st size: Minimal 15m obstacle-free in height Tree 2nd size: Minimal 8m obstacle-free in height Tree 3rd size: Minimal 5m obstacle-free in height Shrubs: Minimal 3m obstacle-free in height
		Presence of underground utilities	Tree 1st size: More than 12.5 m^2 and 2 m in depth Tree 2nd size: More than 10 m^2 and 1.5 m in depth Tree 3rd size: More than 7.5 m^2 and 1 m in depth Shrubs: Minimal 0.5 x 0.5 x 0.5 m obstacle free Perennials & annual plants: Minimal 0.5 x 0.5 x 0.5 meter obstacle free Grass: Minimal 0.2 meter obstacle-free in depth
		Proximity to structures	Tree 1st size: More than 7.5 meters Tree 2nd size: More than 4 meters Tree 3rd size: More than 1.5 meters Shrubs: More than 1 meter
		Slope	Trees: Not steeper than 10 degrees Shrubs and perennials & annual plants: Not steeper than 20 degrees
		Tree protection zone	Tree 1st size: 25 m^3 around existing trees (12.5m^2 x 2m) Tree 2nd size: 15 m^3 around existing trees (10m^2 x 1.5m) Tree 3rd size: 7.5 m^3 around existing trees (7.5m^2 x 1m)

Table 4: List of requirements (continued)

Public space	Land	Type of space	Public space
		Width of paths and roads	Walkway: Minimal 1.5 meters Bicycle lane: Minimal 2 meters (one-way) and minimal 2.5 meters (two-way) Road: Minimal 3 meters (one-way) and minimal 4.5 meters (two-way)
	Water	Land availability	Bankside plants: Minimal 0.5 x 0.5 meter
		Land use	No existing buildings and greenery Bankside plants: Water
		Presence of underground utilities	Bankside plants: Minimal 0.5 x 0.5 x 0.5 meter obstacle free
		Type of space	Public space
		Width of paths and roads	Walkway: Minimal 1.5 meters Bicycle lane: Minimal 2 meters (one-way) and minimal 2.5 meters (two-way) Road: Minimal 3 meters (one-way) and minimal 4.5 meters (two-way)
Built structures	Roof	Building age	Grass and moss, sedum & herbs: >1991 Perennials & annual plants, shrubs and trees 3rd size: >2012
		Building heights	Grass and moss, sedum & herbs: Maximum of 20 meters Perennials & annual plants, shrubs and trees 3rd size: Maximum of 60 meters
		Building rooftop	Grass and moss, sedum & herbs: Minimal 5cm in height Perennials & annual plants and shrubs: Minimal 12 cm in height Trees 3rd size: Minimal 15 cm in height
		Land use	Existing buildings and structures with a roof
		Slope of roof	More than 1 degree Grass, moss, sedum & herbs: maximum of 30 degrees Perennials & annual plants and shrubs: maximum of 10 degrees Trees 3rd size: maximum of 5 degrees
		Type of space	Public space
	Walls	Building age	Climbers: >1972 Grass, moss, sedum & herbs and perennials & annual plants: >2012
		Building heights	Climbers: Maximum of 30 meters
		Land availability	0.5 m next to a vertical element
		Land use	Existing buildings and structures with vertical elements
		Presence of underground utilities	Climbers: 0.5 m next to a vertical element and 0.5 m in depth must be obstacle free
		Type of space	Public space

The requirements of Table 4 determine which vegetation category suits a certain location. Within these different vegetation categories, different kinds of vegetation exist that can be planted. Which kind of vegetation is best to plant depends on the local circumstances and should be decided by an expert such as a gardener. It can be decided based on information about the amount of (root)space, soil type, the humidity of the soil, the demand for open or closed foliage, deciduous or evergreen and the amount of sunlight (Hiemstra, 2012, 2018;

Schollen & Company Inc. & Urban Forest Innovations Inc., 2016). It is important to select the right vegetation for a location because otherwise it will not grow healthy and this will affect the cooling effect of the vegetation (Manan & Nadasiyatus, 2021; Norton et al., 2015; Pötz, 2016).

2.3 Decision-support tools

Decision-support tools are tools that can support stakeholders in their decisions for certain strategies such as the implementation of Urban Green Infrastructure (UGI) in urban areas. The tools can incorporate, analyse and demonstrate data in a way that contains useful information for stakeholders (Kuller et al., 2019; Sarabi et al., 2022; Voskamp & Van de Ven, 2015). This section will review existing decision-support tools developed for different climate adaptation measures such as UGI. The review will give insights into the positive developments and the limitations of existing decision-support tools which can give guidance in the development of an improved decision-support tool.

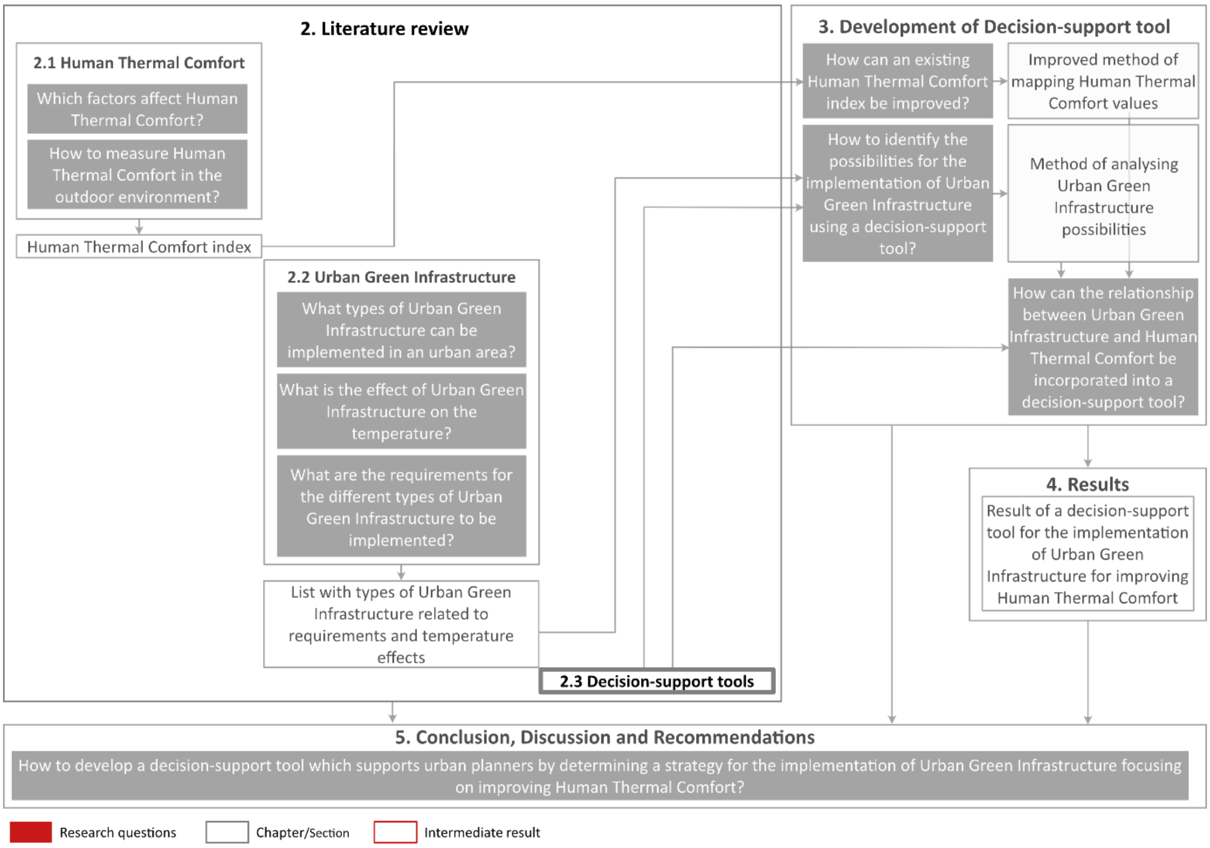


Figure 34: Literature review decision-support tools within research design

A decision-support tool was developed by Lee, Selvakumar, Alvi, Riverson, Zhen, Shoemaker & Lai (2012) which is a tool for Urban Stormwater Treatment and Analysis Integration. The tool assesses projects for the quality management of stormwater and flow abatement techniques. It can determine the location, type, and cost of best management practices (BMPs) for stormwater which are needed to reach better water quality and quantity goals. The tool is built on a base platform interface using ArcGIS and it can be used to analyse stormwater flow, pollutant discharge and management options at multiple scales. The tool is applicable for different kinds of urban planning questions but the tool requires knowledge of the modelling components such as water quality modelling and optimizations which makes it less user-friendly and practical.

Madureira & Andresen (2014) describe the development of a tool that assesses the different functions of green infrastructure and forms a conclusion about the spatial priority areas for green infrastructure. The assessment is based on two factors including the local temperature and the proximity of the population to public green spaces. The method aims to have an integrated assessment of the multifunctionality of green infrastructure and a proper valuation of these functions. The tool was able to demonstrate that the policy for green infrastructure should be based on other factors than was done before because beforehand, it was taken for granted that implementing green infrastructure would bring benefits, however, analysing local assessment factors is required to optimize these benefits in local contexts. The tool includes only two factors while it aims for assessing multifunctionality and therefore, it should include more.

Norton et al. (2015) developed a tool for the prioritisation and selection of UGI to improve the urban climate which is applied to Melbourne in Australia. It quantifies the cooling benefits of four green infrastructure types including green open spaces, shade trees, green roofs and green walls. The steps from the tool go from city-scale to microscale and therefore, it takes a first step in considering the microscale by the implementation of UGI. The tool is a manual process and can be time-consuming. Furthermore, it only focuses on the street canyon context and does not consider the conditions of the green infrastructure types to determine whether it is possible to implement them.

Another tool is developed by Voskamp & Van de Ven (2015) who generated a tool to select site-specific blue-green adaptation solutions for urban redevelopment projects to support urban planners. It is an electronic design table-based tool which is combined with a tool that allows users to evaluate the suitability of the solutions for a location and to select packages of solutions for flooding, drought and heat stress. This combination allows to have a guided and communicative urban planning process and is meant to overcome the gap between planners and engineers. The total tool includes specific green infrastructure types, a site suitability analysis and many assessment requirements. However, the tool does not consider the influence of the weather conditions on the microclimate and this will affect the climate in urban areas and therefore, the need for blue-green adaptation solutions.

Meerow & Newell (2017) introduce a Green Infrastructure Spatial Planning tool which includes six benefits of Green Infrastructure: stormwater management, social vulnerability, green space, air quality, urban heat island amelioration and landscape connectivity. These benefits are used for the GIS-based multi-criteria approach for which stakeholders weigh priorities to find the locations where Urban Green Infrastructure is needed most. In this way, the demand for green infrastructure can be based on its multifunctionality and the tool is used on a city scale. The tool is practicable and widely usable in different urban areas. However, it is not a land suitability analysis because it does not include land characteristics and is only focused on where green infrastructure is necessary. It is not possible to decide on specific green infrastructure solutions with this tool because then other types of factors should be included as well.

Makido et al. (2019) present a more modelling-based tool by which it evaluates the changes in the environmental temperatures across different land uses of different green infrastructure solutions. This microclimate modelling is applied to the city of Portland, Oregon at a city-block level. It is fulfilled to know which built environment characteristics have the most influence on high temperatures and which solutions reduce these temperatures. The results of this modelling can be used to develop cooling solutions for different land uses which can help to achieve climate adaptation goals. The modelling-based tool provides proper insight into the effects on the temperature by different characteristics. However, this modelling tool is very specific to Portland and is not easy to universally reapply in other cities.

Another tool is developed by Kuller et al. (2019) for the suitability of Water Sensitive Urban Design (WSUD). The tool determines spatial suitability from the two perspectives of where a need is and where is a suitable location for implementation. In which the suitability is based on biophysical, socio-economic, planning and governance factors and the need is based on climate adaptation factors. These factors are analysed by GIS-MCDA (multi-criteria decision analysis) techniques. The tool is used to realize a WSUD decision-support tool that automates spatial suitability evaluation to plan green stormwater control systems in urban areas. The tool adds something to existing tools by combing the side of where is a need with a site suitability analysis for where are possibilities. The tool is focused on stormwater and therefore, just includes a small number of UGI types.

Some of the knowledge and tools from the literature mentioned above are combined in the nature-based solutions decision-support tool of Sarabi et al. (2022). The tool helps with finding measures to fulfil the needs of ecosystem services by integrating various functionalities of nature-based solutions on multiple scales. In comparison with the tool of Norton et al. (2015), it adds stakeholder input to weight factors and in comparison with the article of Voskamp & Van de Ven (2015), it includes a site suitability analysis. The tool of Kuller et al. (2019) is not able to prioritize and recommend green infrastructure solutions which the tool of Sarabi et al. (2022) can. Furthermore, the tool can analyse the building and street level. The tool of Sarabi et al. (2022) has also some limitations because the system consists of several steps but it is not easy to move back and forth between these steps and the steps need to be carried out separately. An integrated platform can make it easier to adopt and use the tool. Furthermore, only eight nature-based solutions are included which could be more specific and other requirements such as the presence of overhead obstacles and the amount of street traffic should also be included to analyse site suitability. Furthermore, it would be helpful if the impact of the chosen nature-based solutions can be researched and included in the tool.

All the tools presented in this section have one main limitation in common: they do not include HTC as an assessment criterion. Most tools rely on physical, socio-economic and governance factors but do not include the factors that should improve the thermal comfort of people. The tool of Norton et al. (2015) tries to include HTC but in the end, it only includes social vulnerability as a factor for the comfort of people. Social vulnerability is just a small part of HTC and it is better to include more aspects of HTC to get a better view of the perceived temperature by people.

Therefore, this study aims to develop a new decision-support tool for determining an urban strategy for the implementation of UGI in urban areas that is based on the need for better HTC. The decision-support tool will continue with the developments of already existing decision-support tools as described above. As used by multiple existing tools, the new tool will be developed for a Geographical Information System (GIS) because such a system enables to do location-specific analysis in a universal and replicable manner which is, for example, not possible with the model of Makido et al. (2019). The tool will analyse where a need is for UGI and where suitable locations are for UGI such as done by Kuller et al. (2019) and Sarabi et al. (2022) by making a distinction between need and possibility. As missing by Meerow & Newell (2017), the tool will include a site suitability analysis for different UGI types by including a wide range of requirements including overhead obstacles and amount of street traffic. As has been done by Norton et al. (2015) and Sarabi et al. (2022), the tool will include the micro-scale by using a high resolution in the analysis because it enables a local-specific approach for the implementation of UGI. By enabling a high resolution, it is also possible to apply more specific UGI types than Sarabi et al. (2022) which is partly done by Voskamp & van de Ven (2015). The new tool will improve existing decision-support tools by including a wider range of local assessment requirements and UGI types. The existing decision-support tools focus on assessing the multifunctionality of green infrastructure and the new tool will focus on only assessing HTC because this will bring a new perspective to assessing the heat problem in urban areas. The new perspective can at a later stage be integrated into the assessment of the multifunctionality of UGI.

2.4 Conclusion

Existing literature has been addressed in the literature review to be able to answer research questions 1a to 2c. The literature review is covering the research fields of Human Thermal Comfort, Urban Green Infrastructure and decision-support tools.

To answer sub-question 1a, it has been investigated which factors influence HTC. It could be concluded that HTC is influenced by a wide range of factors which are related to different adaptations. The physical environment, such as UGI and the urban fabric, adapts HTC but also the psychological status of an individual influences how the temperature is perceived by an individual person. The psychological status includes someone’s memories, expectations and perceived control. Furthermore, the physiological environment influences HTC which includes factors such as microclimate, health and skin temperature. Last, different demographic factors influence HTC as well such as age and gender. The relationships between the different factors are presented in Figure 35.

HTC in outdoor environments can be measured by applying an index calculation which includes a wide range of factors that influence HTC as presented in Figure 35. For this study, the PET index is selected to develop further into the decision-support tool because it is a commonly used index in the outdoor environment; a good interpretable index for urban planners by using °C as a unit; it is universally applicable to different climates; and it is chosen as the standard method by the Dutch health organization RIVM. However, the PET index is not the most well-developed index according to the literature and will need some further development. The aspects which require further development are, among other things, based on the positive aspects of the other existing indexes such as the mPET and Comfa*. Figure 36 shows the scope for improvement in comparison with Figure 6 (page 36).

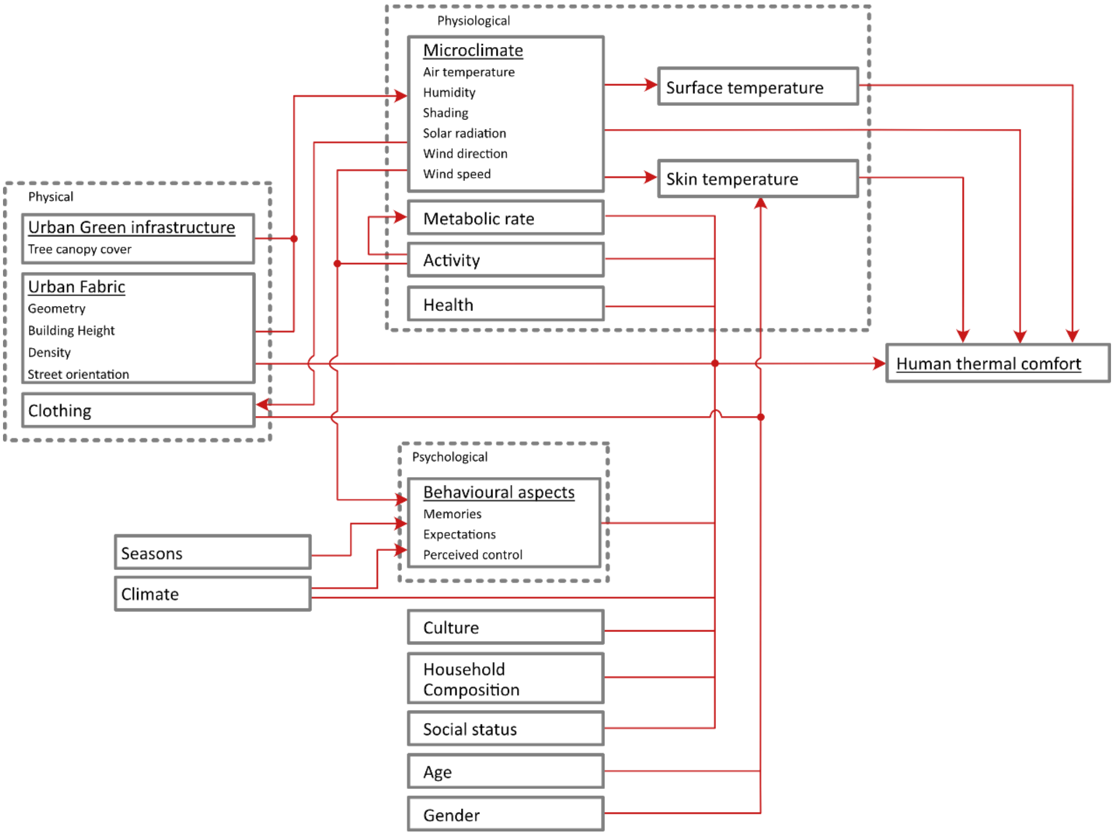


Figure 35: Factors affecting Human Thermal Comfort

To answer sub-question 2a, it has been investigated what different types of UGI exist and how to organize these types in different categories. Urban Green Infrastructure (UGI) can be implemented on different scales in different compositions. The UGI types are structured into the three main categories trees, shrubs and low planting and to link these categories to two different types of locations, namely the public space and built structures. These categories are chosen because, in existing literature, it is mostly categorized in compositions, such as parks, playgrounds and parking lots. Fixing the categories to compositions will make the categories less flexible and by categorizing them based on single elements, more flexibility will be created and also smaller influences on the microclimate can be realized.

Furthermore, it can be concluded that UGI affects temperature mainly by creating shadow and evapotranspiration but also by controlling wind, humidity, albedo and air quality. It is difficult to quantify the effect of UGI on the air and perceived temperature because it depends on many different factors. These factors include the urban fabric around the UGI, the presence of more UGI, the type of vegetation and the weather conditions. Furthermore, for some of the vegetation categories, just a limited number of studies are conducted to be able to certainly quantify the effect. Nevertheless, based on the existing studies, assumptions are made on what approximately the temperature effect is of the different UGI types.

Based on the literature review, it succeeded to define a list of requirements which define the required conditions to implement the different UGI types in urban areas. The requirement categories are summarized in the right part of Figure 37. The requirements depend on the type of location and type of UGI and will be used as input for the development of the decision-support tool.

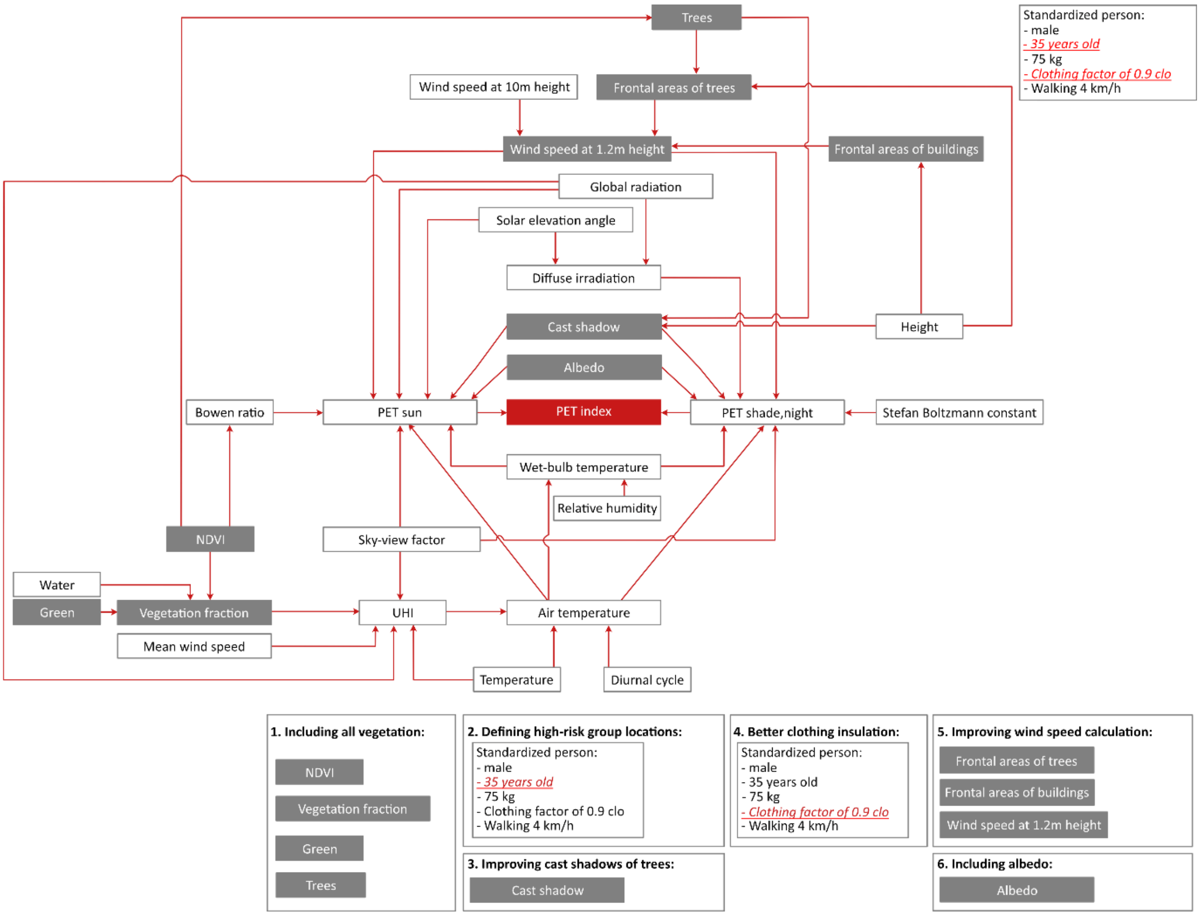


Figure 36: Scope of improvement for the PET index

By bringing the answers to questions 1a to 2c together into a decision-support tool, it will be possible to include HTC in the determination of an urban strategy for the implementation of UGI. The factors and requirements which need to be included in the decision-support tool are summarized in Figure 37.

From the existing literature about decision-support tools could be concluded that HTC-based factors are missing in existing decision-support tools. However, the existing decision-support tools include methods that are successful in analysing urban areas related to climate adaptation. It is taken that GIS is a good system to relate the decision-support tool to and also to bring the need and possibilities for UGI together in one tool. The need for UGI will be defined by the factors of HTC and the possibilities by the requirements of UGI as presented in Figure 37. Furthermore, it can be concluded that further development is required in the range of requirements and UGI.

Human Thermal Comfort

Microclimate
- Air temperature
- Wind speed
- Wind direction
- Humidity
- Solar radiation
- Shadow

Urban Green Infrastructure
- Tree canopy cover
- Vegetation fraction

Urban Fabric
- Building height
- Sky view factor

Albedo

Clothing
- Clothing insulation factor

Activity

Demographic characteristics
- Gender
- Age
- Health
- Culture
- Household composition
- Social status

Behavioural aspects
- Memories
- Expectations
- Perceived control

Urban Green Infrastructure

Urban fabric
- Building age
- Building heights
- Building rooftop
- Proximity to structures
- Slope of roof

Public space
- Amount of street traffic
- Land availability
- Land use
- Type of space
- Presence of overhead obstacles
- Presence of underground utilities
- Slope
- Width of paths and roads

Vegetation
- Hydrology
- Soil
- Tree protection zone

Figure 37: Factors and requirements to be included in new decision-support tool

3. Development of Decision-support tool

The development of the decision-support tool consists of three components which are related to the three research questions as presented in Figure 38. This chapter will explain the components which have been developed to answer research questions 1, 2 and 3. To answer these research questions, the results from the literature review will be applied to develop a decision-support tool. The decision-support tool will be developed by using the programming language Python and QGIS as GIS software program.

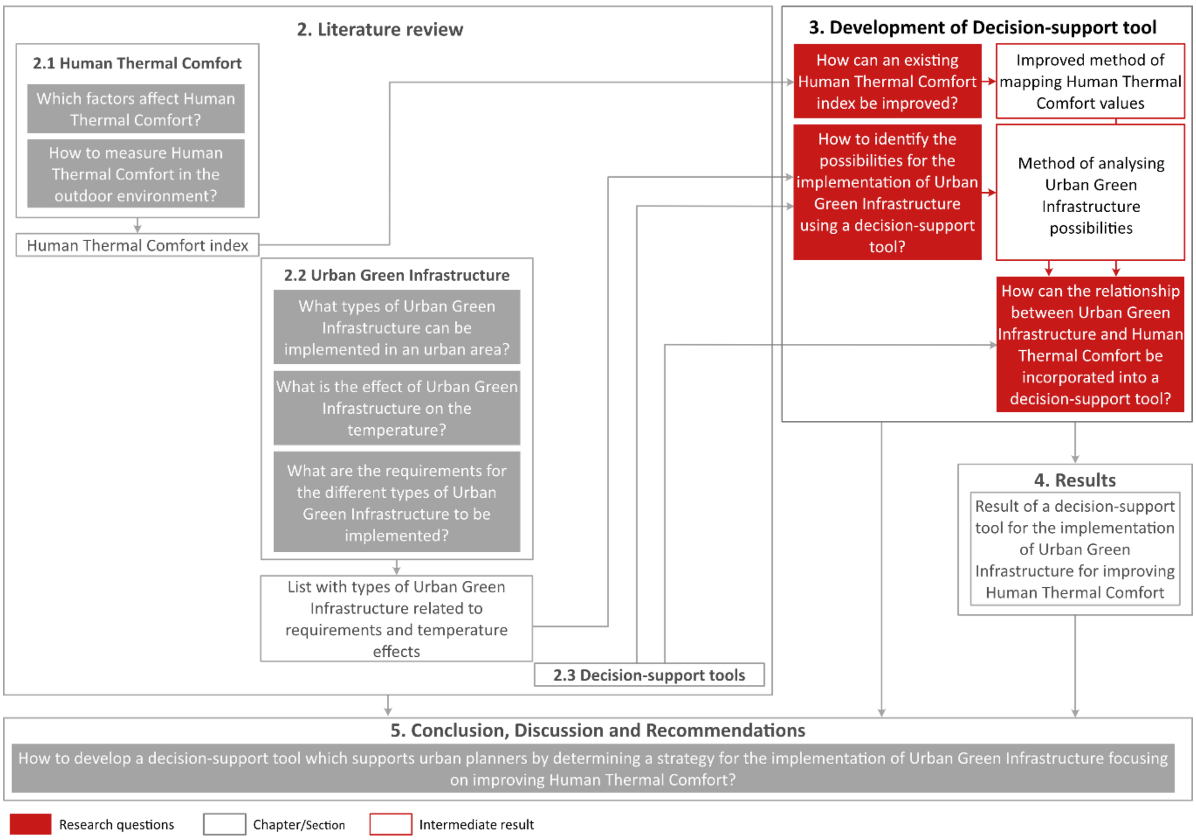


Figure 38: Development of Decision-support tool within research design

The first component is the calculation of Human Thermal Comfort in urban areas which can give insight into the need for UGI by showing the HTC values. For this component, an existing index calculation is expanded with more UGI types. The component is succeeded by the analysis of the possibilities for UGI types based on a list of requirements. This component adds extra requirements and a wider range of UGI types in comparison with the existing decision-support tools reviewed in the literature review. The last component is linking the first two components and implementing the possible UGI types in the HTC

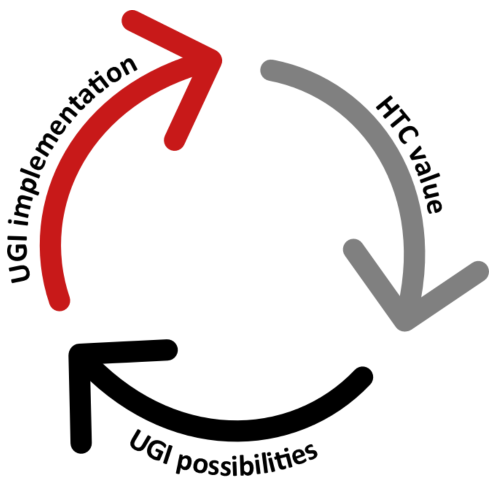


Figure 39: Main components of decision-support tool

calculation to visualize the effect. The components are visualized in Figure 39.

The programs that are used to develop the decision-support tool are Python and QGIS. Python is used in two ways. Firstly, it is used as a programming language in a code editor for the calculation of the HTC values. Secondly, it is used by operating the plugin Python Console in QGIS. A script is developed in the console for the UGI possibilities analysis as a component of the decision-support tool. Furthermore, QGIS is used for visualizing the different data and outcomes of the calculation and analysis.

The structure of the remainder of Chapter 3 is related to the steps of Figure 39. First, the method for calculating HTC values will be explained. Next, the UGI analysis will be described which is succeeded by the explanation of how these two steps are related to each other. The chapter will end with a conclusion.

3.1 Methodology of Human Thermal Comfort (HTC) calculation

The HTC calculation is the first component of the decision-support tool. As concluded from the literature review, HTC can be calculated by applying an index and as stated the PET index is selected as the index to include in the decision-support tool. However, as stated as well, some aspects of the PET index can be improved. These aspects are summarized in Figure 40 and this study will focus on improving the aspect of including all vegetation. The existing PET index calculation does not include all UGI types as defined in the literature review. The vegetation at built structures is missing and therefore, the existing calculation will be expanded by including green roofs and green walls in the calculation. Although all improvements are relevant and should be realized in the future, it is, for now, most relevant to include all different UGI types to create a well-developed link between HTC and UGI in the decision-support tool. Therefore, research question 1 is redefined into:

1. **How can the PET index be improved by including green roofs and green walls?**

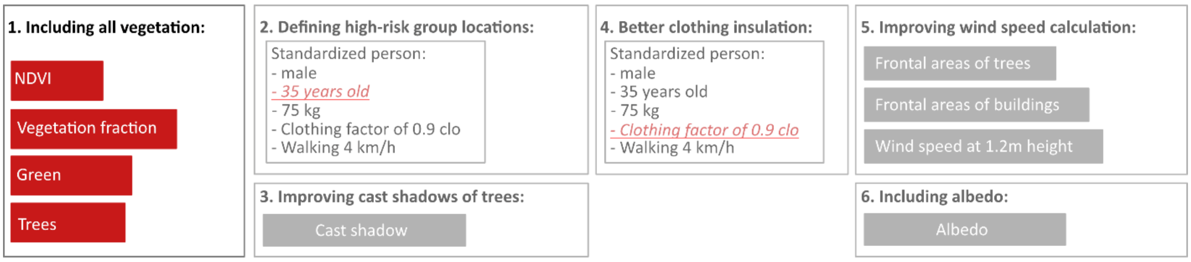


Figure 40: Focus point of possible improvements of the existing PET index

Furthermore, it could be concluded from the literature review that all factors shown in Figure 37 (page 60) should be included in the decision-support tool. Nevertheless, not all will be included in this study and the factors which are excluded are presented in Figure 41. The demographic characteristics age and gender, clothing and activity are part of the standardized person on which the PET index scale is based but these characteristics are not part of the calculation. The demographic characteristics factors together with the albedo could be included in the calculation and are acknowledged as one of the improvement possibilities. It should be noted that they are not the focus point of this study and therefore not included. The behavioural aspects are determinants of HTC but these factors are very individual and are different per person. It is, therefore, not possible to include these factors in the PET index calculation. Thus, the calculation will be based on the factors of the microclimate, UGI and the urban fabric.

Human Thermal Comfort

Microclimate
- Air temperature
- Wind speed
- Wind direction
- Humidity
- Solar radiation
- Shadow

Urban Green Infrastructure
- Tree canopy cover
- Vegetation fraction

Urban Fabric
- Building height
- Sky view factor

~~*Albedo*~~

~~*Clothing*~~
- *Clothing insulation factor*

~~*Activity*~~

~~*Demographic characteristics*~~
- *Gender*
- *Age*
- *Health*
- *Culture*
- *Household composition*
- *Social status*

~~Behavioural aspects~~
- *Memories*
- *Expectations*
- *Perceived control*

Figure 41: Excluded factors of Human Thermal Comfort

The rest of this section will explain the input data used for the calculation and the calculation itself. The calculation will be described in two parts: the first part will explain the most important parts of the existing PET index calculation algorithm as developed by Koopmans et al. (2020) and the second part will explain the method of the adjusted PET index calculation algorithm by including green roofs and green walls. The algorithm is programmed in the programming language Python.

3.1.1 Input data

For the calculation of HTC with the PET index, eight raster data layers and one Excel file are required as input data (Koopmans et al., 2020). For the adjusted PET calculation, an extra two raster data layers are required as input data. The input data is based on eight data sources with different formats as summarized in Table 5. The data sources have three different data formats: Vector, raster (see Figure 42) and text data.

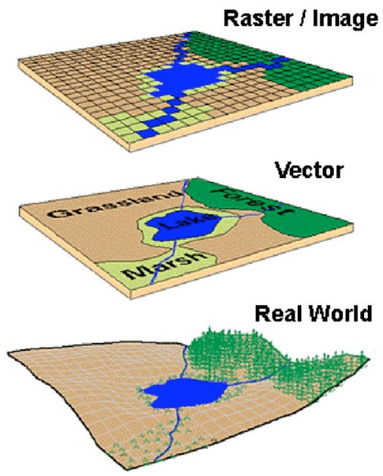


Figure 42: Raster versus vector data (Saab, 2003)

From the data sources mentioned in Table 5, the input data is created. The weather data is translated from a text file to an Excel file. The Excel file should include:

- Weather station number
- Date (Year, Month and Day)
- Hour (from 1 till 24)

- Wind direction in degrees
- Hourly mean wind speed in m/s
- Mean wind speed in m/s
- Temperature at 1.5 m in °C
- Global radiation in J/cm^2
- Relative atmospheric humidity at 1.5 m in percentages

Table 5: Data sources as input for PET calculation

Data sources		**Data format**
Land use	Buildings	Vector
	Water	
	Greenery	
Aerial photos	RGB aerial photo	Raster
	Infrared aerial photo	
Height map	Digital Terrain Model (DTM)	Raster
	Digital Surface Model (DSM)	
Weather data		Text

The calculation is based on raster data with a cell size of 1m (meaning with cells of 1x1m), so the other seven data sources should be translated to a raster layer. The following raster layers should be created in Tagged Image File Format (TIFF):

- Buildings
- Water
- Greenery
- Normalized Difference Vegetation Index (NDVI)
- Height
- Digital Surface Model (DSM)
- Sky-View Factor (SVF)
- Trees

The vector layers of the buildings, water and greenery have to be rasterized in a raster layer with a cell size of 1m (Figure 43). The raster layers should have binary values with 1 meaning that the object is present and 0 means absent at that 1m^2.

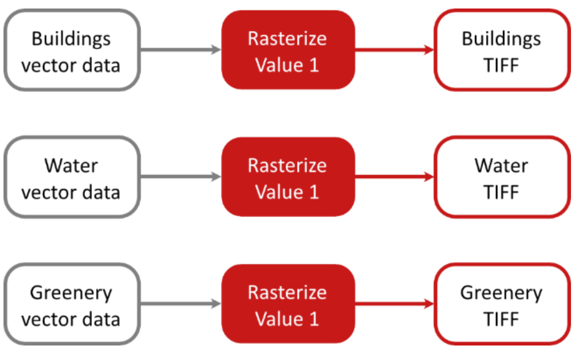


Figure 43: Creating input data buildings, water and greenery

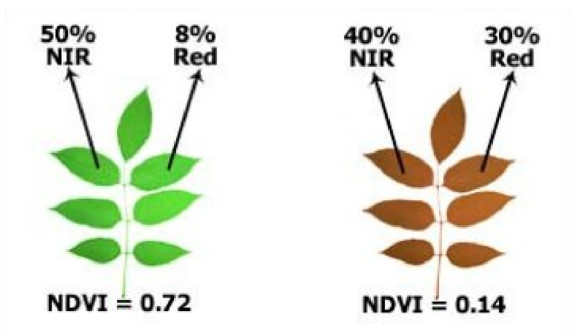


Figure 44: NDVI values explanation (ece.montana.edu, n.d.)

The NDVI is an index that can identify vegetation by calculating the difference between infrared and red light. It can be done because vegetation reflects infrared light and absorbs red light (GISGeography, 2022a). The NDVI can have a value between -1 and 1 and the closer the value to one, the healthier the vegetation. A clear boundary value of when it can be designated as vegetation is not yet defined. For now, it is assumed that a value above 0.16 can be designated as vegetation (Koopmans et al., 2020). However, values smaller than 0.16 can still be vegetation but will probably be unhealthy/dead vegetation (Figure 44). So, values below 0.16 are indicated as paved surfaces (Koopmans et al., 2020).

For the NDVI input layer, the two aerial photos are used as input for the formula to calculate the NDVI (Figure 45):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

With NIR being the infrared aerial photo and RED being the RGB aerial photo.

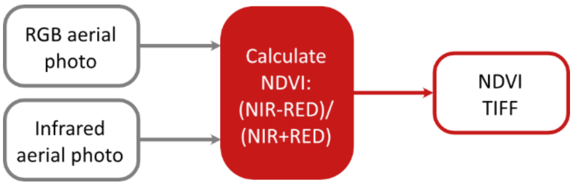


Figure 45: Creating input data NDVI

The Digital Terrain Model (DTM) and Digital Surface Model (DSM) data sources are used as input for creating the height, DSM and Sky-View Factor (SVF) layers. The DTM and DSM data sources are raster maps with the heights of the terrain and surfaces with respect to the Normal Amsterdam Level (NAP) (Rijkswaterstaat, n.d.). The SVF is simply said the fraction of the sky visible from the horizon and depends on the height of objects in the surroundings (see Figure 46) (Dirksen, Ronda & Theeuwes, 2019). The SVF has a value between 0 and 1 whereby 1 means that no hindrance from objects is present to see the whole sky, for example, on top of a mountain (see Figure 47).

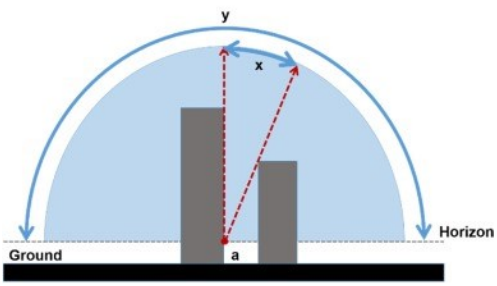


Figure 46: Sky-View Factor explanation (Zhang, Gou, Lu & Lin, 2019)

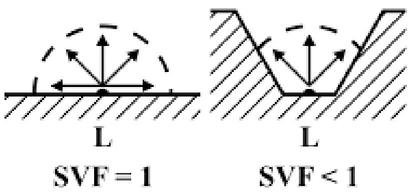


Figure 47: Sky-View Factor value explanation (Hämmerle, Gál, Unger & Matzarakis, 2011)

The DSM, height and SVF layers are created by the existing PET index algorithm as presented in Figure 48. The height is calculated by subtracting the DTM layer from the DSM layer (DSM – DTM). So, the height layer does not represent the height in relation to NAP but to ground level and is therefore different than the DSM layer. The SVF is calculated by the method of

Dozier-Frew and the method is explained by Van der Linden (2021). The formulas can be found in Appendix B.

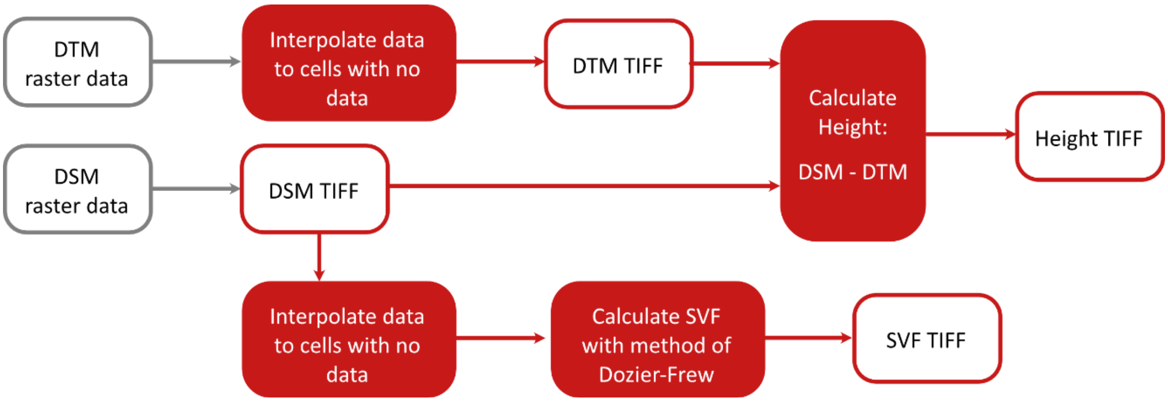


Figure 48: Creating input data DSM, heigth and SVF

The trees layer is calculated from the NDVI and height layer. For trees, it is assumed that greenery higher than 2 meters can be defined as trees (Figure 49).

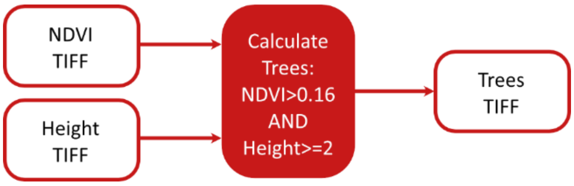


Figure 49: Creating input data trees

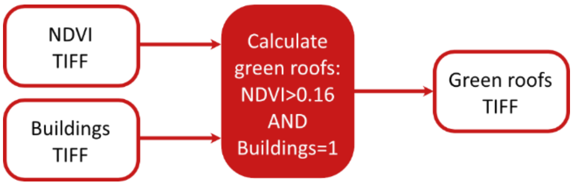


Figure 50: Creating input data green roofs

To include green roofs and green walls in the PET index calculation, two extra input raster layers are required. These two extra layers are a data layer containing the buildings with a green roof and a layer containing the buildings with green walls. For both subjects, no useful (open) data is available. Despite this, the data layer about green roofs could be created by assuming that the NDVI should be larger than 0.16 and should be located at a building (Figure 50).

For green walls, it is more difficult to make a realistic calculation to determine the locations. Therefore, data is created which is just an assumption and not in line with reality. The non-realistic data layer is created with the buildings' data source. It is done by making a random selection of buildings and rasterizing this selection. Around the cells of the buildings' selection, a buffer of 1m is created (Figure 51). The buffer defines the location of the green walls.

Figure 51: Creating input data green walls

The input data of buildings, water, greenery, NDVI, trees, green roofs and green walls can be created by the programmed PyQGIS script which is attached in Appendix C. The script transforms the data sources of Table 5 (page 64) into the defined raster layers. As stated, the DSM, height and SVF input data layers are created by the existing PET index algorithm. The described input data layers will be used as input for the PET index calculation.

3.1.2 Calculation

3.1.2.1 Existing PET index calculation

How the input layers are related to the rest of the calculation is presented in Appendix D. The scheme demonstrates the method of the existing PET index calculation including input data layers, intermediate result layers and the final PET index layer. This section will explain the most important parts of the existing calculation, a more detailed explanation is given in Appendix E and by Koopmans et al. (2020).

The calculation of the PET index starts with calculating the Urban Heat Island (UHI) effect which is an important part because of the calculation of the vegetation fraction (Figure 52).

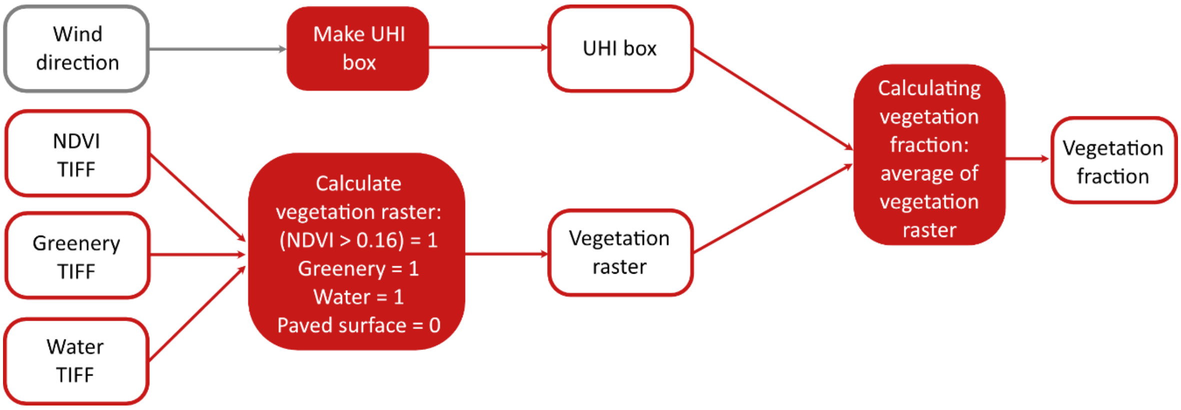


Figure 52: Calculating vegetation fraction

For this calculation, a UHI box is created to be able to calculate the vegetation fraction over an area of 500 x 1100 meters in relation to the wind direction, see Figure 53 (Koopmans et al., 2020). The vegetation fraction is calculated by first determining the vegetation raster which provides information regarding where vegetation is present in a raster with a cell size of 1m. The vegetation raster is calculated by using NDVI, greenery and water as input layers. As stated earlier, NDVI > 0.16 is used as a threshold value to identify vegetation. However, when this is used as a threshold value then cropland may not always be indicated as vegetation because, during some periods of the year, cropland is bare. Bare cropland does not have the same heat capacity as paved surfaces and therefore, it needs to be identified as vegetation (Koopmans et al., 2020). Therefore, greenery is also used as an input layer which also includes the locations of cropland. Furthermore, water is a complicated factor in the vegetation fraction because it has a high heat capacity, but it also evaporates. Therefore, water is assumed as vegetation during daytime and as a paved surface during the night. So, the vegetation raster is calculated by setting all NDVI > 0.16, greenery and water locations as vegetation during daytime and all NDVI > 0.16 and greenery locations as vegetation during the night by giving these locations value 1 in the raster layer. The rest of the locations are assigned as paved surfaces and get a value of 0. The resulting vegetation raster is then averaged over an area of 500 x 1100 meters which conforms to the interaction between land use and urban temperature (Koopmans et al., 2020). The averaged vegetation raster values result in the vegetation fraction.

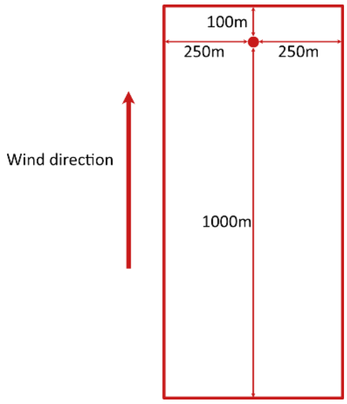


Figure 53: UHI box

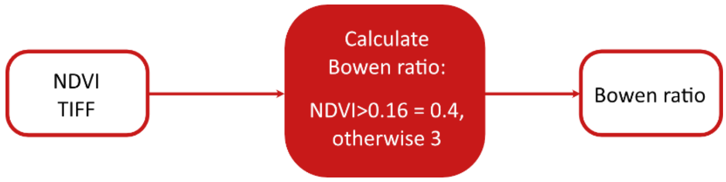


Figure 54: Calculating Bowen ratio

After the UHI effect has been calculated, the wind reduction is calculated. This calculation is done because the weather stations are standing in open terrain and in urban areas, a reduction is present due to buildings and trees. Subsequently, the Bowen ratio is calculated which is the ratio between sensible and latent heat flux and is an important part because it tells something about the evapotranspiration of surfaces such as vegetation. The lower the value, the better the evapotranspiration of the surface. It is stated that paved surfaces have a value of 3 and well-evaporating vegetation has a value of 0.4 (Koopmans et al., 2020). It is stated that locations with an NDVI of 0.16 or larger are well-evaporating vegetation and have a value of 0.4 and all other locations get a value of 3 (Figure 54).

The last intermediate calculation step is the calculation of the shade map. After that the UHI effect including the vegetation fraction, shade map, Bowen ratio and wind reduction have been calculated as intermediate maps, the air temperate (T_a) and wet-bulb temperature (T_w) are calculated.

Based on the intermediate maps, air temperature and wet-bulb temperature, the PET index can be calculated by making a distinction between shadow and sun locations. When PET_{sun} and PET_{shade} have been calculated, then the PET index can be determined by giving all shadow locations the value of PET_{shade} and all other locations the value of PET_{sun} based on the shade map. If it is night then all locations get the value of PET_{shade}. These calculation steps are done for every hour in a defined time period and at the end, all calculated PET index maps are averaged to create one final PET index map.

3.1.2.2 Adjusted PET index calculation

The adjusted PET index calculation developed in this study focuses on including green roofs and green walls in the calculation. The other UGI types are in a simplified way included but vegetation at built structures are not. Including green roofs and green walls in the calculation influences two calculation steps in the existing calculation. It influences the calculation of the vegetation raster and the Bowen ratio. The dimensions of the buildings are already included in the shade and wind reduction map, so it is concluded that it will not influence those intermediate maps of the calculation.

The existing PET index calculation is first adjusted by changing the calculation of the vegetation raster, see Figure 55 which indicates with green the new/adjusted parts in comparison with Figure 52 (page 67).

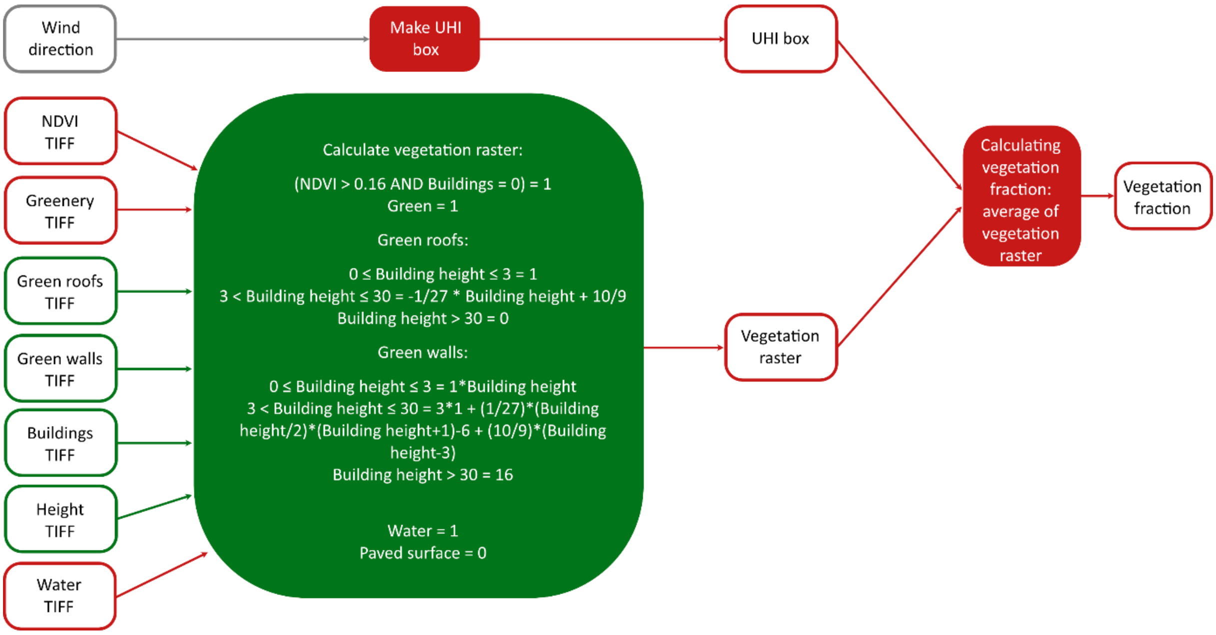


Figure 55: Adjusted vegetation fraction calculation

The green roofs, green walls, height, and buildings TIFFs are added as extra input. The vegetation raster is used as input for the calculation of the vegetation fraction. In the existing calculation, it was simply stated that vegetation gets a value of 1 and paved surfaces a value of 0 in the vegetation raster. As stated in the literature, vegetation at buildings will have a lower effect on the PET index when buildings get higher. Therefore, the vegetation raster will become related to the building heights.

As stated in the literature, an extensive green roof will have no influence anymore when the building is 20 meters or higher and for an intensive green roof, the boundary is at 60 meters in height. In the PET index algorithm, no distinction is made between the different types of vegetation and therefore, also no distinction between extensive or intensive green roofs. Extensive green roofs are more commonly used than intensive green roofs and therefore, it is assumed that the reducing effect of green roofs and green walls on the PET index will end when the building is higher than 30 meters. When the building is between 0 and 30 meters high then the effect will reduce linearly when the building gets higher.

For green roofs, the reducing effect is translated into three conditions for the vegetation raster. It is stated that (explanation in Appendix F):

- 0 ≤ Building height ≤ 3, Vegetation raster value = 1
- 3 < Building height ≤ 30, Vegetation raster value = -1/27 * Building height + 10/9
- Building height > 30, Vegetation raster value = 0

In the vector data of the buildings, some building polygons also include, for example, courtyards with the height being 0m. To be sure, that the vegetation of these courtyards is included, a building height of 0m is considered as well.
For green walls, the situation is a bit different because the surface is in the vertical plane instead of horizontal. For the calculation of the green walls, the surface of the vegetation must be in proportion to the surface of the other vegetation. For green roofs and other

vegetation, the surface is equal to the number of cells in the raster layer that have value 1. For green walls, the surface of one cell of 1m including a green wall is equal to the building height (1*building height). To make the surface in proportion, the vegetation raster value should be calculated for every meter building height in that cell and all values should be added to give the 1m cell a vegetation raster value (see Figure 56). The conditions for the meters in building height are the same as for the green roofs. Although, the total outcome for the cell is different due to the adding up of values.

Therefore, for green walls, it is stated that (explanation in Appendix F):

- 0 ≤ Building height ≤ 3, Vegetation raster value = 1*Building height
- 3 < Building height ≤ 30, Vegetation raster value = 3*1 + (1/27)*(Building height / 2)*(Building height + 1) - 6 + (10/9)*(Building height - 3)
- Building height > 30, Vegetation raster value = 16

In this way, for every 1m cell, it can be determined what the vegetation raster value is by combining these conditions with the values of 0 and 1 of the other vegetation. By including the effect of reducing values with a higher building in the vegetation raster, it is possible to pass on this effect in the calculation of the vegetation fraction, UHI effect and air temperature which will affect the PET index.

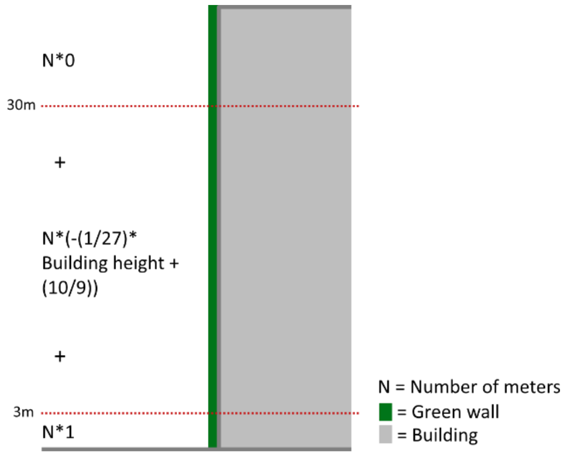


Figure 56: Explanation of green wall vegetation raster value

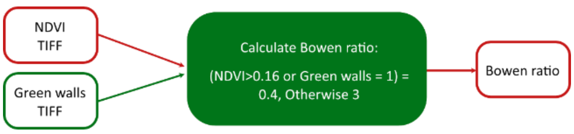


Figure 57: Adjusted Bowen ratio calculation

The next step is to include the vegetation on built structures in the Bowen ratio calculation as well, see Figure 57 which indicates with green the new/adjusted parts in comparison with Figure 54 (page 68). The Bowen ratio is a local effect to add to the PET index, so only for the cells including the vegetation, this effect is noticeable. At the end of the calculation, the buildings and water are filtered out of the calculation because the PET is calculated for street level and therefore, including buildings and water would lead to unusual effects. Therefore, the effect of green roofs on the Bowen ratio will also be filtered out and so, green roofs are excluded from the Bowen ratio calculation. The only extra input layer is therefore green walls. Green walls do create an effect on the Bowen ratio because these are located outside the buildings and therefore, located at the cells around the building. The existing Bowen ratio conditions were that all cells with an NDVI > 0.16 should get a value of 0.4 and the rest of the cells value 3 because it is stated that paved surfaces have a value of 3 and well-evaporating vegetation has a value of 0.4 (Koopmans et al., 2020).

To include green walls in the Bowen ratio calculation, the new conditions are:

- NDVI > 0.16 or Green walls = 1, Bowen ratio = 0.4
- Otherwise, Bowen ratio = 3

The new calculation steps will include green roofs and green walls in the PET index calculation and with that, all vegetation is included in the calculation. The overall new calculation method is presented in Appendix D.

3.2 Methodology of Urban Green Infrastructure (UGI) analysis

The UGI analysis is the second component of the decision-support tool. The analysis is a spatial analysis which will determine what locations are suitable for implementing different types of UGI based on the list of requirements as concluded from the literature review (Table 4, page 52). However, some requirements are not able to be considered in the UGI analysis (Figure 58). The reasons for this are no available data or no suitable data because the information was not useful or the scope was too small. Building heights is not considered because the effect is already implemented in the HTC calculation. Nevertheless, this study expands the number of requirements in comparison with the existing decision-support tools by including the slope of roof, the amount of street traffic and the presence of overhead obstacles.

Urban Green Infrastructure

Urban fabric
- Building age
- ~~Building heights~~
- ~~Building rooftop~~
- Proximity to structures
- Slope of roof

Public space
- Amount of street traffic
- Land availability
- Land use
- ~~Type of space~~
- Presence of overhead obstacles
- ~~Presence of underground utilities~~
- Slope
- Width of paths and roads

Vegetation
- ~~Hydrology~~
- ~~Soil~~
- Tree protection zone

Figure 58: Excluded UGI requirements

The UGI types that will be considered in the UGI analysis are the types concluded from the literature review (Table 6) which is a wider range of types than included in existing decision-support tools. Furthermore, the types are more detailed in comparison with existing decision-support tools which creates more flexibility and detail in determining the possibilities for implementing UGI. The UGI analysis is programmed in QGIS with the programming language Python by developing a script in the Python console. The script of the programmed UGI analysis is attached in Appendix G. The rest of this section will explain how the UGI analysis is structured by explaining the input data and the analysis method which makes a distinction between data preparation, site suitability analysis per UGI type and combining the possibility layers of the UGI types in one map.

3.2.1 Input data

For the UGI analysis, twelve data sources are required divided over three themes. The data sources are either raster or vector data. The sources are summarized in Table 7. Six of the twelve data sources are prepared data layers used in the HTC calculation. All data sources can directly be used in the UGI analysis because the data preparation is part of the programmed UGI analysis.

Table 6: The included UGI types

Tree	Tree avenue	1st size	open foliage
			closed foliage
		2nd size	open foliage
			closed foliage
		3rd size	open foliage
			closed foliage
	single-line trees	1st size	open foliage
			closed foliage
		2nd size	open foliage
			closed foliage
		3rd size	open foliage
			closed foliage
	Group of trees	1st size	open foliage
			closed foliage
		2nd size	open foliage
			closed foliage
		3rd size	open foliage
			closed foliage
	Street tree	1st size	open foliage
			closed foliage
		2nd size	open foliage
			closed foliage
		3rd size	open foliage
			closed foliage
Shrubs	Single shrub		
	Group of shrubs		
Low planting	Grass		
	Moss, sedum & herbs		
	Bankside plants		
	Climbers		
	Perennials & annual plants		

Table 7: Data sources as input for UGI analysis (Used from HTC calculation)*

Data sources		**Data format**
Land use	Water*	Raster
	Greenery*	
	Trees*	
	Railways	Vector
	Roads	
	Banks	
	Walls	
	Other structures	
Basis Register Addresses and Buildings (BAG)	Buildings	Vector
Height map	Digital Terrain Model (DTM)*	Raster
	Digital Surface Model (DSM)*	
	Height*	

3.2.1 Analysis

The UGI analysis consists of three parts: data preparation, site suitability analysis per UGI type and combining the possibility layers of the UGI types in one map. The analysis will, just like the HTC calculation, be done with raster layers with a cell size of 1m (meaning with cells of 1x1m) to be able to link HTC and UGI in a later stage. Therefore, the data preparation part will consist of preparing the data sources for raster analysis. Furthermore, the data preparation part consists of defining the list of requirements into raster layers. The site suitability analysis per UGI type consists of analysing whether the different requirements are met for the defined UGI type. The analysis gives as outcome at which locations the defined UGI type is possible by creating a raster map per UGI type. The last step is then to bring the raster maps together in one map, this is done by creating a priority list which will define which UGI type will have more priority at a certain location. The product of the UGI analysis will then be a map with the possibilities of the different UGI types combined. The total process scheme is attached in Appendix H.

3.2.1.1 Data preparation

The data preparation consists of preparing the input data sources of Table 7 for analysing the ten requirements, as presented in Figure 58 (page 71):

- Land use
- Width of paths and roads
- Land availability
- Amount of street traffic
- Building age
- Presence of overhead obstacles
- Proximity of structures
- Slope
- Slope of roof
- Tree protection zone

The data preparation starts with preparing the land use data layers which have eight data sources as input:

- Greenery
- Water
- Trees
- Buildings
- Railways
- Walls
- Other structures
- Banks

The first three objects are already prepared for the HTC calculation and do not require further preparation. Buildings, railways, walls, other structures and banks are prepared by rasterizing the vector data (see Figure 59). The raster layer gets binary values of 0 and 1 (1 means that the object is present at that 1 m^2 and 0 means absent).

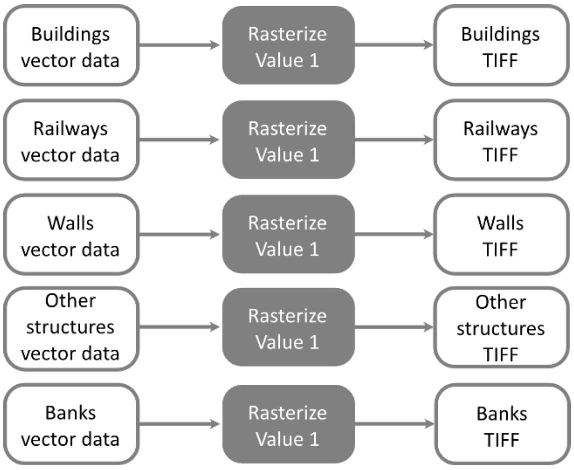


Figure 59: Data preparation Land use requirement

The land use of roads is defined by the requirement of 'Width of paths and roads'. The vector data of roads exists of lines which are defined by a class and number of directions. So, it is needed to define the cycleways, footways and roads and whether they have a one-way or two-way direction. When the one-way cycleways, two-way cycleways, footways, one-way roads and two-way roads are defined, then buffers are created with the corresponding width as defined by the literature in Table 4 (page 52). The buffers define the width of paths and roads (see Figure 60).

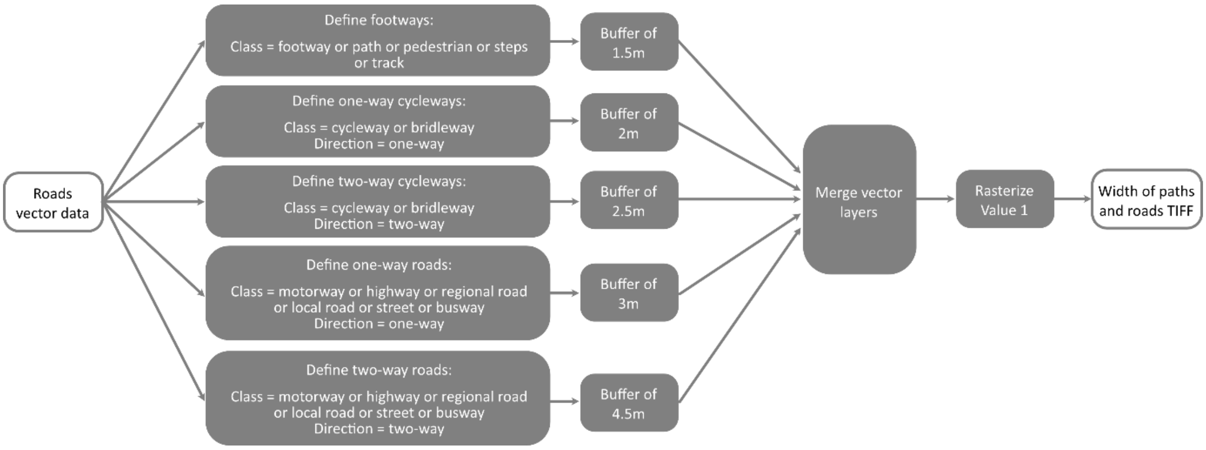


Figure 60: Data preparation Width of paths and roads requirement

The land availability is defined by the land use layers that are not available for UGI due to buildings, railways, water and other structures (Figure 61). Roads are not included in this because these are defined by the width of paths and roads. The other land uses are UGI or could maybe be replaced by UGI.

The amount of street traffic is defined in the same way as the width of paths and roads but other road lines are defined which correspond with the defined roads in Table 4 (page 52) of the literature review, see Figure 62. Two buffer layers are created for one-way roads and two-way roads with much traffic which define the amount of street traffic.

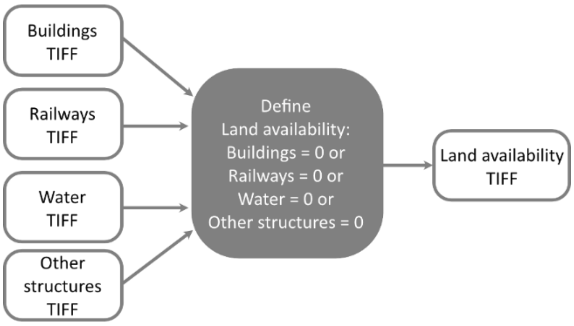


Figure 61: Data preparation Land availability requirement

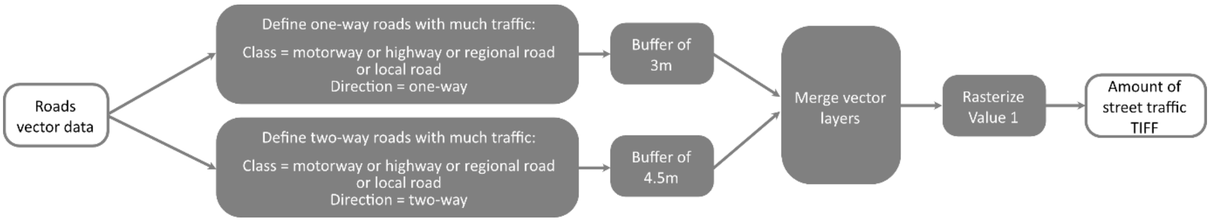


Figure 62: Data preparation Amount of street traffic requirement

The amount of street traffic is further prepared because the roads with much traffic are defined but trees with closed foliage may not be implemented close to these roads. So, a buffer around these roads needs to be created in which these trees are not possible. For the buffer, it is assumed that a tree of 1st size is minimal 4 meters in width and therefore, the buffer is assumed to be 4x2 = 8 meters to be sure that also a larger tree with closed foliage will not grow over a road with much traffic (see Figure 63).

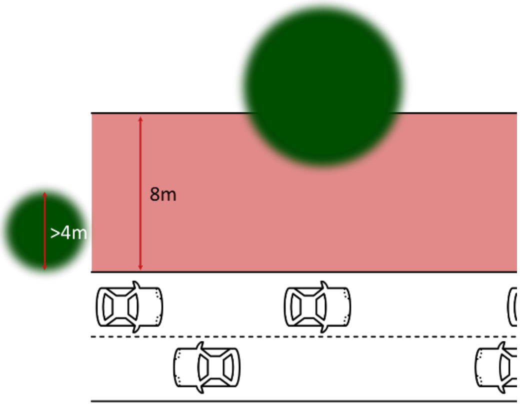


Figure 63: Explanation of 8m buffer

Figure 64: Specific data preparation Amount of street traffic requirement

For the linear elements which are part of the land use requirement (Table 4, page 52), the same buffer is used but the buffer is created around all paths and roads. Furthermore, the buffer is defined to say that tree avenues and single-line trees should be within the buffer instead of outside the buffer (see Figure 65).

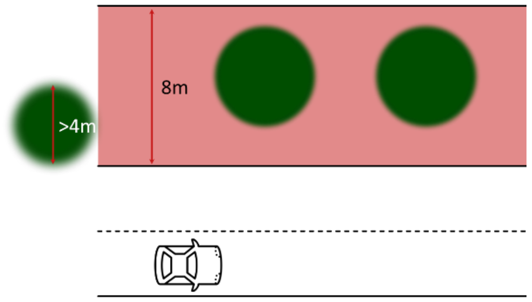


Figure 65: Explanation of 8m buffer

Figure 66: Specific data preparation Linear elements requirement

Building age is defined by rasterizing the buildings data, but this time not by rasterizing the vector layer as value 1 but by rasterizing based on the building age value in the attribute table. A raster is created in which the cells with buildings contain the value of the building age defined by construction year, for example 2006. So, all cells of the same building have the same building age value. The building age raster layer is further prepared to define the different values as defined by the literature in Table 4 (page 52). Three layers are created with buildings having a more recent construction year than 1972, 1991 or 2012 for the building age requirements (Figure 67). The cells that comply with the requirement have a value of 1, and the rest a value of 0.

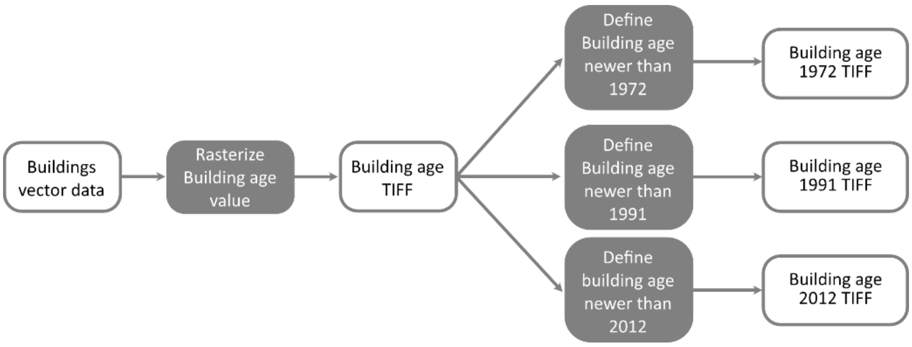


Figure 67: Data preparation Building age requirement

The presence of overhead obstacles is based on the height layer of the HTC calculation. The height layer is used to define the different values as concluded by the literature in Table 4 (page 52). Four layers are created which define the locations where the obstacle-free height is 15, 8, 5 or 3 meters (Figure 68). The cells that comply with the requirement have a value of 1, and the rest a value of 0.

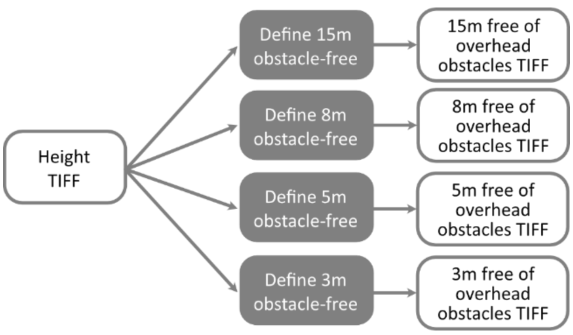


Figure 68: Specific data preparation Presence of overhead obstacles requirement

The proximity to structures requirement is prepared by first defining the structures. More preparation is required to define the values in Table 4 (Page 52, Figure 69). The prepared data layer defines the structures and four different buffer sizes are created around the structures to define whether a location is too close to a structure or not. The cells that contain buffer get a value of 1, and the rest a value of 0.

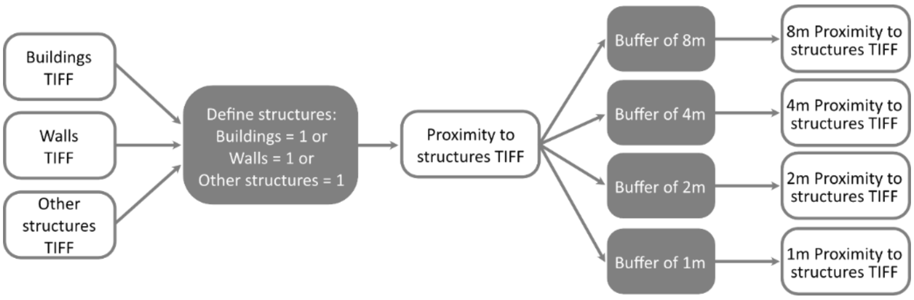


Figure 69: Data preparation Proximity to structures requirement

The slope requirement is defined by the DTM raster layer which defines the height of the terrain towards NAP. The same is done for the 'slope of roof' requirement. Although, this slope is defined with the DSM raster layer and only for the locations with buildings which will define the building height of the buildings towards NAP. The raster layers contain then values per cell between 0 and 90 degrees. Also, the slope and slope of roof require more preparation to define the different values as defined by the literature in Table 4 (page 52). The slope and slope of roof are specifically defined with layers stating which locations have a less steep slope than 10 & 20 and 30, 10 & 5 degrees (Figure 70). The cells that comply with the requirement have a value of 1, and the rest a value of 0.

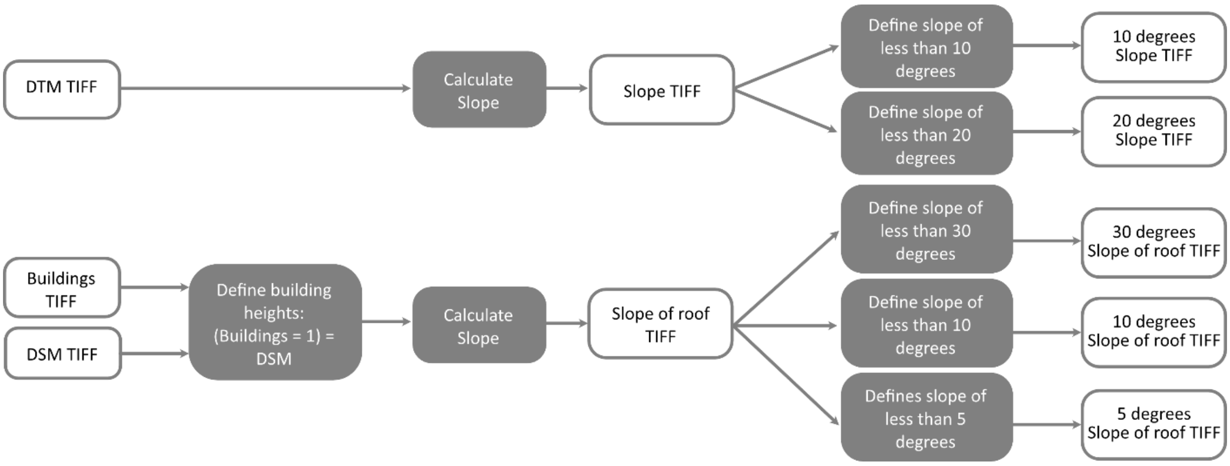


Figure 70: Data preparation Slope and Slope of roof requirement

For the tree protection zone, the zone is not defined by the sizes as stated in the literature review. But by the tree canopies of the different trees with no distinction between 1st, 2nd or 3rd sizes. As defined in Figure 71, the tree protection zone is the surface of the tree canopy with a small buffer. So, the tree protection zone is defined by the trees with a buffer of 1m (see Figure 72). No depth is considered in the analysis.

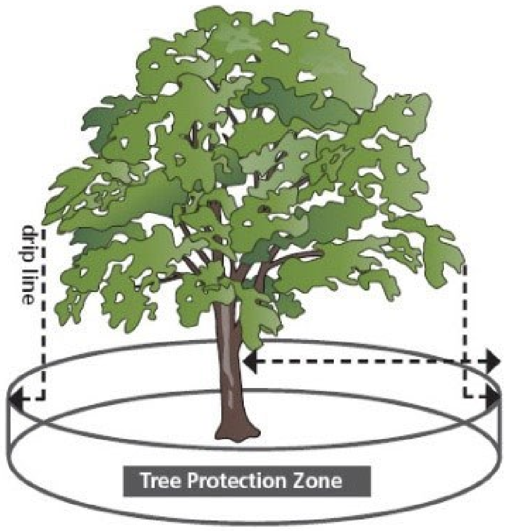


Figure 71: Definition of Tree Protection Zone (City of West Torrens, 2022)

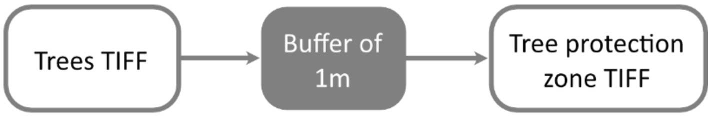


Figure 72: Data preparation Tree protection zone requirement

To determine for green walls the land availability requirement, it is needed to create a buffer around the defined structures because when the buffer is available then the land is available for a green wall. To be able to also analyse the building age for green walls, the same buffer needs to be created around the buildings with a building age newer than 1972 and newer than 2012 (Figure 73).

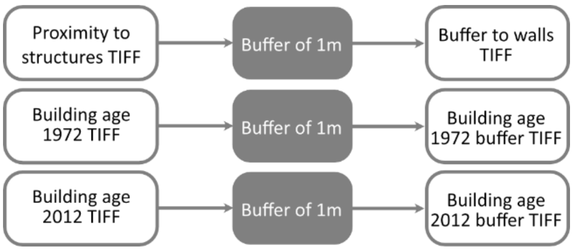


Figure 73: Data preparation Land availability requirement for green walls

In this way, all ten requirements are prepared which will be used to analyse the possibilities of the different UGI types.

3.2.1.2 Analysis per UGI type

To analyse possible locations for every UGI type, different steps need to be taken. The steps differ between two methods (Figures 74 and 75). For the UGI types which have a land availability requirement larger than 1 m^2, the site suitability analysis consists of a possibility and land availability analysis. The rest of the UGI types only have a possibility analysis because they do not have a land availability requirement or the land availability requirement is equal to or smaller than the cell size.

The possibility analysis is performed with an expression. The possibility analysis of a tree avenue and single-line trees with trees of 1st size and open foliage is taken as an example, see Figure 74. The expression defines that the UGI type cannot be located at locations with buildings, water, trees and roads. Furthermore, it should be located along a linear element, outside the tree protection zone and where land is available. The location should also be 15m obstacle-free in height, 8 meters away from structures and have a slope of less than 10 degrees. These requirements are in line with the literature review Table 4 (page 52) and the analysis determines where the UGI is possible and where not by giving the locations that comply with the requirements value 1 and the other locations value 0. This is done for all UGI types, when types have the same requirements then these are combined in the possibility analysis. All analyses for the different UGI types are defined in Appendix I. For the types with a land availability analysis, it is determined what the surface area is of the locations with value 1 after the possibility analysis (see the example of Figure 74). This is done to analyse where enough space is available to implement the UGI type.

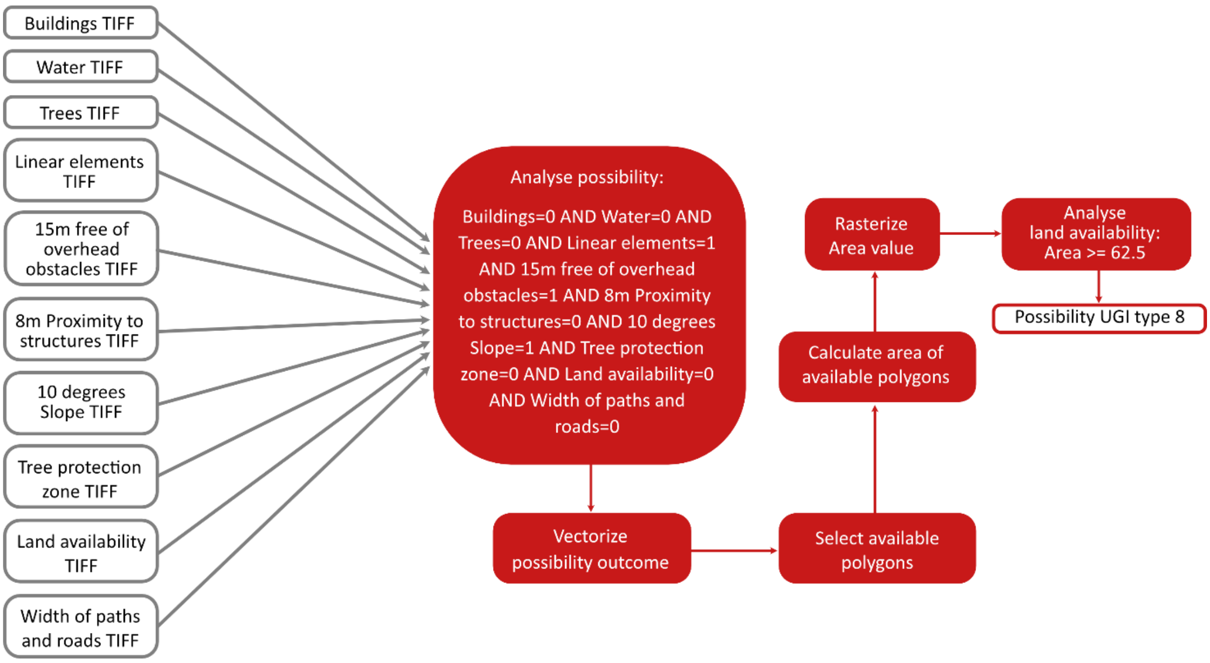


Figure 74: Example requirement analysis with possibility and land availability analysis

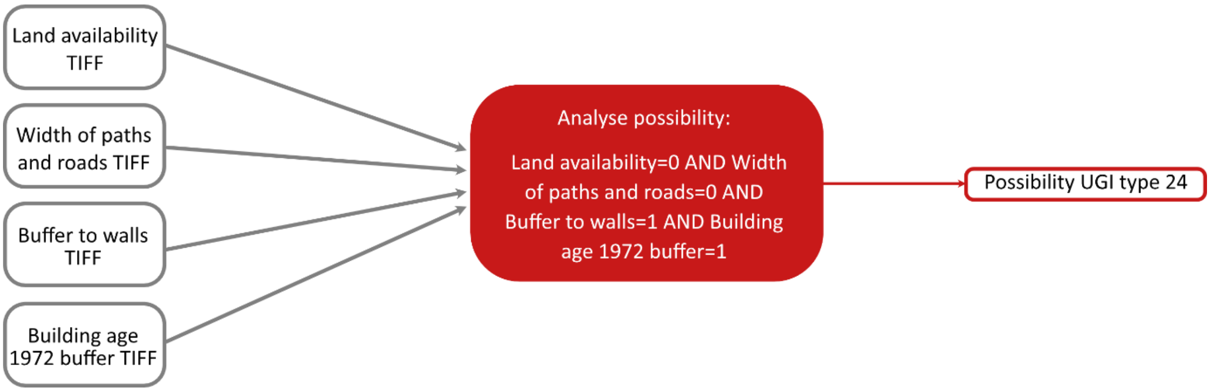


Figure 75: Example requirement analysis with only a possibility analysis

The possibility and land availability analyses make it possible to create a possibility layer per UGI type which defines where the UGI type can be implemented and where not, simply with the values 1 and 0.

3.2.1.3 Combining layers of UGI types

The final part of the analysis is about combining all possibility layers of the UGI types. To do this, a priority list is created based on the temperature effects concluded from the literature review (Table 2, page 48). For the priority list, some UGI types are combined because they have the same requirements and therefore, the same possibility locations. The priority list is defined as:

1. Tree avenue and single-line with trees of 1st size and closed foliage
2. Group with trees 1st size and closed foliage
3. Tree avenue and single-line with trees of 2nd size and closed foliage
4. Tree avenue and single-line with trees of 3rd size and closed foliage
5. Group with trees of 2nd size and closed foliage
6. Group with trees of 3rd size and closed foliage
7. Street tree of 1st size and closed foliage
8. Tree avenue and single-line with trees of 1st size and open foliage
9. Tree avenue and single-line with trees of 2nd size and open foliage
10. Small trees on roof
11. Street tree of 2nd size and closed foliage
12. Group with trees of 1st size and open foliage
13. Grass
14. Street tree of 3rd size with closed foliage
15. Tree avenue and single-line with trees of 3rd size and open foliage
16. Group with trees of 2nd size and open foliage'
17. Street tree of 1st size and open foliage
18. Group with trees of 3rd size with open foliage
19. Street tree of 2nd size with open foliage
20. Grass, moss, sedum, herbs and perennials & annuals plants on wall
21. Street tree of 3rd size with open foliage
22. Group of shrubs
23. Shrubs, perennials and annual plants on roof
24. Climbers
25. Perennials and annual plants
26. Grass, moss, sedum & herbs on roof
27. Bankside plants
28. Single shrub

Based on the priority list, the last expression from the site suitability analysis per UGI type is multiplied by the value of the list. So, for some UGI types, it will be the expression of the possibility analysis (see Figure 76) and for some, the expression of the land availability analysis (see Figure 77). Then, all possibility layers per UGI type will have a value of 0 where not possible and the value on the ranking list, for example 24, when it is possible. All expressions for every UGI type are presented in Appendix I.

By doing this, it is possible to combine the layers into one raster map. This is done by taking the lowest value in a cell when considering all possibility layers. So, if a cell has a possibility for a group of shrubs (value 22) as well as grass, then grass (value 13) is taken as the possibility in the final map because it has the highest ranking/lowest value. This is done for all cells and so a final map with the different UGI possibilities is created (see Figure 78).

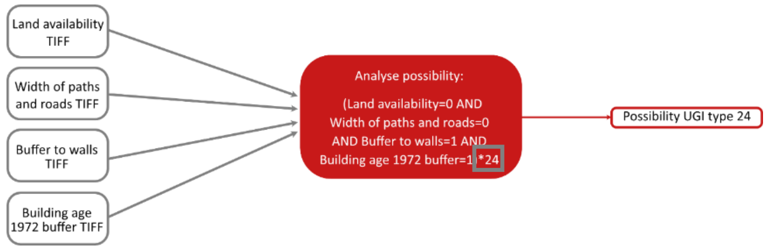


Figure 76: Example possibility analysis multiplied by the ranking value

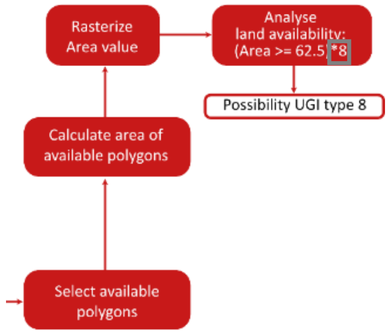


Figure 77: Example land availability analysis multiplied by the ranking value

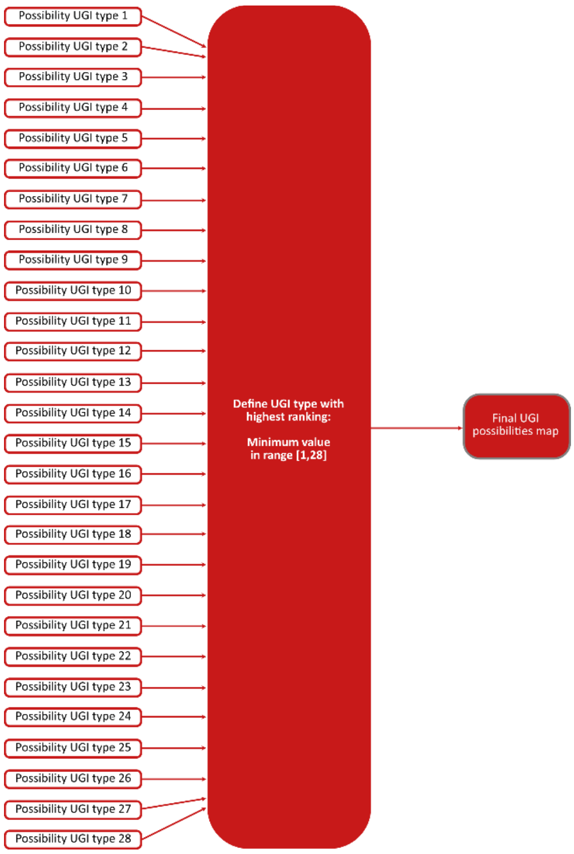


Figure 78: Minimum value analysis for creating Final UGI possibilities map

3.3 Methodology of linking HTC calculation with UGI analysis

The final component of the decision-support tool is the link between the outcome of the HTC calculation and the UGI analysis, see Figure 79. The final component consists of two parts. The first part is reducing the possibilities for UGI to the locations with the highest need for improving HTC. The second part is implementing possibilities back into the HTC calculation to see the effect.

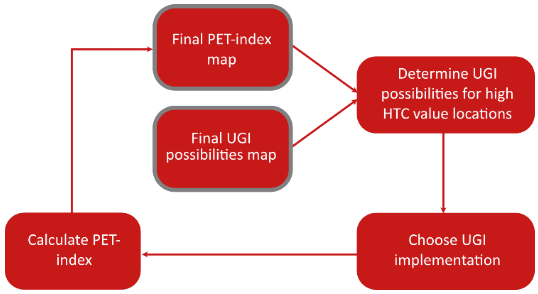


Figure 79: Scheme of the final component of the decision-support tool

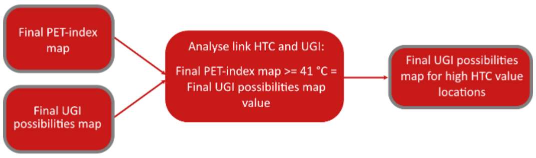


Figure 80: Analysis to define UGI possibilities for high HTC value locations

For the first part, the final PET index map from the HTC calculation is defined as an extra input layer for the UGI analysis. After the final UGI possibilities map is created, an extra analysis is added to the PyQGIS script of the UGI analysis (Appendix G). The extra analysis defines the locations with a high HTC value defined by the PET index. As defined by Figure 7 (page 36), heat stress is experienced by people when the HTC value is higher than 29°C. Nevertheless, the locations with a high need for UGI are defined by 41°C to give more priority to locations with by far the worst HTC. The cells of the locations with a high HTC value of more than 41°C are given the value of the final UGI possibilities map (the ranking of the priority list), see Figure 80.

The second part of the final component of the decision-support tool is based on the final UGI possibilities map linked to the HTC values. Based on the possibilities map, it is possible to choose which UGI types will be implemented at which location to improve HTC. When these are chosen, it is possible to implement the chosen UGI types back into the HTC calculation which can be done with an existing method as explained in Figure 81.

Based on the chosen UGI implementation, a shapefile needs to be created in, for example, QGIS. The shapefile needs to define where new greenery and trees are implemented and the height of the trees. The created shapefile is used as extra input for the Sky-View Factor (SVF) and PET index calculation. The rest of the input layers stay the same and the shapefile is used to update these input layers. For the SVF calculation, the height of the new trees in the shapefile is used to update the DSM input data. Based on the updated DSM data, the new SVF will be calculated. The new SVF and the shapefile will be used to calculate the new PET index. The shapefile is used to update the trees, greenery, green roofs, green walls, NDVI, DSM and height input data. Based on the updated data, the new PET index is calculated. By doing this, it is possible to link the UGI possibilities with the HTC calculation.

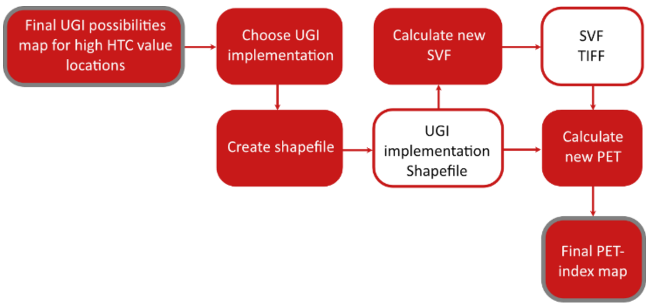


Figure 81: Implementation of UGI possibilities in PET index calculation

3.4 Conclusion

This chapter described the methodology for developing a decision-support tool that incorporates the relationship between HTC and UGI, which is summarized in Figure 82. The methodology is based on the findings of the literature review and should answer the three research questions:

1. How can the PET index be improved by including green roofs and green walls?
2. How to identify the possibilities for the implementation of Urban Green Infrastructure using a decision-support tool?
3. How can the relationship between Urban Green Infrastructure and Human Thermal Comfort be incorporated into a decision-support tool?

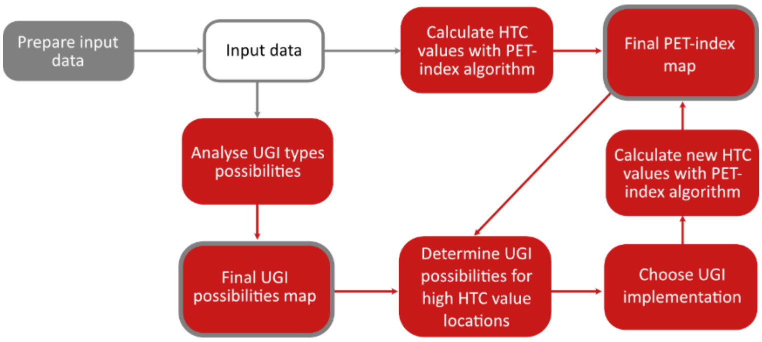


Figure 82: Summary of the decision-support tool

Based on the literature, it was concluded that the PET index is the most appropriate index to use for calculating HTC and that green roofs and green walls were missing as UGI types in the existing index. Based on the described methodology, it can be stated that green roofs and green walls can be included in the PET index calculation by adjusting the vegetation fraction and Bowen ratio calculation. To create a realistic effect of green roofs and green walls on the PET index, the effect is made dependent on the building height of the buildings at which the vegetation is situated. Additionally, the Bowen ratio of green walls is added to the determination of the Bowen ratio to create a local effect. Green roofs and green walls are included in the HTC calculation with these adjustments.

Furthermore, it can be stated that the possibilities for UGI can be identified by developing a new decision-support tool which performs a raster analysis by including requirements as defined by the literature review Table 4 (page 52). The raster analysis can be done by using GIS software which makes it possible to perform analyses on location-specific conditions as taken from the review of existing decision-support tools. The included requirements are expanded in comparison with existing decision-support tools because this study adds the requirements 'slope of roof', 'amount of street traffic' and 'presence of overhead obstacles'. Furthermore, the developed decision-support tool in this study adds the more detailed distinction between the UGI types as concluded from the literature and incorporates the self-defined priority list based on the temperature effects concluded from the literature. By including the defined requirements and priority list, and by making a detailed distinction between the different UGI types, it is possible to identify the possibilities for the implementation of UGI types by using the self-defined expressions and minimum value analysis. However, it must be stated that several assumptions are made which require further research to better specify them.

Lastly, it can be stated that the relationship between UGI and HTC can be incorporated into the newly developed decision-support tool by linking the HTC values calculated with the PET index with the possibilities of the different UGI types by performing a self-defined analysis. The locations with high HTC values will define a high need for UGI and by linking these locations with the UGI possibilities, it is possible to create a map which represents the need and possibilities for UGI. Furthermore, the relationship can be incorporated by defining the UGI implementations and calculating a new PET index with an existing method to define the effect on the HTC values.

The results of the application of the methodology to a case study will be discussed in Chapter 4.

4. Results

This chapter will present the results of applying the methodology described in Chapter 3. The results will be presented by applying the newly developed decision-support tool to a case study which will be described in the first section. Section 4.2 will describe the results of the adjusted HTC calculation by including green roofs and green walls in the PET index algorithm. The results of the developed UGI analysis will be described in section 4.3 and the results of the link between HTC and UGI will be explained in section 4.4. The final section will give a short conclusion about the generated results.

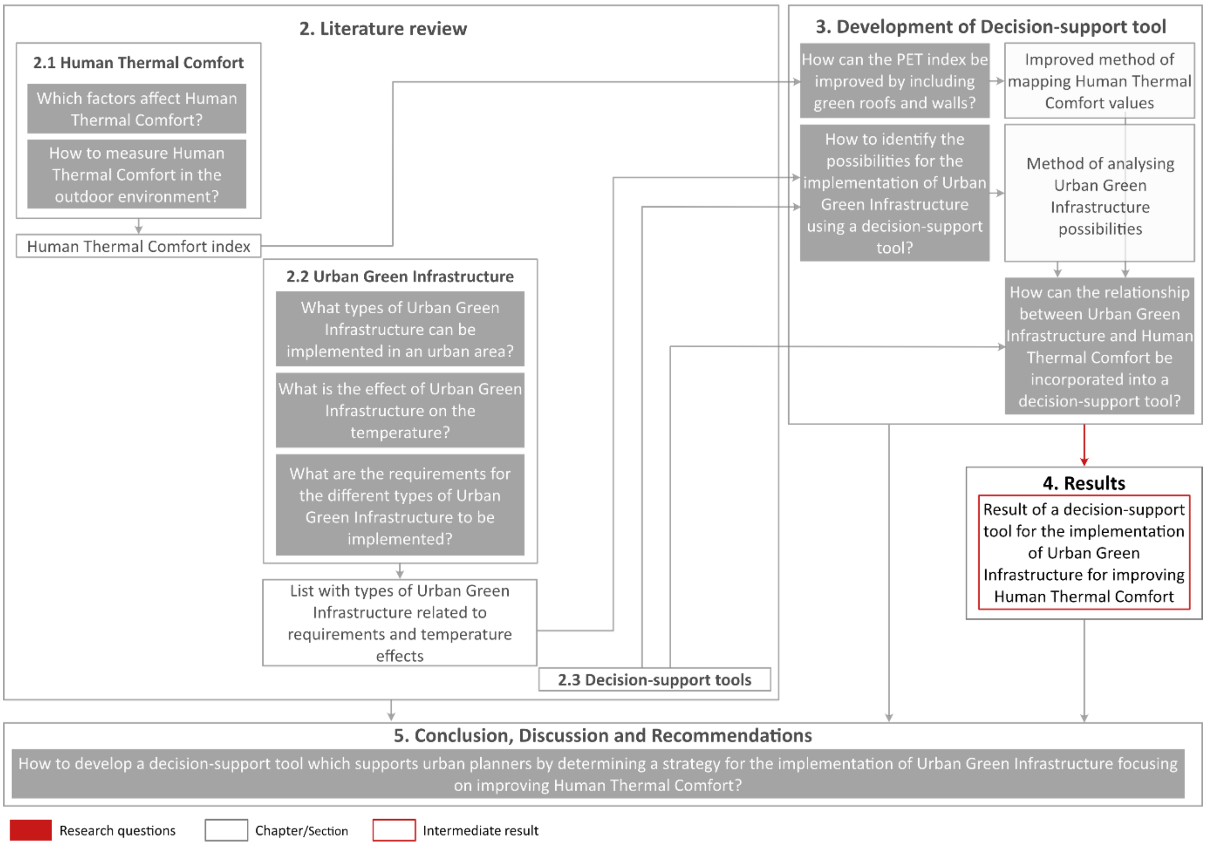


Figure 83: Results within research design

4.1 Case study

The methodology as described in Chapter 3 will be applied to a case study to present the generated results by the developed decision-support tool. The development is applied to the city of Rotterdam because it is together with other cities in the Netherlands, such as The Hague and Amsterdam, scoring poorly on the Urban Heat Island (UHI) effect which causes much heat stress (De Havenloods, 2022; Rijksoverheid, 2019). Among other things, due to a small amount of vegetation and a large amount of paved surfaces such as roads and buildings. Rotterdam is one of the largest cities in the Netherlands and it is one of the lowest-scoring cities in Europe in the amount of vegetation (NL Times, 2019). Showing the possibilities for such a city can make a difference in making clear the need for better HTC and the number of options for implementing UGI. It can make a difference by presenting the effect of what UGI can do for lowering HTC values and so, how UGI can help with reducing heat stress perceived by the population in urban areas. Figure 84 shows the scope of the case study on which the decision-support tool is tested.

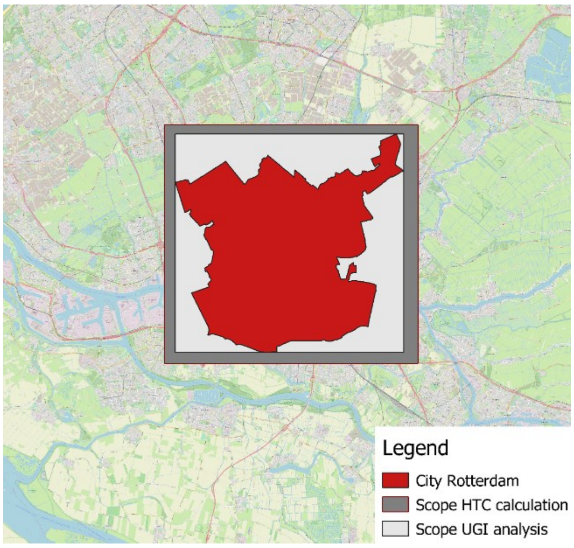


Figure 84: The scope of the case study

Figure 85: The weather stations in the Netherlands (Zijlen, n.d.)

For performing raster analyses, the scope is translated to a square. For the HTC calculation, the scope needed to be rounded to thousands of meter units which is not necessary for the UGI analysis. The scope of the HTC calculation is therefore (85000, 102000, 430000, 446000) ((X_{min}, X_{max}, Y_{min}, Y_{max})) in the Coordinate Reference System (CRS) EPSG:28992 and for the UGI analysis, the scope is (85730, 430740, 101040, 445400).

The data sources used for the input data of Rotterdam for the HTC calculation as well as for the UGI analysis are summarized in Table 8. All six data sources are open data sources and free to download. For some of the data, it is needed to download the data for the whole of the Netherlands and sometimes, it is possible to select a smaller area.

The weather data required for the HTC calculation can come from all weather stations in the Netherlands as shown in Figure 85. Depending on the case of the calculation, it can be needed to download data from multiple weather stations and interpolate this. For the case study of this study, it is possible to make the calculation with only the weather data of weather station 344 – Rotterdam.

The HTC calculation is done for 1 July 2015 from 10:00 to 16:00 because it was a hot summer day with weather conditions of 1 in 1000 for the summer period from April to September (Koopmans et al., 2020). However, it is already occurring more often with the changing climate and it is therefore relevant to show the need for cooler spots by presenting this day.

For this time period, the weather data is needed from 1 July 2015 at 1:00 to 2 July 2015 at 7:00. A larger time period is needed to calculate a correct UHI effect. The input weather data table is attached in Appendix J.

Table 8: Data sources used for the city of Rotterdam

	Data sources	Data format
Weather data	KNMI data from: https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens Weather station 344 - Rotterdam	Text (.txt)
Height map	PDOK data from: https://app.pdok.nl/rws/ahn3/download-page/ • 0.5m Digital Terrain Model (DTM) • 0.5m Digital Surface Model (DSM)	Raster (.tif)
Buildings Water Railways Roads	OpenStreetMap data from: http://download.geofabrik.de/europe/netherlands/zuid-holland-latest-free.shp.zip • gis_osm_buildings_a_free_1.shp • gis_osm_water_a_free_1.shp • gis_osm_railways_free_1.shp • gis_osm_roads_free_1.shp	Vector (.shp)
Greenery Banks Walls Other structures	PDOK data from: https://app.pdok.nl/lv/bgt/download-viewer/ • bgt_begroeidterreindeel.gml • bgt_ondersteunendwaterdeel.gml • bgt_scheiding.gml • bgt_overigbouwwerk.gml	Vector (.gml)
Aerial photos	PDOK data from: PDOK plugin QGIS • Luchtfoto Actueel Ortho 25cm RGB • Luchtfoto Actueel Ortho 25cm Infrarood	Raster (.tif)
BAG	PDOK data from: https://service.pdok.nl/lv/bag/atom/bag.xml • bag-light.gpkg	Vector (.gpkg)

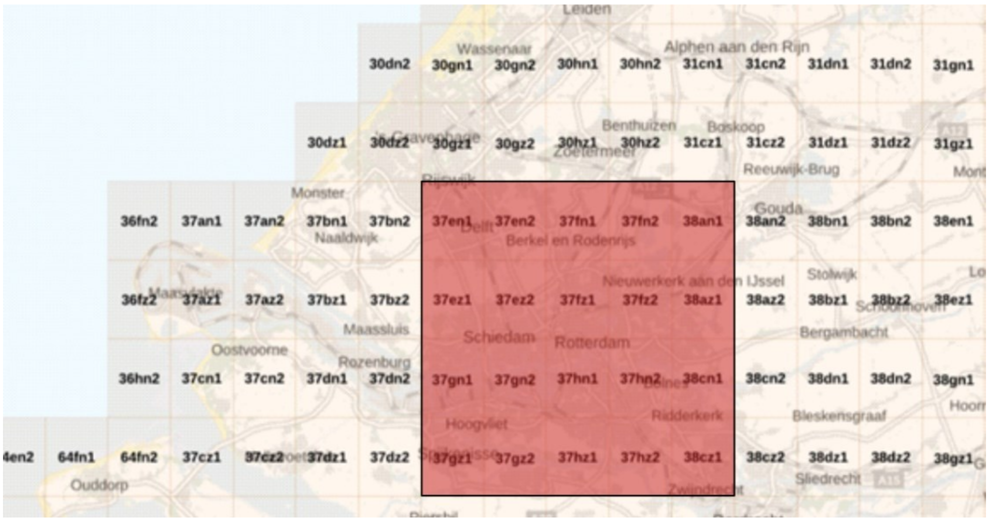


Figure 86: The height data tiles

The height data of the Netherlands is divided into tiles of 5 by 6.25 kilometres (see Figure 86). For the case study, the tiles in red are downloaded.

The results are presented for one tile of 1000 by 1000 meters, to be able to show more details. The chosen tile is the tile with coordinates (93000, 94000, 435000, 436000) in EPSG:28992. The scope is presented in Figure 87 by showing the basic map of the existing situation.

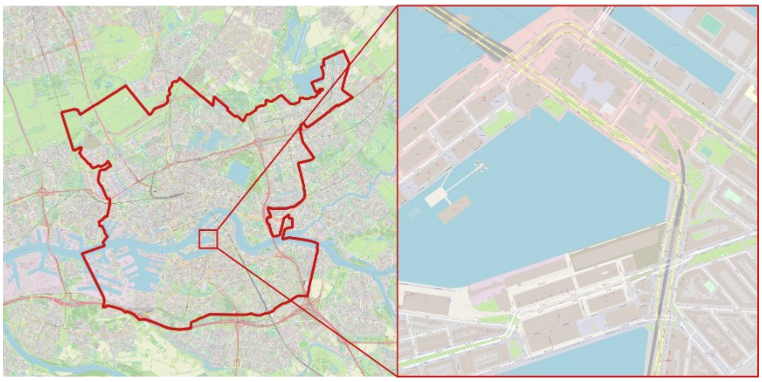


Figure 87: The scope of the tile

By applying the method as described in section 3.1.1, the input data layers for the HTC calculation are created and presented in Figures 88 to 97. For green walls, a random selection of 1% of the buildings is chosen to create the data. Most of the layers have binary values, where 1 means that the object is present and 0 means absent. For the DSM and Height layer, the range indicates the height in meters compared to NAP (Figure 92) or ground level (Figure 93). The SVF layer (Figure 94) indicates the fraction of the sky that is visible at a certain point where 0 means no sky visible and 1 means no hindrance from objects to see the sky. The NDVI layer (Figure 95) presents where vegetation is located with values higher than 0.16.

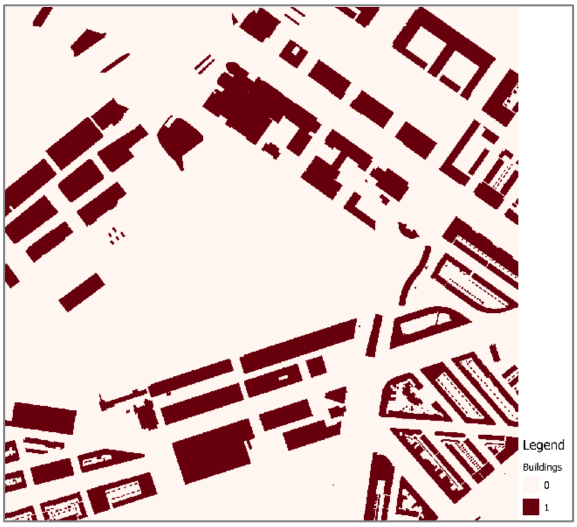


Figure 88: Buildings input layer

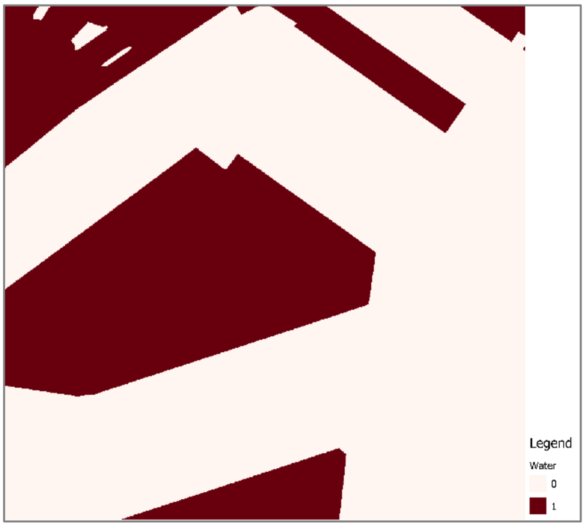


Figure 89: Water input layer

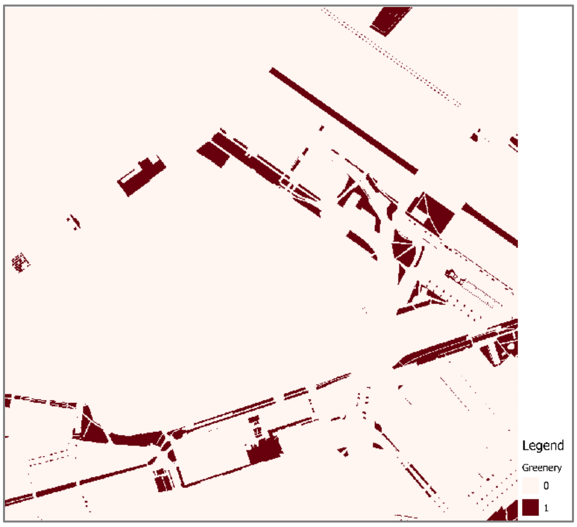


Figure 90: Greenery input layer

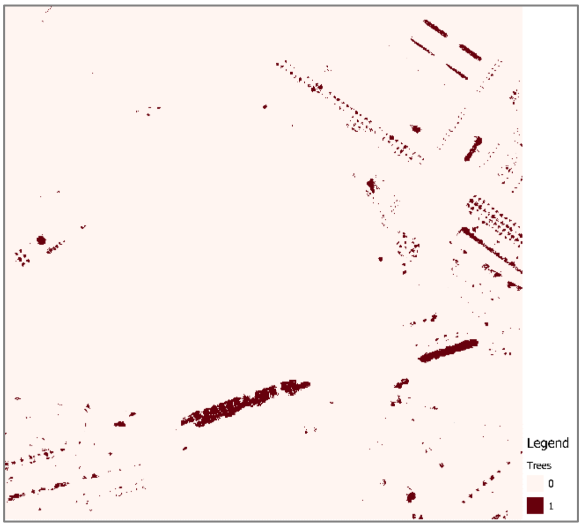


Figure 91: Trees input layer

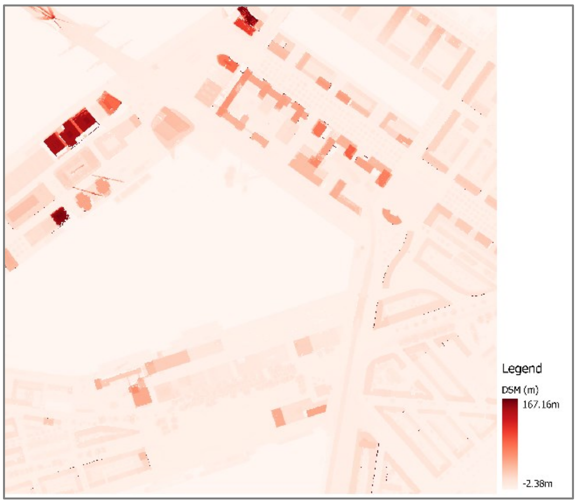


Figure 92: DSM input layer

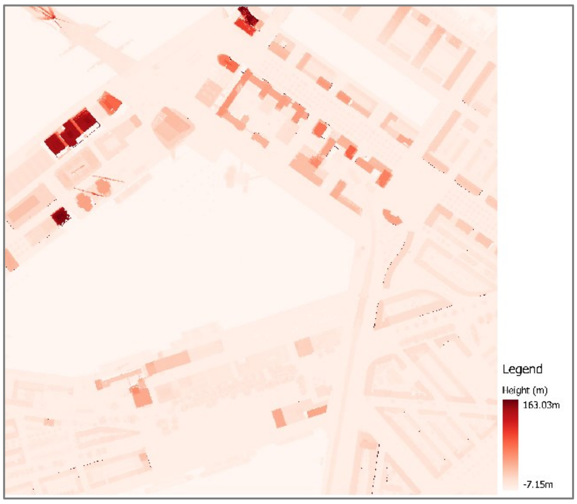


Figure 93: Height input layer

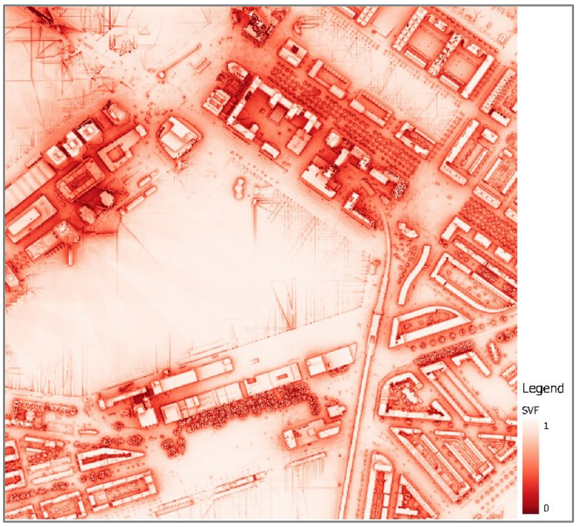


Figure 94: SVF input layer

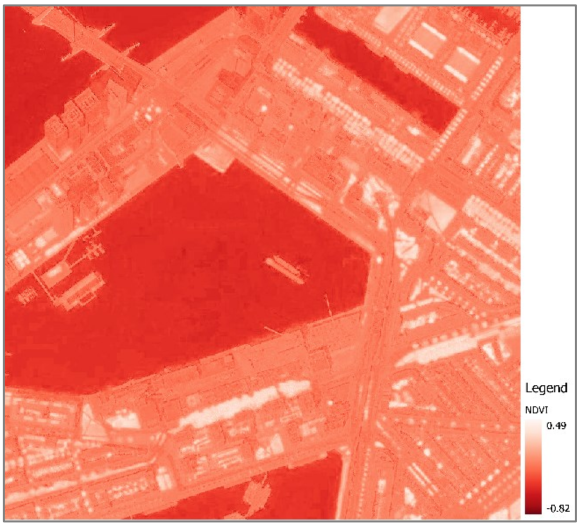


Figure 95: NDVI input layer

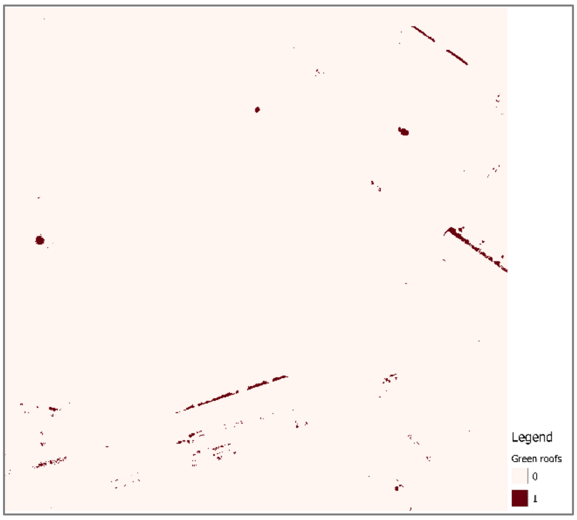


Figure 96: Green roofs input layer

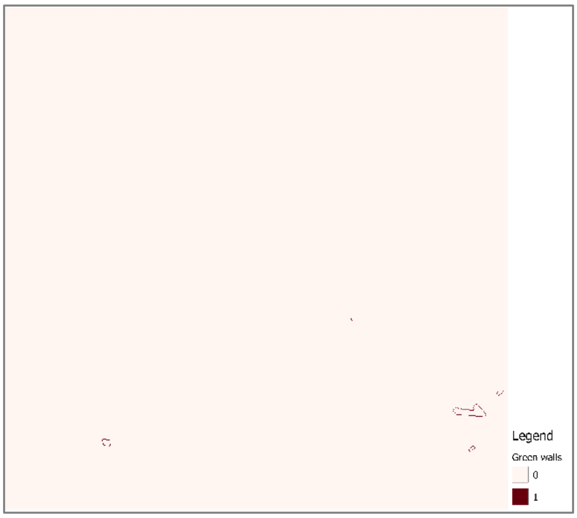


Figure 97: Green walls input layer

The input data of the UGI analysis is prepared as described in section 3.2.2.1 and for all requirements, the data is prepared in raster layers with binary values. Two examples are: Width of paths and roads and Building age newer than 1972. The Width of paths and roads requirement is directly from the shapefile created in the raster layer with binary values, see Figure 98.

Figure 98: Width of paths and roads input layer

The Building age newer than 1972 requirement is created by first creating the building age raster layer with a range from 0 to 2023. Where 0 means no buildings and the values between 1850 and 2023 are related to the construction years of the buildings. The layer is further analysed for buildings newer than 1972 which creates a raster layer with binary values for buildings with a construction year newer than 1972, see Figures 99 en 100.

With the input layers for the HTC calculation and UGI analysis, the rest of the results are generated.

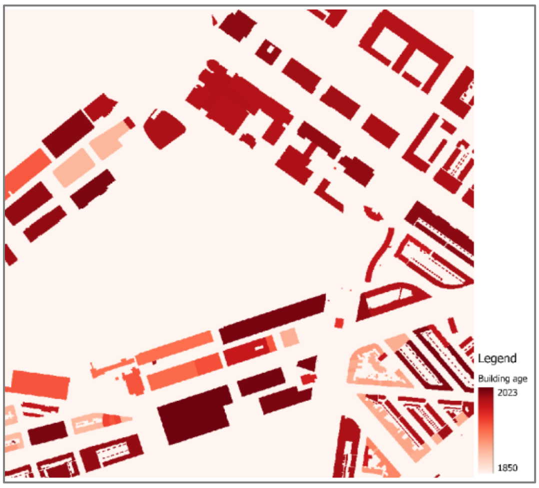


Figure 99: Building age

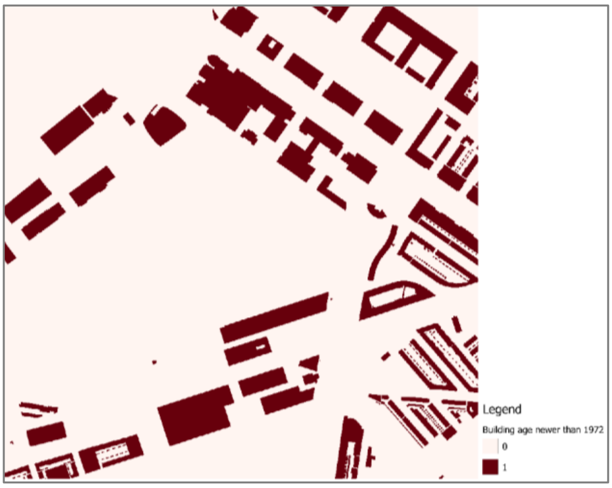


Figure 100: Building age ≥ 1972

4.2 Results Human Thermal Comfort (HTC) calculation

The created input data layers (Figures 88 to 97) are used to apply the method described in section 3.1. First, the results of the existing PET index calculation will shortly be presented. Then, the results of the adjusted PET index calculation will be described and compared with the existing PET index calculation results.

4.2.1 Existing PET index calculation

The existing PET index calculation is the method without applying the green roofs and green walls calculation method as explained in section 3.1.2.1. The eight data layers of Figures 88 to 95 are used as input. When the PET index is calculated, the outcome is as presented in Figure 101. The map shows the values of the PET index by showing for every cell with cell size 1m, the calculated PET index value which ranges from 30 to 48°C. As heat stress is experienced from 29°C, it can be stated that much heat stress was experienced on the hot summer day of 1 July 2015.

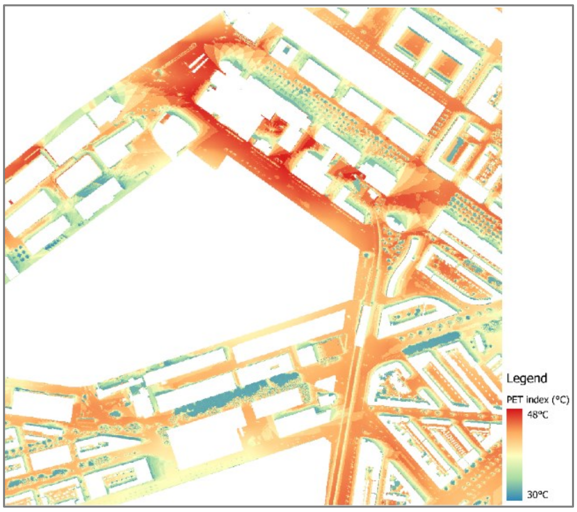


Figure 101: Outcome of existing PET index calculation

4.2.2 Adjusted PET index calculation

After the calculation of the starting point for this research with the existing method, step by step the adjusted PET index calculation is applied. To test the method of section 3.1.2.2, different scenarios for green roofs and green walls are defined. For green roofs as well as green walls, three scenarios are defined as input (see Figures 102 to 107).

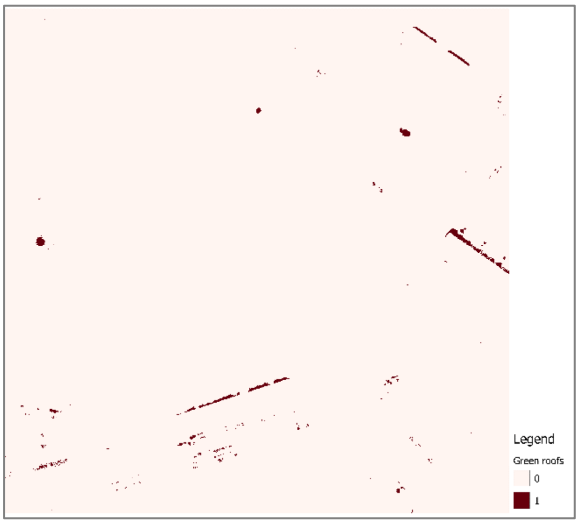


Figure 102: Green roof calculated from NDVI

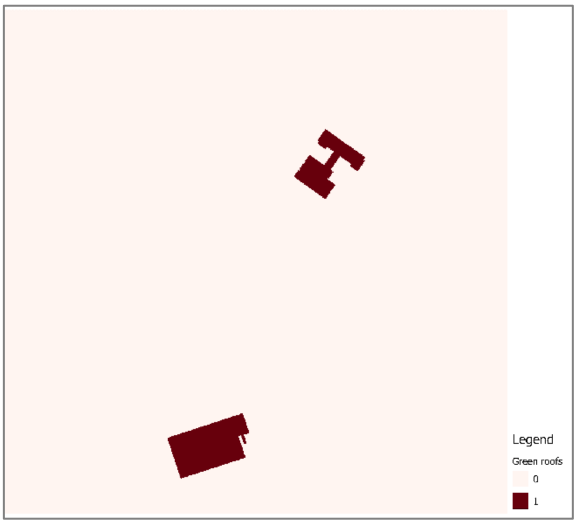


Figure 103: Two buildings with a green roof

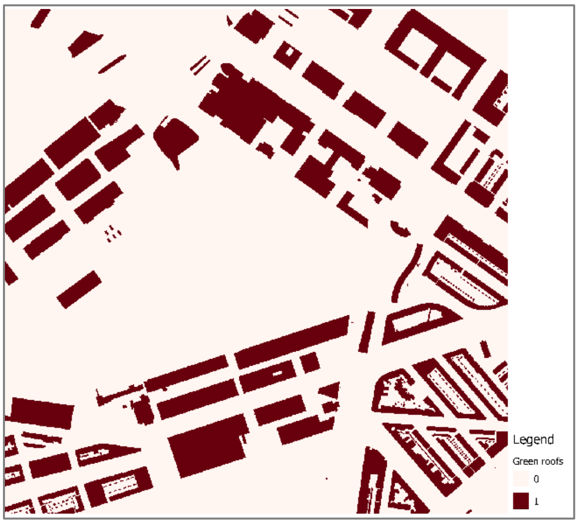


Figure 104: All buildings with a green roof

Figure 105: Two buildings with green walls

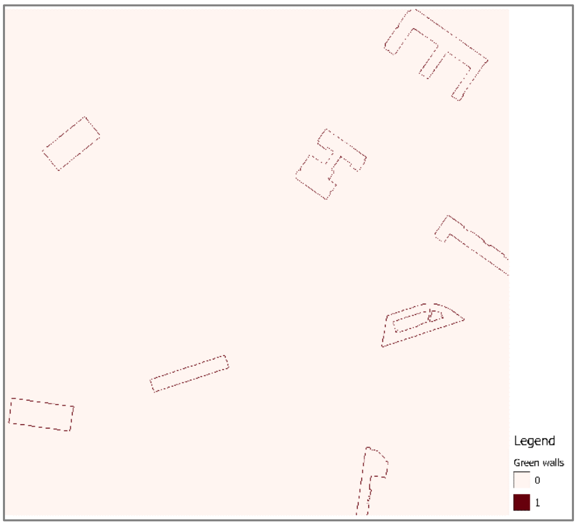


Figure 106: Multiple buildings with green walls

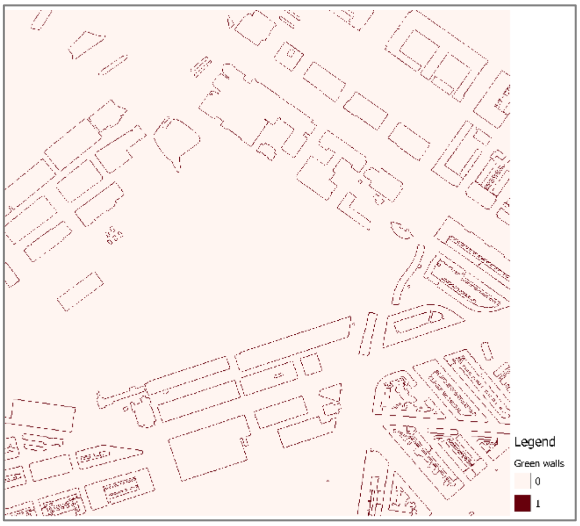


Figure 107: All buildings with green walls

The first step was to test the adjusted vegetation raster calculation. To show what the maximum effect is, the scenario including all green roofs and green walls is tested (Figures 104 and 107). The outcomes of the new and existing PET are presented in Figures 108 and 109 (same as Figure 101). When comparing the outcome with the existing PET calculation outcome, a really small difference is present, but this is not visible. Table 9 shows the small difference between the two calculations even when all buildings have a green roof and green walls.

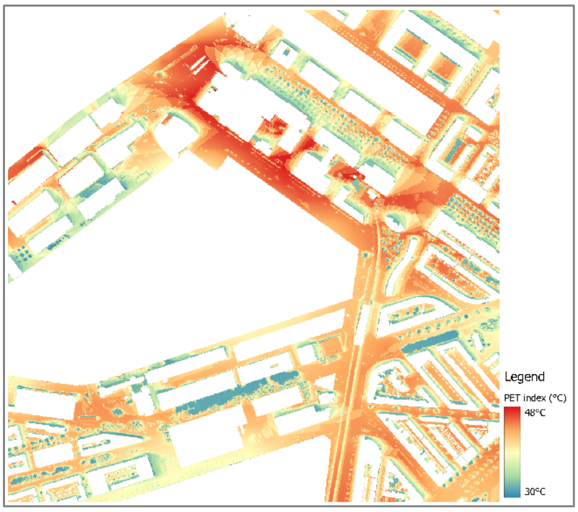


Figure 108: New PET with all green roofs and green walls

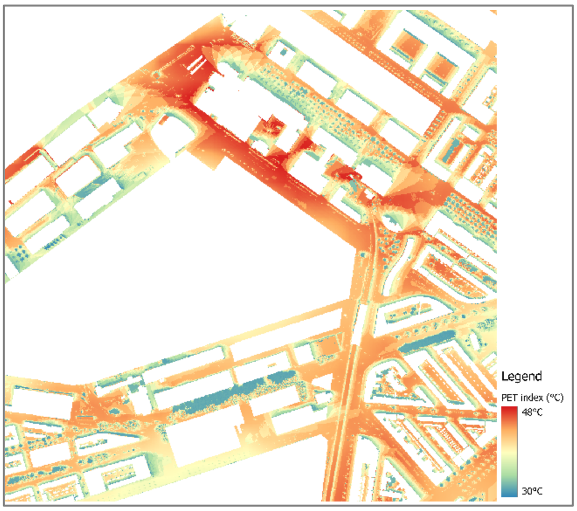


Figure 109: Existing PET with no green roofs and green walls

Table 9: Comparison of new and existing PET index

	Minimum	*Mean*	*Maximum*
Existing PET	30.61°C	40.68°C	47.94°C
PET with all green roofs and green walls	30.60°C	40.64°C	47.92°C

To be able to verify the outcome of the new PET in more detail, the effect of the adjusted calculation is tested by calculating the difference between two scenarios. By doing this, it is possible to interpret whether a difference is present and whether the difference is located at the right location. To compare scenarios, a scenario is calculated with the adjusted calculation in which no green roofs and green walls are present (Scenario 0). The vegetation raster and PET index of scenario 0 are presented in Figures 110 and 111.

Scenario 0 is compared with 3 scenarios:

- Scenario 1: Two buildings with a green roof (Figure 103)
- Scenario 2: Two buildings with green walls (Figure 105)
- Scenario 3: Two buildings with a green roof and multiple buildings with green walls (Figures 103 and 106)

The calculated vegetation raster and PET index for scenario 1 are presented in Figures 112 and 114. Table 10 presents the numbers related to the PET index in comparison with scenario 0 (Figure 111).

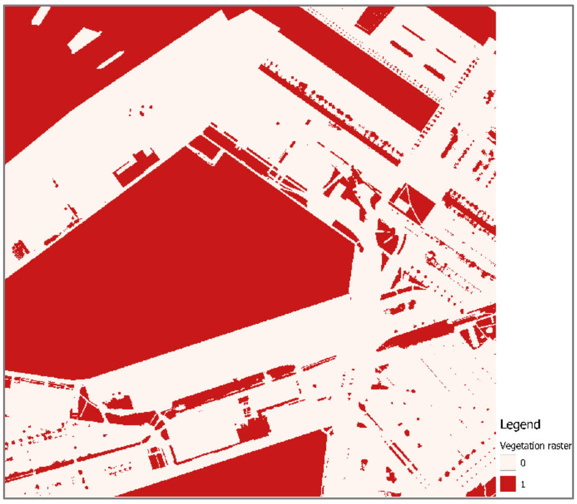


Figure 110: Vegetation raster scenario 0

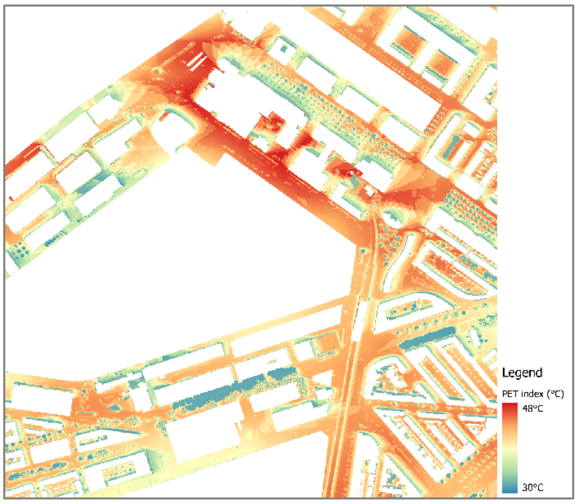


Figure 111: PET index scenario 0

Table 10: Comparison PET scenarios 0 and 1

	Minimum	*Mean*	*Maximum*
PET scenario 0	30.685°C	40.692°C	47.976°C
PET scenario 1	30.685°C	40.690°C	47.975°C

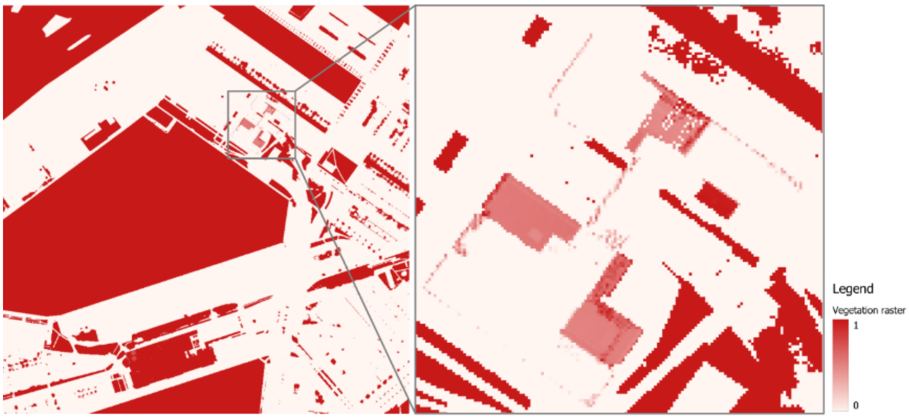


Figure 112: Vegetation raster scenario 1

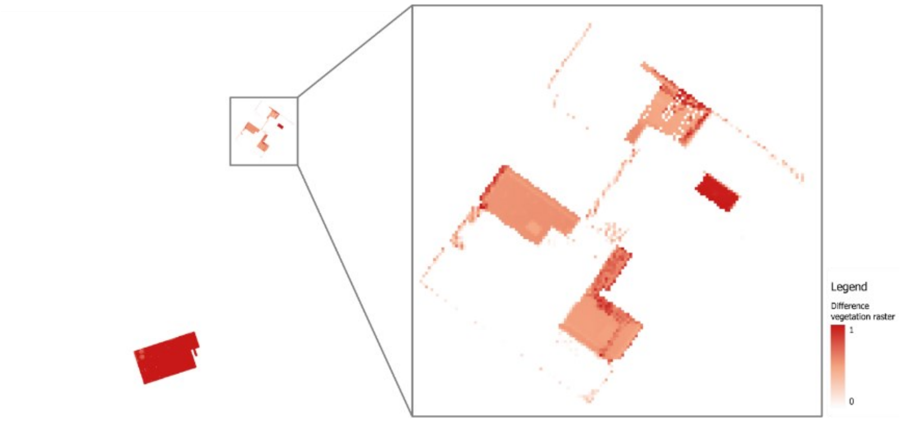


Figure 113: Difference vegetation rasters scenarios 0 and 1

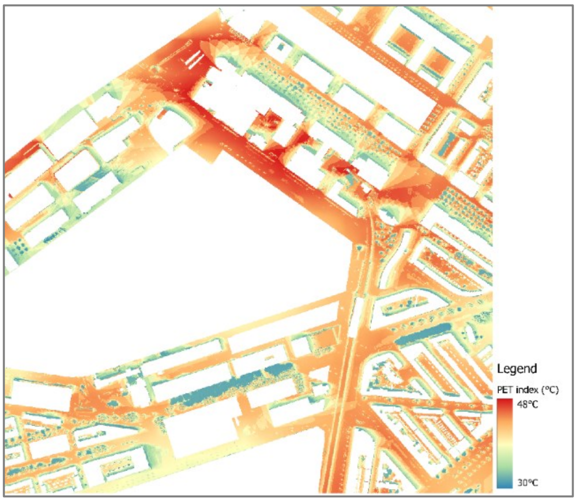


Figure 114: PET index scenario 1

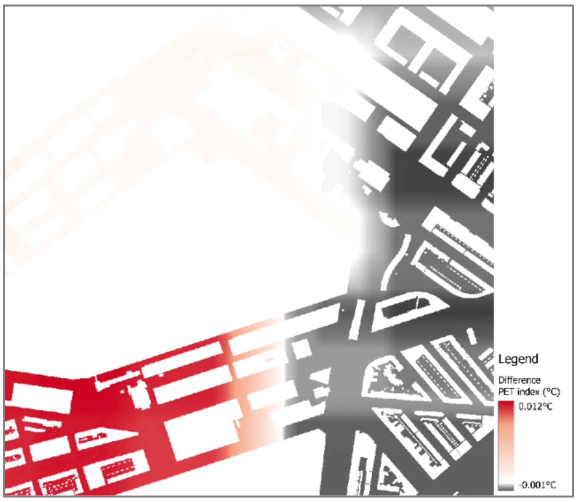
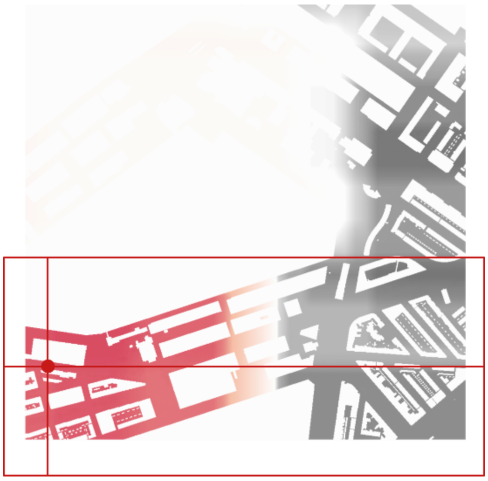


Figure 115: Difference PETs scenarios 0 and 1

The vegetation raster for green roofs is between 0 and 1 which is in line with the conditions defined in the methodology chapter. To verify the difference between scenarios 0 and 1 with the location of the difference, the differences of the vegetation rasters (Figures 110 and 112) and PETs (Figures 111 and 114) are calculated by subtracting the output of scenario 0 from the output of scenario 1. The output of these calculations is presented in Figures 113 and 115.

As shown by the difference between scenarios 0 and 1, the difference of the vegetation raster is in line with the locations of the buildings with a green roof as defined by Figure 103 (page 92). As can be seen in Figure 113, the largest difference is caused by the building at the bottom (which is not in the zoomed part) which is caused by the building's height. The building at the bottom is between 0 and 3 meters high and gets a value of 1 as defined by the vegetation raster (Figure 112). The building at the top (which is in the zoomed part) is partly between 3 and 30 meters and gets a smaller value than 1 and is partly above 30 meters and gets a value of 0 (Figure 112). This is in line with the conditions defined for the vegetation raster calculation. The difference in PET value, Figure 115, shows the largest difference at the bottom as well which is in line with where the most greenery is added. The maximum difference is a difference of 0.012°C which is a very small difference and therefore, not well visible in the presented PET maps (Figure 111 versus Figure 114). Nevertheless, it can be stated that a small reducing effect of adding green roofs is present at the right location. It is also correct that the difference is spread out to the west side of the building. This has to do with the fact that the vegetation fraction is calculated over the UHI box by averaging the vegetation raster over this area for the indicated point. The wind direction of the calculation is east and therefore, the vegetation fraction is calculated from east to west (as presented in Figures 116 and 117). Furthermore, it must be stated that in the surroundings of the presented tile no greenery is added, otherwise another effect would be expected when considering the UHI box. The difference outcome is, therefore, in line with what should be expected for green roofs.



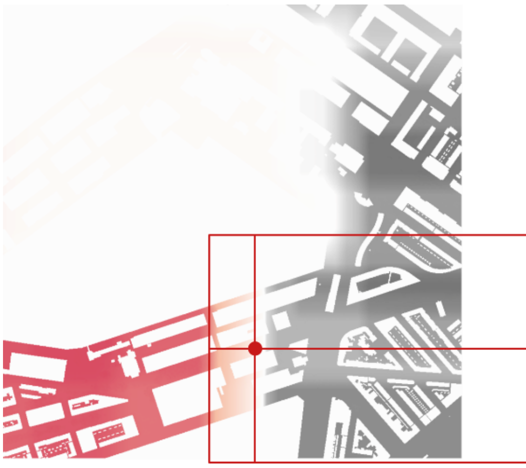


Figure 116: UHI box explanation for a location with a large difference

Figure 117: UHI box explanation for a location with a small difference

For scenario 2 with two buildings with green walls as defined by Figure 105 (page 92), the calculated vegetation raster and PET index are presented in Figures 118 and 120. Table 11 presents the numbers related to the PET index in comparison with scenario 0 (Figure 111, page 94).

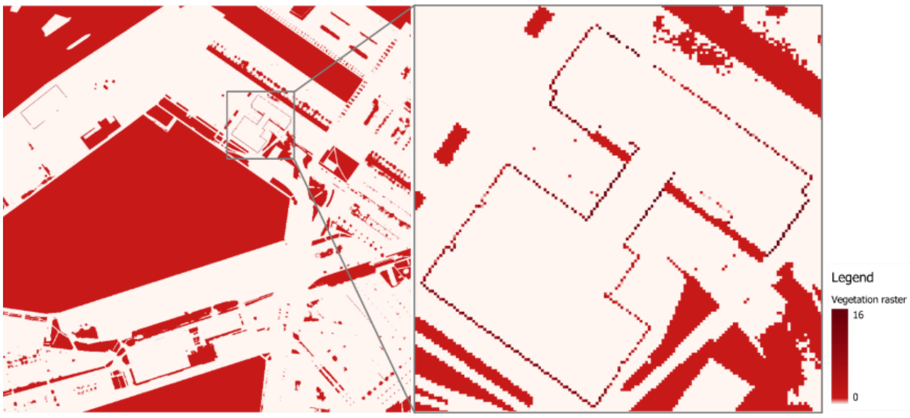


Figure 118: Vegetation raster scenario 2

The vegetation raster for green walls is between 0 and 16 which is in line with the conditions defined in the methodology chapter where it is stated that the vegetation raster value for green walls is the adding up of values in the vertical plane. For scenario 2, the differences of the vegetation rasters (Figures 110 and 118) and the PETs (Figures 111 and 120) between scenarios 0 and 2 are calculated as well. The results are presented in Figures 119 and 121.

Table 11: Comparison PET scenarios 0 and 2

	Minimum	*Mean*	*Maximum*
PET scenario 0	30.685°C	40.692°C	47.976°C
PET scenario 2	30.681°C	40.690°C	47.971°C

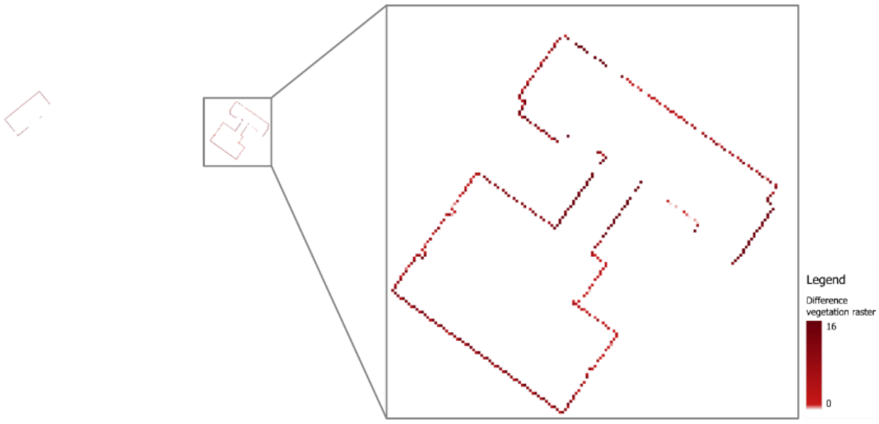


Figure 119: Difference vegetation rasters scenarios 0 and 2

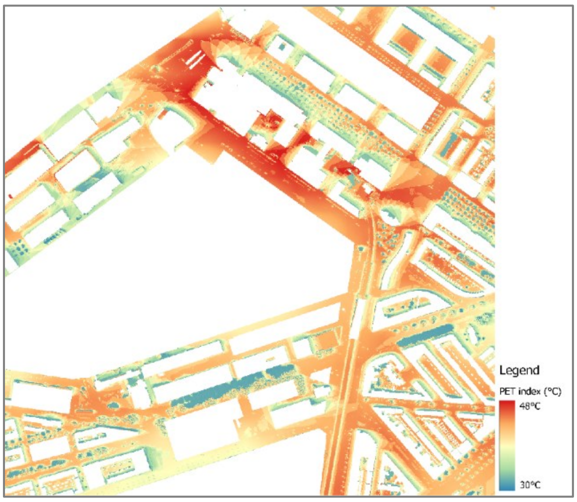


Figure 120: PET index scenario 2

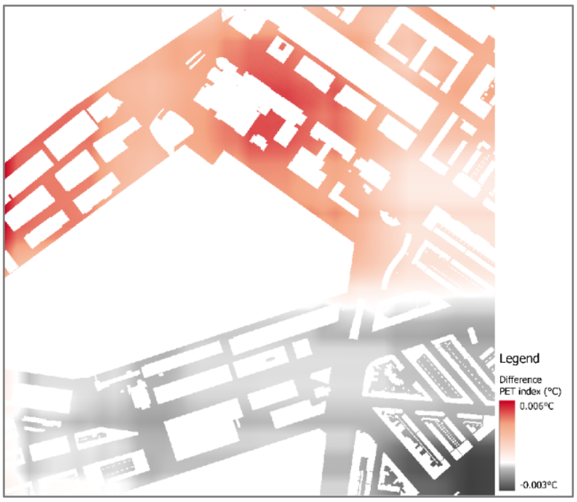


Figure 121: Difference PETs scenarios 0 and 2

For scenario 2, the difference is calculated for checking the effect of green walls. The difference in vegetation raster, Figure 119, shows a clear difference at the locations where green walls are added (Figure 105, page 92) and is therefore in line with what can be expected in similar situations. The difference in the PET index, Figure 121, is also in the surrounding of the two buildings that have green walls. The largest difference is 0.006°C and is located in the middle left which is in line with what is expected when considering the UHI box (as presented by Figures 122 and 123).

Table 12: Comparison of surface area and vegetation raster values of green roofs and green walls

	Sum of surface areas	*Sum of vegetation raster values*
Green roofs	19735	13554
Green walls	14888	5638

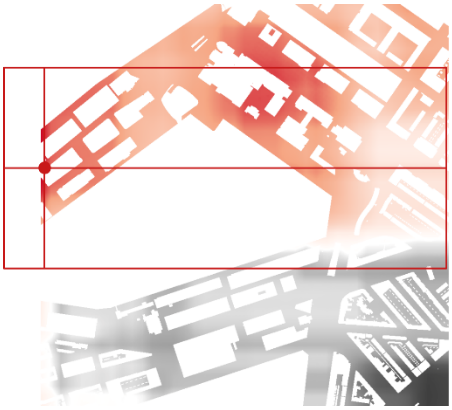


Figure 122: UHI box explanation for a location with a large difference

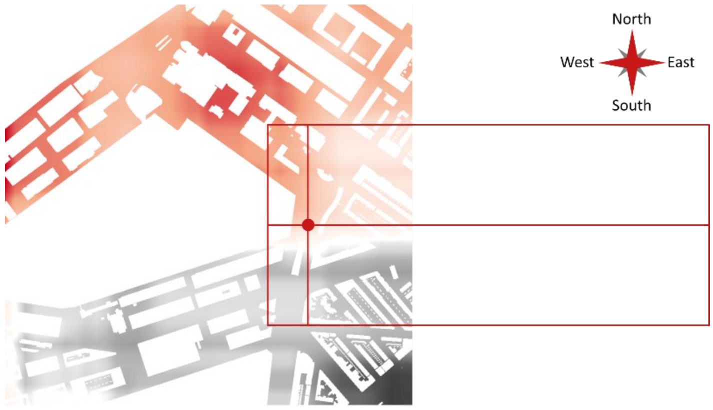


Figure 123: UHI box explanation for a location with a small difference

However, the maximum difference is small in relation to the difference of green roofs. While the difference in the green walls surface area and green roof surface area added is not that much, see Table 12. Nevertheless, the difference in the vegetation raster is large (all vegetation raster values summed up) and is relatively the same as the difference in effect.

For scenario 3 with two buildings with a green roof and multiple buildings with green walls as defined by Figures 103 and 106 (page 92), the calculated vegetation raster and PET index are presented in Figures 124 and 126. Table 13 presents the numbers related to the PET index in comparison with scenario 0 (Figure 111, page 94). The differences of the vegetation rasters (Figures 110 and 124) and PETs (Figures 111 and 126) between scenarios 0 and 3 are presented in Figures 125 and 127.

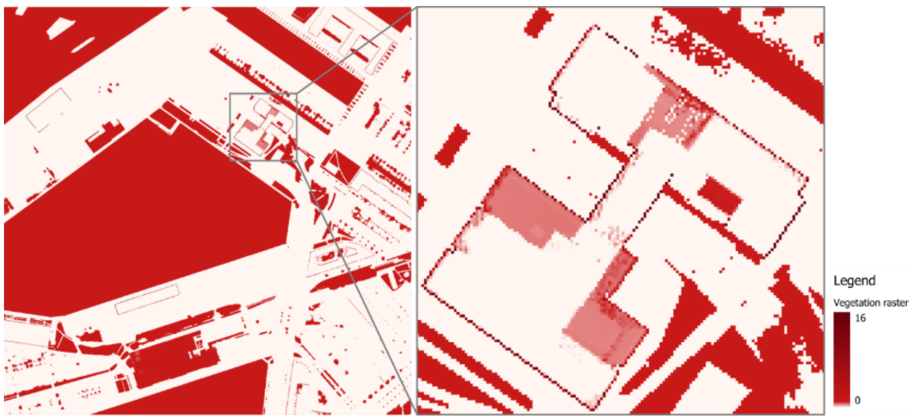


Figure 124: Vegetation raster scenario 3

Table 13: Comparison PET scenarios 0 and 3

	Minimum	Mean	Maximum
PET scenario 0	30.685°C	40.692°C	47.976°C
PET scenario 3	30.675°C	40.684°C	47.966°C

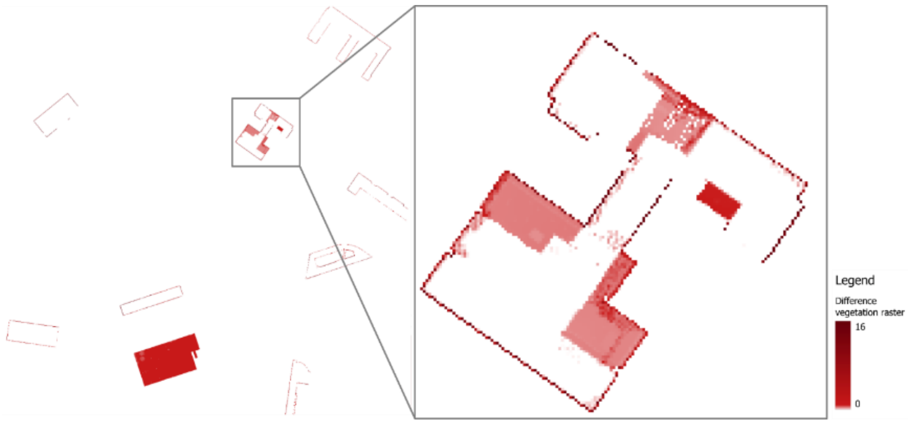


Figure 125: Difference vegetation raster scenarios 0 and 3

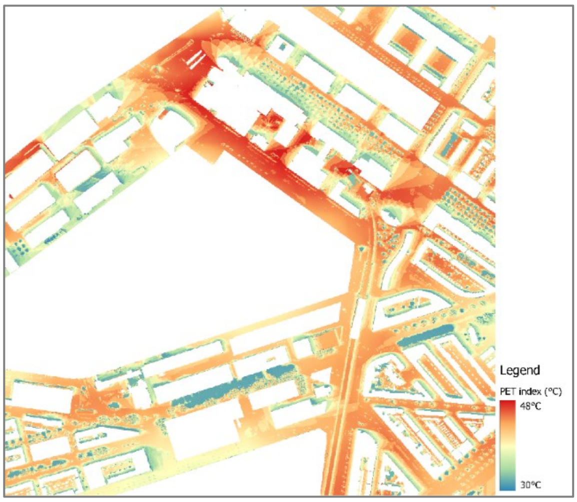


Figure 126: PET index scenario 3

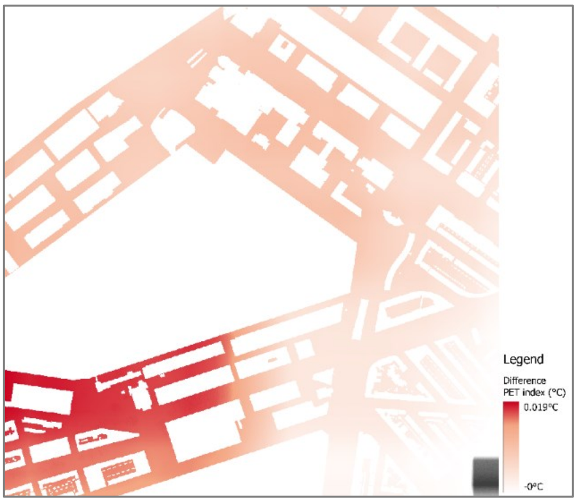


Figure 127: Difference PET scenarios 0 and 3

The last scenario difference shows the effect of combining green roofs and green walls. In this case, the vegetation raster difference, Figure 125, is also located at the locations where greenery is added (see Figures 103 and 106). The output of the vegetation raster, Figure 124, is in line with what can be expected in relation to the building heights of the different buildings. As shown by the difference of the PET index (Figure 127), the reducing effect of green roofs is larger than the effect of green walls. The largest difference is 0.019°C and is located at the left bottom close to the building with the highest green roof values in the vegetation raster. Nevertheless, 0.019°C is higher than the reducing effect of green roofs alone and therefore the effect is enlarged by the green walls. However, it would be expected that the effect of green walls would be larger in relation to green roofs because the surface area added is larger (see Table 14). But by relating the effect to the UHI box, the result can be explained (see Figures 128 and 129). Despite that the vegetation raster value of green walls is made higher to compensate for the fact that the surface is vertical instead of horizontal, the UHI box makes the calculation based on the horizontal surface. The surface of a green roof is more often present in calculating the vegetation fraction than a green wall. The effect is further calculated into the PET index.

Table 14: Comparison of surface area and vegetation raster values of green roofs and green walls

	Sum of surface areas	Sum of vegetation raster values
Green roofs	19735	13554
Green walls	29293	16817

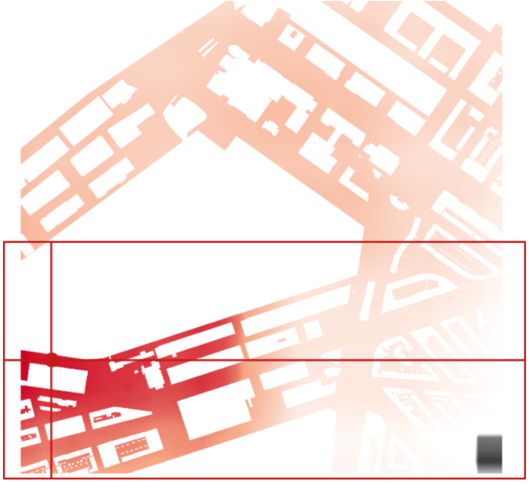


Figure 128: UHI box explanation for a location with a large difference

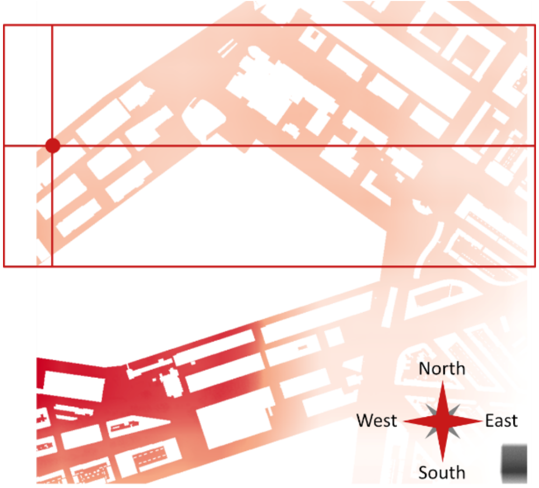


Figure 129: UHI box explanation for a location with a small difference

When also considering the adjusted Bowen ratio calculation, then the difference in the PETs between scenarios 0 and 3 is as presented in Figure 130. As explained, the Bowen ratio is only added for green walls because it is a very local effect which will make it impossible to show the effect of green roofs. The difference for the green walls is barely visible because it is a very local effect close to the buildings with a maximum of 1.44°C. The building pointed at with the arrow has a green wall and the other buildings in the zoomed picture do not (right part of Figure 130). The buildings with no green walls do not have a large difference around them and the building with green walls does have a large difference around it. The difference is visible in the cells directly around the building which is the location of green walls. Therefore, the location of the difference is in line with what can be expected. So, in contradiction with the vegetation raster effect, the green walls are causing the largest difference when the Bowen ratio is considered. However, this effect is very local and not noticeable in a larger area and the effect of the vegetation raster is noticeable in a larger area where green roofs have a larger effect.

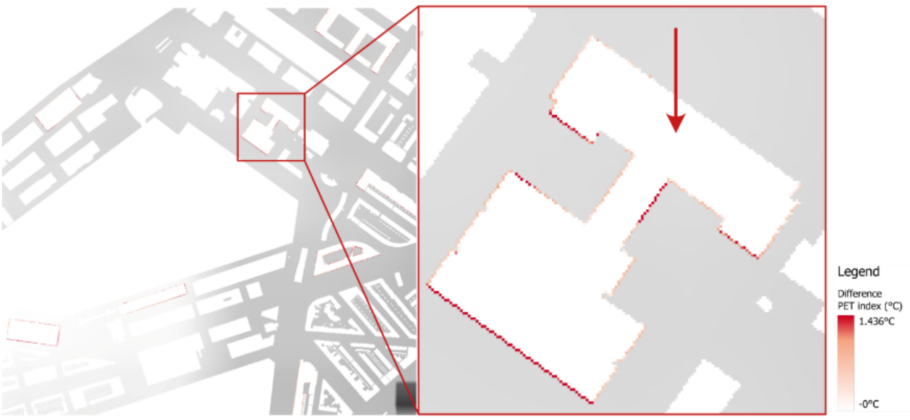


Figure 130: Difference PET scenarios 0 and 3 including Bowen ratio

4.3 Results Urban Green Infrastructure (UGI) analysis

This section will present the results of the developed UGI analysis by first showing the outcomes of the requirement analysis per UGI type and after that, the outcome of combining the possibility layers of the UGI types. The created data layers as a result of the data preparation will be used as further input for the UGI analysis as described in sections 3.2.2.2 and 3.2.2.3. The results are presented for three UGI types: Tree avenue and single-line with trees of 1st size and closed foliage; Group of shrubs; and Climbers. These types are chosen because the tree avenue and single-line trees is the most complex type which requires to comply with most requirements. The climbers are a divergent variant due to another type of analysis with buffers and the group of shrubs is added to be able to show a more extensive example for the land availability and combining analysis. The results will be presented for the same tile of 1000 by 1000 meters as the other results (Figure 87, page 88). Furthermore, part of the results will also be presented for example cells with an area of 15 by 15 meters (Figure 131).

Figure 131: Scope of the example cells

4.3.1 Analysis per UGI type

For the analysis per UGI type, the method of section 3.2.2.2 is applied to the city of Rotterdam. The results will be explained for the three UGI types.

For the requirement analysis of Tree avenue and single-line trees with trees of 1st size and closed foliage, the data layers presented in Figures 132 to 142 are used as a result of the data preparation which represents eleven requirements. The Figures also show the location of the example cells which will be used later on and the missing values for the requirements slope of less than 10 degrees and 15m free of overhead obstacles are filled with value 0 because these locations due not fulfil the requirements.

The data layers of Figures 132 to 142 are used as input for the site suitability analysis of the UGI type which consists of a possibility and land availability analysis. The expression for the possibility analysis is:

Amount of street traffic=0 AND Buildings=0 AND Water=0 AND Trees=0 AND Linear elements=1 AND Presence of overhead obstacles 15m=1 AND Proximity to structures 8m=0 AND Slope 10 degrees=1 AND Tree protection zone=0 AND Land availability=0 AND Width of paths and roads=0

Figure 132: Data preparation outcome Presence of overhead obstacles 15m requirement

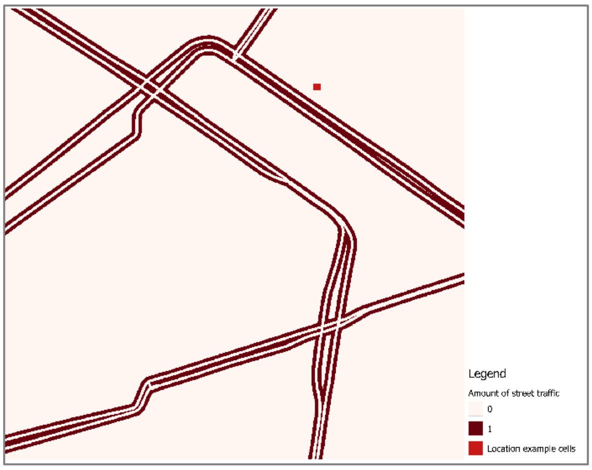


Figure 133: Data preparation outcome Amount of street traffic requirement

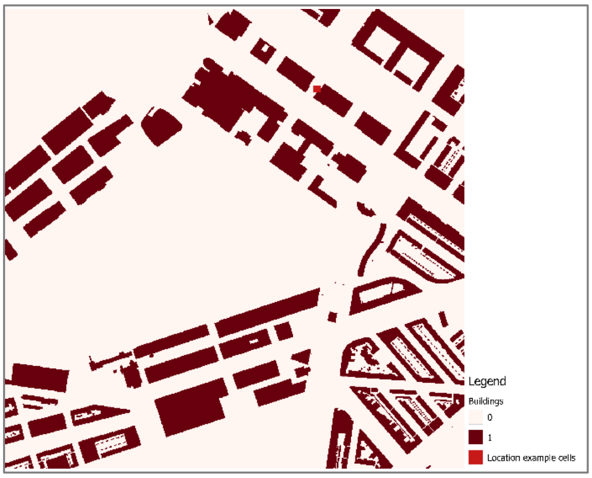


Figure 134: Data preparation outcome Land use Buildings requirement

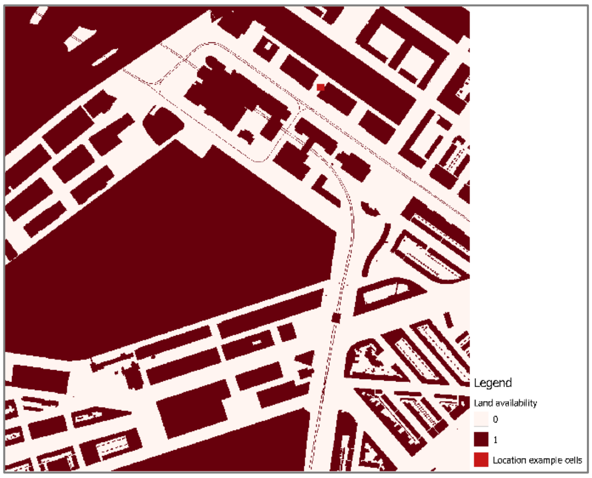


Figure 135: Data preparation outcome Land availability requirement

Figure 136: Data preparation outcome Land use Linear elements requirement

Figure 137: Data preparation outcome Proximity to structures 8m requirement

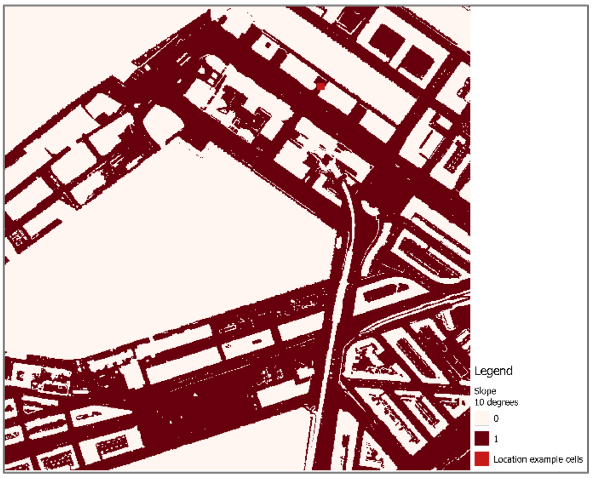


Figure 138: Data preparation outcome Slope 10 degrees requirement

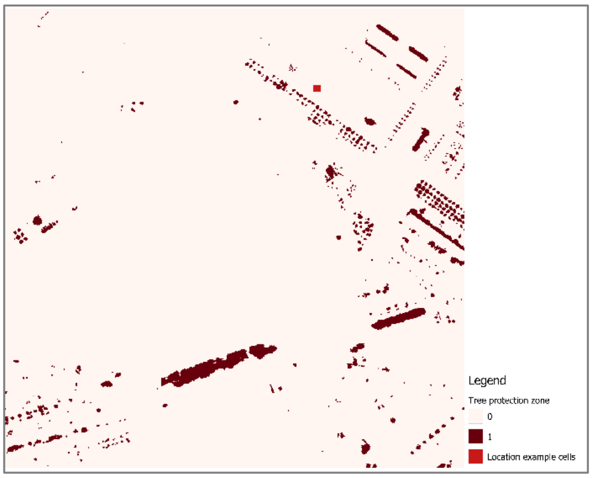


Figure 139: Data preparation outcome Tree protection zone requirement

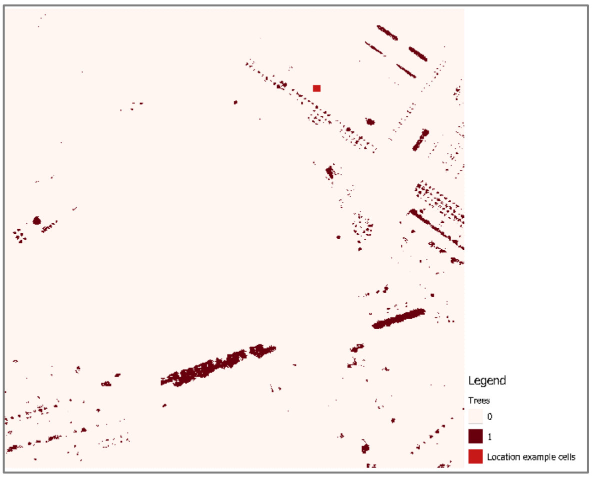


Figure 140: Data preparation outcome Land use Trees requirement

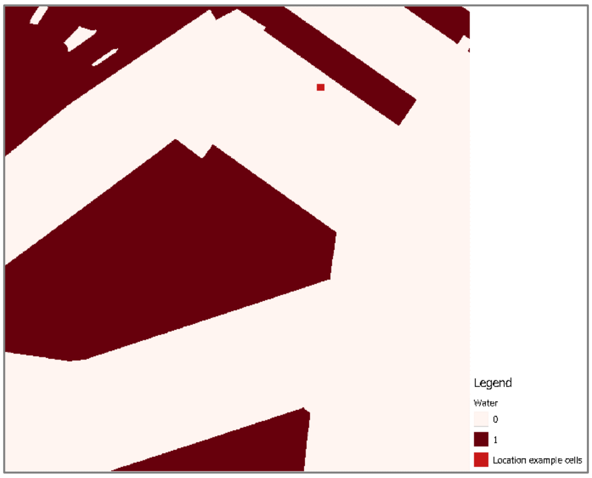


Figure 141: Data preparation outcome Land use Water requirements

Figure 142: Data preparation outcome Width of paths and roads requirement

As stated, some requirements are fulfilled when defined as 0 and some as 1 which has to do with whether a defined element should be included or excluded as a possibility for the UGI type. When looking at the example cells, then the possibility analysis is as presented in Figure 143 including all eleven requirements.

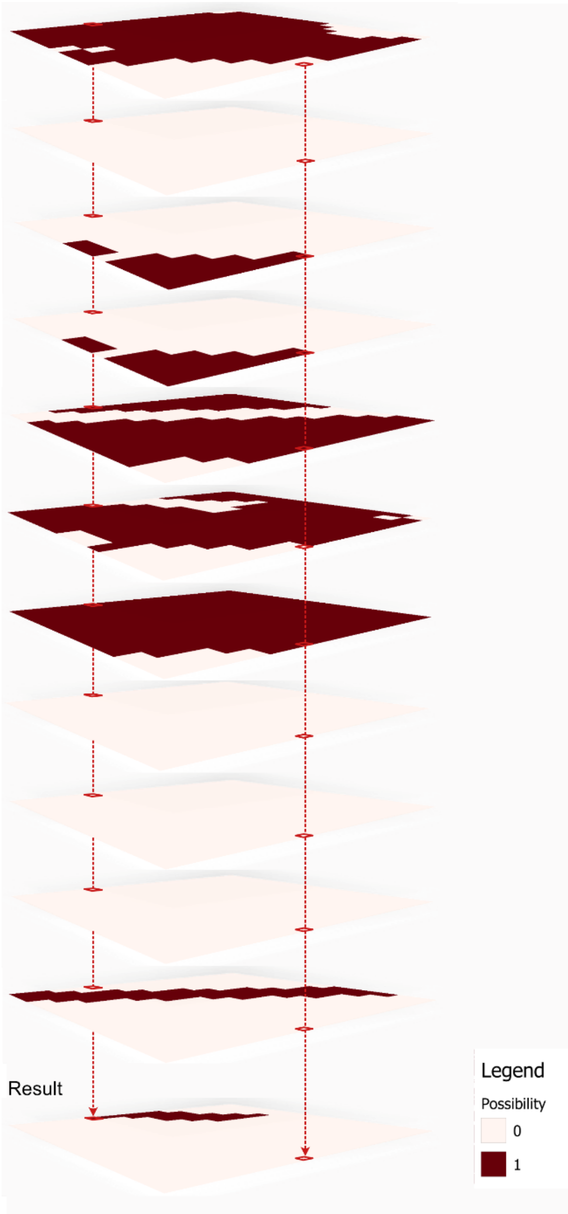


Figure 143: Possibility analysis example cells

Figure 144: Outcome Possibility analysis for tile

In the cells of the result layer with value 0, as presented in Figure 143, it is not possible to implement the UGI type mostly due to the location of a building. Value 1 means that the UGI possibly can be implemented because all requirements are fulfilled at that location. The complete outcome of the tile for the possibility analysis is presented in Figure 144 (without the land availability analysis).

Then the land availability analysis is prepared which first results in polygons representing areas with values 0 and 1 for availability (the same as from possibility analysis), see Figure 145 which represents the result for the example cells. For the polygons with value 1 which represent availability, the surface area is calculated in m^2, see Table 15. The outcome of the surface area is rasterized in a raster layer with a cell size of 1m. For the example cells, the outcome is presented in Figure 146 which means that the cells which are not available have gotten a value of 0 and the others have gotten the value of the surface area of the related polygon (151.02 m^2). So, all cells of the same polygon have the same value.

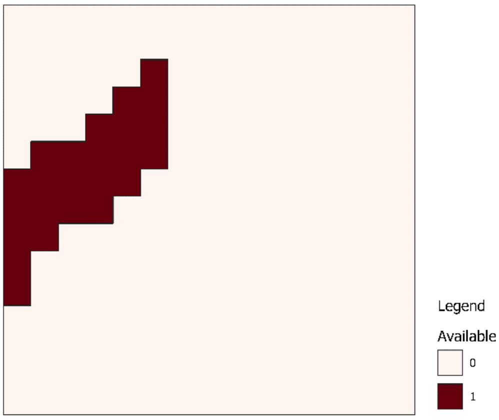


Figure 145: Polygons for Land availability

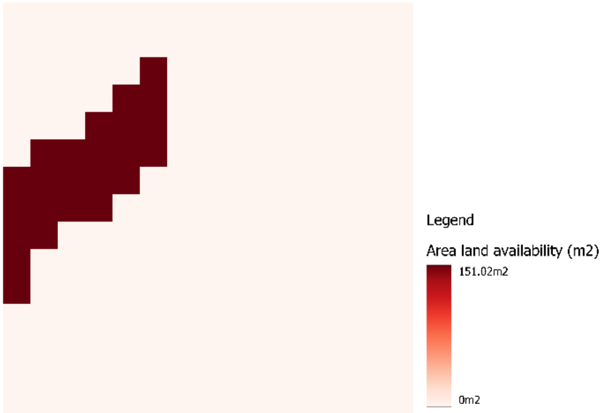


Figure 146: Surface area raster Land availability

Table 15: Attribute table available polygon

	Available	Surface area (m^2)
1	1	151.02

The raster layer of the surface area can then be used for the land availability analysis. The expression for the land availability analysis is:

Area >= 62.5

This means that all cells with a value equal to or larger than 62.5m^2 get value 1 which means that it is possible to implement Tree avenue and single-line trees with trees of 1st size and closed foliage. 62.5m^2 is defined by stating that a line of trees consists of a minimum of 5 trees, so 5*12.5 = 62.5m^2 (12.5m^2 is defined by Table 4 (page 52) of the literature review). Furthermore, it is not possible to analyse whether the surface area is available on both sides of a linear element. Therefore, the possibilities for tree avenues and single-line trees will be the same and so the UGI analysis for single-line trees and tree avenues are combined. Figure 147 presents the outcome of the tile in comparison with the outcome of the possibility analysis (Figure 144).

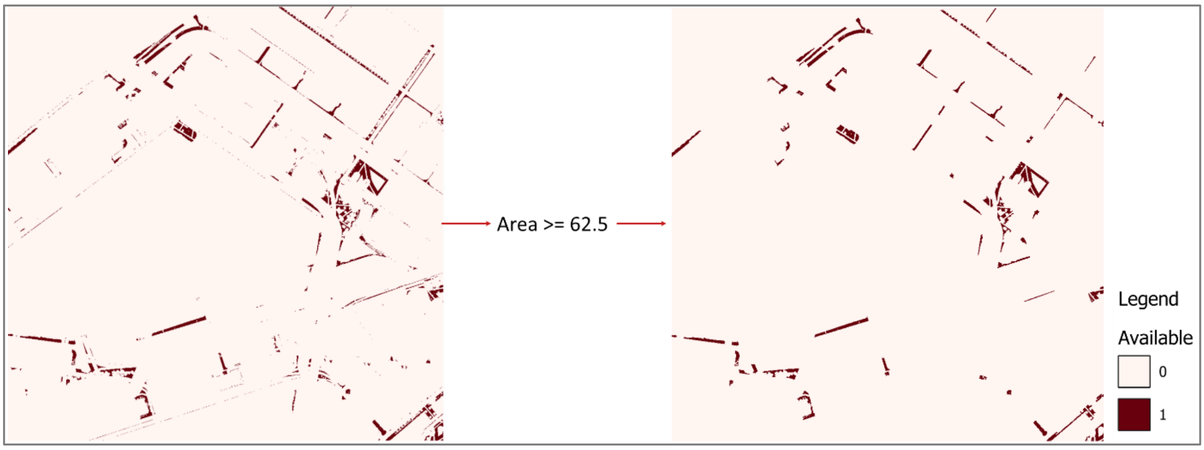


Figure 147: Outcome land availability analysis (right) in comparison with outcome possibility analysis (left)

For the group of shrubs, the same analyses are executed with as difference that other requirements and other expressions are applied. The data layers of Figures 148 to 157 are used as a result of the data preparation representing ten requirements. The example cells are here indicated as well and the missing values for the requirements slope of less than 20 degrees and 3m free of overhead obstacles are filled with value 0 because these locations do not fulfil the requirements.

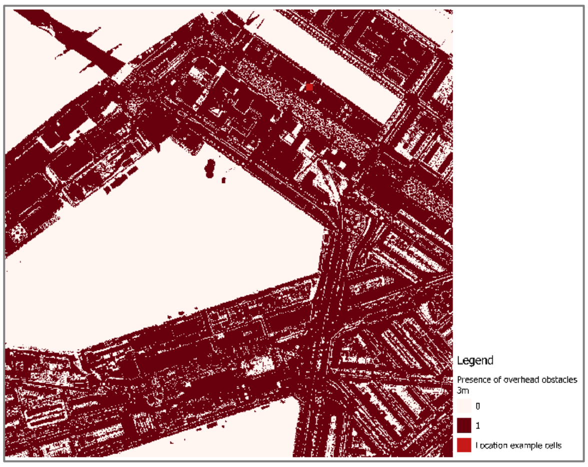


Figure 148: Data preparation outcome Presence of overhead obstacles 3m requirement

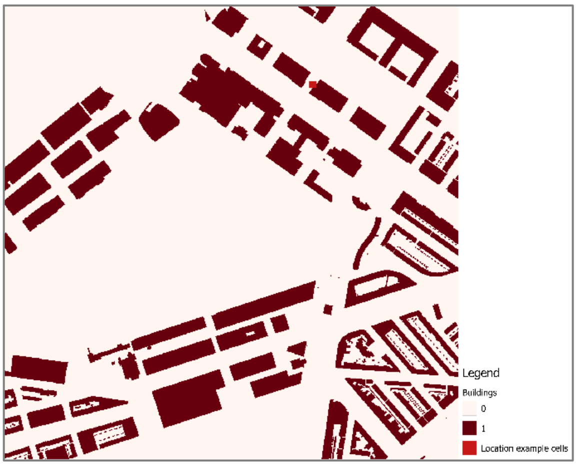


Figure 149: Data preparation outcome Land use Buildings requirement

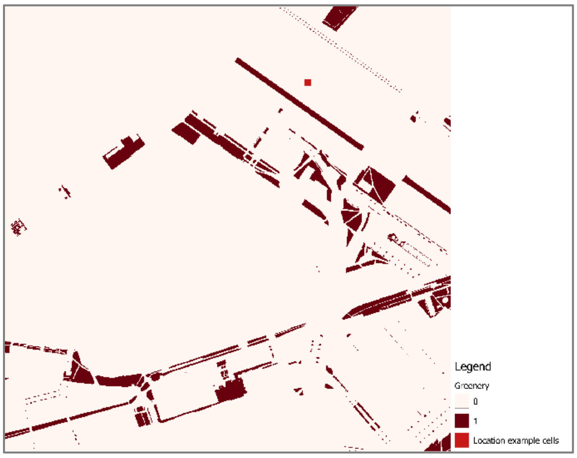


Figure 150: Data preparation outcome Land use Greenery requirement

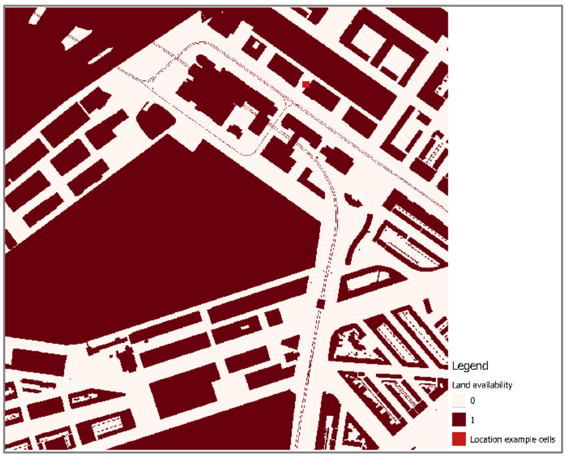


Figure 151: Data preparation outcome Land availability requirement

The data layers of Figures 148 to 157 are used as input for the site suitability analysis of the UGI type which consists of a possibility and land availability analysis. The expression of the possibility analysis is:

Buildings=0 AND Water=0 AND Trees=0 AND Greenery=0 AND Presence of overhead obstacles 3m=1 AND Proximity to structures 1m=0 AND Slope 20 degrees=1 AND Tree protection zone=0 AND Land availability=0 AND Width of paths and roads=0

This results in the possibility analysis for the example cells of Figure 158 and the possibility outcome for the tile in Figure 159 (without land availability analysis). Both result layers represent possible locations for a group of shrubs by the value of 1.

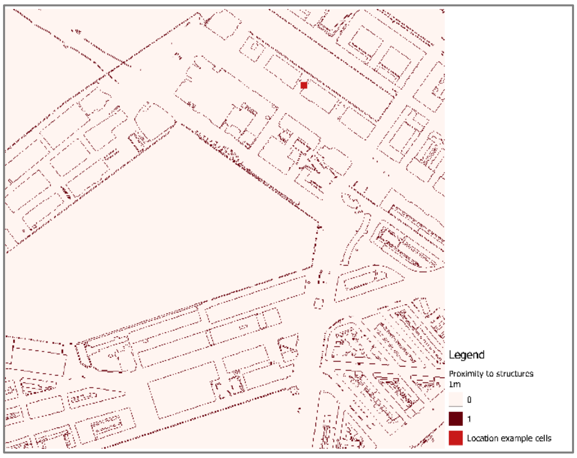


Figure 152: Data preparation outcome Proximity to structures 1m requirement

Figure 153: Data preparation outcome Slope 20 degrees requirement

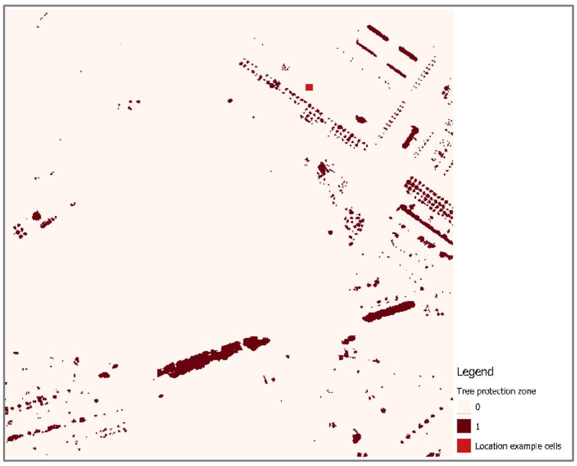


Figure 154: Data preparation outcome Tree protection zone requirement

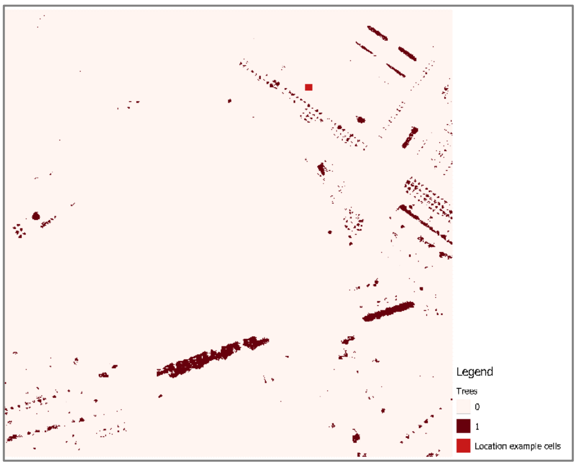


Figure 156: Data preparation outcome Land use Trees requirement

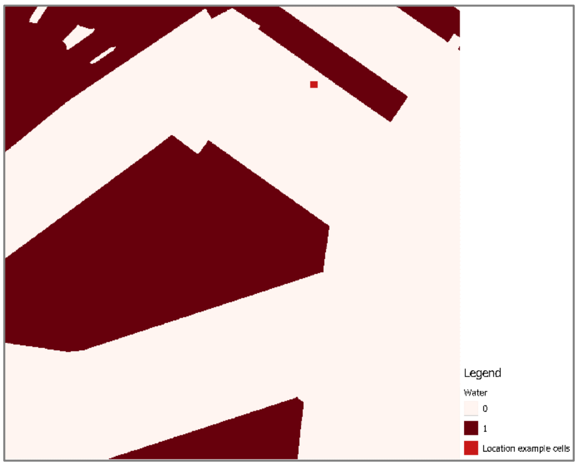


Figure 155: Data preparation outcome Land use Water requirement

Figure 157: Data preparation outcome Width of paths and roads requirement

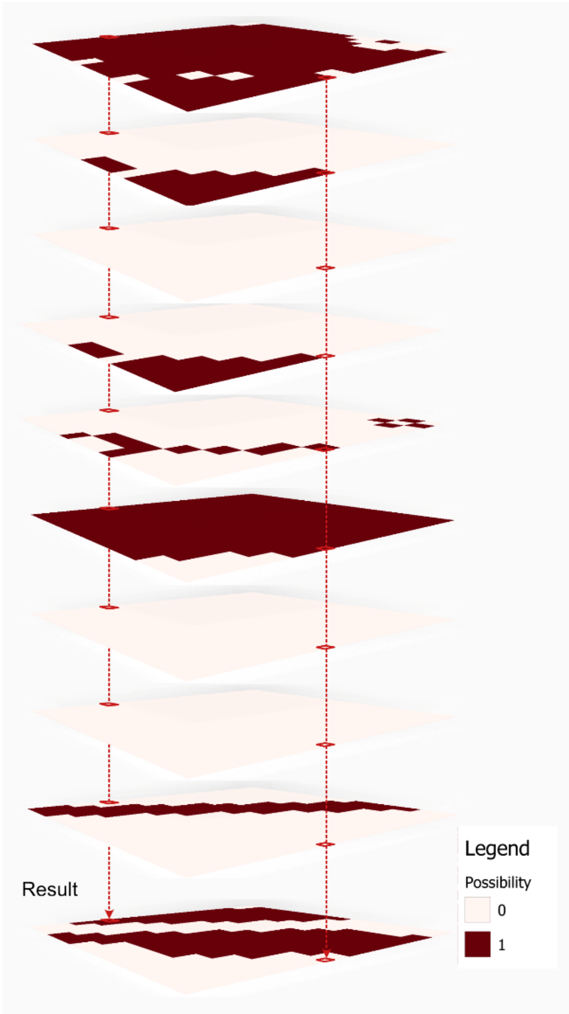


Figure 158: Possibility analysis of example cells

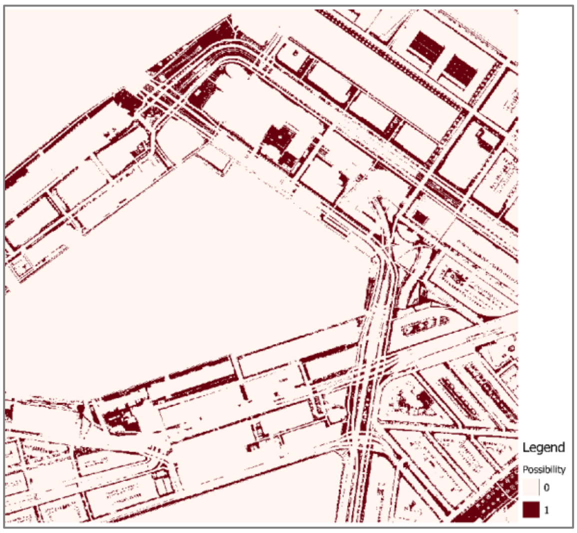


Figure 159: Outcome possibility analysis for tile

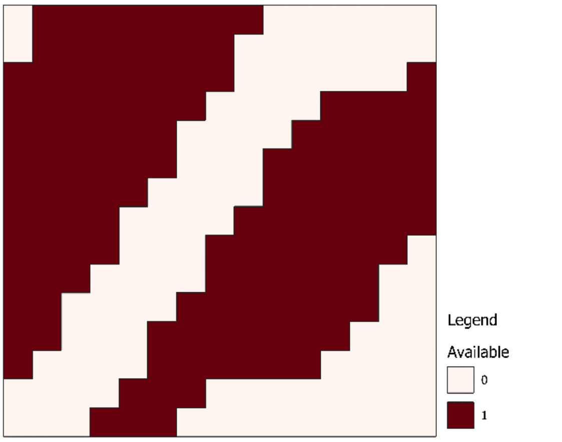


Figure 160: Polygons for land availability

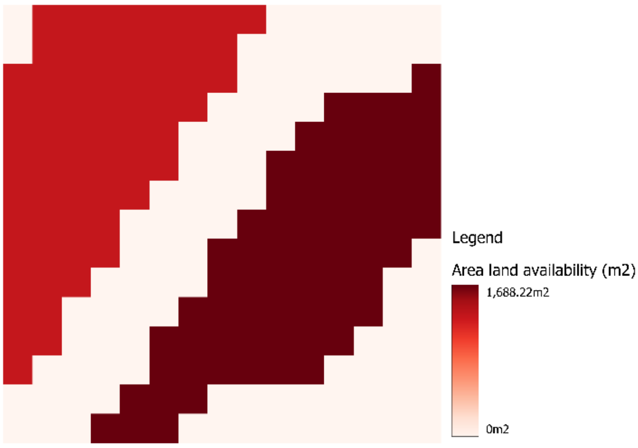


Figure 161: Surface area raster land availability

Then the land availability analysis is prepared, Figure 160 shows the polygons created for the examples cells representing availability. For the polygons with value 1 which represent availability, the surface area is calculated in m^2, see Table 16. The outcome of the surface area is rasterized in a raster layer as presented in Figure 161. In comparison with the tree avenue and single-line trees, larger areas are available for a group of shrubs (see Table 15 (page 105) versus Table 16). So, for a group of shrubs, larger areas have the possibility to implement the UGI type which is in line with that fewer requirements need to be fulfilled.

Table 16: Attribute table available polygons

	Available	*Surface area (m²)*
1	1	1,355.18
2	1	1,688.22

The raster layer of the surface area can then be used for the land availability analysis. The expression for the land availability analysis is:

Area >= 3

The value of 3 m^2 is in line with the land availability requirement as defined in Table 4 of the literature review (page 52). The result for the tile is presented in Figure 162 in comparison with the outcome of the possibility analysis (Figure 159).

Figure 162: Outcome land availability analysis (right) in comparison with outcome possibility analysis (left)

For the climbers, a possibility analysis is the only analysis executed with the input layers of data preparation as presented in Figures 163 to 166 representing four requirements. The Figures also indicate the example cells used later on. For the climbers, the requirements must be related to the cells around the buildings because climbers will be implemented at those locations. So, as explained in section 3.2.2.1, for the building age and the defined structures, a buffer is created which is presented in Figures 163 and 165.

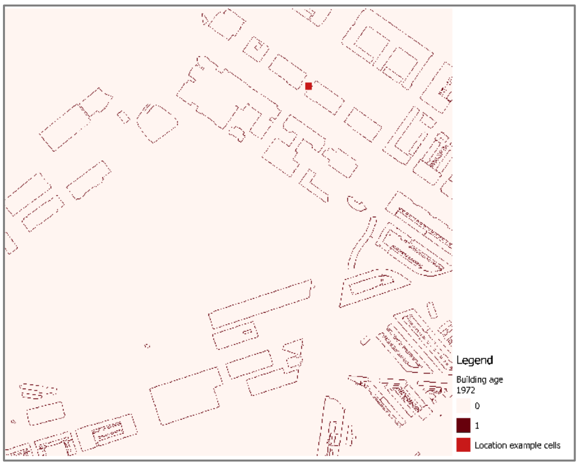


Figure 163: Data preparation outcome Building age 1972 buffer requirement

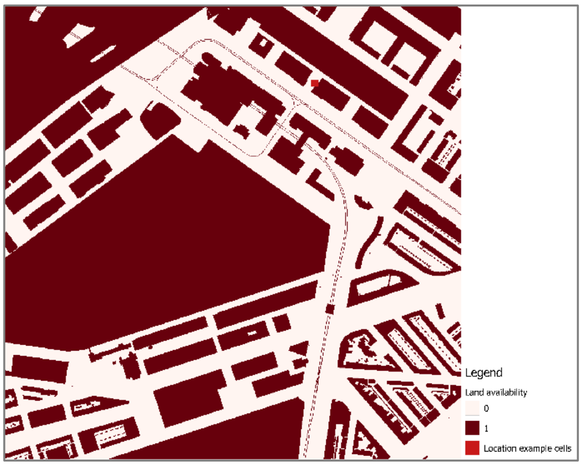


Figure 164: Data preparation outcome Land availability requirement

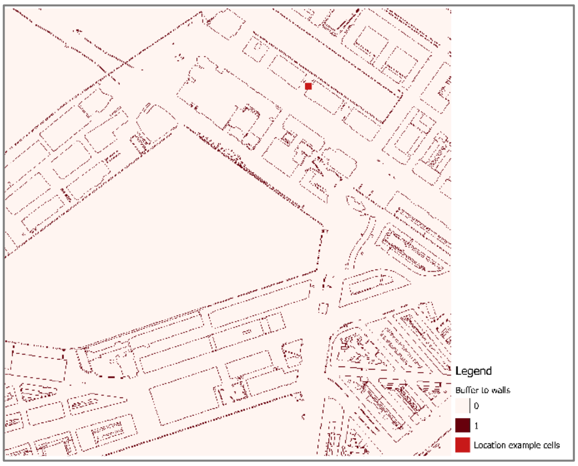


Figure 165: Data preparation outcome Buffer to walls requirement

Figure 166: Data preparation outcome Width of paths and roads requirement

The data layers of Figures 163 to 166 are used as input for the requirement analysis which only includes a possibility analysis. The expression of the possibility analysis is:

Building age 1972 buffer=1 AND Buffer to walls=1 AND Land availability=0 AND Width of paths and roads=0

The expression results in the analysis of Figure 167 for the example cells and the outcome of the tile in Figure 168. Both result layers represent possible locations for climbers by the value of 1.

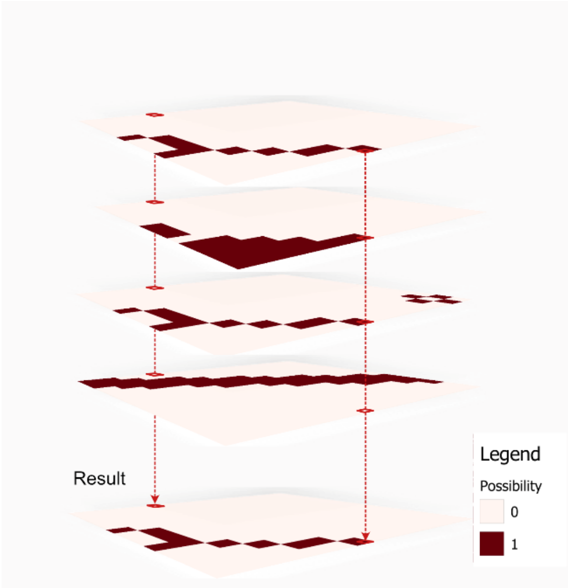


Figure 167: Possibility analysis example cells

Figure 168: Outcome possibility analysis for tile

The results are in line with what could be expected with the analysed requirements. However, some locations such as the airport, sports fields and highways show possibilities for UGI types which are logically not possible (Figures 169 to 171). Extra requirements are required to exclude such locations from the possibilities. Nevertheless, the possibility maps per UGI type show an indication of where the different types are possible.

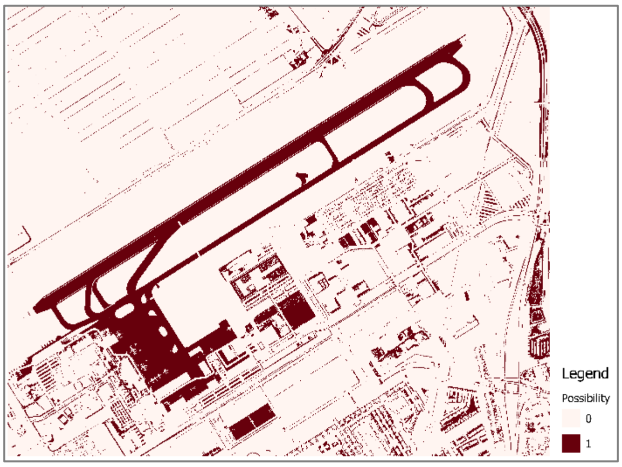


Figure 169: Possibility for Airport

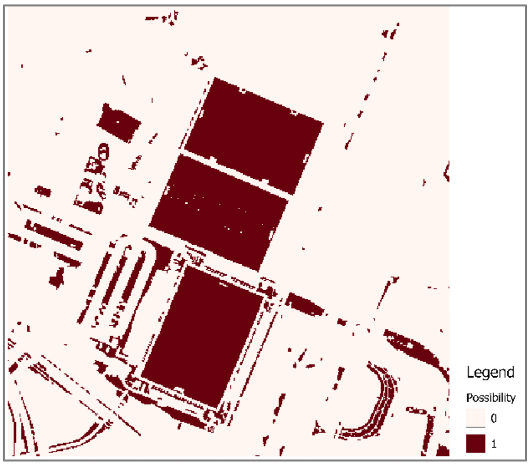


Figure 170: Possibility for Sports fields

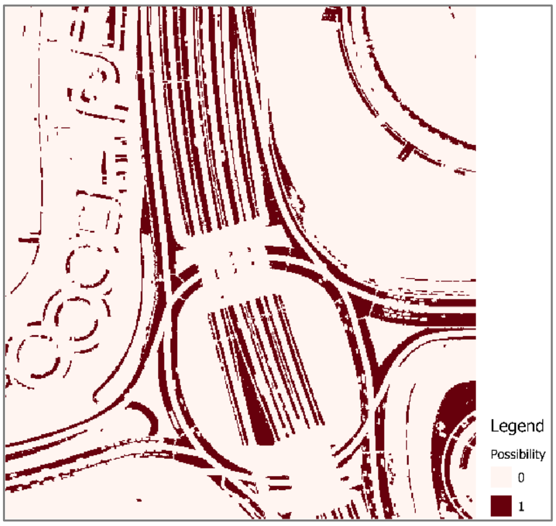


Figure 171: Possibility for Highways

4.3.2 Combining layers of UGI types

The results of the analysis per UGI type are used as input for combining the possibility layers of the UGI types into one map. The results are presented by using the three example UGI types. The first step is to multiply the last expression in the analysis per UGI type with the ranking of the priority list, as explained in section 3.2.2.3. The three example UGI types are ranked as follows:

1. Tree avenue and single-line trees with trees of 1st size and closed foliage
22. Group of shrubs
24. Climbers

For UGI type 1 and 22, the land availability analysis expression is multiplied by the value of the ranking and for UGI type 24, the possibility analysis expression is multiplied by the value of the ranking. The land availability and possibility analysis expressions are adjusted to:

(Area >= 62.5) * 1

(Area >= 3) * 22

(Building age 1972 buffer=1 AND Buffer to walls=1 AND Land availability=0 AND Width of paths and roads=0) * 24

The results of the possibility layers per UGI type stay the same as in Figures 147, 162 and 168 but instead of having values 0 and 1, the maps do now have values 0 and 1, 0 and 22 & 0 and 24 (see Figures 172, 173 and 174).

Figure 172: Map layer UGI type 1

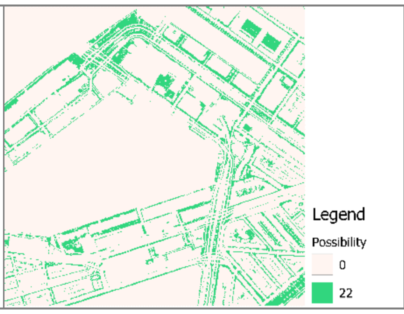


Figure 173: Map layer UGI type 22

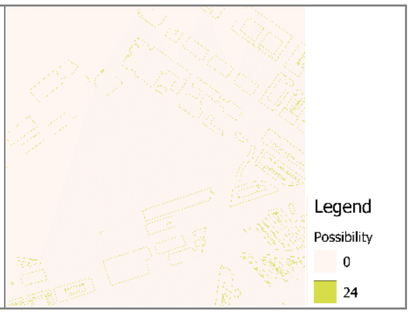


Figure 174: Map layer UGI type 24

All map layers of the UGI types are used to calculate the minimum value per cell. When in the same cell of 1m, a tree avenue and single-line trees (UGI type 1) as well as a group of shrubs (UGI type 22) is possible then 1 is taken as the value because it is the lowest value. Figure 175 presents the minimum value analysis of the example cells when considering the three example UGI types. Figure 176 presents the result for the example cells when considering all 28 UGI types and Figure 177 presents the outcome for the tile with the whole legend. The cells with a value of 0 in the map layers per UGI type are not considered when calculating the minimum value per cell, otherwise, 0 would be the best value which is not the case. If no UGI type is possible at a location then the cell has no value in the final UGI possibility map as presented in Figure 176.

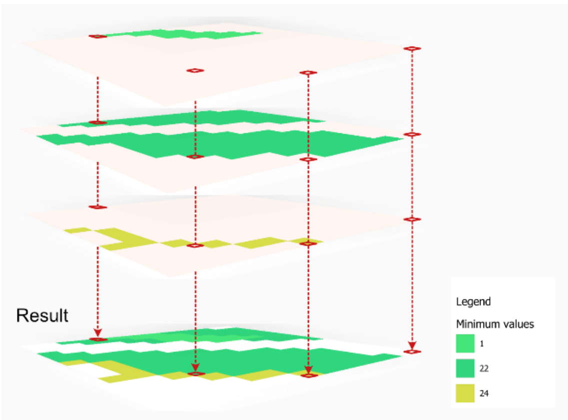


Figure 175: Minimum value analysis of example cells

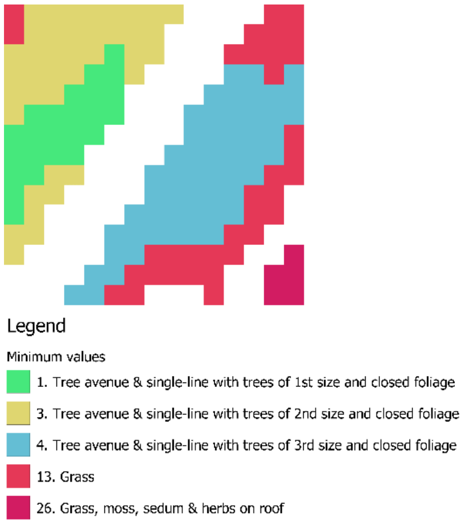


Figure 176: Outcome minimum value analysis example cells

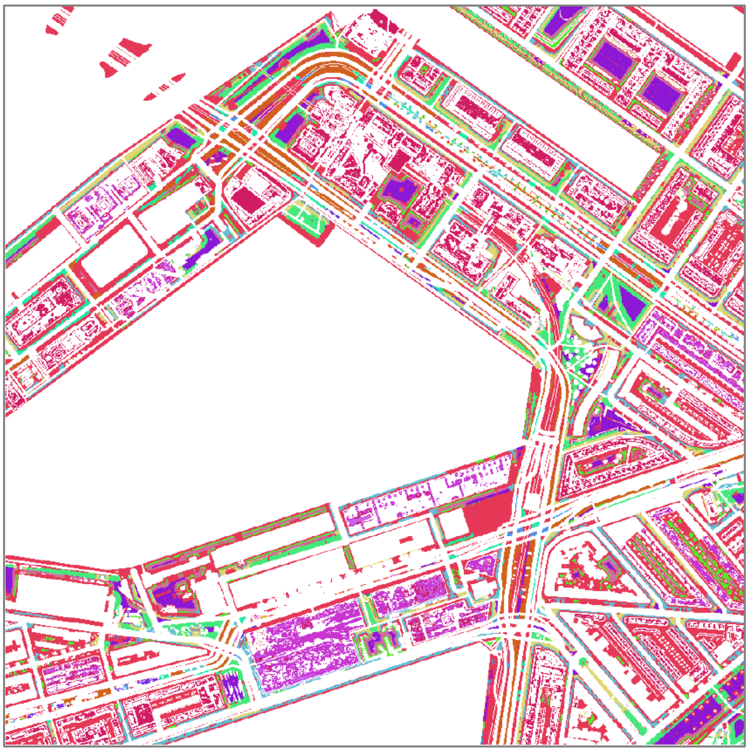


Figure 177: Final UGI possibility map including all 28 UGI types for tile

The final UGI possibility map presents with the colours and legend, the locations of the possibilities of 28 UGI types. The map gives an understandable indication of what UGI type can be best implemented based on the highest expected reducing effect on the PET index.

4.4 Results linking HTC calculation with UGI analysis

This section will describe the results of the link between the HTC calculation and UGI analysis. The outcome of the HTC calculation and the UGI analysis are used to apply the method of section 3.3 to the city of Rotterdam. The link consists of two parts: the analysis of UGI possibilities for locations with high HTC values and the implementation of UGI types back into the PET index calculation. The maps as presented in Figures 178 (the PET index map representing the HTC values) and 179 (the UGI possibility map) are used as input for the analysis of UGI possibilities for locations with high HTC values. The analysis is executed by applying the expression:

(Final PET index map >= 41) * Final UGI possibility map

The outcome of the expression is presented in Figure 180 for the city of Rotterdam which shows only the UGI possibilities for locations with a higher HTC value than 41°C. Figure 181 presents the result for the tile, by also presenting the PET index map and the UGI possibility map of the tile. 41°C is chosen as the boundary value because then more priority is given to locations with poor HTC. However, heat stress is experienced from 29°C so this could also be chosen as the boundary value which would result in Figure 182. As shown, for the calculated day, more priority would be given to locations as 41°C is chosen as the boundary value because, on the day of calculation, the maximum temperature was 34°C. So, 29°C is experienced at every location and no priority is given to locations. For 41°C as the boundary value, priority is given to locations that are located outside the shade of buildings and trees.

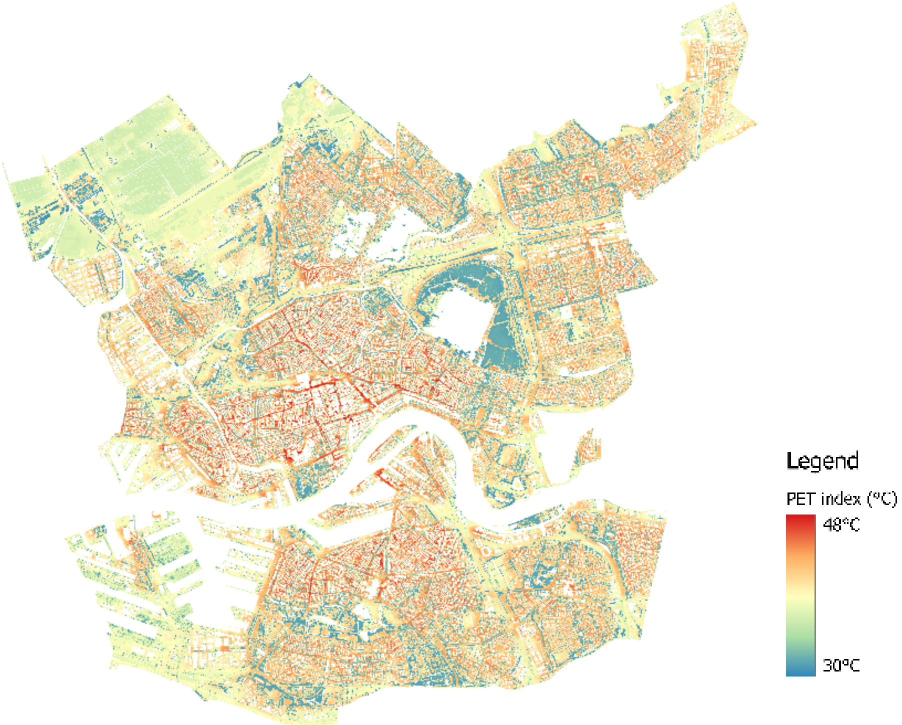


Figure 178: The final PET index map of Rotterdam presenting the HTC values

Figure 179: The final UGI possibility map of Rotterdam

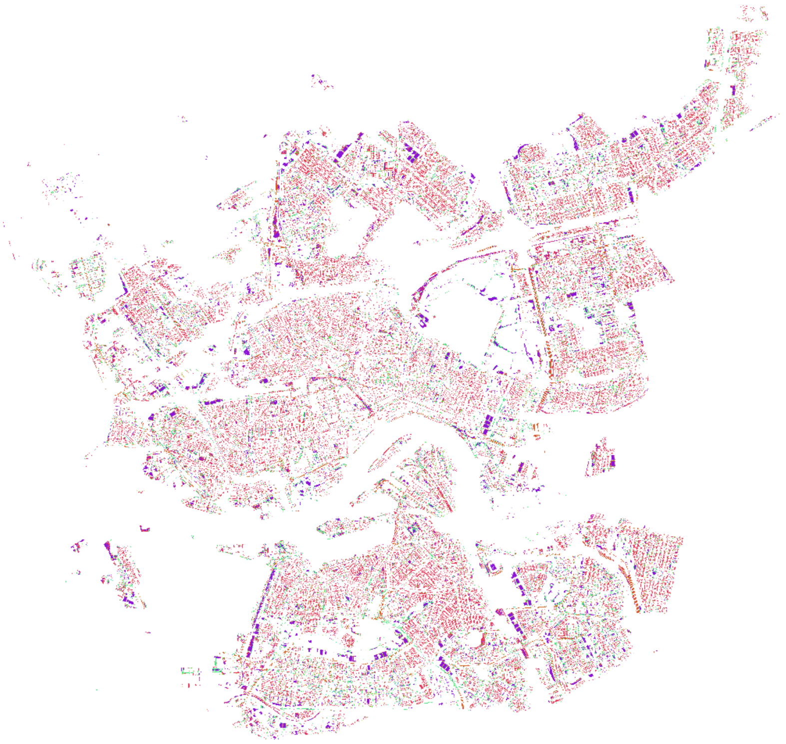


Figure 180: The UGI possibilities for locations with high HTC values for the city of Rotterdam

The analysis was the first part of the link between HTC and UGI. The second part is about implementing the possible UGI types back into the HTC calculation to show the effect. First, it is needed to choose the UGI types which can be implemented. For this study, it is done by using three scenarios for the same location within the tile (see Figure 183, page 119):

1. The implementation of trees
2. The implementation of low planting
3. Combining the implementation of trees and low planting

Figures 184 to 189 present an example of where trees can be implemented and the effect of it. Figure 184 shows the zoomed UGI possibility map for the location which is linked to the high HTC values of 41°C. It is visible that the location has multiple options for implementing UGI at locations with HTC values. For the first scenario, a tree avenue of UGI type 8 is implemented as presented in the shapefile of Figure 185. Due to the height of the trees, a new SVF is calculated which shows in Figure 187 a difference at the locations of the trees in comparison with Figure 186. The new SVF of Figure 187 and the shapefile of Figure 185 are used as input for the new PET calculation. The new PET of Figure 189 shows a clear effect on the locations of trees and also on the surroundings of the trees in comparison with Figure 188 (the old PET). The effect is not always reducing but sometimes it also has an increasing effect. Besides the effect of trees on shadow and the vegetation fraction, it also influences wind reduction which can lead to an increasing effect.

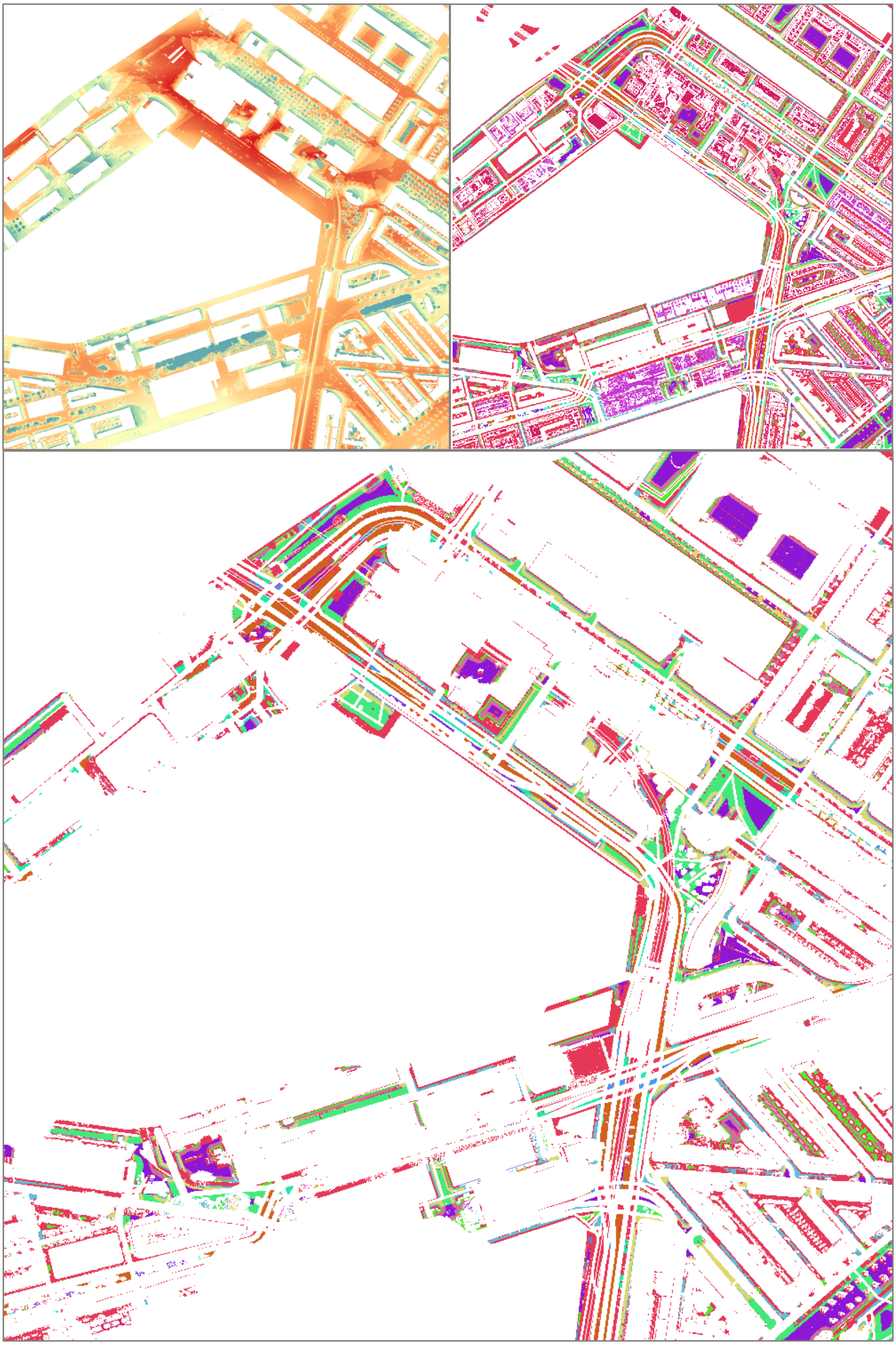


Figure 181: The result of linking the PET index map (upper left) with the UGI possibility map (upper right) in a map (bottom) for 41°C

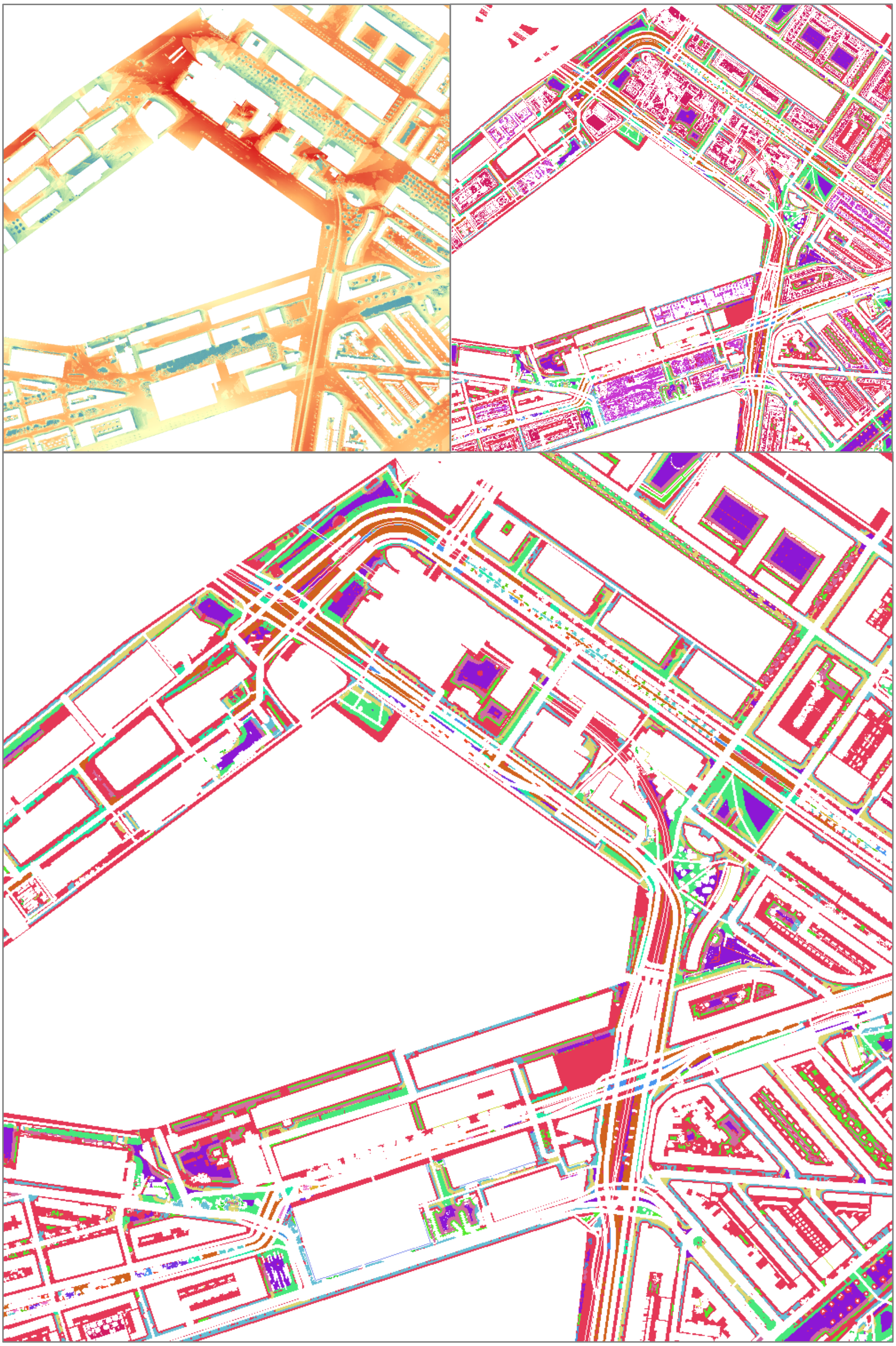


Figure 182: The result of linking the PET index map (upper left) with the UGI possibility map (upper right) in a map (bottom) for 29°C

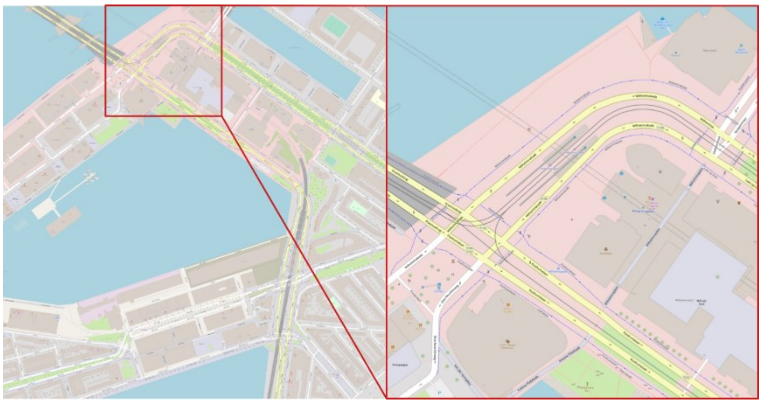


Figure 183: Location of scenarios within the tile

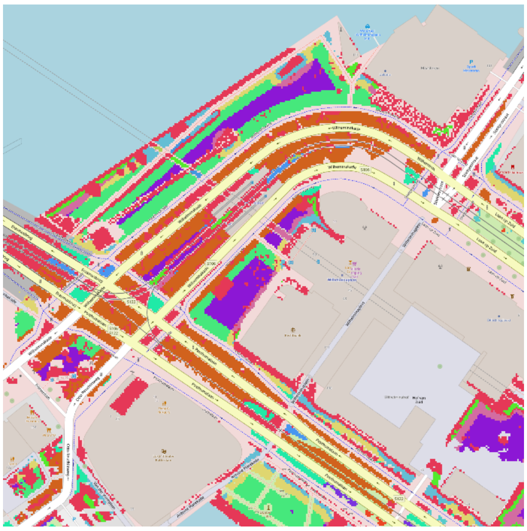


Figure 184: The UGI possibilities linked to HTC values

Figure 185: The shapefile with UGI type 8

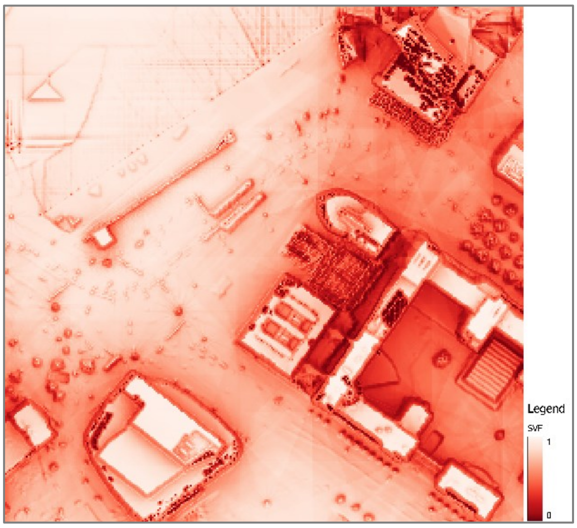


Figure 186: Old SVF

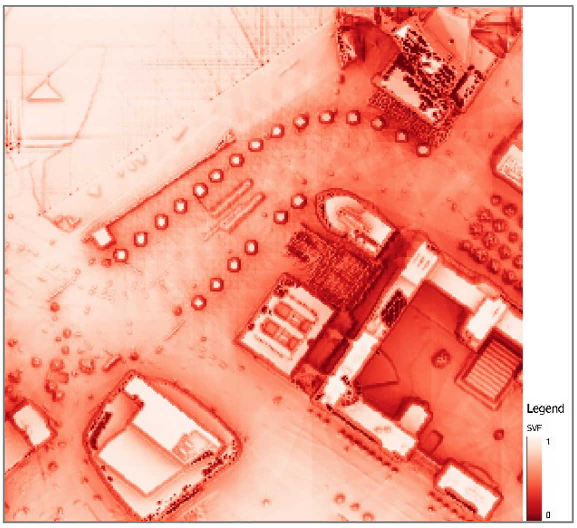


Figure 187: New SVF

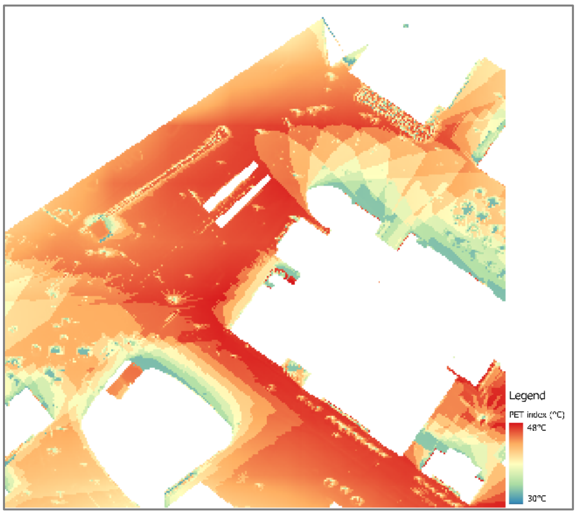


Figure 188: Old PET index

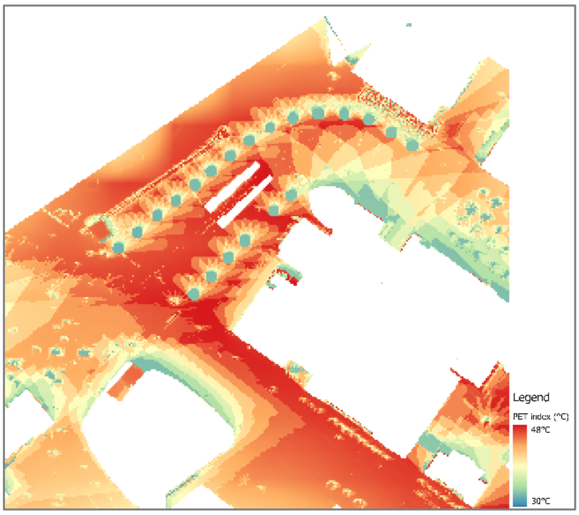


Figure 189: New PET index

For the second scenario, it can be helpful to not only investigate the final UGI possibility map (Figure 190) but also to take a look at the possibility map of a specific UGI type. Because many locations will be dominated by the possibilities for trees because these are higher in the ranking. For this scenario, the UGI type 'Grass' (number 13) will be investigated. Figure 191 presents the possibility map for grass which shows that at many locations where trees are possible, grass is possible as well. Figure 192 presents the chosen locations for implementing grass with the shapefile. To grass, no height is added and therefore, the SVF input layer stays the same as the old SVF (Figure 186). Figures 194 and 195 present the difference between the old and new PET indices. The reducing effect is locally visible due to the effect on the Bowen ratio but it also has a small reducing effect between 0 and 0.01°C on the surroundings due to adding vegetation to the vegetation fraction, see Figure 193 which presents the difference between the old and new PET index.

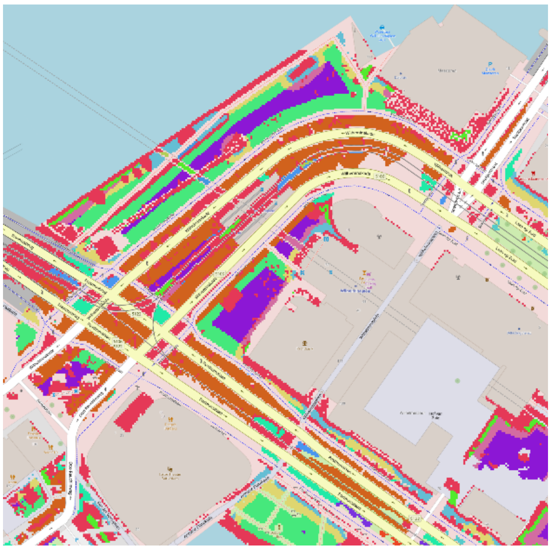


Figure 190: The UGI possibilities linked to HTC values

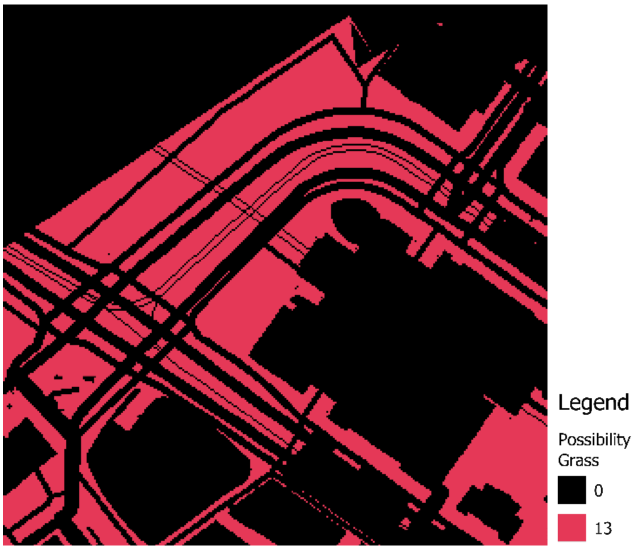


Figure 191: Possibility map Grass (UGI type 13)

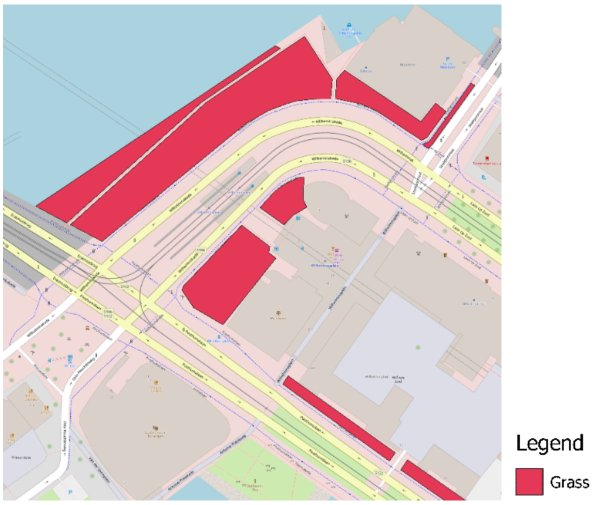


Figure 192: Shapefile with UGI type 13

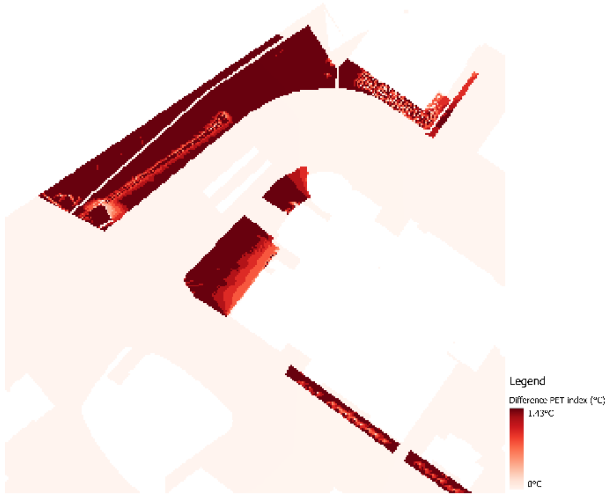


Figure 193: Difference between old and new PET index

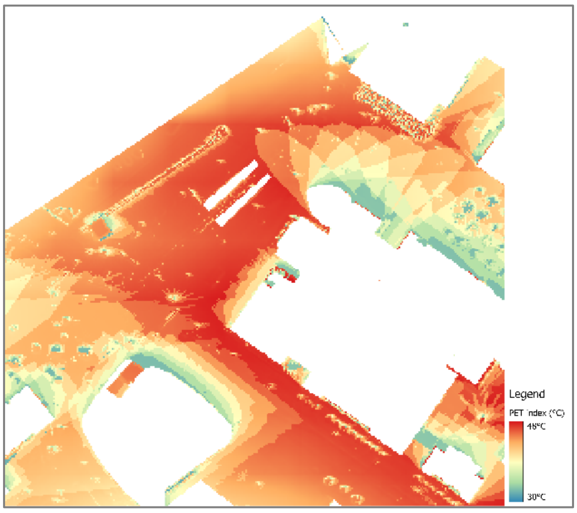


Figure 194: The old PET index

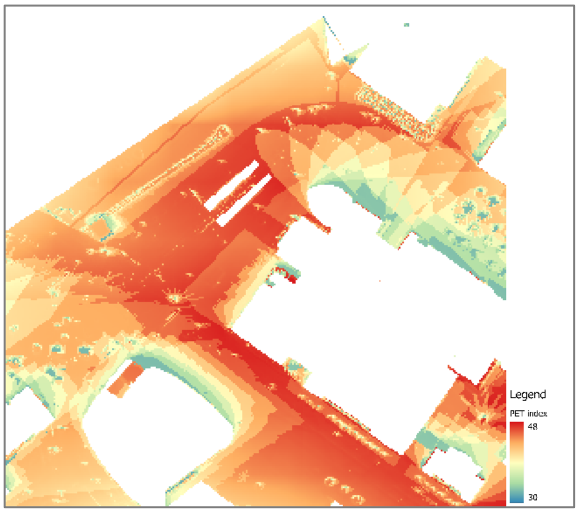


Figure 195: The new PET index

The last scenario deals with the implementation of both trees and low planting. Different types of trees and grass are implemented as presented by the shapefile in Figure 197. The height of the different trees results in the new SVF as presented in Figure 199 in comparison with the old SVF (Figure 198). The new SVF of Figure 199 and the shapefile of Figure 197 are used to calculate the new PET index. The new PET (Figure 201) shows a clear difference at the location of trees in comparison to the old PET (Figure 200). The reducing effect of trees is higher than grass due to the shadow they create.

The two parts present how the outcomes of the HTC calculation and UGI analysis can be linked with each other based on different scenarios.

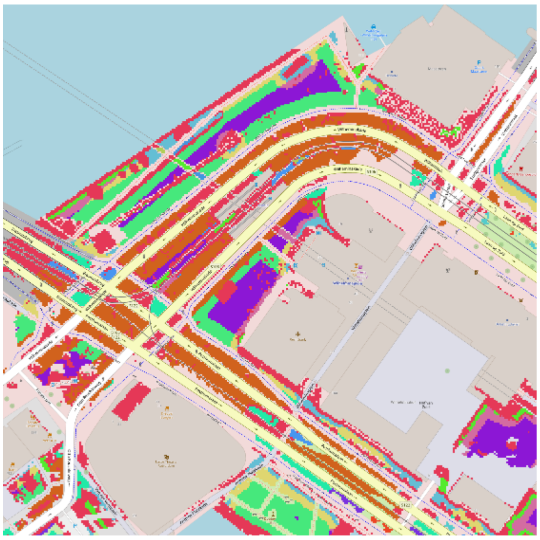


Figure 196: The UGI possibilities linked to HTC values

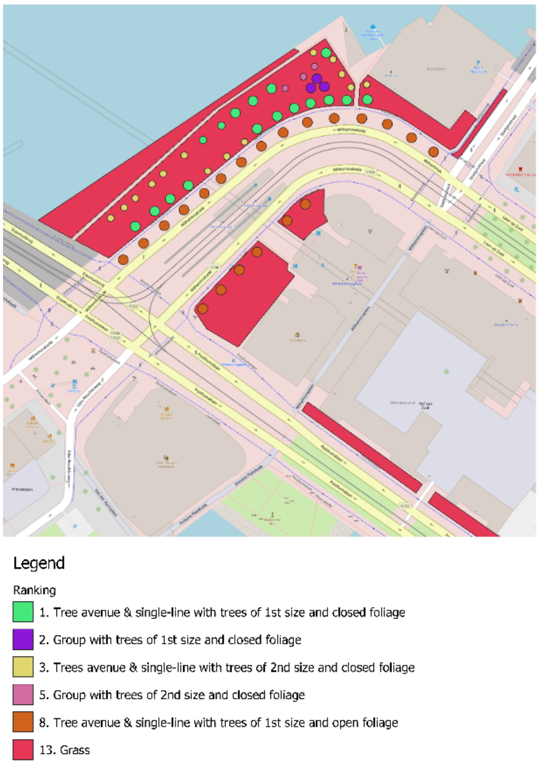


Figure 197: Shapefile with UGI types 1, 2, 3, 5, 8 and 13

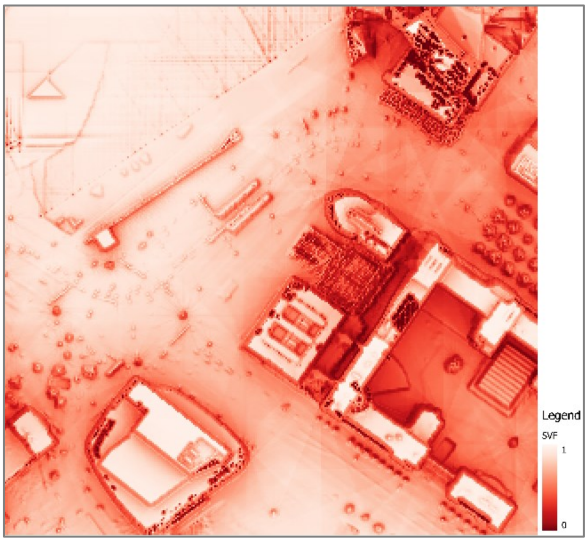


Figure 198: The old SVF

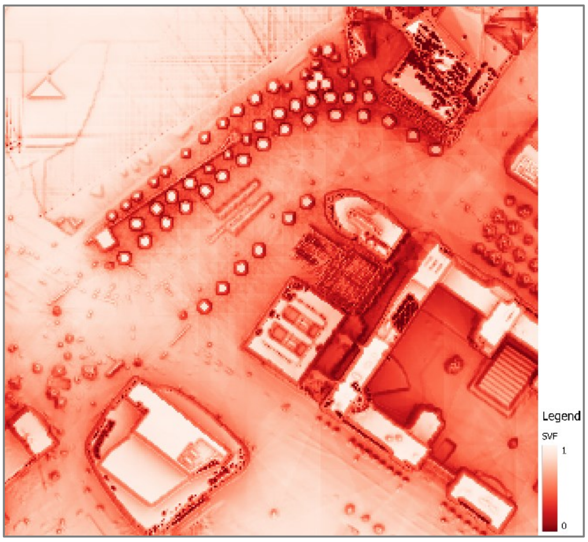


Figure 199: The new SVF

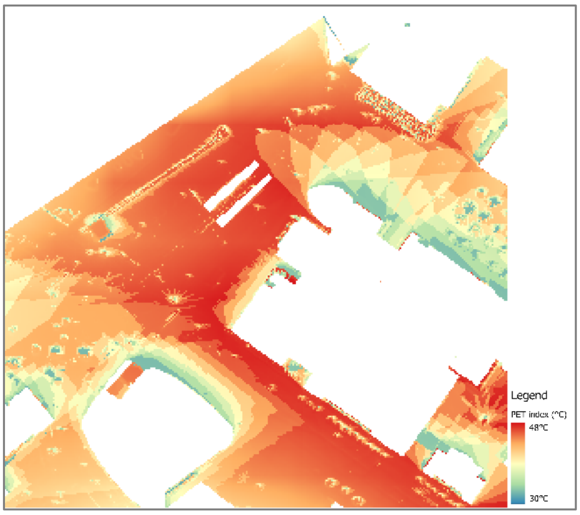


Figure 200: The old PET index

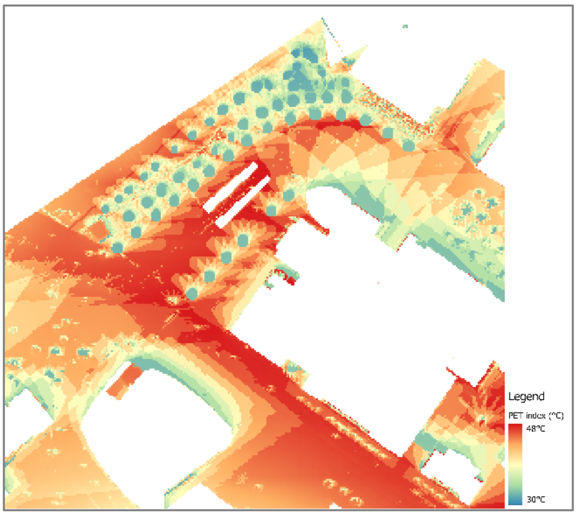


Figure 201: The new PET index

4.5 Conclusion

This chapter presented the results of applying the newly developed decision-support tool to the case study of Rotterdam. The results aim to gain more insight into the answers to the sub-research questions:

1. How can the PET index be improved by including green roofs and green walls?
2. How to identify the possibilities for the implementation of Urban Green Infrastructure using a decision-support tool?
3. How can the relationship between Urban Green Infrastructure and Human Thermal Comfort be incorporated into a decision-support tool?

The results confirm that the methodology described in Chapter 3 is a way to include green roofs and green walls in the PET index which determines HTC values in urban areas. The results show that this can make a difference in determining HTC. The differences in the PET index are in line with what is generally expected. By adding green roofs and green walls, the PET index value decreases. Furthermore, when more green roofs and green walls are added the difference becomes larger. Moreover, the differences are at locations where they are expected. Also, when the building height increases, the reducing effect of green roofs decreases as expected from the literature. However, it was not expected that the effect of the green walls would be smaller than green roofs as concluded from the literature (Table 17). The reducing effect of green walls is overshadowed by the effect of green roofs due to the vegetation fraction calculation which is calculated over the horizontal plane. Also, the effect of a decrease of 0.006°C is smaller than what is expected from the literature. For green roofs, the reducing effect of 0.012°C is more in line with what is concluded from the literature when considering that the reducing effect will become larger when more is added and no volume is given to the green roofs. So, assuming the green roofs are similar to roofs with grass, moss, sedum & herbs. When also considering the Bowen ratio, green walls can have a local reducing effect of 1.4°C which is more in line with the literature and the ratio creates a larger effect for green walls than for green roofs. However, the effect is very local and not noticeable in the surroundings.

Table 17: Reducing temperature effects (°C) of green roofs and green walls concluded from the literature

			Roof	Walls
Group of trees	3rd size	open foliage	1 -2	
		closed foliage	3 - 5	
Street tree	3rd size	open foliage	0.4 - 1.4	
		closed foliage	2 - 4	
Single shrub			0	
Group of shrubs			0.2 - 1.2	
Grass			0 - 0.7	0.5 - 2
Moss, sedum & herbs			0 - 0.7	0.5 - 2
Climbers				0.2 - 1
Perennials & annual plants			0.1 - 0.9	1 - 2.5

The results also confirm that it is possible to identify UGI type possibilities in urban areas with the newly developed decision-support tool. The results show that the defined requirements from the literature (Table 18) including the added requirements 'slope of roof', 'amount of street traffic' and 'presence of overhead obstacles' can identify where the different types of UGI are possible in a way that is clear and understandable. Furthermore, the generated results by the newly developed decision-support tool present that the self-defined priority list based on the temperature effects concluded from literature is a way to combine all possibility layers of the different UGI types in one map. So, the newly developed decision-support tool in this study is able to identify the possibilities for the implementation of UGI by incorporating a more detailed distinction between UGI types, a more extensive list of requirements, and the self-defined priority list. Nevertheless, the results also show room for improvement. Some locations such as the airport, sports fields and highways show possibilities for different types of UGI. However, in the existing situation, it is not possible to implement UGI at these locations. More requirements should be added to exclude these locations from the possibility map and the width of paths and roads should be defined in another way for highways. Last, in the current version of the decision-support tool, no distinction is made between public and private space which would be of added value to give more specific advice to urban planners who can steer the public space.

The results also demonstrate that by showing the priority locations for UGI based on high HTC values, it is possible to incorporate the relationship between UGI and HTC in the decision-support tool. This is done by showing in the final map only the possibilities for locations with PET values higher than 41°C. It must also be stated that another boundary value could be chosen as well to show a different amount of priority locations or for another weather type of day. Furthermore, by applying this boundary value to a raster layer, local possibilities for that cell are presented and not possible UGI types for locations in the surrounding which could also influence the HTC of that cell. Another part of linking the UGI analysis with the HTC calculation is by implementing the UGI possibilities back into the HTC calculation. So, the decision-support tool can be used to show the effect of UGI implementation on HTC values in urban areas.

Table 18: Overview of the requirements from the literature review incorporated in the newly developed decision-support tool

Amount of street traffic	Trees with closed foliage: No motorway, highway, regional road or local road
Building age	Grass and moss, sedum & herbs: >1991 Perennials & annual plants, shrubs and trees of 3rd size: >2012
Land availability	Single tree 1st size: More than 12.5 m^2 Single tree 2nd size: More than 10 m^2 Single tree 3rd size: More than 7.5 m^2 Group of trees: A location of more than 3x 12.5, 10 or 7.5 m^2 space Tree avenues: Both sides of a linear element, a row of multiple 1st, 2nd or 3rd size possibilities Single line tree: One side of a linear element, a row of multiple 1st, 2nd or 3rd size possibilities Single shrub: Minimal 0.5 x 0.5 m Group of shrubs: Minimal 3 m^2 Bankside plants: Minimal 0.5 x 0.5 meter Perennials & annual plants: Minimal 0.5 x 0.5 meter Grass: Minimal 1 m^2 Green walls: 0.5 m next to a vertical element
Land use	Trees: No existing trees, water and buildings Shrubs and low planting: No existing greenery, water and buildings Single-line trees and tree avenues: linear elements (roads, bicycle paths etc.) Bankside plants: Water and no existing buildings and greenery Green roofs: Existing buildings and structures with a roof Green walls: Existing buildings and structures with vertical elements
Presence of overhead obstacles	Tree 1st size: Minimal 15m obstacle-free in height Tree 2nd size: Minimal 8m obstacle-free in height Tree 3rd size: Minimal 5m obstacle-free in height Shrubs: Minimal 3m obstacle-free in height
Proximity to structures	Tree 1st size: More than 7.5 meters Tree 2nd size: More than 4 meters Tree 3rd size: More than 1.5 meters Shrubs: More than 1 meter
Slope	Trees: Not steeper than 10 degrees Shrubs and perennials & annual plants: Not steeper than 20 degrees
Slope of roof	More than 1 degree Grass, moss, sedum & herbs: maximum of 30 degrees Perennials & annual plants and shrubs: maximum of 10 degrees Trees 3rd size: maximum of 5 degrees
Tree protection zone	Tree 1st size: 25 m^3 around existing trees (12.5m^2 x 2m) Tree 2nd size: 15 m^3 around existing trees (10m^2 x 1.5m) Tree 3rd size: 7.5 m^3 around existing trees (7.5m^2 x 1m)
Width of paths and roads	Walkway: Minimal 1.5 meters Bicycle lane: Minimal 2 meters (one-way) and minimal 2.5 meters (two-way) Road: Minimal 3 meters (one-way) and minimal 4.5 meters (two-way)

5. Conclusion, Discussion & Recommendations

This study aimed to develop a decision-support which can support urban planners in determining a strategy for the implementation of UGI in urban areas by focusing on improving HTC. As presented in Figure 202, this chapter will bring together the findings from the previous chapters Literature review, Development of decision-support tool and Results by giving a conclusion, discussion, and recommendations for further research.

The chapter will start with a conclusion by answering the main research question: How to develop a decision-support tool which supports urban planners by determining a strategy for the implementation of Urban Green Infrastructure focusing on improving Human Thermal Comfort? Secondly, the limitations of the decisions and results of the study conducted will be discussed. Lastly, recommendations for further research will be given for developing further the described decision-support tool and how urban planners can use the insights provided in this study.

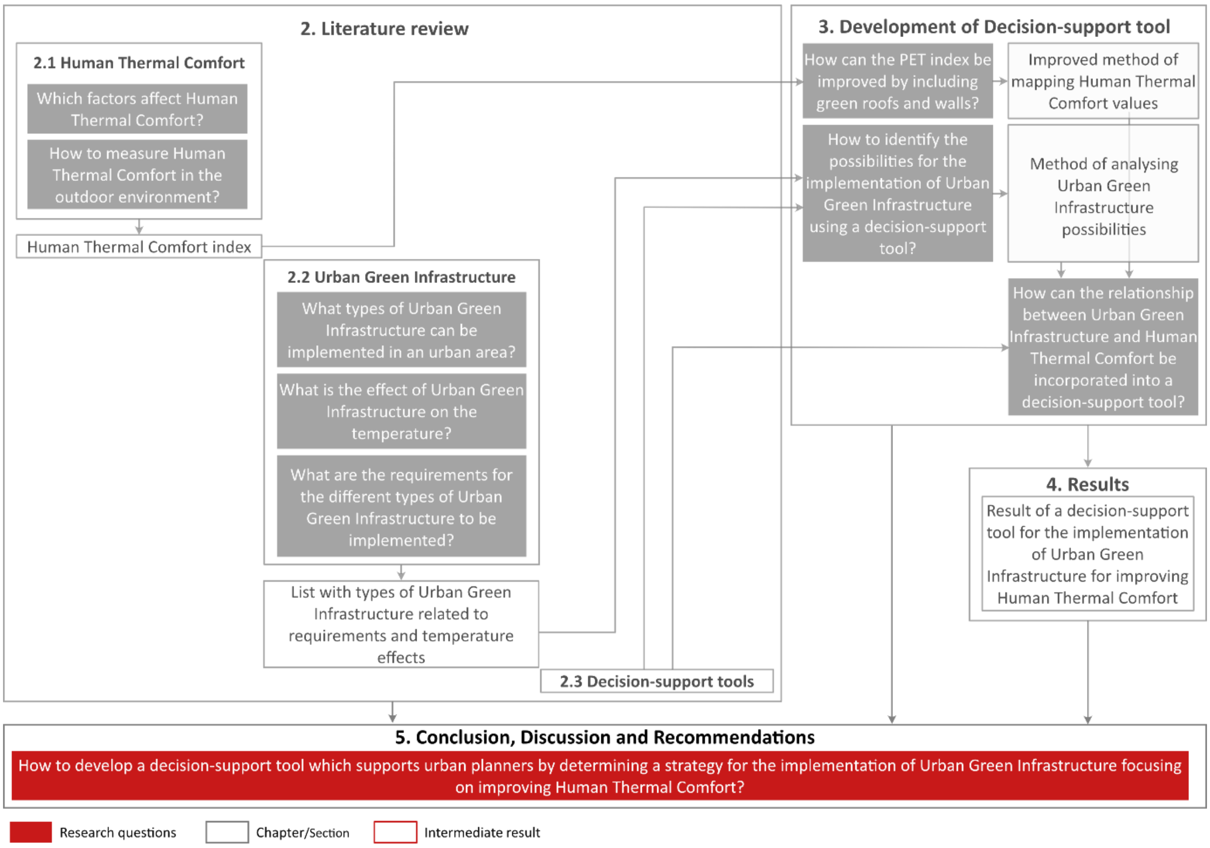


Figure 202: Conclusion, discussion, and recommendations within research design

5.1 Conclusion

From the literature review, it could be concluded that a wide range of factors affect HTC which could be divided into physiological, physical, and psychological. The factors are aspects of the microclimate, UGI, urban fabric, clothing, activity, demographics, and behaviour. Many of these factors can be included in measuring HTC in outdoor environments by using an index calculation. From a comparative analysis between many different indexes, it is concluded that the PET index is the most practical because it is a commonly used index in the outdoor environment; it is a good interpretable index for urban planners by using °C as a unit; it is universally applicable to different climates; and it is chosen as the standard method by the Dutch health organization RIVM.

Based on the literature review, it was concluded that the PET index could use further improvement. Therefore, the PET index is not only included in the decision-support tool but an existing Python algorithm has been expanded to have a better determination of HTC. The existing PET index calculation was missing the vegetation at built structures and therefore, the existing calculation was expanded by including green roofs and green walls in the calculation. It can be stated that green roofs and green walls can be included in the PET index calculation by adjusting the vegetation fraction and Bowen ratio calculation. To create a realistic effect of green roofs and green walls on the PET index, the effect is made dependent on the building height of the buildings. Additionally, the Bowen ratio of green walls is added to create a local effect. The results show that the addition can make a difference in determining HTC. The differences are in line with what can be expected. By adding green roofs and green walls, the HTC value decreases and the differences are at locations where they are expected. However, based on the findings in the literature, it was not expected that the effect of the green walls would be smaller than the effect of green roofs. The reducing effect of green walls is smaller than expected from the literature and overshadowed by the effect of green roofs due to the vegetation fraction calculation which is calculated over the horizontal plane. When also considering the Bowen ratio, a larger effect for green walls is created than for green roofs which is more in line with the literature. Although, this effect is very local and not noticeable in the surroundings. Nevertheless, the adjustments made for including green roofs and green walls in the calculation are of added value because it contributes to a better link between UGI and HTC and provides more insights for urban planners into what the effect is of vegetation at built structures. Furthermore, the overall calculation gives a good impression of what the effect is of adding more vegetation and where heat stress will be experienced.

To identify the possibilities for the implementation of UGI, research has been done to define which types of UGI exist and how to categorize them. The UGI types have been categorized based on types of vegetation including trees, shrubs, and low planting with a distinction between public space and built structures. Furthermore, for the different UGI types, the requirements have been investigated which need to be fulfilled to be able to implement the types in urban areas. A list of requirements is defined including different built environment aspects such as the slope, land availability and building heights and the list is expanded with the related requirement values. Additional investigation of the literature led to the conclusion that UGI affects the temperature in urban areas mainly through shadow and evapotranspiration. The PET index calculation confirms this finding because the addition of green walls had the largest effect caused by the Bowen ratio which represents evapotranspiration. Furthermore, based on the literature, the reducing effects of the different UGI types on the PET are quantified ranging from 0 to 14°C with the largest effect for trees because they create shade.

The findings about UGI in the literature are included in the newly developed decision-support tool by programming a raster analysis for different UGI types which includes the defined requirements. The included requirements are expanded in comparison with existing decision-support tools because this study adds the requirements 'slope of roof', 'amount of street traffic' and 'presence of overhead obstacles'. The different requirements are converted into raster layers which are analysed per UGI type by using self-defined expressions which results in a raster layer which represents where which UGI type is possible. The possibilities are combined into one raster map based on the self-defined priority list, which is based on the effects on the PET concluded from the literature, and minimum value analysis. The combined raster map presents in a presentable manner which UGI type can be best implemented at certain locations. The results confirm that it is possible to identify UGI type possibilities in urban areas with the newly developed decision-support tool which is of added value because it incorporates a more detailed distinction between UGI types, a more extensive list of requirements, and the self-defined priority list in comparison with existing decision-support tools.

The relationship between UGI and HTC can be incorporated into the newly developed decision-support tool by including vegetation in the calculation of the PET index. The index is part of the link between UGI and HTC. The relationship is further incorporated by linking the requirement analysis of UGI types with the PET index calculation by programming a self-defined analysis. Whereas the outcome of the PET index defines where UGI is needed by defining the locations with poor HTC, the requirement analysis defines where UGI is possible. By linking these outcomes, it is possible to define which UGI types can be implemented at locations with poor HTC. Furthermore, bringing these possibilities back into the PET index calculation makes it possible to show the effect of the UGI types on the HTC values. In this way, the decision-support tool can incorporate the relationship between UGI and HTC.

Overall, this study contributes to bringing together the knowledge in the field of UGI and HTC by performing an extensive literature review and by developing a new decision-support tool which incorporates the relationship between UGI and HTC. Although further improvement will be needed, it will already be possible to improve the thermal comfort of people based on this study which will reduce heat stress, increase productivity, and create better health circumstances.

5.2 Discussion

From the literature review, it has become clear that HTC is influenced by more factors than the aspects of the microclimate, UGI and the urban fabric. It is stated that more of the factors should be included in the determination of HTC which partly is also mentioned as improvements of the PET index. As concluded from the literature, the PET index was not the best-developed index to determine HTC. Some other indexes include better elements such as the determination of more realistic clothing insulation. Nevertheless, it is deliberately chosen to work with the PET index because it is in line with the development of the standard heat stress test of the Dutch health organization RIVM. By choosing and developing further the PET index, a more user-friendly decision-support tool is developed because it is an already commonly used index that multiple organizations are familiar with and for other organizations it will be easier to understand. However, more of the limitations of the PET index should be improved to make it as well developed as other indexes. It was not possible to include all possible improvements in the scope of this study.

In line with the improvements of the PET index, the distinction between the UGI types as included in the UGI analysis is not in the same detail defined in the HTC calculation. For example, the difference between open and closed foliage of trees, which have a different temperature effect, is related to the improvement of better calculating the cast shadow of trees. For the link between the UGI analysis and the HTC calculation, it would have been better if the distinction between the different vegetation categories would have been the same. Nevertheless, by implementing green roofs and green walls, a step is taken in this distinction which at least includes all UGI types now in the HTC calculation in a simplified way. More detail in the different UGI types would have made the HTC values more realistic. The same applies to the implementation of green roofs and green walls because no distinction between extensive and intensive green roofs and ground-based and façade-bound is made. Due to simplifying the vegetation of green roofs and green walls, an assumption had to be made for the building height. The assumption is based on the finding in the literature which stated that at a certain height, no effect would be present on the PET index. The same applies to the data of the locations of green walls which is assumed and not in line with reality due to the lack of existing data of green wall locations. Nevertheless, it was possible with the made assumptions to show how the HTC calculation could work by including green roofs and green walls which led to results which are mostly in line with existing literature studies. When in the future, data will be available for the locations of green walls, it should be tested whether this data can be prepared in the same way as is done during this study.

Due to a lack of extended literature about the effect of some UGI types, assumptions are made for the temperature effects of the different UGI types. Based on these assumptions, it is stated that it is not in line with the literature that green walls have a relatively smaller effect on the PET than green roofs. The smaller effect of green walls can be justified by the lack of horizontal surface in the vegetation fraction calculation. Besides the justification, more research should be done to declare with certainty that green walls should have a larger effect than green roofs on the PET index. Based on the same temperature assumptions, the ranking for the UGI type possibilities is made. To have less uncertainty, it would have been better to base the temperature effects on self-made measurements. However, it would have been best to do these measurements in the summertime which was not within the timeframe of this study. When in the future, more measurements are done regarding all UGI types, it may be useful to adjust the ranking. Nevertheless, the applied methodology shows how the decision-support tool can work with the made temperature assumptions which leaves room for improvement in the future.

The same applies to the assumptions made for the requirements of the UGI analysis. Some of the requirements have uncertainty in it and are not based on clearly defined statements, such as the translation of the load of vegetation at built structures into building age. Furthermore, the translation of the requirements into raster layers is based on some assumptions as well, such as the buffer for linear elements and the amount of street traffic. More certainty should be created in the assumptions made. Furthermore, the included requirements should be expanded with more requirements by including the excluded requirements due to lack of appropriate data and to exclude locations such as airports, sports fields and highways from the possibilities. Also, in the current version of the decision-support tool, no distinction is made between public and private space which would be of added value to give more specific advice to urban planners who can steer the public space. Nevertheless, by making the assumptions and by using the current requirements, it is possible to show how different requirements can be analysed which results at most locations in realistic results for possibilities of UGI types on which an urban strategy for the implementation of UGI can be based.

By excluding all cells in the final UGI possibility map that have an HTC value of lower than 41°C, the possibilities are shown for a very local square. Furthermore, by excluding the locations of buildings and water due to the exclusion in the PET calculation, the possibilities for green roofs are excluded from the final possibility map as well. Nevertheless, by also presenting the possibilities per UGI type, it is still possible to see the possibilities in the wider context of a location with high HTC values including green roofs.

In general, the tool consists of multiple components in different environments which leads to a less user-friendly tool and makes it less efficient to move back and forward between the different components of the tool. This study has shown how the tool can work with the different components needed and this could be improved by creating the different components in one environment which would also reduce computational costs. Lastly, it must be stated that the current decision-support tool is focused on the interaction between UGI and HTC to determine the strategy for UGI. Although, the determination of a UGI strategy includes more aspects than HTC alone, such as the influence on air pollution, biodiversity, and water management. Furthermore, not only UGI can affect HTC, but also blue infrastructure and the use of other surface materials influence HTC due to differences in evapotranspiration and albedo. The focus of this study did contribute to a better understanding of the link between UGI and HTC, however, the results of the decision-support tool should be seen in a wider context.

Despite the limitations mentioned, it can be stated that the presented methodology is a suitable starting point for incorporating the relationship between UGI and HTC in a decision-support tool.

5.3 Recommendations

As stated, the study answers the research questions and meets the research aim, however, limitations are mentioned as well which are translated in four main directions for further research:

1. Further research into the temperature effects of the different UGI types.
2. Improving the decision-support tool further with the other concluded improvements of the PET index; excluded factors of HTC; and excluded requirements of UGI from the literature.
3. Developing further the decision-support tool into one environment with less computational costs.
4. Expanding the decision-support tool with other measures for improving HTC and UGI strategy aspects.

By further investigating the temperature effects of the different UGI types, it is possible to remove some uncertainty from the study. It would make it possible to better validate the results from adding green roofs and green walls in the PET index calculation. Furthermore, it would result in more reliable results of the priority ranking of the different UGI types. Therefore, it is relevant to conduct more studies in measuring the temperature effects of the different UGI types.

Expanding the requirements of the UGI analysis with all defined requirements such as hydrology and underground facilities would make the decision-support tool more in line with the real world. The locations which are in the current tool indicated as a possible location for UGI still need further investigation into the presence of underground facilities and water level before definitely can be determined that the UGI type can be implemented. Including all requirements and expanding it further with other requirements would make the tool more reliable.

Expanding the calculation of HTC with the factors that are excluded goes together with improving the PET index calculation with the defined improvement points. The two most important points of further improvement would be to improve the cast shadows of trees and to give more priority to locations with high-risk groups. The cast shadows should be improved because this would make it possible to make a distinction between trees with open and closed foliage which would show a more realistic effect of UGI on HTC. But most importantly would be to be able to give more priority to locations with high-risk groups. A better distinction can be made between different population groups by including demographic characteristics in the PET-index calculation or identifying different PET index scales for different kinds of population groups. It is of relevance because it will give more priority to specific locations which need improvement of the experienced heat stress due to the vulnerable population such as the elderly.

For a more user-friendly decision-support tool, it is relevant to look further into how the different components can be combined in one environment which is easily understandable. Furthermore, it would make it easier to move back and forth between the different components without losing track. For example, by bringing the different components together into a GIS-plugin.

At last, it would be of relevance to expand the decision-support tool by including more measures to improve HTC besides UGI. For example, by including different blue infrastructure and hardening measures such as fountains and white roofs. Measures such as white roofs go together with expanding the PET index calculation with the factor 'Albedo'. Furthermore, expanding the decision-support tool with more aspects of climate change such as the effect of the different measures on air quality, biodiversity and water management would create a tool which makes the different considerations easier for urban planners. Different themes are related to climate change and implementing them in one tool would make it easier to consider the different measures which would contribute to creating more resilient urban areas.

Moreover, based on this study, it is possible to give urban planners recommendations for determining a strategy for implementing UGI for achieving better HTC which decreases heat stress perceived by the population. The recommendations can be summarized in four suggestions:

1. Use the PET index for determining the need for better HTC because it is well-interpretable.
2. Define an extensive list of requirements to be able to define possibilities for UGI.
3. Generate a priority list for UGI types based on assumed PET effects to be able to determine which UGI type can be best implemented at certain locations.
4. Focus on the microclimate to create differences in HTC values at a local scale and expand the scale to a network of UGI through urban areas. This will increase the reducing effect of HTC values which will contribute to an overall decrease in heat stress perceived by the population.

Although the study mentioned opportunities for further research, this study has provided a useful decision-support tool which incorporates the relationship between UGI and HTC by bringing together the knowledge in the field of UGI and HTC. Despite some uncertainty in temperature effects, the tool can be used by urban planners for designing or redeveloping public space with UGI which can give insight into which vegetation category to use based on the list of requirements and priority list. By just starting to use the tool, urban planners can compare different scenarios and they will get a better understanding of HTC and the influence of its factors by using the PET index. The use of the tool by urban planners will contribute to gaining better insight into the missing elements and the need for improvement of the tool. It will contribute to a better link between theory and practice and therefore, the developed tool is a suitable starting point for improving HTC in outdoor environments by implementing UGI in urban areas. The use of the tool will improve the thermal comfort of people which will reduce heat stress, increase productivity, and create better health circumstances for the population in urban areas.

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Appendix A – Comparative Analysis of Human Thermal Comfort Indexes

Table 19: Comparative analysis of indexes

Index	Advantages	Disadvantages	Better than PET? (yes/no, because ...)
PET (Chen & Ng, 2012; Golasi et al., 2018; Höppe, 1999; Knez & Thorsson, 2006; Koopmans et al., 2020; Ruiz & Correa, 2015b; Tseliou et al., 2010; Zhao et al., 2021)	- The outcome is interpretable for urban planning - One of the most used indexes in outdoor environments - Used in different climate regions - It uses °C as the unit - It can be calculated with a high resolution	-It is a static model and does not include dynamic elements, such as a static wind direction and clothing insulation - Not all green infrastructure types are taken into consideration - Cannot predict cast shadows under trees - It does not include albedo	
ASHRAE 55-2016 (Rupp et al., 2015; Zhao et al., 2021)	- An international standard which is generally in use	- Not suitable for the outdoor environment - Not always agreed on the optimal thermal conditions - Does not consider different climates circumstances /comfort ranges - It is a static model	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
ASV (Golasi et al., 2018; Nikolopoulou & Lykoudis, 2006)	- It includes the global temperature which correlates better than the air temperature	- It has a small range - It has for every city a different formula - Weak correlations - Small number of factors included	No, because the PET includes more relevant factors.
Comfa (Kenny et al., 2009a, 2009b; Ruiz & Correa, 2015b; Zhao et al., 2021)	- It includes many factors - Precise in its prediction	- For persons performing at low metabolic rates of activity - It is limited to low wind speeds - Focused on individual and activity	Yes, because according to the research of Ruiz and Correa (2015), the COMFA model is a better predictor than PET. However, it is individual/activity related which does not fit the purpose of the study.

Table 19: Comparative analysis of indexes (continued)

Comfa* (Kenny et al., 2009b)	- Improved clothing insulation and vapour resistance in comparison with COMFA	- Focused on individual and activity	Yes, because according to the research of Ruiz and Correa (2015), the COMFA model is a better predictor than PET. However, it is individual/activity related which does not fit the purpose of the study.
CV (Golasi et al., 2018; Metje et al., 2008)		- More tests are required - Small number of factors included	No, because the PET includes more relevant factors.
Decision Tree (Yang et al., 2022)	- High accuracy (Machine-learning)	- For indoor environments - It is sensitive to overfitting - It is not verified	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
ET* (Nagano & Horikoshi, 2011b, 2011a; Zhao et al., 2021)	- It uses °C as the unit	- Only uses the dry bulb temperature and not the wet bulb temperature	No, because it only includes the dry bulb temperature and this index is already developed further into the ETVO.
ETFe (Kurazumi, Fukagawa, et al., 2011; Kurazumi, Tsuchikawa, et al., 2011; Zhao et al., 2021)	- It is the corrected ETF by including solar radiation which makes it applicable to outdoor environments - It can give separate effects for factors and the universal effect - Does consider heat conduction	- Only useful for uniform conditions	Yes, it is better than the PET but already developed further into the ETU
ETU (Nagano & Horikoshi, 2011b; Rupp et al., 2015; Zhao et al., 2021)	- Useful for non-uniform situations, but also in indoor, outdoor and uniform situations - It can give separate effects for factors and the universal effect - Does consider heat conduction		Yes, because it can consider separate effects, heat conduction and non-uniform conditions which the PET is not able to.
ETVO (Nagano & Horikoshi, 2011a, 2011b; Rupp et al., 2015; Zhao et al., 2021)	- It can give separate effects for factors and the universal effect - It uses °C as the unit	- Only useful for uniform conditions	Yes, because it can consider separate effects which PET is not able to.

Table 19: Comparative analysis of indexes (continued)

GOCI (Golasi et al., 2018; Zhao et al., 2021)	- It considers differences between regions - Can be used for regions where no specific index is for - Can be used for different population groups	- Only validated in one city	Yes, according to Golasi (2018), PET is less predictive than GOCI. But, it also concludes that it is useable for regions with no specific index and is just validated in one city.
ISO 7730 (Rupp et al., 2015; Salata, Golasi, De Lieto Vollaro, De Lieto Vollaro, 2016; Zhao et al., 2021)		- Only for uniform indoor environments - Does not consider different climate circumstances /comfort ranges - It is a static model	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
IZA (Golasi et al., 2018; Ruiz & Correa, 2015b, 2015a)	- High predictive ability - Useful for assessing a public space	- Only for Arid zones - Small number of factors included	No, because the Netherlands is no arid zone and the index is too specifically oriented to this. Furthermore, the PET includes more relevant factors.
K (Tseliou et al., 2010)		- Poor performance in comparison with other indexes - It is wind-oriented - Only accurate within certain limits	No, because according to Tseliou et al (2010), PET performs better and it does not fit the purpose of the study.
Klima-Michel-Model (Golasi et al., 2018; Jendritzky & Nübler, 1981; Zhao et al., 2021)	- Useable for urban planners	- Only useable for steady-state environments - Small number of factors included	No, because the PET includes more relevant factors.
K-Nearest Neighbour (Xiong & Yao, 2021; Yang et al., 2022; Zhao et al., 2021)	- High accuracy and efficiency (Machine-learning) - An adaptive model	- Only for indoor environments - It requires much data	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
MDI (Moran et al., 1998)		- It only includes two factors	No, because the PET includes more relevant factors.

Table 19: Comparative analysis of indexes (continued)

MEMI (Golasi et al., 2016; Höppe, 1999; Zhao et al., 2021)	- It uses °C as the unit	- Already developed further into the PET index	No, because PET is based on this model and so an improvement.
MOCI (Golasi et al., 2016, 2018; Salata et al., 2016)	- Better predicter than GOCI and PET	- Only for Mediterranean locations	No, because the Netherlands is no Mediterranean environment and the index is too specifically oriented to this.
mPET (Chen & Matzarakis, 2018; Golasi et al., 2018)	- It includes a multi-layer clothing model - It has a changing clothing insulation - It has an improved thermoregulation model - It uses °C as the unit	- It is complex	Yes, according to Chen & Matzarakis (2018), it has a more realistic estimation of HTC than PET.
Multi-node model (Rupp et al., 2015; Zhao et al., 2021)	- It includes an active and passive system	- It is only accurate in steady-state environments - It is already developed further - Developed for indoor environments	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
Naïve Bayes (Yang et al., 2019; Zhao et al., 2021)	- High accuracy (Machine-learning)	- Only for indoor environments	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
OUT_SET* (Nagano & Horikoshi, 2011a; Pickup & De Dear, 2000; Zhao et al., 2021)	- It uses °C as the unit	- Not specifically developed for an urban environment but for an open field	No, because the PET includes more factors and is useful for urban areas.
Vinje's Comfort Index (Ruiz & Correa, 2015b)		- It is only applicable between 0 and 20°C - It only includes two factors	No, because the PET includes more relevant factors.

Table 19: Comparative analysis of indexes (continued)

PMV (Fanger, 1972; Golasi et al., 2018; Ruiz & Correa, 2015b; Rupp et al., 2015; Zhao et al., 2021)	- It includes a passive and active system - It is the basic model for the rest	- Used for indoor and steady-state environments - It is not a good predictor of the overall body sensation - It has parameters limits	No, because it is developed for air-conditioned buildings and has a significant deviation from the thermal votes in outdoor environments.
PMV-PPD (Fabbri, 2013; Fanger, 1972; Rupp et al., 2015)	- It gives the percentage of people feeling uncomfortable in the environment	- Used for indoor and steady-state environments	No, because it is developed for air-conditioned buildings and has a significant deviation from the thermal votes in outdoor environments.
Random Forest (Yang et al., 2022; Zhao et al., 2021)	- High accuracy (Machine-learning) - Aggregates small and weak models into strong and large models	- Only for indoor environments	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
STI (Farajzadeh et al., 2015)		- Expressed in mean radiant temperature - Weak correlation with UTCI and PET (relatively high values)	No, according to Farajzadeh et al. (2015), PET is predicting better results. Furthermore, the PET includes more relevant factors.
Support Vector Machine (Yang et al., 2022; Zhao et al., 2021; Zhou et al., 2020)	- Highest accuracy (Machine-learning)	- Only for indoor environments	No, because it cannot be used for the purpose of this study because only useful for indoor environments.
TEP (Johansson et al., 2013; Monteiro & Alucci, 2011)		- Developed for São Paulo (subtropical climate) and is not universal for other climates and cultures.	No, because no universal index which is not suitable for the Netherlands. Furthermore, the PET includes more relevant factors.

Table 19: Comparative analysis of indexes (continued)

THI (Clarke & Bach, 1971; Giles et al., 1990; Manos, 1959; Ruiz & Correa, 2015b; Tseliou et al., 2010)	- It is developed for the design of cities - It is usable for comfort on streets	- It only includes two factors - It is only tested in Argentina	No, because the PET includes more relevant factors.
TS (Gaitani et al., 2007; Givoni, Noguchi, Saaroni, Pochter, Yaakov, Feller & Becker, 2003; Ruiz & Correa, 2015b)	- It shows a difference in effect when greenery or water is added to the scenario - It is including the surrounding soil temperature	- It has a low predictive ability	Yes, because it includes the surrounding soil temperature. But, it has a low predictive ability.
TSP (Golasi et al., 2018; Monteiro & Alucci, 2009)	- It is a simple and reliable index	- It is developed for sub-tropical environments	No, because the Netherlands is no sub-tropical environment and the index is too specifically oriented to this.
Two-node model (Foda & Sirén, 2011; Kaynakli & Kilic, 2005; Zhao et al., 2021; Zolfaghari & Maerefat, 2010)	- It includes an active and passive system	- It simplifies the human body into two segments - It is only accurate in steady-state environments - It is already developed further - Developed for man and indoor environments	No, because it cannot be used for the purpose of this study because only useful for indoor environments.

Table 19: Comparative analysis of indexes (continued)

UTCI (Blazejczyk et al., 2012; Bröde, Krüger, Rossi & Fiala, 2012; Chen & Matzarakis, 2018; Golasi et al., 2018; Jendritzky, De Dear & Havenith, 2012; Nagano & Horikoshi, 2011a, 2011b)	- It uses °C as the unit - It is valid in all climates - It has a varying clothing model - It is suitable for an urban planning tool	- It only has a universal effect - It cannot be applied to non-uniform environments - It has limitations to the input factors.	No, according to Golasi et al. (2018), the PET index has more correct predictions. However, Blazejczyk et al. (2012) conclude something else because it includes a better clothing insulation model than the PET.
WBGT (Budd, 2008; Clarke & Bach, 1971; Jendritzky et al., 2012; Pötz, 2016)	- It is popular for the consideration of humidity and thermal radiation in warm environments	- It is built for direct measurements of environmental factors - It is developed for the heat stress of hard workers - It includes a small number of factors - It is only useful as a general index	No, because the PET includes more relevant factors.

Appendix B – SVF calculation explanation

This Appendix will explain the formulas of the Sky-View Factor (SVF). The Digital Surface Model (DSM) data source is used as input for creating the SVF layer. The DSM data source is a raster map with the heights of the surfaces with respect to the Normal Amsterdam Level (NAP) (Rijkswaterstaat, n.d.). The SVF is simply said the fraction of the sky visible from the horizon and depends on the height of objects in the surroundings (see Figure 203) (Dirksen et al., 2019). The SVF has a value between 0 and 1 whereby 1 means that no hindrance from objects is present to see the whole sky, for example, on top of a mountain (see Figure 204).

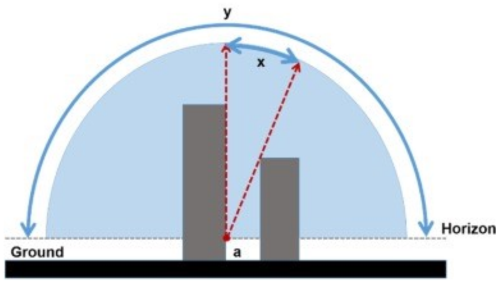


Figure 203: Sky-View Factor explanation (Zhang et al., 2019)

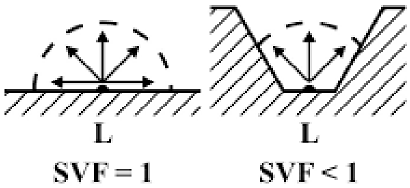


Figure 204: Sky-View Factor value explanation (Hämmerle et al., 2011)

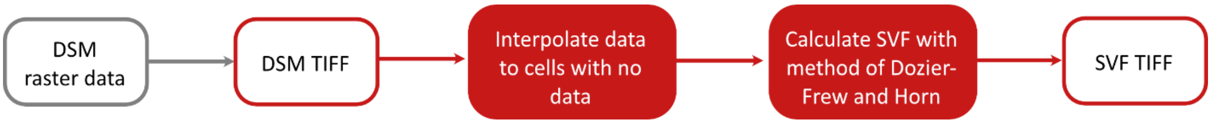


Figure 205: Creating input data SVF

The SVF layer is created by the existing PET index algorithm as presented in Figure 205. The SVF is calculated by the method of Dozier-Frew and the gradient for the slope and aspect is calculated by the method of Horn. The methods are explained by Van der Linden (2021) and the formula for the method of Dozier-Frew is as follows:

$$SVF = \frac{1}{N}\sum_{i=1}^{N}[\cos S\, sin^2 H_\phi + \sin S \cos(\phi - A) * (H_\phi - \sin H_\phi cos H_\phi)]$$

Including:

- N = The number of iterations
- S = Slope
- A = Aspect (The direction of the slope in degrees, Figure 206)
- H_ϕ = Altitude (Figures 207 and 208)
- ϕ = Angle of the azimuth (Figures 207 and 209)

The gradient for the slope and aspect are calculated in eight directions with the method of Horn with the following formulas:

$$\frac{dz}{dx} = \frac{[(c + 2f + i) - (a + 2d + g)]}{8\Delta stepsize}$$

$$\frac{dz}{dy} = \frac{[(g + 2h + i) - (a + 2b + c)]}{8\Delta stepsize}$$

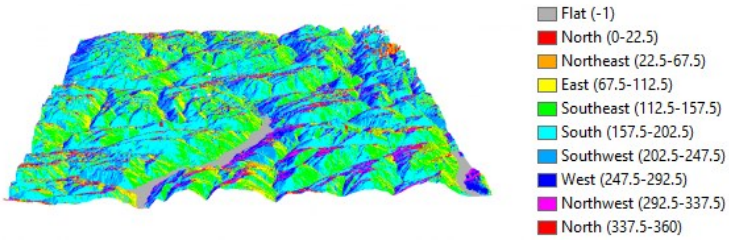


Figure 206: The aspect explanation (GISGeography, 2022b)

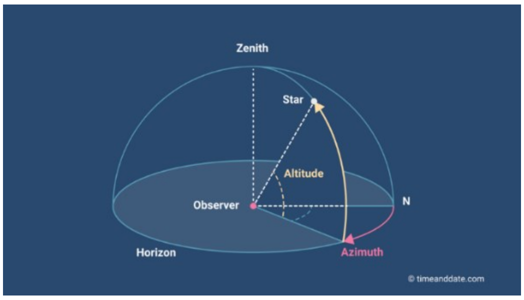


Figure 207: Horizontal coordinate system (Bikos, 2023)

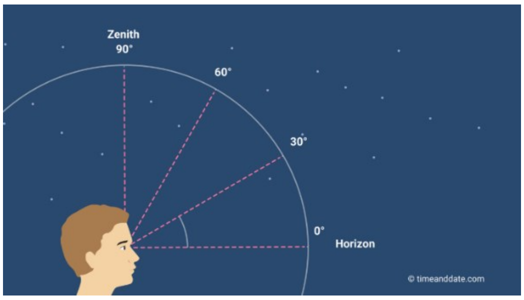


Figure 208: The altitude explanation (Bikos, 2023)

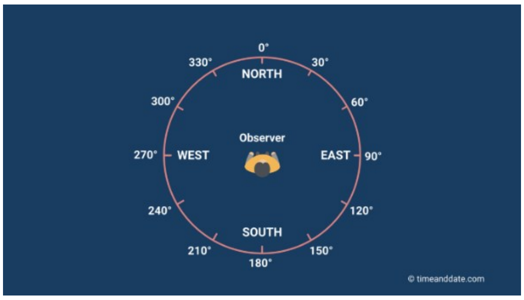


Figure 209: The angle of azimuth explanation (Bikos, 2023)

Appendix C – PyQGIS script for creating input data HTC calculation

```
from qgis import processing

#Adding input data (already clipped to right box and set to right CRS)
fn_water ='D:/Data afstuderen/DATA_PET/Input data/water rotterdam.gpkg'
Water = iface.addVectorLayer(fn_water, 'Water', 'ogr')

fn_buildings ='D:/Data afstuderen/DATA_PET/Input data/\
buildings rotterdam.gpkg'
Buildings = iface.addVectorLayer(fn_buildings, 'Buildings', 'ogr')

fn_green = 'D:/Data afstuderen/DATA_PET/Input data/groen clip.gpkg'
Green = iface.addVectorLayer(fn_green, 'Green', 'ogr')

fn_rgb ="D:/Data afstuderen/DATA_PET/Luchtfoto's/RGB clip.tif"
RGB_clip = iface.addRasterLayer(fn_rgb, 'RGB')

fn_infrared = "D:/Data afstuderen/DATA_PET/Luchtfoto's/Infrarood clip.tif"
Infrared_clip= iface.addRasterLayer(fn_infrared, 'Infrared')

#Add Height layer (calculated from algorithm)
fn_height = 'D:/Data afstuderen/DATA_code/PET_tiles_Rotterdam/Rotterdam/\
height_1m.tif'
Height = iface.addRasterLayer (fn_height, 'height')

#Setting general settings data preparation
extent = QgsRectangle(84000.00,429000.00,103000.00,447000.00)
width = 19000
height = 18000
CRS = QgsCoordinateReferenceSystem('EPSG:28992')

#Preparing Input data
#Rasterizing buildings
Raster_buildings = 'D:\Data afstuderen\DATA_PET\Tussenstappen tiles\
\Buildings1.tif'
Buildings_output = 'D:\Data afstuderen\DATA_code\PET_tiles_Rotterdam\
\Rotterdam\Buildings.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_buildings, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : -999999999, 'OPTIONS' : '',
 'OUTPUT' : Raster_buildings, 'UNITS' : 0, 'USE_Z' : False})

processing.run("native:rasterlogicalor",
```

```
{'INPUT': Raster_buildings, 'OUTPUT': Buildings_output,
 'REF_LAYER': Raster_buildings, 'DATA_TYPE': 5, 'NODATA_AS_FALSE': True,
 'NO_DATA': -9999})

#Add Building layer
Buildings_layer = iface.addRasterLayer(Buildings_output, 'Buildings')

#Rasterizing water
Raster_water = 'D:\Data afstuderen\DATA_PET\Tussenstappen tiles\Water1.tif'
Water_output = 'D:\Data afstuderen\DATA_code\PET_tiles_Rotterdam\Rotterdam\
\Water.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_water, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : -999999999, 'OPTIONS' : '',
 'OUTPUT' : Raster_water, 'UNITS' : 0, 'USE_Z' : False})

processing.run("native:rasterlogicalor",
{'INPUT': Raster_water, 'OUTPUT': Water_output, 'REF_LAYER': Raster_water,
 'DATA_TYPE': 5, 'NODATA_AS_FALSE': True, 'NO_DATA': -9999})

#Add Water layer
Water_layer = iface.addRasterLayer(Water_output, 'Water')

#Rasterizing Green
Raster_green = 'D:\Data afstuderen\DATA_PET\Tussenstappen tiles\Green1.tif'
Green_output = 'D:\Data afstuderen\DATA_code\PET_tiles_Rotterdam\Rotterdam\
\Green.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_green, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : -999999999, 'OPTIONS' : '',
 'OUTPUT' : Raster_green, 'UNITS' : 0, 'USE_Z' : False})

processing.run("native:rasterlogicalor",
{'INPUT': Raster_green, 'OUTPUT': Green_output, 'REF_LAYER': Raster_green,
 'DATA_TYPE': 5, 'NODATA_AS_FALSE': True, 'NO_DATA': -9999})

#Add Green layer
Green_layer = iface.addRasterLayer(Green_output, 'Green')

#Calculate NDVI
NDVI_output = "D:\\Data afstuderen\\DATA_code\\PET_tiles_Rotterdam\\Rotterdam\
\\ndvi_1m.tif"

processing.run("qgis:rastercalculator",
```

```
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Infrared@1" - "RGB@1") / ("Infrared@1" + "RGB@1")',
 'EXTENT' : extent, 'LAYERS' : None, 'OUTPUT' : NDVI_output})

#Add NDVI layer
NDVI = iface.addRasterLayer(NDVI_output, 'NDVI')

#Calculate Trees
Raster_trees = "D:\Data afstuderen\DATA_PET\Tussenstappen tiles\Trees1.tif"
Trees_output = 'D:\Data afstuderen\DATA_code\PET_tiles_Rotterdam\Rotterdam\
\Trees.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"NDVI@1">0.16 AND "height@1">=2',
 'EXTENT' : extent, 'LAYERS' : None, 'OUTPUT' : Raster_trees})

processing.run("native:rasterlogicalor",
{'INPUT': Raster_trees, 'OUTPUT': Trees_output, 'REF_LAYER': Raster_trees,
 'DATA_TYPE': 5, 'NODATA_AS_FALSE': True, 'NO_DATA': -9999})

#Add Trees layer
Trees = iface.addRasterLayer(Trees_output, 'Trees')

#Calculate Green roofs
Greenroof_output = "D:\Data afstuderen\DATA_code\PET_tiles_Rotterdam\
\Rotterdam\Greenroof.tif"

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"NDVI@1">0.16 AND "Buildings@1"=1',
 'EXTENT' : extent, 'LAYERS' : None, 'OUTPUT' : Greenroof_output})

#Add Greenroof layer
Greenroof = iface.addRasterLayer(Greenroof_output, 'Greenroof')

#Create Green walls
#Select 1% of buildings
Selected_buildings = "D:\Data afstuderen\DATA_PET\Tussenstappen tiles\
\SelectedBuildings.gpkg"

processing.run("native:randomextract",
{'INPUT' : fn_buildings, 'METHOD' : 1, 'NUMBER' : 1,
 'OUTPUT': Selected_buildings})

#Rasterize selected buildings
Raster_selected_buildings = "D:\Data afstuderen\DATA_PET\
\Tussenstappen tiles\SelectedBuildings.tif"
```

```
processing.run("gdal:rasterize",
{'INPUT' : Selected_buildings, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : -999999999, 'OPTIONS' : '',
 'OUTPUT' : Raster_selected_buildings, 'UNITS' : 0, 'USE_Z' : False})

#Create 1m buffer around selected buildings
Raster_Buffer = "D:\Data afstuderen\DATA_PET\Tussenstappen tiles\
\GreenwallBuffer.tif"

processing.run("grass7:r.buffer",
{'-z' : False, 'GRASS_RASTER_FORMAT_META' : '',
 'GRASS_RASTER_FORMAT_OPT' : '', 'GRASS_REGION_CELLSIZE_PARAMETER' : 1,
 'GRASS_REGION_PARAMETER' : extent, 'distances' : '1',
 'input' : Raster_selected_buildings, 'output' : Raster_Buffer, 'units' : 0})

GreenwallBuffer = iface.addRasterLayer(Raster_Buffer, 'Greenwall Buffer')

#Calculate Green walls
Raster_greenwall = "D:\Data afstuderen\DATA_PET\Tussenstappen tiles\
\Greenwall1.tif"
Greenwall_output = "D:\Data afstuderen\DATA_code\PET_tiles_Rotterdam\
\Rotterdam\Greenwall.tif"

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Greenwall Buffer@1"=2',
 'EXTENT' : extent, 'LAYERS' : None, 'OUTPUT' : Raster_greenwall})

processing.run("native:rasterlogicalor",
{'INPUT': Raster_greenwall, 'OUTPUT': Greenwall_output,
 'REF_LAYER': Raster_greenwall, 'DATA_TYPE': 5, 'NODATA_AS_FALSE': True,
 'NO_DATA': -9999})

#Add Greenwall layer
Greenwall = iface.addRasterLayer(Greenwall_output, 'Greenwall')
```

Appendix D – Schemes of PET index calculations

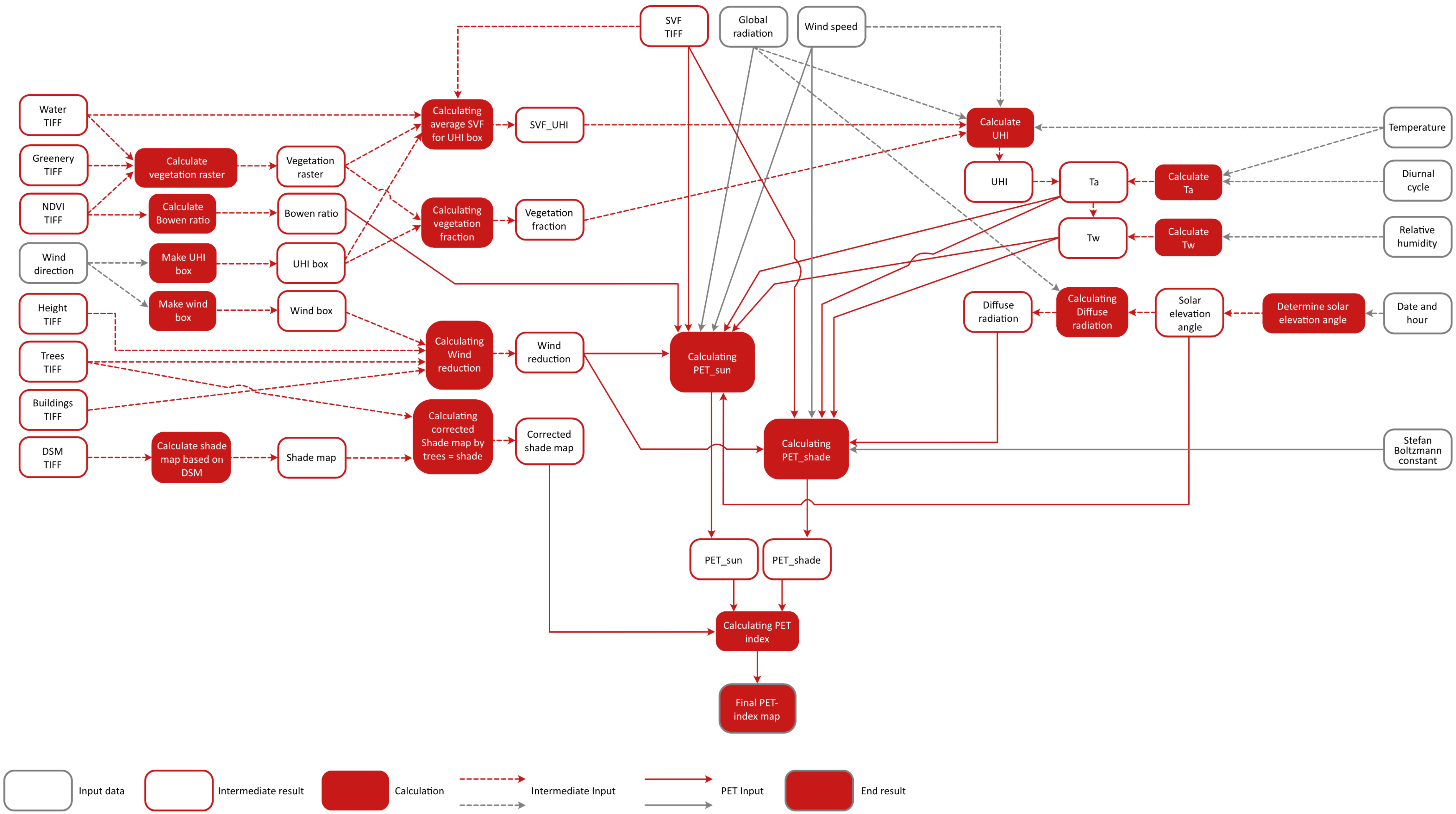


Figure 210: Existing PET index calculation scheme

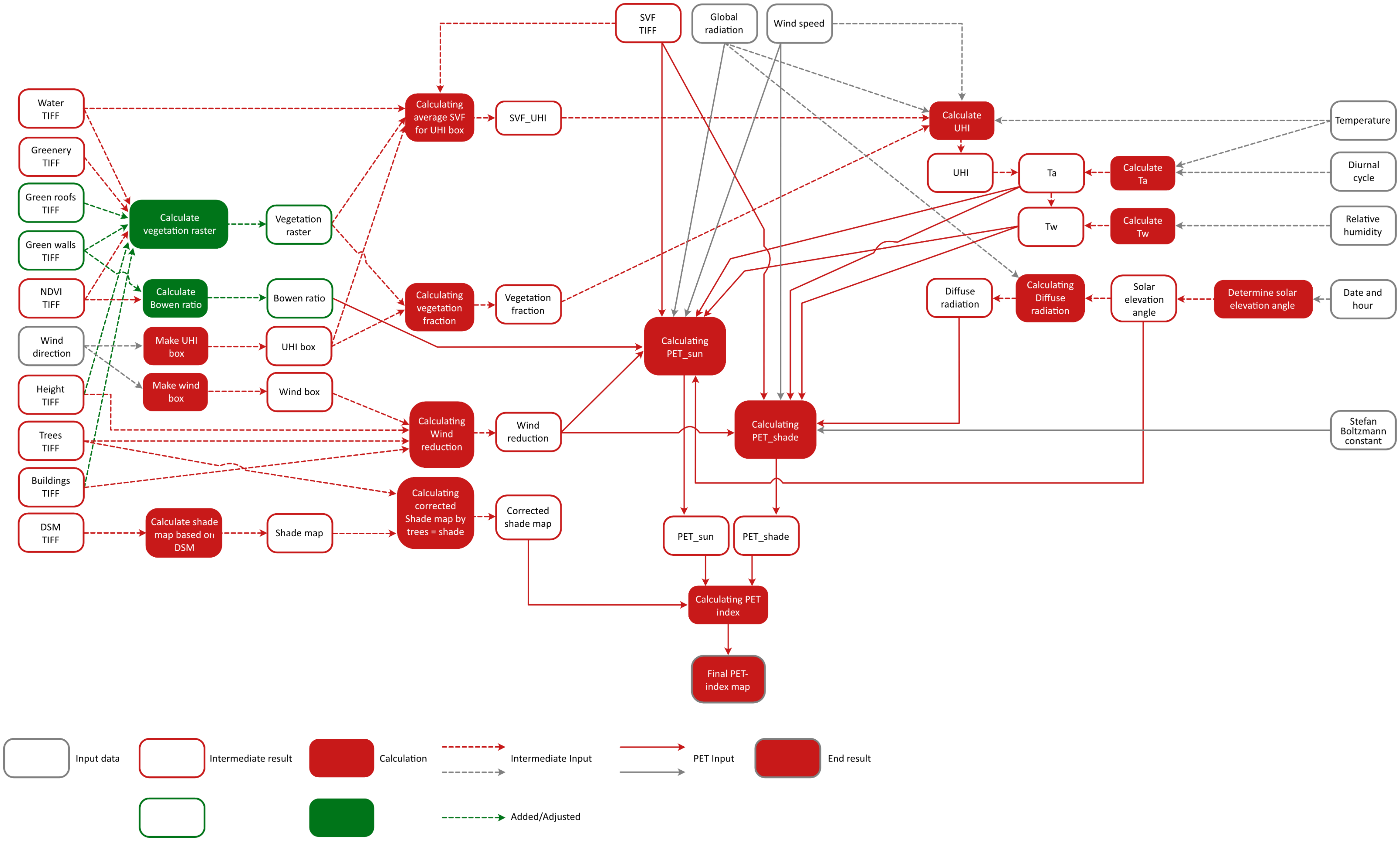


Figure 211: Adjusted PET index calculation scheme

Appendix E – Existing HTC calculation explanation

This Appendix will explain the existing calculation in more detail as developed by Koopmans et al. (2020). The calculation of the PET index starts with calculating the Urban Heat Island (UHI) effect (Figure 212).

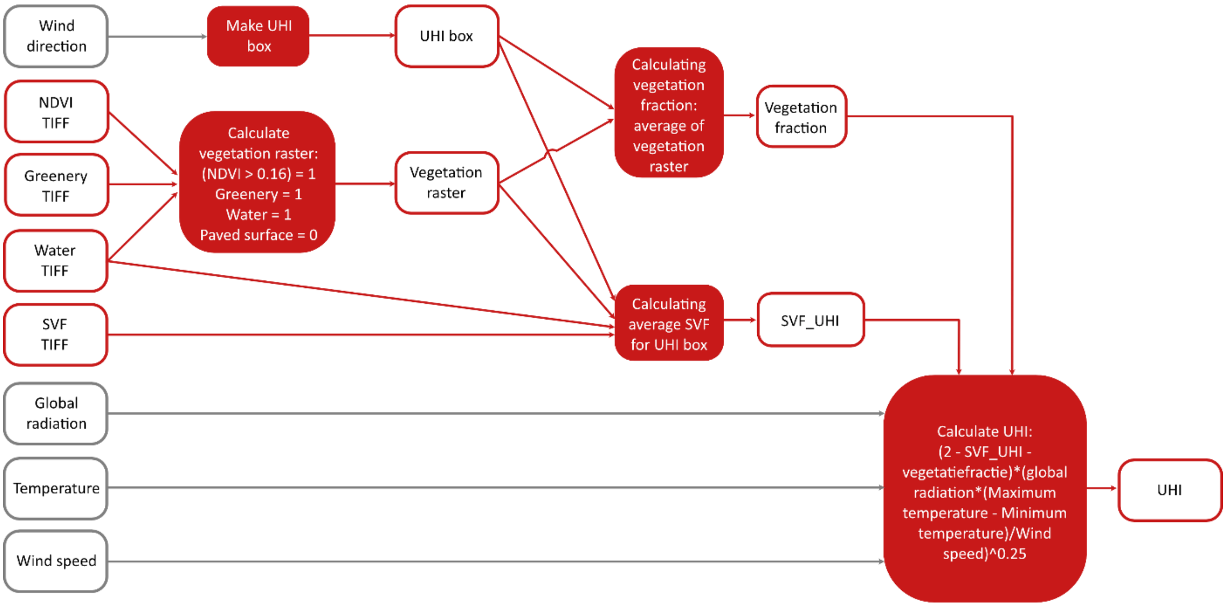


Figure 212: Calculating UHI effect

The UHI effect is calculated with the following formula:

$$\text{UHI} = \left(2 - S_{vf} - F_{veg}\right)\sqrt[4]{\frac{S^{\downarrow} * (T_{max} - T_{min})^3}{U}}$$

Including:

- S_{vf} = the spatially averaged Sky-View Factor (SVF_UHI)
- F_{veg} = the vegetation fraction
- $S^{\downarrow}$ = Mean downward shortwave radiation in K/ms (Global radiation)
- T_{max} & T_{min} = the maximum and minimum temperature
- U = the mean wind speed

For this calculation, a UHI box is created to be able to calculate the vegetation fraction and average Sky-View Factor (SVF_UHI) over an area of 500 x 1100 meters in relation to the wind direction, see Figure 213 (Koopmans et al., 2020).

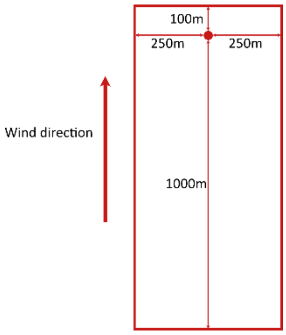


Figure 213: The UHI box

The vegetation fraction is calculated by first determining the vegetation raster which provides information regarding where vegetation is present in a raster with a cell size of 1m. The vegetation raster is calculated by using NDVI, greenery and water as input layers. As stated, NDVI > 0.16 is used as a threshold value to identify vegetation. However, when this is used as a threshold value then cropland may not always be indicated as vegetation because, during some periods of the year, cropland is bare. Bare cropland does not have the same heat capacity as paved surfaces and therefore, it needs to be identified as vegetation (Koopmans et al., 2020). Therefore, greenery is also used as an input layer which also includes the locations of cropland. Furthermore, water is a complicated factor in the vegetation fraction because it has a high heat capacity but it also evaporates. Therefore, water is assumed as vegetation during daytime and as a paved surface during the night. So, the vegetation raster is calculated by setting all NDVI > 0.16, greenery and water locations as vegetation during daytime and all NDVI > 0.16 and greenery locations as vegetation during the night by giving these locations value 1 in the raster layer. The rest of the locations are assigned as paved surfaces and get a value of 0. The resulting vegetation raster is then averaged over an area of 500 x 1100 meters which conforms to the interaction between land use and urban temperature (Koopmans et al., 2020). The averaged vegetation values result in the vegetation fraction.

The average Sky-View Factor (SVF_UHI) is calculated by first excluding some locations. Water is excluded from the SVF_UHI because SVF_UHI cannot be identified for water. Furthermore, buildings and vegetation are excluded to be able to calculate the air temperature in a later state with less uncertainty. All these locations of water, buildings and vegetation are set as missing values in the average Sky-View Factor calculation. Then the average is calculated over the UHI box by stating that if more than 90% of the cell has no data that the whole cell is set as a missing value.

Now, the UHI effect can be calculated by filling in the formula. The mean downward shortwave radiation is calculated as the average of all global radiation values in the weather data excel-file from 8 o'clock on the day of calculation till 7 o'clock on the next day. Over the same time period, the maximum and minimum temperature is picked and the average mean wind speed at 10 m is calculated.

After the UHI effect has been calculated, the wind reduction is calculated (Figure 214). This calculation is done because the weather stations are standing in open terrain and in urban areas, a reduction is present due to buildings and trees.

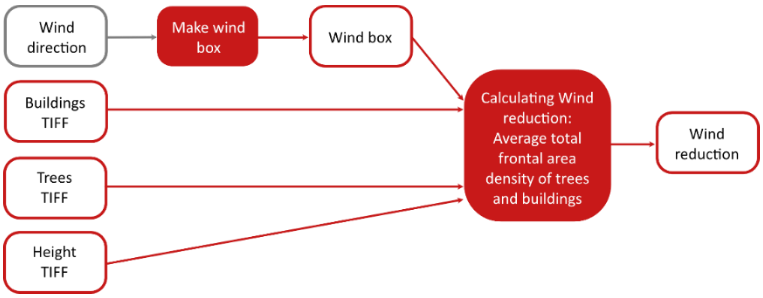


Figure 214: Calculating wind reduction

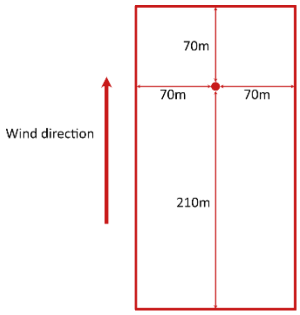


Figure 215: The wind box

For this calculation, a wind box is created to be able to average the building and tree height over an area of 280 x 140 meters in relation to the wind direction, see Figure 215 (Koopmans et al., 2020). The box has these dimensions because that is in line with the urban density of the Netherlands as explained by Koopmans et al. (2020).

For the calculation, it is first separately determined what the average building and tree height is in an area of 280 x 140 meters. The perpendicular frontal areas are separately calculated with the average height for buildings and trees. When the frontal area is determined, then the frontal area density is separately calculated for buildings and trees by dividing the total frontal area by the area of 280 x 140 meters. Then, the total frontal area density is calculated by the following formula:

$$\lambda_{tot} = 0.6\lambda_{buildings} + 0.3\lambda_{trees} + 0.015$$

Including:

- λ_{tot} = total frontal area density of trees and buildings
- $\lambda_{buildings}$ = frontal area density of buildings
- λ_{trees} = frontal area density of trees

The coefficients are determined by assuming that the crown area of a tree is 55% of a rectangular shape and that trees have a smaller reducing effect by trees due to porosity. So, it is determined that the coefficient of trees is half of the coefficient of buildings. The 0.015 is added because larger frontal areas can have more chance that the buildings and trees keep each other out of the wind. This total frontal area density is used to translate the wind speed of the weather station at 10 meters high to a wind speed in urban areas at 1.2 meters high.

Subsequently, the Bowen ratio is calculated which is the ratio between sensible and latent heat flux and it tells something about the evapotranspiration of surfaces such as vegetation. The lower the value, the better the evapotranspiration of the surface. It is stated that paved surfaces have a value of 3 and well-evaporating vegetation has a value of 0.4 (Koopmans et al., 2020). It is stated that locations with an NDVI of 0.16 or larger are well-evaporating vegetation and have a value of 0.4 and all other locations get a value of 3 (Figure 216).

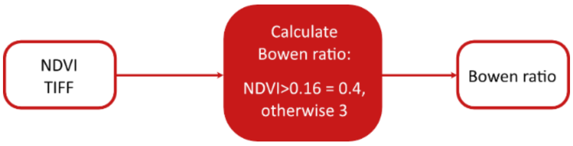


Figure 216: Calculating Bowen ratio

The last intermediate calculation step is the calculation of the shade map with DSM and trees as input layers. First, the shade map is calculated with the DSM layer and the UMEP GIS tool. By applying the tool, it is possible to calculate the shadow for all solar elevation angles during the day and season. After the calculation, the shade map is corrected by stating that shadow is present under trees because the tool is not able to calculate the shadow at these locations.

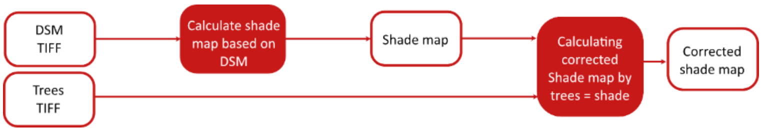


Figure 217: Calculating corrected shade map

After that the UHI effect including the vegetation fraction, shade map, Bowen ratio and wind reduction have been calculated as intermediate maps, the air temperate (T_a) and wet-bulb temperature (T_w) are calculated.

The formulas are:

$$T_a[h] = T_{refstation} + UHI_{max} * diurnal\_cycle[h]$$

$$T_w = T_a \operatorname{atan}(0.151977(\phi + 8.313659)^{0.5}) + \operatorname{atan}(T_a + \phi) - \operatorname{atan}(\phi - 1.676331) + 0.00391838\phi^{\left(\frac{3}{2}\right)} \operatorname{atan}(0.023101\phi) - 4.686035$$

Including:

- $T_{refstation}$ = the temperature of the weather station
- UHI_{max} = the intermediate calculated UHI effect
- Diurnal_cycle = the cycle of the weather during the day under the influence of the sun
- T_a = the calculated air temperature
- ϕ = the relative humidity

The temperature of the weather station is corrected with the UHI effect because the temperature in urban areas is mostly higher than in rural areas. It is stated that the UHI effect is at maximum 4 hours after sunset and is therefore corrected with a factor determined by the diurnal cycle. The factor is between 0.02 and 1 depending on the time of the day. By filling in the formula, the air temperature is calculated for the preferred hour. The relative humidity, from the weather data in the Excel file, is used to calculate the wet-bulb temperature at the preferred hour.

Based on the intermediate calculated parts, the PET index can be calculated by making a distinction between shadow and sun locations. PET_{sun} and PET_{shade} are calculated with the following formulas:

$$PET_{sun} = -13.26 + 1.25T_a + 0.011Q_s - 3.37\ln(u_{1.2}) + 0.078T_w + 0.0055Q_s\ln(u_{1.2}) + 5.56\sin(\varphi) + 0.546B_b + 1.94\,S_{vf}$$

$$PET_{shade,night} = -12.14 + 1.25T_a - 1.47\ln(u_{1.2}) + 0.060T_w + 0.015S_{vf}Q_d + 0.0060(S_{vf})\sigma(T_a + 273.15)^4$$

Including:

- T_a = the calculated air temperature
- Q_s = solar irradiation (Global radiation)
- $U_{1.2}$ = wind speed at 1.2 m height (Wind speed x Wind reduction)
- T_w = the calculated wet-bulb temperature
- σ = the Stefan Boltzmann constant of 5.67 * 10^{-8} W/m^2/K
- φ = solar elevation angle
- B_b = the calculated Bowen ratio
- S_{vf} = Sky-View Factor (SVF)
- Q_d = diffuse radiation

Solar irradiation is the global radiation from the weather data Excel file and is picked for the preferred hour. The wind speed at 1.2 m height is calculated by multiplying the mean wind speed and the wind reduction that is calculated. The solar elevation angle is based on the date and hour of the day. The Sky-View Factor is the SVF input data layer. The diffuse irradiation is calculated with the global radiation from the weather data and the solar elevation angle, with the following formula (τ_a = atmospheric transmissivity):

$$\tau_a = \frac{Q_s}{1367 \sin(\varphi)}$$

It is stated that:

- if τ_a is smaller than 0.3 then $Q_d = Q_s$
- if τ_a is between 0.3 and 0.7 then $Q_d = (1.6 - 2 * \tau_a) * Q_s$
- if τ_a is larger than 0.7 then $Q_d = 0.2 * Q_s$

When PET_{sun} and PET_{shade} have been calculated, then the PET index can be determined by giving all shadow locations the value of PET_{shade} and all other locations the value of PET_{sun} based on corrected the shade map. If it is night then all locations get the value of PET_{shade}. These calculation steps are done for every hour in a defined time period and at the end, all calculated PET index maps are averaged to create one final PET index map.

The calculation is based on a standardized person who is defined as a male, 35 years old, 1.75m, 75 kg, clothing insulation of 0.9 clo and performing walking with a speed of 4 km/h as metabolic rate. The standardized person determines the different PET index classes and those indicate that moderate heat stress can be experienced with a PET of 29°C or higher, see Figure 218.

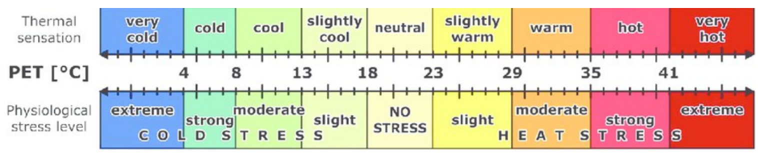


Figure 218: The PET index scale (Kántor, 2016)

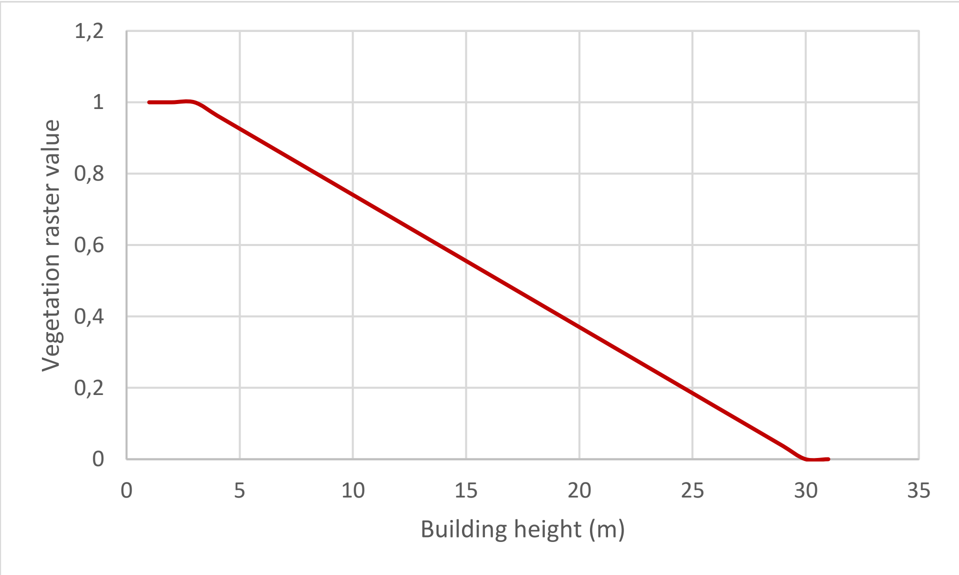
Appendix F – Explanation of the formulas for green roofs and walls in HTC

This Appendix explains the vegetation raster value formulas for green roofs and green walls.

<u>The linear function of the green roofs for the vegetation raster value:</u>
A linear function has a standard form of $y = ax + b$.

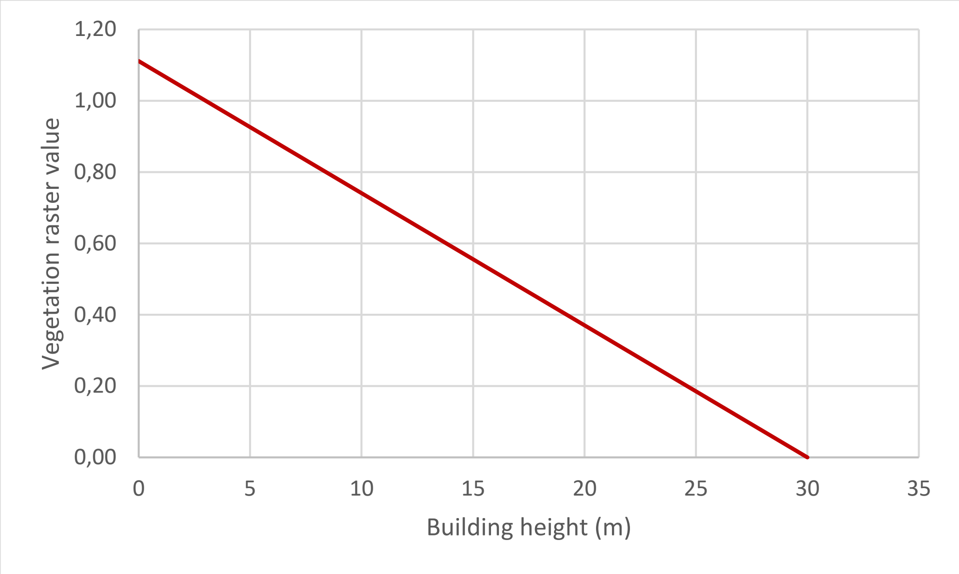
a = the slope of the graph
b = the intersection with x = 0
y = vegetation raster value
x = building height

The graph can be drawn by stating that $y = 1$ when $0 \leq x \leq 3$ and $y = 0$ when $x > 30$.
In between a linear decreasing graph can be defined.



$a = \Delta y/\Delta x$
$a = (0-1)/(30-3)$
$= -1/27$

b = interpolating the linear function to the x-axis:



When x=0 → y = 10/9
So, the linear function is y = -1/27 x + 10/9

When filling in the y and x, the final function is:
Vegetation raster value = (-1/27) * Building height + 10/9

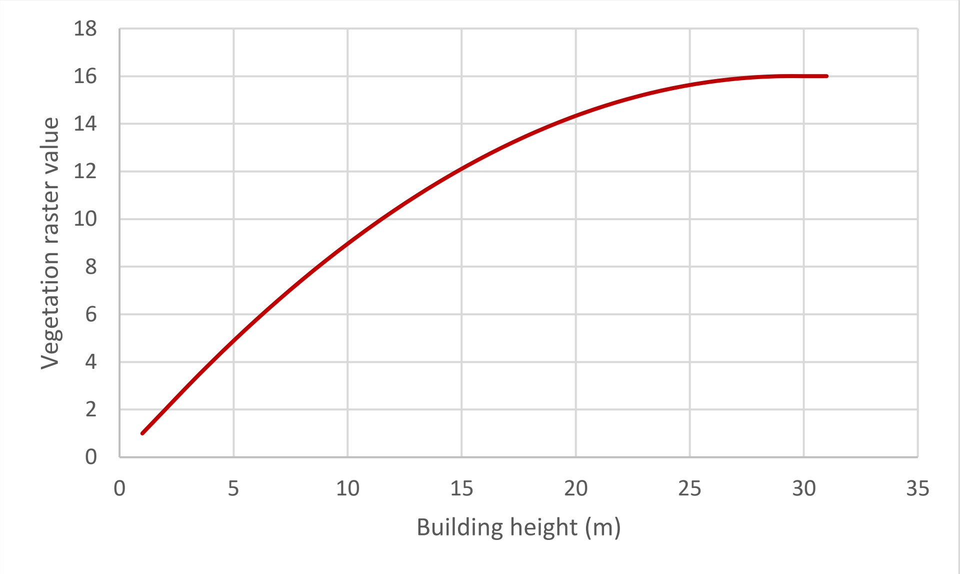
<u>The function of the green walls for the vegetation raster value:</u>
By applying the function defined above and stating that:

- 0 ≤ Building height ≤ 3, Vegetation raster value is 1 for every meter height
- 3 < Building height ≤ 30, Vegetation raster value is (-1/27) * Building height + 10/9 for every meter height
- Building height > 30, Vegetation raster value is 0 for every meter height,

it will be possible to draw the graph.

For example, when the building is 7 meters high:
y = 3 * 1 + (-1/27) * 4 + 10/9 + (-1/27) * 5 + 10/9 + (-1/27) * 6 + 10/9 + (-1/27) * 7 + 10/9
= 6.63

By calculating this for every meter between 3 and 30 meters, it is possible to draw the following graph:



After the 30 meters, no extra value will be added anymore and the fixed value will then be 16.

To be able to put the function in the Python script, it is required to simplify the function which makes it possible to fill in the building height as x and get as outcome y, the right vegetation raster value.

To rewrite the function, the function of Building height = 7 is taken as the starting point.

y = 3 * 1 + (-1/27) * 4 + 10/9 + (-1/27) * 5 + 10/9 + (-1/27) * 6 + 10/9 + (-1/27) * 7 + 10/9
= 3 + (-1/27) * 4 + (-1/27) * 5 + (-1/27) * 6 + (-1/27) * 7 + 10/9 + 10/9 + 10/9 + 10/9
= 3 + (-1/27) * (4 + 5 + 6 + 7) + 10/9 * (7-3)

Then, the following can be defined from math:
Adding up all whole natural numbers = (N/2) * (N + 1)
So when N = 7 → 7 + 6 + 5 + 4 + 3 + 2 + 1 = 28 → (7/2) * (7+1) = 28
When N = 3 → 3 + 2 + 1 = 6 → (3/2) * (3+1) = 6

So, the red part above can be defined as follows:
7 + 6 + 5 + 4 = (7 + 6 + 5 + 4 + 3 + 2 + 1) – (3 + 2 + 1)
= (7/2) * (7+1) – (3/2) * (3+1)
= (7/2) * (7+1) - 6

7 = Building height = x, so:
7 + 6 + 5 + 4 = (x/2) * (x+1) – 6

By filling this in in the formula of building height = 7, the formula is as follows:
y = 3 + (-1/27) * ((x/2) * (x+1) - 6) + 10/9 * (x - 3)

To conclude, the formula is:
Vegetation raster value = 3 + (-1/27) * ((Building height/2) * (Building height + 1) - 6) + 10/9 * (Building height - 3)

Building height should be filled in as an integer to get the right output value.

Appendix G – PyQGIS script UGI analysis

```
from qgis import processing

#Adding input data (already clipped to right scope and set to right CRS)
#Adding city polygon from local path
fn_location ='D:/Data afstuderen/DATA_Requirement_Analyse/Rotterdam.gml'

#Adding Land use data from local path
#Data already prepared for HTC calculation
fn_water ='D:/Data afstuderen/DATA_code/PET_tiles_Rotterdam/Rotterdam/\
water_x084000_y447000.tif'

fn_green ='D:/Data afstuderen/DATA_code/PET_tiles_Rotterdam/Rotterdam/\
green_x084000_y447000.tif'

fn_trees ='D:/Data afstuderen/DATA_code/PET_tiles_Rotterdam/Rotterdam/\
trees_x084000_y447000.tif'

#Other Land use data
fn_railway ='D:/Data afstuderen/DATA_Requirement_Analyse/BGT/\
Spoor met juiste CRS.gpkg'

fn_roadlines ='D:/Data afstuderen/DATA_Requirement_Analyse/BGT/\
Road_lines met juiste CRS.gpkg'

fn_otherstructures ='D:/Data afstuderen/DATA_Requirement_Analyse/BGT/\
bgt_overigbouwwerk.gml'

fn_banks ='D:/Data afstuderen/DATA_Requirement_Analyse/BGT/\
bgt_ondersteunendwaterdeel.gml'

fn_walls ='D:/Data afstuderen/DATA_Requirement_Analyse/BGT/bgt_scheiding.gml'

#Adding BAG (Buildings) data from local path
fn_bag ='D:/Data afstuderen/DATA_Requirement_Analyse/BAG/BAG-clip.gpkg'

#Adding Height data from local path
#Data already prepared for HTC calculation
fn_dtm ='D:/Data afstuderen/DATA_PET/AHN data/Clip dtm.tif'

fn_dsm ='D:/Data afstuderen/DATA_code/PET_tiles_Rotterdam/Rotterdam/\
dsm_1m.tif'

fn_height ='D:/Data afstuderen/DATA_code/PET_tiles_Rotterdam/Rotterdam/\
height_1m.tif'
```

```
#Adding Human Thermal Comfort map of HTC calculation from local path
fn_HTC ='D:/Data afstuderen/DATA_code/Output/Rotterdam_verbetering/\
Rotterdam PET kaart_verbetering.tif'



#Setting general settings for analysis
extent = QgsRectangle(85730.00,430740.00,101040.00,445400.00)
width = 15310 #number of raster cells of 1m
height = 14660 #number of raster cells of 1m
CRS = QgsCoordinateReferenceSystem('EPSG:28992')



#Data Preparation
#Preparing Land use
#Add Green, Water and Trees layers to QGIS Layer panel
Green = iface.addRasterLayer(fn_green, 'Green')

Water = iface.addRasterLayer(fn_water, 'Water')

Trees = iface.addRasterLayer(fn_trees, 'Trees')

#Rasterizing Buildings data
Raster_buildings ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\Land use\
\Buildings.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_bag, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5, 'EXTENT': extent,
 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '','INIT' : None,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_buildings, 'UNITS' : 0, 'USE_Z' : False})

#Add Building layer to QGIS Layer panel
Buildings = iface.addRasterLayer(Raster_buildings, 'Buildings')

#Extracting Banks from Banks input data
Banks_extracted ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\Land use\
\Oevers.gpkg'

processing.run("native:extractbyattribute",
{'FIELD' : 'class', 'INPUT' : fn_banks, 'OPERATOR' : 0,
 'OUTPUT' : Banks_extracted, 'VALUE' : 'oever, slootkant'})

#Rasterizing Banks data
Raster_banks ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\Land use\
\Banks.tif'
```

```
processing.run("gdal:rasterize",
{'INPUT' : Banks_extracted, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_banks, 'UNITS' : 0, 'USE_Z' : False})

#Add Banks layer to QGIS Layer panel
Banks = iface.addRasterLayer(Raster_banks, 'Banks')

#Rasterizing Railway data
Raster_railway ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\Land use\
\Railway.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_railway, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_railway, 'UNITS' : 0, 'USE_Z' : False})

#Add Railway layer to QGIS Layer panel
Railway = iface.addRasterLayer(Raster_railway, 'Railway')

#Rasterizing Walls data
Raster_walls ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\Land use\
\Walls.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_walls, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_walls, 'UNITS' : 0, 'USE_Z' : False})

#Add Walls layer to QGIS Layer panel
Walls = iface.addRasterLayer(Raster_walls, 'Walls')

#Rasterizing Other Structures data
Raster_otherstructures ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Land use\Other Structures.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_otherstructures, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_otherstructures, 'UNITS' : 0, 'USE_Z' : False})

#Add Other Structures layer to QGIS Layer panel
OtherStructures = iface.addRasterLayer(Raster_otherstructures,
                                       'Other Structures')
```

```
#Preparing Width of paths and roads
#Defining Cycleway and one-way or two-way
Cycleway_oneway_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Oneway Cycleway.gpkg'
Cycleway_not_oneway_output ="D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Twoway Cycleway.gpkg"

processing.run("native:extractbyexpression",
{'EXPRESSION' : ' ("fclass" = \'cycleway\' or "fclass" = \'bridleway\') and\
 "oneway" = \'F\'', 'INPUT' : fn_roadlines,
 'OUTPUT' : Cycleway_oneway_output})

processing.run("native:extractbyexpression",
{'EXPRESSION' : ' ("fclass" = \'cycleway\' or "fclass" = \'bridleway\') and\
 "oneway" = \'B\'', 'INPUT' : fn_roadlines,
 'OUTPUT' : Cycleway_not_oneway_output})

#Defining Footway
Footway_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Footway.gpkg'

processing.run("native:extractbyexpression",
{'EXPRESSION' : '("fclass" = \'footway\' or "fclass" = \'path\' or\
 "fclass" = \'pedestrian\' or "fclass" = \'steps\' or "fclass" = \'track\' or\
 "fclass" = \'track_grade1\' or "fclass" = \'track_grade2\' or\
 "fclass" = \'track_grade3\' or "fclass" = \'track_grade4\' or\
 "fclass" = \'track_grade5\')', 'INPUT' : fn_roadlines,
 'OUTPUT' : Footway_output})

#Defining Road and one-way or two-way
Road_oneway_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Oneway road.gpkg'
Road_not_oneway_output ="D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Twoway Road.gpkg"

processing.run("native:extractbyexpression",
{'EXPRESSION' : '("fclass" = \'busway\' or "fclass" = \'living_street\' or\
 "fclass" = \'motorway\' or "fclass" = \'motorway_link\' or\
 "fclass" = \'primary\' or "fclass" = \'primary_link\' or\
 "fclass" = \'residential\' or "fclass" = \'secondary\' or\
 "fclass" = \'secondary_link\' or "fclass" = \'service\' or\
 "fclass" = \'tertiary\' or "fclass" = \'tertiary_link\' or \
 "fclass" = \'trunk\' or "fclass" = \'trunk_link\' or\
 "fclass" = \'unclassified\' or "fclass" = \'unknown\') and "oneway" = \'F\'',
 'INPUT' : fn_roadlines, 'OUTPUT' : Road_oneway_output})

processing.run("native:extractbyexpression",
```

```
{'EXPRESSION' : '("fclass" = \'busway\' or "fclass" = \'living_street\' or\
 "fclass" = \'motorway\' or "fclass" = \'motorway_link\' or\
 "fclass" = \'primary\' or "fclass" = \'primary_link\' or\
 "fclass" = \'residential\' or "fclass" = \'secondary\' or\
 "fclass" = \'secondary_link\' or "fclass" = \'service\' or\
 "fclass" = \'tertiary\' or "fclass" = \'tertiary_link\' or \
 "fclass" = \'trunk\' or "fclass" = \'trunk_link\' or\
 "fclass" = \'unclassified\' or "fclass" = \'unknown\') and "oneway" = \'B\'',
 'INPUT' : fn_roadlines, 'OUTPUT' : Road_not_oneway_output})

#Creating buffers around different road types to define width
Cycleway_oneway_buffer_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Cycleway_oneway_buffer.gpkg'
Cycleway_not_oneway_buffer_output ='D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Width of paths and roads\
\Cycleway_not_oneway_buffer.gpkg'
Footway_buffer_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Footway_buffer.gpkg'
Road_oneway_buffer_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Road_oneway_buffer.gpkg'
Road_not_oneway_buffer_output ='D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Road_not_oneway_buffer.gpkg'

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 2, 'END_CAP_STYLE' : 0,
 'INPUT' : Cycleway_oneway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2, 'OUTPUT' : Cycleway_oneway_buffer_output, 'SEGMENTS' : 5})

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 2.5, 'END_CAP_STYLE' : 0,
 'INPUT' : Cycleway_not_oneway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2, 'OUTPUT' : Cycleway_not_oneway_buffer_output,
 'SEGMENTS' : 5})

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 1.5, 'END_CAP_STYLE' : 0,
 'INPUT' : Footway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2, 'OUTPUT' : Footway_buffer_output, 'SEGMENTS' : 5})

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 3, 'END_CAP_STYLE' : 0,
 'INPUT' : Road_oneway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2, 'OUTPUT' : Road_oneway_buffer_output, 'SEGMENTS' : 5})

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 4.5, 'END_CAP_STYLE' : 0,
 'INPUT' : Road_not_oneway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2, 'OUTPUT' : Road_not_oneway_buffer_output, 'SEGMENTS' : 5})
```

```
#Merge the Buffers to define width of path and roads
Paths_with_buffer_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Paths_with_buffer.gpkg'

processing.run("native:mergevectorlayers",
{'CRS' : CRS, 'LAYERS' : [Cycleway_oneway_buffer_output,
                           Cycleway_not_oneway_buffer_output,
                           Footway_buffer_output, Road_oneway_buffer_output,
                           Road_not_oneway_buffer_output],
 'OUTPUT' : Paths_with_buffer_output})

#Rasterizing Width of path and roads data
Raster_Path_width = "D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Width of paths and roads\Paths_width.tif"

processing.run("gdal:rasterize",
{'INPUT' : Paths_with_buffer_output, 'FIELD' : '', 'BURN' : 1, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_Path_width, 'UNITS' : 0, 'USE_Z' : False })

#Add width of paths and roads layer to QGIS Layer panel
Paths_width = iface.addRasterLayer(Raster_Path_width,
                                   'Width of paths and roads')

#Preparing Land Availability
Raster_Landavailability_without_road = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Land availability\Land Availability.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=1 or "Railway@1"=1 or "Water@1"=1 or \
 "Other Structures@1"=1', 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Raster_Landavailability_without_road})

#Add Land availability layer to QGIS Layer panel
Landavailability_without_road = iface.addRasterLayer(
    Raster_Landavailability_without_road, 'Land availability')

#Preparing Amount of street traffic
#Defining roads with much traffic
Amount_of_street_traffic_oneway_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Oneway Amount of street traffic.gpkg'
Amount_of_street_traffic_not_oneway_output = "D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Twoway Amount of street traffic.gpkg"
```

```
processing.run("native:extractbyexpression",
{'EXPRESSION' : '("fclass" = \'motorway\'or "fclass" = \'motorway_link\' or \
 "fclass" = \'primary\' or "fclass" = \'primary_link\' or \
 "fclass" = \'secondary\' or "fclass" = \'secondary_link\' or \
 "fclass" = \'tertiary\' or "fclass" = \'tertiary_link\') and \
 "oneway" =\'F\'', 'INPUT' : fn_roadlines,
 'OUTPUT' : Amount_of_street_traffic_oneway_output})

processing.run("native:extractbyexpression",
{'EXPRESSION' :  '("fclass" = \'motorway\'or "fclass" = \'motorway_link\' or\
 "fclass" = \'primary\' or "fclass" = \'primary_link\' or \
 "fclass" = \'secondary\' or "fclass" = \'secondary_link\' or \
 "fclass" = \'tertiary\' or "fclass" = \'tertiary_link\') and \
 "oneway" =\'B\'', 'INPUT' : fn_roadlines,
 'OUTPUT' : Amount_of_street_traffic_not_oneway_output})

#Creating buffer around roads with much traffic to define width
Amount_of_street_traffic_oneway_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Oneway Amount of street traffic buffer.gpkg'
Amount_of_street_traffic_not_oneway_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Twoway Amount of street traffic buffer.gpkg'

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 3, 'END_CAP_STYLE' : 0,
 'INPUT' : Amount_of_street_traffic_oneway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2, 'OUTPUT' : Amount_of_street_traffic_oneway_buffer_output,
 'SEGMENTS' : 5})

processing.run("native:buffer",
{'DISSOLVE' : False, 'DISTANCE' : 4.5, 'END_CAP_STYLE' : 0,
 'INPUT' : Amount_of_street_traffic_not_oneway_output, 'JOIN_STYLE' : 0,
 'MITER_LIMIT' : 2,
 'OUTPUT' : Amount_of_street_traffic_not_oneway_buffer_output,
 'SEGMENTS' : 5})

#Merge Buffers to define Amount of street traffic
Amount_of_street_traffic_Paths_with_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Amount of street traffic roads with buffer.gpkg'

processing.run("native:mergevectorlayers",
{'CRS' : CRS, 'LAYERS' : [Amount_of_street_traffic_oneway_buffer_output,
                          Amount_of_street_traffic_not_oneway_buffer_output],
 'OUTPUT' : Amount_of_street_traffic_Paths_with_buffer_output})
```

```
#Rasterizing Amount of street traffic data
Raster_Amount_of_street_traffic_Path_width = "D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Amount of street traffic roads.tif"

processing.run("gdal:rasterize",
{'INPUT' : Amount_of_street_traffic_Paths_with_buffer_output, 'FIELD' : '',
 'BURN' : 1, 'DATA_TYPE': 5, 'EXTENT': extent, 'HEIGHT' : height,
 'WIDTH' : width,'EXTRA' : '', 'INIT' : None, 'INVERT' : False,
 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_Amount_of_street_traffic_Path_width, 'UNITS' : 0,
 'USE_Z' : False})

#Add Amount of street traffic layer to QGIS Layer panel
Amount_of_street_traffic = iface.addRasterLayer(
    Raster_Amount_of_street_traffic_Path_width, 'Amount of street traffic')

#Preparing Building age
#Rasterizing BAG data based on building age
Raster_Building_age = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Building age\Building_age.tif'

processing.run("gdal:rasterize",
{'INPUT' : fn_bag, 'FIELD' : 'bouwjaar', 'BURN' : 0, 'DATA_TYPE': 5,
 'EXTENT': extent, 'HEIGHT' : height, 'WIDTH' : width,'EXTRA' : '',
 'INIT' : None, 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Raster_Building_age, 'UNITS' : 0, 'USE_Z' : False})

#Add Building age layer to QGIS Layer panel
Building_age = iface.addRasterLayer(Raster_Building_age, 'Building Age')

#Preparing Presence of overhead obstacles (Using height from HTC calculation)
#Add Presence of overhead obstacles layer to QGIS Layer panel
Presence_of_overhead_obstacles = iface.addRasterLayer(
    fn_height, 'Presence of overhead obstacles')

#Preparing Proximity to structures
#Define Structures by combining buildings, walls and other structures
Raster_Proximity_to_structures = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Proximity to strucutures\Structures.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=1 or "Walls@1"=1 or "Other Structures@1"=1',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Raster_Proximity_to_structures})

#Add Proximity to structures layer to QGIS Layer panel
```

```
Proximity_to_structures = iface.addRasterLayer(Raster_Proximity_to_structures,
                                               'Proximity to structures')

#Preparing Slope
#Define Slope of ground level by dtm data
Raster_Slope = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\Slope\Slope.tif'

processing.run("qgis:slope",
{'INPUT' : fn_dtm, 'OUTPUT' : Raster_Slope, 'Z_FACTOR' : 1})

#Add Slope layer to QGIS Layer panel
Slope = iface.addRasterLayer(Raster_Slope, 'Slope')

#Preparing Slope of roof
#Define height buildings by dsm data
dsm = iface.addRasterLayer(fn_dsm, 'dsm')

dsm_clip_buildings = 'D:\Data afstuderen\DATA_Requirement_Analyse\AHN\
\dsm_clip_buildings.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Buildings@1"=1)*"dsm@1"',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : dsm_clip_buildings})

#Define Slope of roof
Raster_slope_of_roof = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Slope of roof\Slope of roof.tif'

processing.run("native:slope",
{'INPUT' : dsm_clip_buildings, 'OUTPUT' : Raster_slope_of_roof,
 'Z_FACTOR' : 1})

#Add slope of roof layer to QGIS Layer panel
Slope_of_roof = iface.addRasterLayer(Raster_slope_of_roof, 'Slope of roof')

#Preparing tree protection zone
#Add one meter buffer to trees
Tree_buffer= "D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tree protection zone\Tree_buffer.tif"

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '', 'INPUT' : Trees,
 'MAX_DISTANCE' : 1, 'NODATA' : 0, 'OPTIONS' : '', 'OUTPUT' : Tree_buffer,
 'REPLACE' : 1, 'UNITS' : 1, 'VALUES' : '1' })

Tree_buffer_output = iface.addRasterLayer(Tree_buffer, 'Tree with 1m buffer')
```

```
#Combine buffer with trees to define tree protection zone
Raster_Tree_protection_zone= 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tree protection zone\Tree_protection_zone.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Tree with 1m buffer@1"=1 OR "Trees@1"',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Raster_Tree_protection_zone})

#Add Tree protection zone layer to QGIS Layer panel
Tree_protection_zone = iface.addRasterLayer(Raster_Tree_protection_zone,
                                            'Tree protection zone')



#More specific data preparation
#Preparing amount of street traffic with 8m buffer
Amount_of_street_traffic_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Amount of street traffic\
\Amount of street traffic buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '',
 'INPUT' : Raster_Amount_of_street_traffic_Path_width, 'MAX_DISTANCE' : 8,
 'NODATA' : 0, 'OPTIONS' : '',
 'OUTPUT' : Amount_of_street_traffic_buffer_output, 'REPLACE' : 1,
 'UNITS' : 1, 'VALUES' : '1'})

#Add Amount of street traffic buffer layer to QGIS Layer panel
Amount_of_street_traffic_buffer = iface.addRasterLayer(
    Amount_of_street_traffic_buffer_output, 'Amount of street traffic buffer')

#Preparing Land use linear elements with 8m buffer
Linear_elements_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Land use\Linear elements.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '', 'INPUT' : Raster_Path_width,
 'MAX_DISTANCE' : 8, 'NODATA' : 0, 'OPTIONS' : '',
 'OUTPUT' : Linear_elements_buffer_output, 'REPLACE' : 1, 'UNITS' : 1,
 'VALUES' : '1'})

#Add Linear elements layer to QGIS Layer panel
Linear_element_buffer = iface.addRasterLayer(Linear_elements_buffer_output,
                                             'Linear elements')

#Preparing presence of overhead obstacles per UGI type requirement
```

```python
#Raster with 15m free of overhead obstacles
Obstacle_free_15m_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Presence of overhead obstacles\Obstacle_free_15m.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Presence of overhead obstacles@1"=0 OR \
 "Presence of overhead obstacles@1">15', 'EXTENT' : extent,
 'LAYERS' : Raster_buildings, 'OUTPUT' : Obstacle_free_15m_output})

#Add 15m obstacle free layer to QGIS Layer panel
Obstacle_free_15m = iface.addRasterLayer(Obstacle_free_15m_output,
                                         '15m obstacle free')

#Raster with 8m free of overhead obstacles
Obstacle_free_8m_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Presence of overhead obstacles\Obstacle_free_8m.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Presence of overhead obstacles@1"=0 OR \
 "Presence of overhead obstacles@1">8', 'EXTENT' : extent,
 'LAYERS' : Raster_buildings, 'OUTPUT' : Obstacle_free_8m_output})

#Add 8m obstacle free layer to QGIS Layer panel
Obstacle_free_8m = iface.addRasterLayer(Obstacle_free_8m_output,
                                        '8m obstacle free')

#Raster with 5m free of overhead obstacles
Obstacle_free_5m_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Presence of overhead obstacles\Obstacle_free_5m.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Presence of overhead obstacles@1"=0 OR \
 "Presence of overhead obstacles@1">5', 'EXTENT' : extent,
 'LAYERS' : Raster_buildings, 'OUTPUT' : Obstacle_free_5m_output})

#Add 5m obstacle free layer to QGIS Layer panel
Obstacle_free_5m = iface.addRasterLayer(Obstacle_free_5m_output,
                                        '5m obstacle free')

#Raster with 3m free of overhead obstacles
Obstacle_free_3m_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Presence of overhead obstacles\Obstacle_free_3m.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
```

```
 'EXPRESSION' : '"Presence of overhead obstacles@1"=0 OR \
 "Presence of overhead obstacles@1">3', 'EXTENT' : extent,
 'LAYERS' : Raster_buildings, 'OUTPUT' : Obstacle_free_3m_output})

#Add 3m obstacle free layer to QGIS Layer panel
Obstacle_free_3m = iface.addRasterLayer(Obstacle_free_3m_output,
                                        '3m obstacle free')

#Preparing proximity of structures per UGI type requirement
#Raster with 7.5m buffer to structures (rounded to 8)
Proximity_8_buffer_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Proximity to strucutures\Proximity 8m buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '',
 'INPUT' : Raster_Proximity_to_structures, 'MAX_DISTANCE' : 8, 'NODATA' : 0,
 'OPTIONS' : '', 'OUTPUT' : Proximity_8_buffer_output, 'REPLACE' : 1,
 'UNITS' : 1, 'VALUES' : '1'})

#Add Proximity to structures 8m buffer layer to QGIS Layer panel
Proximity_8_buffer = iface.addRasterLayer(Proximity_8_buffer_output,
                                          'Proximity to structures 8m buffer')

#Raster with 4m buffer to structures
Proximity_4_buffer_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Proximity to strucutures\Proximity 4m buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '',
 'INPUT' : Raster_Proximity_to_structures, 'MAX_DISTANCE' : 4, 'NODATA' : 0,
 'OPTIONS' : '', 'OUTPUT' : Proximity_4_buffer_output, 'REPLACE' : 1,
 'UNITS' : 1, 'VALUES' : '1'})

#Add Proximity to structures 4m buffer layer to QGIS Layer panel
Proximity_4_buffer = iface.addRasterLayer(Proximity_4_buffer_output,
                                          'Proximity to structures 4m buffer')

#Raster with 1.5m buffer to structures (rounded to 2)
Proximity_2_buffer_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Proximity to strucutures\Proximity 2m buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '',
 'INPUT' :  Raster_Proximity_to_structures, 'MAX_DISTANCE' : 2, 'NODATA' : 0,
 'OPTIONS' : '', 'OUTPUT' : Proximity_2_buffer_output, 'REPLACE' : 1,
 'UNITS' : 1, 'VALUES' : '1'})

#Add Proximity to structures 2m buffer layer to QGIS Layer panel
```

```
Proximity_2_buffer = iface.addRasterLayer(Proximity_2_buffer_output,
                                          'Proximity to structures 2m buffer')

#Raster with 1m buffer to structures
Proximity_1_buffer_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Proximity to strucutures\Proximity 1m buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '',
 'INPUT' :  Raster_Proximity_to_structures,'MAX_DISTANCE' : 1, 'NODATA' : 0,
 'OPTIONS' : '', 'OUTPUT' : Proximity_1_buffer_output, 'REPLACE' : 1,
 'UNITS' : 1, 'VALUES' : '1'})

#Add Proximity to structures 1m buffer layer to QGIS Layer panel
Proximity_1_buffer = iface.addRasterLayer(Proximity_1_buffer_output,
                                          'Proximity to structures buffer 1m')

#Preparing land availability green walls (0.5 meter buffer (rounded to 1)
#to walls because this should be available for green walls)
#Use Proximity to structures 1m buffer
#Add Buffer to walls layer to QGIS Layer panel
Buffer_walls = iface.addRasterLayer(Proximity_1_buffer_output, 'BufferWalls')

#Preparing building age per UGI type requirement
#Raster with building year newer than 1972
BuildingAge_1972_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Building age\Building age 1972.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Building Age@1">=1972',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : BuildingAge_1972_output})

#Add Building age of newer than 1972 layer to QGIS Layer panel
BuildingAge_1972 = iface.addRasterLayer(BuildingAge_1972_output,
                                        'Building age of newer than 1972')

#Raster with building year newer than 1991
BuildingAge_1991_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Building age\Building age 1991.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Building Age@1">=1991',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : BuildingAge_1991_output})
```

```
#Add Building age of newer than 1991 layer to QGIS Layer panel
BuildingAge_1991 = iface.addRasterLayer(BuildingAge_1991_output,
                                        'Building age of newer than 1991')

#Raster with building year newer than 2012
BuildingAge_2012_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Building age\Building age 2012.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Building Age@1">=2012',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : BuildingAge_2012_output})

#Add Building age of newer than 2012 layer to QGIS Layer panel
BuildingAge_2012 = iface.addRasterLayer(BuildingAge_2012_output,
                                        'Building age of newer than 2012')

#1m buffer for newer than 1972 layer
#For land availability analysis green walls
Building_age1972_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Land availability\Building age 1972 buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '', 'INPUT' : BuildingAge_1972_output,
 'MAX_DISTANCE' : 1, 'NODATA' : 0, 'OPTIONS' : '',
 'OUTPUT' : Building_age1972_buffer_output, 'REPLACE' : 1, 'UNITS' : 1,
 'VALUES' : '1'})

#Add Building age of newer than 1972 buffer layer to QGIS Layer panel
Building_age1972_buffer = iface.addRasterLayer(Building_age1972_buffer_output,
                                               'Building age 1972 buffer')

#1 meter buffer for newer than 2012 layer
#For land availability analysis green walls
Building_age2012_buffer_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Land availability\Building age 2012 buffer.tif'

processing.run("gdal:proximity",
{'BAND' : 1, 'DATA_TYPE' : 5, 'EXTRA' : '', 'INPUT' : BuildingAge_2012_output,
 'MAX_DISTANCE' : 1, 'NODATA' : 0, 'OPTIONS' : '',
 'OUTPUT' : Building_age2012_buffer_output, 'REPLACE' : 1, 'UNITS' : 1,
 'VALUES' : '1'})

#Add Building age of newer than 2012 buffer layer to QGIS Layer panel
Building_age2012_buffer = iface.addRasterLayer(Building_age2012_buffer_output,
                                               'Building age 2012 buffer')
```

```
#Preparing slope per UGI type requirement
#Raster with Slope of less than 10 degrees
Slope_10degrees_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\Slope\
\Slope 10 degrees.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Slope@1"<=10', 'EXTENT' : extent,
 'LAYERS' : Raster_buildings, 'OUTPUT' : Slope_10degrees_output})

#Add Slope of less than 10 degrees layer to QGIS Layer panel
Slope_10degrees = iface.addRasterLayer(Slope_10degrees_output,
                                       'Slope of less than 10 degrees')

#Raster with Slope of less than 20 degrees
Slope_20degrees_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\Slope\
\Slope 20 degrees.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Slope@1"<=20', 'EXTENT' : extent,
 'LAYERS' : Raster_buildings, 'OUTPUT' : Slope_20degrees_output})

#Add Slope of less than 20 degrees layer to QGIS Layer panel
Slope_20degrees = iface.addRasterLayer(Slope_20degrees_output,
                                       'Slope of less than 20 degrees')

#Preparing slope of roof per UGI type requirement
#Raster with Slope of less than 30 degrees and more than 1 degree
SlopeofRoof_30degrees_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Slope of roof\Slope of roof 30 degrees.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Slope of roof@1">=1 AND "Slope of roof@1"<=30 ',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : SlopeofRoof_30degrees_output})

#Add Slope of less than 30 degrees layer to QGIS Layer panel
SlopeofRoof_30degrees = iface.addRasterLayer(
    SlopeofRoof_30degrees_output, 'Slope of roof of less than 30 degrees')

#Raster with Slope of less than 10 degrees and more than 1 degree
SlopeofRoof_10degrees_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Slope of roof\Slope of roof 10 degrees.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
```

```
 'EXPRESSION' : '"Slope of roof@1">=1 AND "Slope of roof@1"<=10 ',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : SlopeofRoof_10degrees_output})

#Add Slope of less than 10 degrees layer to QGIS Layer panel
SlopeofRoof_10degrees = iface.addRasterLayer(
    SlopeofRoof_10degrees_output, 'Slope of roof of less than 10 degrees')

#Raster with Slope of less than 5 degrees and more than 1 degree
SlopeofRoof_5degrees_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Slope of roof\Slope of roof 5 degrees.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Slope of roof@1">=1 AND "Slope of roof@1"<=5 ',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : SlopeofRoof_5degrees_output})

#Add Slope of less than 5 degrees layer to QGIS Layer panel
SlopeofRoof_5degrees = iface.addRasterLayer(
    SlopeofRoof_5degrees_output, 'Slope of roof of less than 5 degrees')



#Analysis per UGI type
#Analysis Possibility
#Tree avenue and single-line trees with trees of 1st size with open foliage
#without land availability m2 analysis
Avenue_Line_tree_1st_size_open_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size open foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "Linear elements@1"=1 AND "15m obstacle free@1"=1 AND \
 "Proximity to structures 8m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 \
 AND "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen1})

#Preparing land availability analysis
#Tree avenue and single-line trees with trees of 1st size with open foliage
Avenue_Line_tree_1st_size_open_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size open foliage tussen2.shp'
Avenue_Line_tree_1st_size_open_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
```

```
\Avenue&Line Tree 1st size open foliage tussen3.shp'
Avenue_Line_tree_1st_size_open_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size open foliage tussen4.shp'
Avenue_Line_tree_1st_size_open_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size open foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen1,
 'OUTPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen3,
 'OUTPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen4, 'INVERT' : False,
 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Avenue_Line_tree_1st_size_open_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Tree avenue and single-line trees with trees of 1st size
#with open foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Avenue_Line_tree_1st_size_open_foliage_tussen = iface.addRasterLayer(
    Avenue_Line_tree_1st_size_open_foliage_tussen5,
    'Avenue&Lines with trees of 1st size with open foliage (tussenstap)')

#Analysis Possibility
#Tree avenue and single-line trees with trees of 1st size with closed foliage
#without land availability m2 analysis
Avenue_Line_tree_1st_size_closed_foliage_tussen1 = 'D:\Data afstuderen\
```

```
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size closed foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Amount of street traffic buffer@1"=0 AND "Buildings@1"=0 \
 AND "Water@1"=0 AND "Trees@1"=0 AND "Linear elements@1"=1 AND \
 "15m obstacle free@1"=1 AND "Proximity to structures 8m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen1})

#Preparing land availability analysis
#Tree avenue and single-line trees with trees of 1st size with closed foliage
Avenue_Line_tree_1st_size_closed_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size closed foliage tussen2.shp'
Avenue_Line_tree_1st_size_closed_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size closed foliage tussen3.shp'
Avenue_Line_tree_1st_size_closed_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size closed foliage tussen4.shp'
Avenue_Line_tree_1st_size_closed_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 1st size closed foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen1,
 'OUTPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen3,
 'OUTPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen4})
```

```
#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Avenue_Line_tree_1st_size_closed_foliage_tussen5,
 'UNITS' : 0, 'USE_Z' : False, 'WIDTH' : width})

#Add Tree avenue and single-line trees with trees of 1st size
#with closed foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Avenue_Line_tree_1st_size_closed_foliage_tussen = iface.addRasterLayer(
    Avenue_Line_tree_1st_size_closed_foliage_tussen5,
    'Avenue&Lines with trees of 1st size with closed foliage (tussenstap)')

#Analysis Possibility
#Tree avenue and single-line trees with trees of 2nd size with open foliage
#without land availability m2 analysis
Avenue_Line_tree_2nd_size_open_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size open foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "Linear elements@1"=1 AND "8m obstacle free@1"=1 AND \
 "Proximity to structures 4m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen1})

#Preparing land availability analysis
#Tree avenue and single-line trees with trees of 2nd size with open foliage
Avenue_Line_tree_2nd_size_open_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size open foliage tussen2.shp'
Avenue_Line_tree_2nd_size_open_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size open foliage tussen3.shp'
Avenue_Line_tree_2nd_size_open_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size open foliage tussen4.shp'
Avenue_Line_tree_2nd_size_open_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size open foliage tussen5.tif'
```

```
#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen1,
 'OUTPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen3,
 'OUTPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Avenue_Line_tree_2nd_size_open_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Tree avenue and single-line trees with trees of 2nd size
#with open foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Avenue_Line_tree_2nd_size_open_foliage_tussen = iface.addRasterLayer(
    Avenue_Line_tree_2nd_size_open_foliage_tussen5,
    'Avenue&Lines with trees of 2nd size with open foliage (tussenstap)')

#Analysis Possibility
#Tree avenue and single-line trees with trees of 2nd size with closed foliage
#without land availability m2 analysis
Avenue_Line_tree_2nd_size_closed_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size closed foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Amount of street traffic buffer@1"=0 AND "Buildings@1"=0 \
 AND "Water@1"=0 AND "Trees@1"=0 AND "Linear elements@1"=1 AND \
 "8m obstacle free@1"=1 AND "Proximity to structures 4m buffer@1"=0 AND \
```

```
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen1})

#Preparing land availability analysis
#Tree avenue and single-line trees with trees of 2nd size with closed foliage
Avenue_Line_tree_2nd_size_closed_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size closed foliage tussen2.shp'
Avenue_Line_tree_2nd_size_closed_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size closed foliage tussen3.shp'
Avenue_Line_tree_2nd_size_closed_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size closed foliage tussen4.shp'
Avenue_Line_tree_2nd_size_closed_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 2nd size closed foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen1,
 'OUTPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen3,
 'OUTPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Avenue_Line_tree_2nd_size_closed_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})
```

```
#Add Tree avenue and single-line trees with trees of 2nd size
#with closed foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Avenue_Line_tree_2nd_size_closed_foliage_tussen = iface.addRasterLayer(
    Avenue_Line_tree_2nd_size_closed_foliage_tussen5,
    'Avenue&Lines with trees of 2nd size with closed foliage (tussenstap)')

#Analysis Possibility
#Tree avenue and single-line trees with trees of 3rd size with open foliage
#without land availability m2 analysis
Avenue_Line_tree_3rd_size_open_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size open foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND\
 "Linear elements@1"=1 AND "5m obstacle free@1"=1 AND \
 "Proximity to structures 2m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen1})

#Preparing land availability analysis
#Tree avenue and single-line trees with trees of 3rd size with open foliage
Avenue_Line_tree_3rd_size_open_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size open foliage tussen2.shp'
Avenue_Line_tree_3rd_size_open_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size open foliage tussen3.shp'
Avenue_Line_tree_3rd_size_open_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size open foliage tussen4.shp'
Avenue_Line_tree_3rd_size_open_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size open foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen1,
 'OUTPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen2})

#Extract Available = 1
```

```
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen3,
 'OUTPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Avenue_Line_tree_3rd_size_open_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Tree avenue and single-line trees with trees of 3rd size
#with open foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Avenue_Line_tree_3rd_size_open_foliage_tussen = iface.addRasterLayer(
    Avenue_Line_tree_3rd_size_open_foliage_tussen5,
    'Avenue&Lines with trees of 3rd size with open foliage (tussenstap)')

#Analysis Possibility
#Tree avenue and single-line trees with trees of 3rd size with closed foliage
#without land availability m2 analysis
Avenue_Line_tree_3rd_size_closed_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size closed foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Amount of street traffic buffer@1"=0 AND "Buildings@1"=0 \
 AND "Water@1"=0 AND "Trees@1"=0 AND "Linear elements@1"=1 AND \
 "5m obstacle free@1"=1 AND "Proximity to structures 2m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen1})

#Preparing land availability analysis
#Tree avenue and single-line trees with trees of 3rd size with closed foliage
Avenue_Line_tree_3rd_size_closed_foliage_tussen2 = 'D:\Data afstuderen\
```

```
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size closed foliage tussen2.shp'
Avenue_Line_tree_3rd_size_closed_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size closed foliage tussen3.shp'
Avenue_Line_tree_3rd_size_closed_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size closed foliage tussen4.shp'
Avenue_Line_tree_3rd_size_closed_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Avenue&Line Tree 3rd size closed foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen1,
 'OUTPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen3,
 'OUTPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Avenue_Line_tree_3rd_size_closed_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Tree avenue and single-line trees with trees of 3rd size
#with closed foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Avenue_Line_tree_3rd_size_closed_foliage_tussen = iface.addRasterLayer(
    Avenue_Line_tree_3rd_size_closed_foliage_tussen5,
    'Avenue&Lines with trees of 3rd size with closed foliage (tussenstap)')
```

```
#Analysis Possibility
#Group of trees and street tree with trees of 1st size with open foliage
#without land availability m2 analysis
Group_street_tree_1st_size_open_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size open foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "15m obstacle free@1"=1 AND "Proximity to structures 8m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_street_tree_1st_size_open_foliage_tussen1})

#Preparing land availability analysis
#Group of trees and street tree with trees of 1st size with open foliage
Group_street_tree_1st_size_open_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size open foliage tussen2.shp'
Group_street_tree_1st_size_open_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size open foliage tussen3.shp'
Group_street_tree_1st_size_open_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size open foliage tussen4.shp'
Group_street_tree_1st_size_open_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size open foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Group_street_tree_1st_size_open_foliage_tussen1,
 'OUTPUT' : Group_street_tree_1st_size_open_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Group_street_tree_1st_size_open_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_street_tree_1st_size_open_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
```

```
 'INPUT' : Group_street_tree_1st_size_open_foliage_tussen3,
 'OUTPUT' : Group_street_tree_1st_size_open_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_street_tree_1st_size_open_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Group_street_tree_1st_size_open_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Group of trees and street tree with trees of 1st size
#with open foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Group_street_tree_1st_size_open_foliage_tussen = iface.addRasterLayer(
    Group_street_tree_1st_size_open_foliage_tussen5,
    'Group&street with trees of 1st size with open foliage (tussenstap)')

#Analysis Possibility
#Group of trees and street tree with trees of 1st size with closed foliage
#without land availability m2 analysis
Group_street_tree_1st_size_closed_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size closed foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Amount of street traffic buffer@1"=0 AND "Buildings@1"=0 \
 AND "Water@1"=0 AND "Trees@1"=0 AND "15m obstacle free@1"=1 AND \
 "Proximity to structures 8m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_street_tree_1st_size_closed_foliage_tussen1})

#Preparing land availability analysis
#Group of trees and street tree with trees of 1st size with closed foliage
Group_street_tree_1st_size_closed_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size closed foliage tussen2.shp'
Group_street_tree_1st_size_closed_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size closed foliage tussen3.shp'
Group_street_tree_1st_size_closed_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size closed foliage tussen4.shp'
Group_street_tree_1st_size_closed_foliage_tussen5 = 'D:\Data afstuderen\
```

```
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 1st size closed foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Group_street_tree_1st_size_closed_foliage_tussen1,
 'OUTPUT' : Group_street_tree_1st_size_closed_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Group_street_tree_1st_size_closed_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_street_tree_1st_size_closed_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Group_street_tree_1st_size_closed_foliage_tussen3,
 'OUTPUT' : Group_street_tree_1st_size_closed_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_street_tree_1st_size_closed_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Group_street_tree_1st_size_closed_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Group of trees and street tree with trees of 1st size
#with closed foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Group_street_tree_1st_size_closed_foliage_tussen = iface.addRasterLayer(
    Group_street_tree_1st_size_closed_foliage_tussen5,
    'Group&street with trees of 1st size with closed foliage (tussenstap)')

#Analysis Possibility
#Group of trees and street tree with trees of 2nd size with open foliage
#without land availability m2 analysis
Group_street_tree_2nd_size_open_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size open foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
```

```
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "8m obstacle free@1"=1 AND "Proximity to structures 4m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_street_tree_2nd_size_open_foliage_tussen1})

#Preparing land availability analysis
#Group of trees and street tree with trees of 2nd size with open foliage
Group_street_tree_2nd_size_open_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size open foliage tussen2.shp'
Group_street_tree_2nd_size_open_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size open foliage tussen3.shp'
Group_street_tree_2nd_size_open_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size open foliage tussen4.shp'
Group_street_tree_2nd_size_open_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size open foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Group_street_tree_2nd_size_open_foliage_tussen1,
 'OUTPUT' : Group_street_tree_2nd_size_open_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Group_street_tree_2nd_size_open_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_street_tree_2nd_size_open_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Group_street_tree_2nd_size_open_foliage_tussen3,
 'OUTPUT' : Group_street_tree_2nd_size_open_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_street_tree_2nd_size_open_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
```

```
 'OUTPUT' : Group_street_tree_2nd_size_open_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Group of trees and street tree with trees of 2nd size
#with open foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Group_street_tree_2nd_size_open_foliage_tussen = iface.addRasterLayer(
    Group_street_tree_2nd_size_open_foliage_tussen5,
    'Group&street with trees of 2nd size with open foliage (tussenstap)')

#Analysis Possibility
#Group of trees and street tree with trees of 2nd size with closed foliage
#without land availability m2 analysis
Group_street_tree_2nd_size_closed_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size closed foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Amount of street traffic buffer@1"=0 AND "Buildings@1"=0 \
 AND "Water@1"=0 AND "Trees@1"=0 AND "8m obstacle free@1"=1 AND \
 "Proximity to structures 4m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_street_tree_2nd_size_closed_foliage_tussen1})

#Preparing land availability analysis
#Group of trees and street tree with trees of 2nd size with closed foliage
Group_street_tree_2nd_size_closed_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size closed foliage tussen2.shp'
Group_street_tree_2nd_size_closed_foliage_tussen3= 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size closed foliage tussen3.shp'
Group_street_tree_2nd_size_closed_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size closed foliage tussen4.shp'
Group_street_tree_2nd_size_closed_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 2nd size closed foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Group_street_tree_2nd_size_closed_foliage_tussen1,
 'OUTPUT' : Group_street_tree_2nd_size_closed_foliage_tussen2})
```

```
#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Group_street_tree_2nd_size_closed_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_street_tree_2nd_size_closed_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Group_street_tree_2nd_size_closed_foliage_tussen3,
 'OUTPUT' : Group_street_tree_2nd_size_closed_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_street_tree_2nd_size_closed_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Group_street_tree_2nd_size_closed_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Group of trees and street tree with trees of 2nd size
#with closed foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Group_street_tree_2nd_size_closed_foliage_tussen = iface.addRasterLayer(
    Group_street_tree_2nd_size_closed_foliage_tussen5,
    'Group&street with trees of 2nd size with closed foliage (tussenstap)')

#Analysis Possibility
#Group of trees and street tree with trees of 3rd size with open foliage
#without land availability m2 analysis
Group_street_tree_3rd_size_open_foliage_tussen1 = 'D:\Data afstuderen\
    \OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
    \Group&street Tree 3rd size open foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "5m obstacle free@1"=1 AND "Proximity to structures 2m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_street_tree_3rd_size_open_foliage_tussen1})

#Preparing land availability analysis
#Group of trees and street tree with trees of 3rd size with open foliage
```

```
Group_street_tree_3rd_size_open_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size open foliage tussen2.shp'
Group_street_tree_3rd_size_open_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size open foliage tussen3.shp'
Group_street_tree_3rd_size_open_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size open foliage tussen4.shp'
Group_street_tree_3rd_size_open_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size open foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Group_street_tree_3rd_size_open_foliage_tussen1,
 'OUTPUT' : Group_street_tree_3rd_size_open_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Group_street_tree_3rd_size_open_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_street_tree_3rd_size_open_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Group_street_tree_3rd_size_open_foliage_tussen3,
 'OUTPUT' : Group_street_tree_3rd_size_open_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_street_tree_3rd_size_open_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Group_street_tree_3rd_size_open_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Group of trees and street tree with trees of 3rd size
#with open foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Group_street_tree_3rd_size_open_foliage_tussen = iface.addRasterLayer(
    Group_street_tree_3rd_size_open_foliage_tussen5,
    'Group&street with trees of 3rd size with open foliage (tussenstap)')
```

```
#Analysis Possibility
#Group of trees and street tree with trees of 3rd size with closed foliage
#without land availability m2 analysis
Group_street_tree_3rd_size_closed_foliage_tussen1 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size closed foliage tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Amount of street traffic buffer@1"=0 AND "Buildings@1"=0 \
 AND "Water@1"=0 AND "Trees@1"=0 AND "5m obstacle free@1"=1 AND \
 "Proximity to structures 2m buffer@1"=0 AND \
 "Slope of less than 10 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_street_tree_3rd_size_closed_foliage_tussen1})

#Preparing land availability analysis
#Group of trees and street tree with trees of 3rd size with closed foliage
Group_street_tree_3rd_size_closed_foliage_tussen2 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size closed foliage tussen2.shp'
Group_street_tree_3rd_size_closed_foliage_tussen3 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size closed foliage tussen3.shp'
Group_street_tree_3rd_size_closed_foliage_tussen4 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size closed foliage tussen4.shp'
Group_street_tree_3rd_size_closed_foliage_tussen5 = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Tussenstappen Possibility lagen\
\Group&street Tree 3rd size closed foliage tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available',
 'INPUT' : Group_street_tree_3rd_size_closed_foliage_tussen1,
 'OUTPUT' : Group_street_tree_3rd_size_closed_foliage_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available',
 'INPUT' : Group_street_tree_3rd_size_closed_foliage_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_street_tree_3rd_size_closed_foliage_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
```

```
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Group_street_tree_3rd_size_closed_foliage_tussen3,
 'OUTPUT' : Group_street_tree_3rd_size_closed_foliage_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_street_tree_3rd_size_closed_foliage_tussen4,
 'INVERT' : False, 'NODATA' : None, 'OPTIONS' : '',
 'OUTPUT' : Group_street_tree_3rd_size_closed_foliage_tussen5, 'UNITS' : 0,
 'USE_Z' : False, 'WIDTH' : width})

#Add Group of trees and street tree with trees of 3rd size
#with closed foliage (tussenstap) layer for land availability analysis
#to QGIS Layer panel
Group_street_tree_3rd_size_closed_foliage_tussen = iface.addRasterLayer(
    Group_street_tree_3rd_size_closed_foliage_tussen5,
    'Group&street with trees of 3rd size with closed foliage (tussenstap)')

#Analysis Possibility
#Group of shrubs and single shrub without land availability m2 analysis
Group_single_shrub_tussen1 = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tussenstappen Possibility lagen\Group&single shrub tussen1.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '"Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "Green@1"=0 AND "3m obstacle free@1"=1 AND \
 "Proximity to structures buffer 1m@1"=0 AND \
 "Slope of less than 20 degrees@1"=1 AND "Tree protection zone@1"=0 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_single_shrub_tussen1})

#Preparing land availability analysis for Group of shrubs and single shrub
Group_single_shrub_tussen2 = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tussenstappen Possibility lagen\Group&single shrub tussen2.shp'
Group_single_shrub_tussen3 = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tussenstappen Possibility lagen\Group&single shrub tussen3.shp'
Group_single_shrub_tussen4 = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tussenstappen Possibility lagen\Group&single shrub tussen4.shp'
Group_single_shrub_tussen5 = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Tussenstappen Possibility lagen\Group&single shrub tussen5.tif'

#Vectorizing raster layer
processing.run("gdal:polygonize",
```

```
{'BAND' : 1, 'EIGHT_CONNECTEDNESS' : False, 'EXTRA' : '',
 'FIELD' : 'Available', 'INPUT' : Group_single_shrub_tussen1,
 'OUTPUT' : Group_single_shrub_tussen2})

#Extract Available = 1
processing.run("native:extractbyattribute",
{'FIELD' : 'Available', 'INPUT' : Group_single_shrub_tussen2, 'OPERATOR' : 0,
 'OUTPUT' : Group_single_shrub_tussen3, 'VALUE' : '1'})

#Calculate area
processing.run("native:fieldcalculator",
{'FIELD_LENGTH' : 10, 'FIELD_NAME' : 'Area', 'FIELD_PRECISION' : 3,
 'FIELD_TYPE' : 0, 'FORMULA' : ' $area ',
 'INPUT' : Group_single_shrub_tussen3,
 'OUTPUT' : Group_single_shrub_tussen4})

#Rasterize area
processing.run("gdal:rasterize",
{'BURN' : 0, 'DATA_TYPE' : 5, 'EXTENT' : extent, 'EXTRA' : '',
 'FIELD' : 'Area', 'HEIGHT' : height, 'INIT' : None,
 'INPUT' : Group_single_shrub_tussen4, 'INVERT' : False,
 'NODATA' : None, 'OPTIONS' : '', 'OUTPUT' : Group_single_shrub_tussen5,
 'UNITS' : 0, 'USE_Z' : False, 'WIDTH' : width})

#Add Group of shrubs and single shrub (tussenstap) layer
#for land availability analysis to QGIS Layer panel
Group_single_shrub_tussen = iface.addRasterLayer(
    Group_single_shrub_tussen5, 'Group&single shrub (tussenstap)')


#Creating end products per UGI type (with land availability analysis)
#Land availability Analysis
#Tree avenue and single-line with trees of 1st size with open foliage
#(times value on priority ranking list)
Avenue_line_tree_1st_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Avenue & Line Tree 1st size open foliage tussen.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' : '(\
 "Avenue&Lines with trees of 1st size with open foliage (tussenstap)@1"\
 >=62.5) * 8',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_line_tree_1st_size_open_foliage_output})

#Add Possibility
#Tree avenue and single-line with trees of 1st size with open foliage layer
#to QGIS Layer panel
```

```
Avenue_line_tree_1st_size_open_foliage = iface.addRasterLayer(
    Avenue_line_tree_1st_size_open_foliage_output,
    'Possibility avenue and single-line with trees of 1st size \
    with open foliage')

#Land availability Analysis
#Tree avenue and single-line with trees of 1st size with closed foliage
#(times value on priority ranking list)
Avenue_line_tree_1st_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Avenue & Line Tree 1st size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' : '(\
 "Avenue&Lines with trees of 1st size with closed foliage (tussenstap)@1"\
 >=62.5) * 1',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_line_tree_1st_size_closed_foliage_output})

#Add Possibility
#Tree avenue and single-line with trees of 1st size with closed foliage layer
#to QGIS Layer panel
Avenue_line_tree_1st_size_closed_foliage = iface.addRasterLayer(
    Avenue_line_tree_1st_size_closed_foliage_output,
    'Possibility avenue and single-line with trees of 1st size \
    with closed foliage')

#Land availability Analysis
#Tree avenue and single-line with trees of 2nd size with open foliage
#(times value on priority ranking list)
Avenue_line_tree_2nd_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Avenue & Line Tree 2nd size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' : '(\
 "Avenue&Lines with trees of 2nd size with open foliage (tussenstap)@1"\
 >=50) * 9',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_line_tree_2nd_size_open_foliage_output})

#Add Possibility
#Tree avenue and single-line with trees of 2nd size with open foliage layer
#to QGIS Layer panel
Avenue_line_tree_2nd_size_open_foliage = iface.addRasterLayer(
    Avenue_line_tree_2nd_size_open_foliage_output,
    'Possibility avenue and single-line with trees of 2nd size \
    with open foliage')
```

```
#Land availability Analysis
#Tree avenue and single-line with trees of 2nd size with closed foliage
#(times value on priority ranking list)
Avenue_line_tree_2nd_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Avenue & Line Tree 2nd size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' : '(\
 "Avenue&Lines with trees of 2nd size with closed foliage (tussenstap)@1"\
 >=50) * 3',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_line_tree_2nd_size_closed_foliage_output})

#Add Possibility
#Tree avenue and single-line with trees of 2nd size with closed foliage layer
#to QGIS Layer panel
Avenue_line_tree_2nd_size_closed_foliage = iface.addRasterLayer(
    Avenue_line_tree_2nd_size_closed_foliage_output,
    'Possibility avenue and single-line with trees of 2nd size \
    with closed foliage')

#Land availability Analysis
#Tree avenue and single-line with trees of 3rd size with open foliage
#(times value on priority ranking list)
Avenue_line_tree_3rd_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Avenue & Line Tree 3rd size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' : '(\
 "Avenue&Lines with trees of 3rd size with open foliage (tussenstap)@1"\
 >=37.5) * 15',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_line_tree_3rd_size_open_foliage_output})

#Add Possibility
#Tree avenue and single-line with trees of 3rd size with open foliage layer
#to QGIS Layer panel
Avenue_line_tree_3rd_size_open_foliage = iface.addRasterLayer(
    Avenue_line_tree_3rd_size_open_foliage_output,
    'Possibility avenue and single-line with trees of 3rd size \
    with open foliage')

#Land availability Analysis
#Tree avenue and single-line with trees of 3rd size with closed foliage
#(times value on priority ranking list)
```

```
Avenue_line_tree_3rd_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Avenue & Line Tree 3rd size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' : '(\
 "Avenue&Lines with trees of 3rd size with closed foliage (tussenstap)@1"\
 >=37.5) * 4',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Avenue_line_tree_3rd_size_closed_foliage_output})

#Add Possibility
#Tree avenue and single-line with trees of 3rd size with closed foliage layer
#to QGIS Layer panel
Avenue_line_tree_3rd_size_closed_foliage = iface.addRasterLayer(
    Avenue_line_tree_3rd_size_closed_foliage_output,
    'Possibility avenue and single-line with trees of 3rd size \
    with closed foliage')

#Land availability Analysis
#Group of trees with trees of 1st size with open foliage
#(times value on priority ranking list)
Group_tree_1st_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Group Tree 1st size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 1st size with open foliage (tussenstap)@1"\
 >=37.5) * 12',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_tree_1st_size_open_foliage_output})

#Add Possibility
#Group of trees with trees of 1st size with open foliage layer
#to QGIS Layer panel
Group_tree_1st_size_open_foliage = iface.addRasterLayer(
    Group_tree_1st_size_open_foliage_output,
    'Possibility group with trees of 1st size with open foliage')

#Land availability Analysis
#Group of trees with trees of 1st size with closed foliage
#(times value on priority ranking list)
Group_tree_1st_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Group Tree 1st size closed foliage.tif'

processing.run("qgis:rastercalculator",
```

```
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 1st size with closed foliage (tussenstap)@1"\
 >=37.5) * 2',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_tree_1st_size_closed_foliage_output})

#Add Possibility
#Group of trees with trees of 1st size with closed foliage layer
#to QGIS Layer panel
Group_tree_1st_size_closed_foliage = iface.addRasterLayer(
    Group_tree_1st_size_closed_foliage_output,
    'Possibility group with trees of 1st size with closed foliage')

#Land availability Analysis
#Group of trees with trees of 2nd size with open foliage
#(times value on priority ranking list)
Group_tree_2nd_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Group Tree 2nd size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 2nd size with open foliage (tussenstap)@1"\
 >=30) * 16',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_tree_2nd_size_open_foliage_output})

#Add Possibility
#Group of trees with trees of 2nd size with open foliage layer
#to QGIS Layer panel
Group_tree_2nd_size_open_foliage = iface.addRasterLayer(
    Group_tree_2nd_size_open_foliage_output,
    'Possibility group with trees of 2nd size with open foliage')

#Land availability Analysis
#Group of trees with trees of 2nd size with closed foliage
#(times value on priority ranking list)
Group_tree_2nd_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Group Tree 2nd size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 2nd size with closed foliage (tussenstap)@1"\
 >=30) * 5',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_tree_2nd_size_closed_foliage_output})
```

```
#Add Possibility
#Group of trees with trees of 2nd size with closed foliage layer
#to QGIS Layer panel
Group_tree_2nd_size_closed_foliage = iface.addRasterLayer(
    Group_tree_2nd_size_closed_foliage_output,
    'Possibility group with trees of 2nd size with closed foliage')

#Land availability Analysis
#Group of trees with trees of 3rd size with open foliage
#(times value on priority ranking list)
Group_tree_3rd_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Group Tree 3rd size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 3rd size with open foliage (tussenstap)@1"\
 >=22.5) * 18',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_tree_3rd_size_open_foliage_output})

#Add Possibility
#Group of trees with trees of 3rd size with open foliage layer
#to QGIS Layer panel
Group_tree_3rd_size_open_foliage = iface.addRasterLayer(
    Group_tree_3rd_size_open_foliage_output,
    'Possibility group with trees of 3rd size with open foliage')

#Land availability Analysis
#Group of trees with trees of 3rd size with closed foliage
#(times value on priority ranking list)
Group_tree_3rd_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Group Tree 3rd size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 3rd size with closed foliage (tussenstap)@1"\
 >=22.5) * 6',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_tree_3rd_size_closed_foliage_output})

#Add Possibility
#Group of trees with trees of 3rd size with closed foliage layer
#to QGIS Layer panel
Group_tree_3rd_size_closed_foliage = iface.addRasterLayer(
    Group_tree_3rd_size_closed_foliage_output,
    'Possibility group with trees of 3rd size with closed foliage')
```

```
#Land availability Analysis
#Street tree of 1st size with open foliage
#(times value on priority ranking list)
Street_tree_1st_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Street Tree 1st size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 1st size with open foliage (tussenstap)@1"\
 >=12.5) * 17',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Street_tree_1st_size_open_foliage_output})

#Add Possibility
#Street tree of 1st size with open foliage layer to QGIS Layer panel
Street_tree_1st_size_open_foliage = iface.addRasterLayer(
    Street_tree_1st_size_open_foliage_output,
    'Possibility street tree of 1st size with open foliage')

#Land availability Analysis
#Street tree of 1st size with closed foliage
#(times value on priority ranking list)
Street_tree_1st_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Street Tree 1st size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 1st size with closed foliage (tussenstap)@1"\
 >=12.5) * 7',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Street_tree_1st_size_closed_foliage_output})

#Add Possibility
#Street tree of 1st size with closed foliage layer to QGIS Layer panel
Street_tree_1st_size_closed_foliage = iface.addRasterLayer(
    Street_tree_1st_size_closed_foliage_output,
    'Possibility street tree of 1st size with closed foliage')

#Land availability Analysis
#Street tree of 2nd size with open foliage
#(times value on priority ranking list)
Street_tree_2nd_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Street Tree 2nd size open foliage.tif'
```

```
processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 2nd size with open foliage (tussenstap)@1"\
 >=10) * 19',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Street_tree_2nd_size_open_foliage_output})

#Add Possibility
#Street tree of 2nd size with open foliage layer to QGIS Layer panel
Street_tree_2nd_size_open_foliage = iface.addRasterLayer(
    Street_tree_2nd_size_open_foliage_output,
    'Possibility street tree of 2nd size with open foliage')

#Land availability Analysis
#Street tree of 2nd size with closed foliage
#(times value on priority ranking list)
Street_tree_2nd_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Street Tree 2nd size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 2nd size with closed foliage (tussenstap)@1"\
 >=10) * 11',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Street_tree_2nd_size_closed_foliage_output})

#Add Possibility
#Street tree of 2nd size with closed foliage layer to QGIS Layer panel
Street_tree_2nd_size_closed_foliage = iface.addRasterLayer(
    Street_tree_2nd_size_closed_foliage_output,
    'Possibility street tree of 2nd size with closed foliage')

#Land availability Analysis
#Street tree of 3rd size with open foliage
#(times value on priority ranking list)
Street_tree_3rd_size_open_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Street Tree 3rd size open foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 3rd size with open foliage (tussenstap)@1"\
 >=7.5) * 21',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Street_tree_3rd_size_open_foliage_output})

#Add Possibility
```

```
#Street tree of 3rd size with open foliage layer to QGIS Layer panel
Street_tree_3rd_size_open_foliage = iface.addRasterLayer(
    Street_tree_3rd_size_open_foliage_output,
    'Possibility street tree of 3rd size with open foliage')

#Land availability Analysis
#Street tree of 3rd size with closed foliage
#(times value on priority ranking list)
Street_tree_3rd_size_closed_foliage_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Street Tree 3rd size closed foliage.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS, 'EXPRESSION' :
 '("Group&street with trees of 3rd size with closed foliage (tussenstap)@1"\
 >=7.5) * 14',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Street_tree_3rd_size_closed_foliage_output})

#Add Possibility
#Street tree of 3rd size with closed foliage layer to QGIS Layer panel
Street_tree_3rd_size_closed_foliage = iface.addRasterLayer(
    Street_tree_3rd_size_closed_foliage_output,
    'Possibility street tree of 3rd size with closed foliage')

#Land availability Analysis
#Group of shrubs (times value on priority ranking list)
Group_shrub_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Group shrub.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Group&single shrub (tussenstap)@1">=3) * 22',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Group_shrub_output})

#Add Possibility Group of shrubs layer to QGIS Layer panel
Group_shrub = iface.addRasterLayer(Group_shrub_output,
                                   'Possibility group of shrubs')

#Land availability Analysis
#Single shrub (times value on priority ranking list)
Single_shrub_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Single shrub.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Group&single shrub (tussenstap)@1">=0.5) * 28',
```

```
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Single_shrub_output})

#Add Possibility Single shrub layer to QGIS Layer panel
Single_shrub = iface.addRasterLayer(Single_shrub_output,
                                    'Possibility single shrub')

#Analysis Possibility Grass (times value on priority ranking list)
Grass_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Grass.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "Green@1"=0 AND "Land availability@1"=0 AND \
 "Width of paths and roads@1"=0) * 13',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings, 'OUTPUT' : Grass_output})

#Add Possibility Grass layer to QGIS Layer panel
Grass = iface.addRasterLayer(Grass_output, 'Possibility grass')

#Analysis Possibility
#Perennials & annual plants (times value on priority ranking list)
Perennials_Annual_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Perennials&annual plants.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Buildings@1"=0 AND "Water@1"=0 AND "Trees@1"=0 AND \
 "Green@1"=0 AND "Slope of less than 20 degrees@1"=1 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0) * 25',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Perennials_Annual_output})

#Add Possibility Perennials & annual plants layer to QGIS Layer panel
Perennials_Annual = iface.addRasterLayer(Perennials_Annual_output,
                            'Possibility Perennials & Annual plants')

#Analysis Possibility
#Bankside plants (times value on priority ranking list)
Bankside_plants_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Bankside plants.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Buildings@1"=0 AND "Banks@1"=1 AND \
 "Trees@1"=0 AND "Green@1"=0 AND "Width of paths and roads@1"=0 AND \
 "Railway@1"=0 AND "Other Structures@1"=0) * 27',
```

```
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Bankside_plants_output})

#Add Possibility Bankside plants layer to QGIS Layer panel
Bankside_plants = iface.addRasterLayer(Bankside_plants_output,
                                       'Possibility Bankside plants')

#Analysis Possibility
#Grass, moss, sedum and herbs on roofs (times value on priority ranking list)
Grass_moss_sedum_herbs_roofs_output = "D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Grass Moss Sedum Herbs on roofs.tif"

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '(("Buildings@1"=1 OR "Other Structures@1"=1) AND \
 "Building age of newer than 1991@1"=1 AND \
 "Slope of roof of less than 30 degrees@1"=1) * 26',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Grass_moss_sedum_herbs_roofs_output})

#Add Possibility
#Grass, moss, sedum and herbs on roofs layer to QGIS Layer panel
Grass_moss_sedum_herbs_roofs = iface.addRasterLayer(
    Grass_moss_sedum_herbs_roofs_output,
    'Possibility Grass, moss, sedum & herbs on roofs')

#Analysis Possibility
#Perennials, annual plants & shrubs on roofs
#(times value on priority ranking list)
Perennials_annual_shrub_roofs_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Perennials Annual Shrubs on roofs.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '(("Buildings@1"=1 OR "Other Structures@1"=1) AND \
 "Building age of newer than 2012@1"=1 AND \
 "Slope of roof of less than 10 degrees@1"=1) * 23',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Perennials_annual_shrub_roofs_output})

#Add Possibility
#Perennials, annual plants & shrubs on roofs layer to QGIS Layer panel
Perennials_annual_shrub_roofs = iface.addRasterLayer(
    Perennials_annual_shrub_roofs_output,
    'Possibility Perennials, annual plants & shrubs on roofs')
```

```
#Analysis Possibility
#Small trees on roofs (times value on priority ranking list)
Small_trees_roofs_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Small trees on roofs.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '(("Buildings@1"=1 OR "Other Structures@1"=1) AND \
 "Building age of newer than 2012@1"=1 AND \
 "Slope of roof of less than 5 degrees@1"=1) * 10',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Small_trees_roofs_output})

#Add Possibility Small trees on roofs layer to QGIS Layer panel
Small_trees_roofs = iface.addRasterLayer(Small_trees_roofs_output,
                                         'Possibility Small trees on roofs')

#Analysis Possibility
# Climbers with green wall land availability analysis
#(times value on priority ranking list)
Climbers_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Possibility lagen\Climbers.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Building age 1972 buffer@1"=1 AND \
 "BufferWalls@1"=1 AND "Land availability@1"=0 AND \
 "Width of paths and roads@1"=0) * 24',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
 'OUTPUT' : Climbers_output})

#Add Possibility Climbers layer to QGIS Layer panel
Climbers = iface.addRasterLayer(Climbers_output,
                                'Possibility Climbers')

#Analysis Possibility
#Grass, moss, sedum, herbs, perennials & annual plants on walls
#with green wall land availability analysis
#(times value on priority ranking list)
Grass_moss_sedum_herbs_perennials_annual_wall_output = 'D:\Data afstuderen\
\OUTPUT_Requirement_Analyse\Possibility lagen\
\Grass, moss, sedum, herbs, perennials & annual on wall.tif'

processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Building age 2012 buffer@1"=1 AND "BufferWalls@1"=1 AND \
 "Land availability@1"=0 AND "Width of paths and roads@1"=0) * 20',
 'EXTENT' : extent, 'LAYERS' : Raster_buildings,
```

```
 'OUTPUT' : Grass_moss_sedum_herbs_perennials_annual_wall_output})

#Add Possibility
#Grass, moss, sedum, herbs, perennials & annual plants on walls layer
#to QGIS Layer panel
Grass_moss_sedum_herbs_perennials_annual_wall = iface.addRasterLayer(
    Grass_moss_sedum_herbs_perennials_annual_wall_output,
    'Possibility Grass, moss, sedum, herbs, perennials & annual on wall')



#Creating Final map
#Merging all 28 possibility layers by selecting lowest value per cell
#(highest priority)
Final_map_tussen = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Final map\Final map tussen.tif'

processing.run("grass7:r.series",
{'-n' : False, 'GRASS_RASTER_FORMAT_META' : '',
 'GRASS_RASTER_FORMAT_OPT' : '',
 'GRASS_REGION_CELLSIZE_PARAMETER' : 0, 'GRASS_REGION_PARAMETER' : extent,
 'input' : [Avenue_line_tree_1st_size_open_foliage_output,
 Avenue_line_tree_1st_size_closed_foliage_output,
 Avenue_line_tree_2nd_size_open_foliage_output,
 Avenue_line_tree_2nd_size_closed_foliage_output,
 Avenue_line_tree_3rd_size_open_foliage_output,
 Avenue_line_tree_3rd_size_closed_foliage_output,
 Group_tree_1st_size_open_foliage_output,
 Street_tree_1st_size_open_foliage_output,
 Group_tree_1st_size_closed_foliage_output,
 Street_tree_1st_size_closed_foliage_output,
 Group_tree_2nd_size_open_foliage_output,
 Street_tree_2nd_size_open_foliage_output,
 Group_tree_2nd_size_closed_foliage_output,
 Street_tree_2nd_size_closed_foliage_output,
 Group_tree_3rd_size_open_foliage_output,
 Street_tree_3rd_size_open_foliage_output,
 Group_tree_3rd_size_closed_foliage_output,
 Street_tree_3rd_size_closed_foliage_output, Group_shrub_output,
 Single_shrub_output, Grass_output, Perennials_Annual_output,
 Bankside_plants_output, Grass_moss_sedum_herbs_roofs_output,
 Perennials_annual_shrub_roofs_output, Small_trees_roofs_output,
 Climbers_output, Grass_moss_sedum_herbs_perennials_annual_wall_output],
 'method' : [4], 'output' : Final_map_tussen, 'quantile' : '',
 'range' : [1,28], 'weights' : ''})

#Reducing Final map to Rotterdam with city polygon
Final_map_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Final map\Final map.tif'
```

```
processing.run("gdal:cliprasterbymasklayer",
{'ALPHA_BAND' : False, 'CROP_TO_CUTLINE' : True, 'DATA_TYPE' : 0,
 'EXTRA' : '', 'INPUT' : Final_map_tussen, 'KEEP_RESOLUTION' : True,
 'MASK' : fn_location, 'MULTITHREADING' : False, 'NODATA' : None,
 'OPTIONS' : '', 'OUTPUT' : Final_map_output, 'SET_RESOLUTION' : False,
 'SOURCE_CRS' : CRS, 'TARGET_CRS' : CRS, 'TARGET_EXTENT' :
 '85731.000400000,101032.598500000,430742.056100000,445396.540700000 \
 [EPSG:28992]', 'X_RESOLUTION' : None, 'Y_RESOLUTION' : None})

#Add Final map to QGIS Layer panel
Final_map = iface.addRasterLayer(Final_map_output, 'Final map')

#Linking possibility values with locations with high need for UGI
#(HTC values above 41 degrees celsius)
#Add Human Thermal Comfort map to QGIS Layer panel
HTC = iface.addRasterLayer(fn_HTC, 'Human Thermal Comfort map')

Final_map_with_HTC_output = 'D:\Data afstuderen\OUTPUT_Requirement_Analyse\
\Final map\Final map with HTC.tif'

#Reducing Final map to cells with HTC values above 41 degrees celsius
processing.run("qgis:rastercalculator",
{'CELLSIZE' : 1, 'CRS' : CRS,
 'EXPRESSION' : '("Human Thermal Comfort map@1" >= 41 )*"Final map@1"',
 'EXTENT' : extent, 'LAYERS' : None, 'OUTPUT' : Final_map_with_HTC_output})

#Add Final map linked to HTC values layer to GQIS Layer panel
Final_map_with_HTC = iface.addRasterLayer(Final_map_with_HTC_output,
                                          'Final map linked to HTC values')

#Giving colours to Possibility values in Final map linked to HTC values
#and creating legend
Colour_ramp = QgsColorRampShader()
Colour_ramp.setColorRampType(QgsColorRampShader.Exact)

list = [QgsColorRampShader.ColorRampItem(1, QColor(70,232,124),
    '1. Tree avenue & single-line with trees of 1st size and closed foliage'),
  QgsColorRampShader.ColorRampItem(2, QColor(140,23,213),
    '2. Group with trees of 1st size and closed foliage'),
  QgsColorRampShader.ColorRampItem(3, QColor(223,214,112),
    '3. Tree avenue & single-line with trees of 2nd size and closed foliage'),
  QgsColorRampShader.ColorRampItem(4, QColor(100,190,212),
    '4. Tree avenue & single-line with trees of 3rd size and closed foliage'),
  QgsColorRampShader.ColorRampItem(5, QColor(211,108,161),
    '5. Group with trees of 2nd size and closed foliage'),
  QgsColorRampShader.ColorRampItem(6, QColor(83,235,45),
    '6. Group with trees of 3rd size and closed foliage'),
```

```
  QgsColorRampShader.ColorRampItem(7, QColor(65,151,223),
    '7. Street tree of 1st size with closed foliage'),
  QgsColorRampShader.ColorRampItem(8, QColor(209,98,29),
    '8. Tree avenue & single-line with trees of 1st size and open foliage'),
  QgsColorRampShader.ColorRampItem(9, QColor(32,234,167),
    '9. Tree avenue & single-line with trees of 2nd size and open foliage'),
  QgsColorRampShader.ColorRampItem(10, QColor(201,53,209),
    '10. Small trees on roof'),
  QgsColorRampShader.ColorRampItem(11, QColor(176,206,86),
    '11. Street tree of 2nd size with closed foliage'),
  QgsColorRampShader.ColorRampItem(12, QColor(72,150,240),
    '12. Group with trees of 1st size and open foliage'),
  QgsColorRampShader.ColorRampItem(13, QColor(229,56,87),
    '13. Grass'),
  QgsColorRampShader.ColorRampItem(14, QColor(21,206,46),
    '14. Street tree of 3rd size with closed foliage'),
  QgsColorRampShader.ColorRampItem(15, QColor(122,50,223),
    '15. Tree avenue & single-line with trees of 3rd size and open foliage'),
  QgsColorRampShader.ColorRampItem(16, QColor(226,175,47),
    '16. Group with trees of 2nd size and open foliage'),
  QgsColorRampShader.ColorRampItem(17, QColor(85,203,203),
    '17. Street tree of 1st size with open foliage'),
  QgsColorRampShader.ColorRampItem(18, QColor(238,122,205),
    '18. Group with trees of 3rd size and open foliage'),
  QgsColorRampShader.ColorRampItem(19, QColor(95,200,20),
    '19. Street tree of 2nd size with open foliage'),
  QgsColorRampShader.ColorRampItem(20, QColor(136,150,239),
    '20. Grass, moss, sedum, herbs & Perennials and annual plants on wall'),
  QgsColorRampShader.ColorRampItem(21, QColor(236,69,36),
    '21. Street tree of 3rd size with open foliage'),
  QgsColorRampShader.ColorRampItem(22, QColor(49,214,126),
    '22. Group of shrubs'),
  QgsColorRampShader.ColorRampItem(23, QColor(202,99,236),
    '23. Shrubs, Perennials & annual plants on roof'),
  QgsColorRampShader.ColorRampItem(24, QColor(214,221,73),
    '24. Climbers'),
  QgsColorRampShader.ColorRampItem(25, QColor(50,153,204),
    '25. Perennials & annual plants'),
  QgsColorRampShader.ColorRampItem(26, QColor(210,28,98),
    '26. Grass, moss, sedum & herbs on roof'),
  QgsColorRampShader.ColorRampItem(27, QColor(102,227,91),
    '27. Bank side plants'),
  QgsColorRampShader.ColorRampItem(28, QColor(96,61,233),
    '28. Single shrub')]

Colour_ramp.setColorRampItemList(list)
```

Appendix H – Scheme of UGI analysis

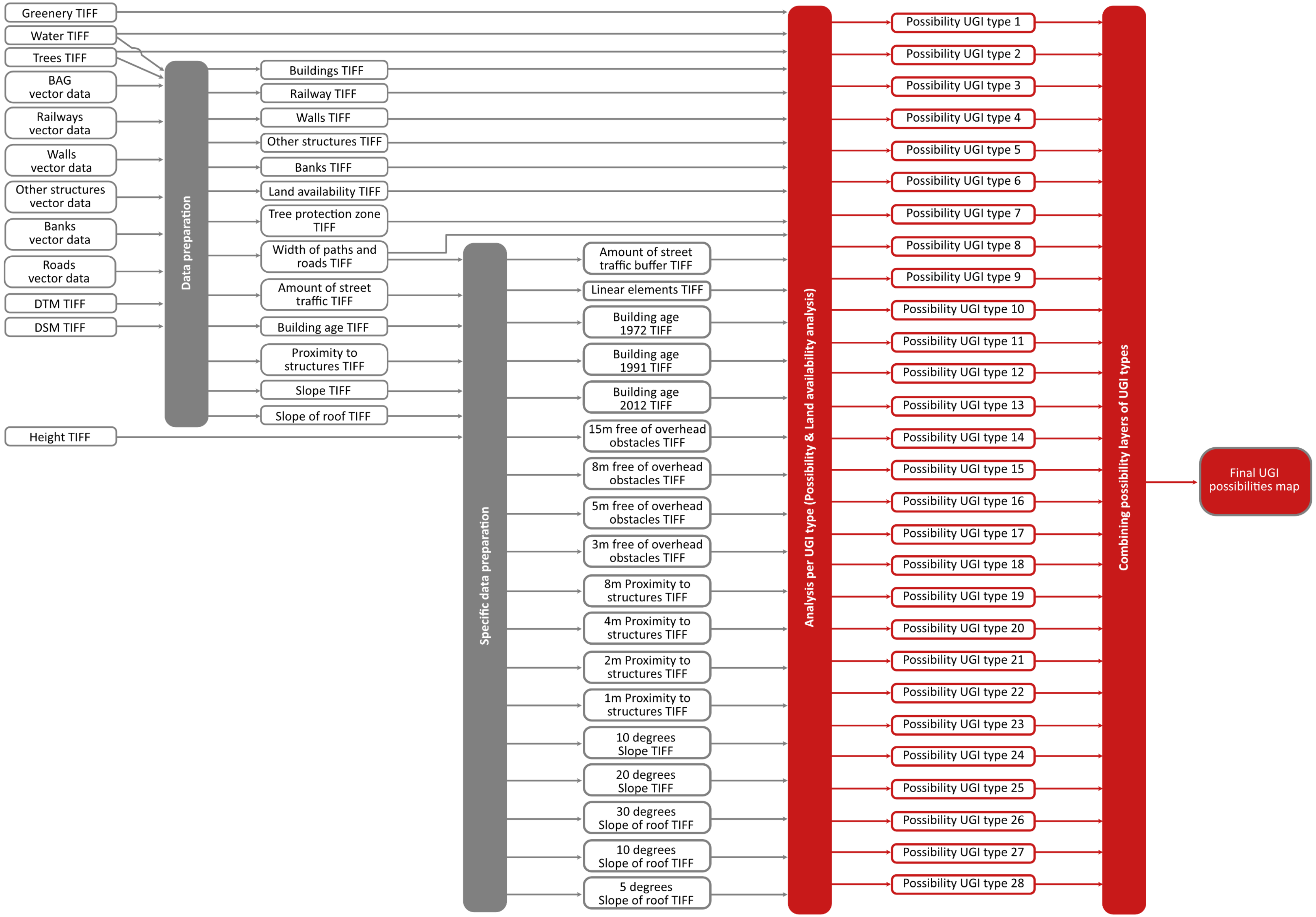


Figure 219: Total UGI analysis scheme

Appendix I – Analysis per UGI type schemes

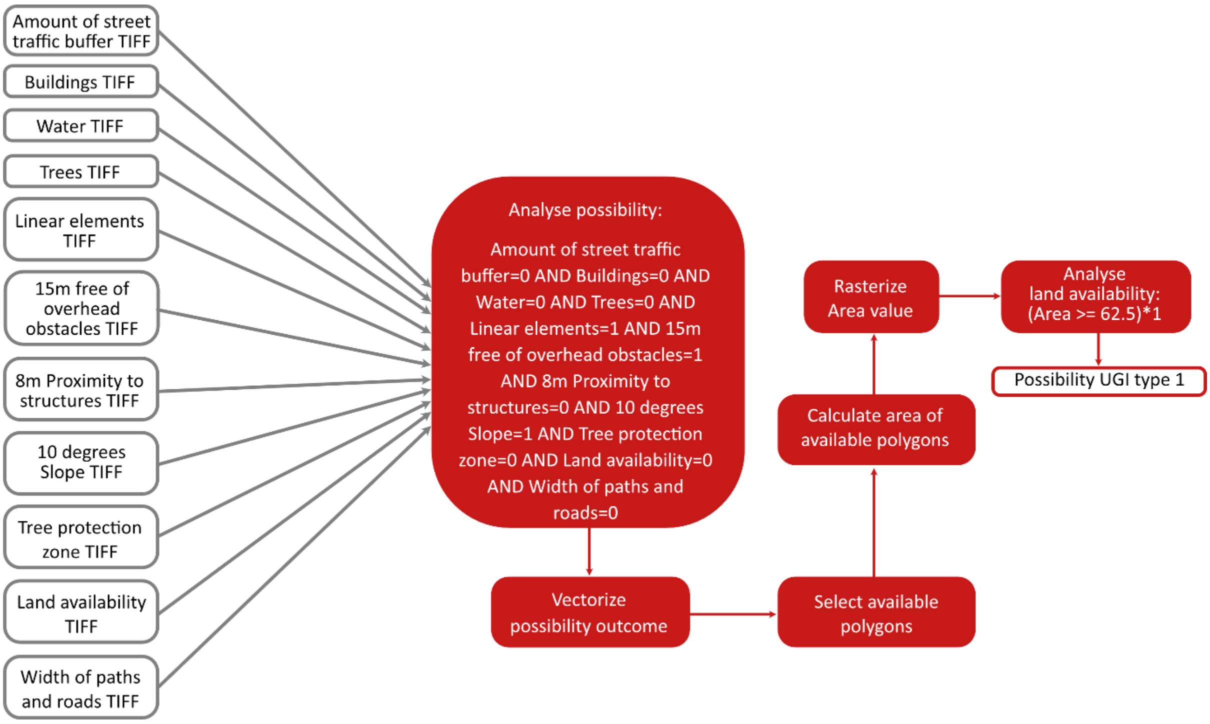


Figure 220: Possibility and land availability analyses UGI type 1

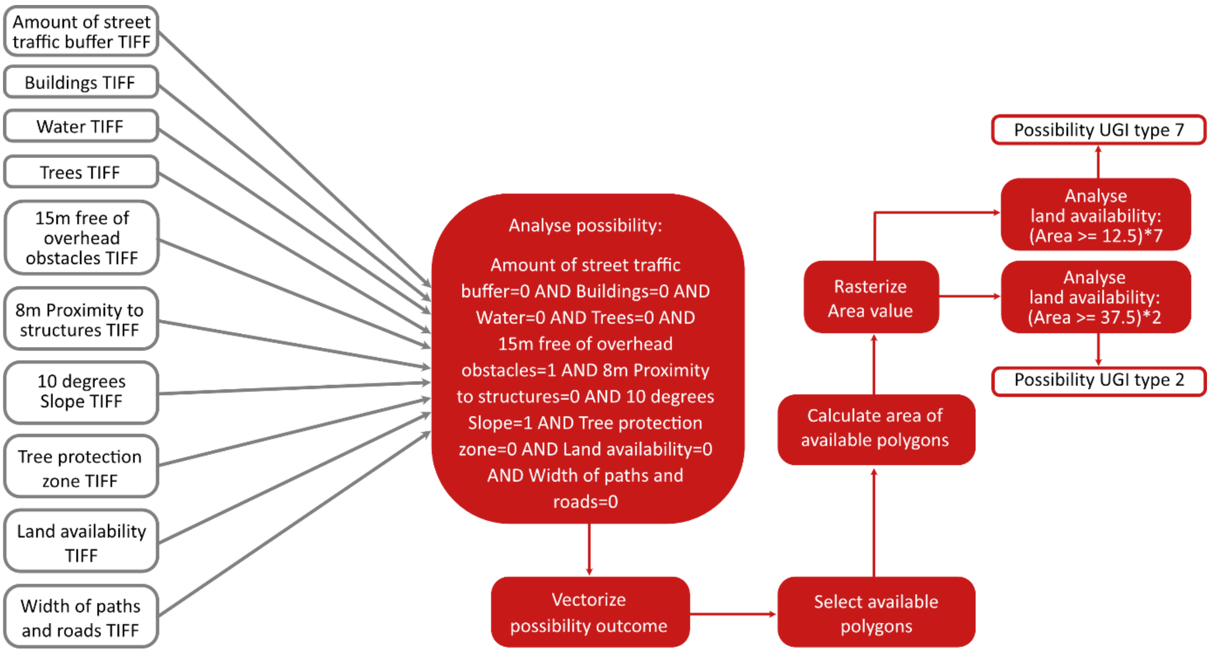


Figure 221: Possibility and land availability analyses UGI types 2 and 7

Figure 222: Possibility and land availability analyses UGI type 3

Figure 223: Possibility and land availability analyses UGI type 4

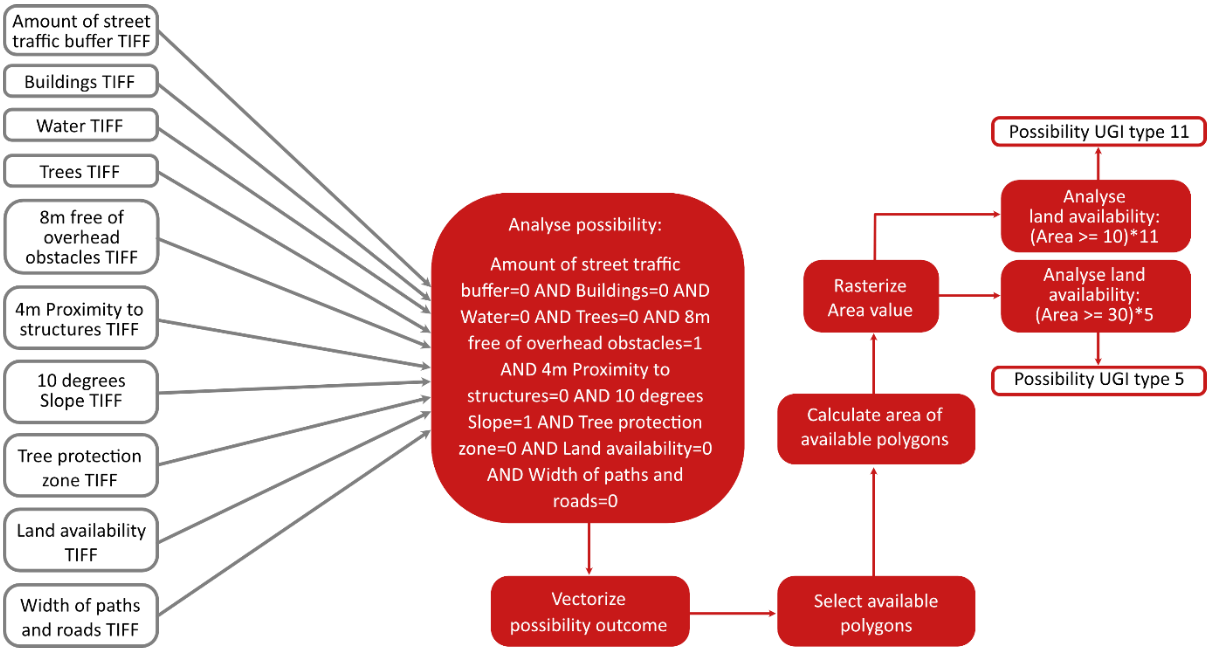


Figure 224: Possibility and land availability analyses UGI types 5 and 11

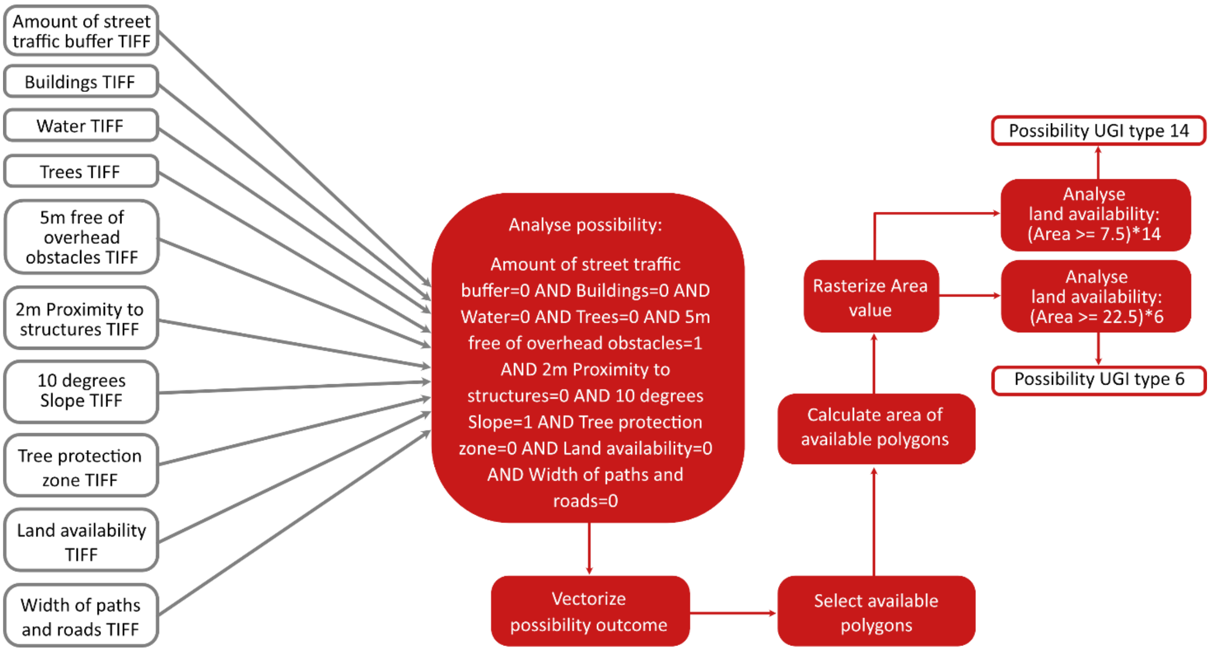


Figure 225: Possibility and land availability analyses UGI types 6 and 14

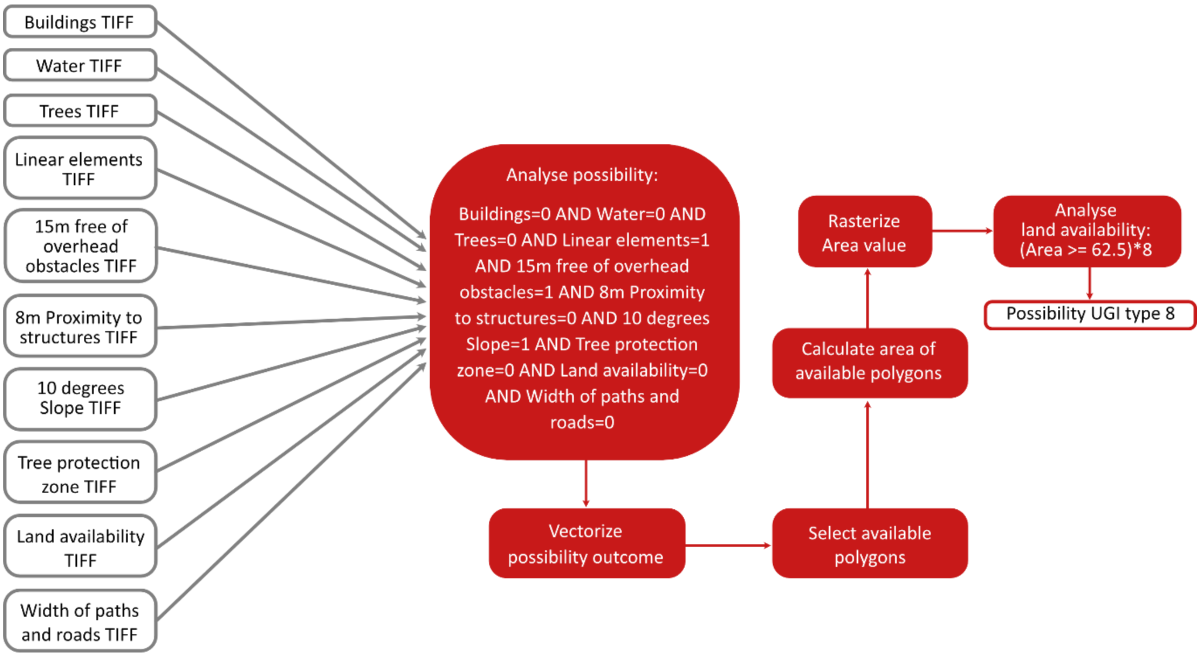


Figure 226: Possibility and land availability analyses UGI type 8

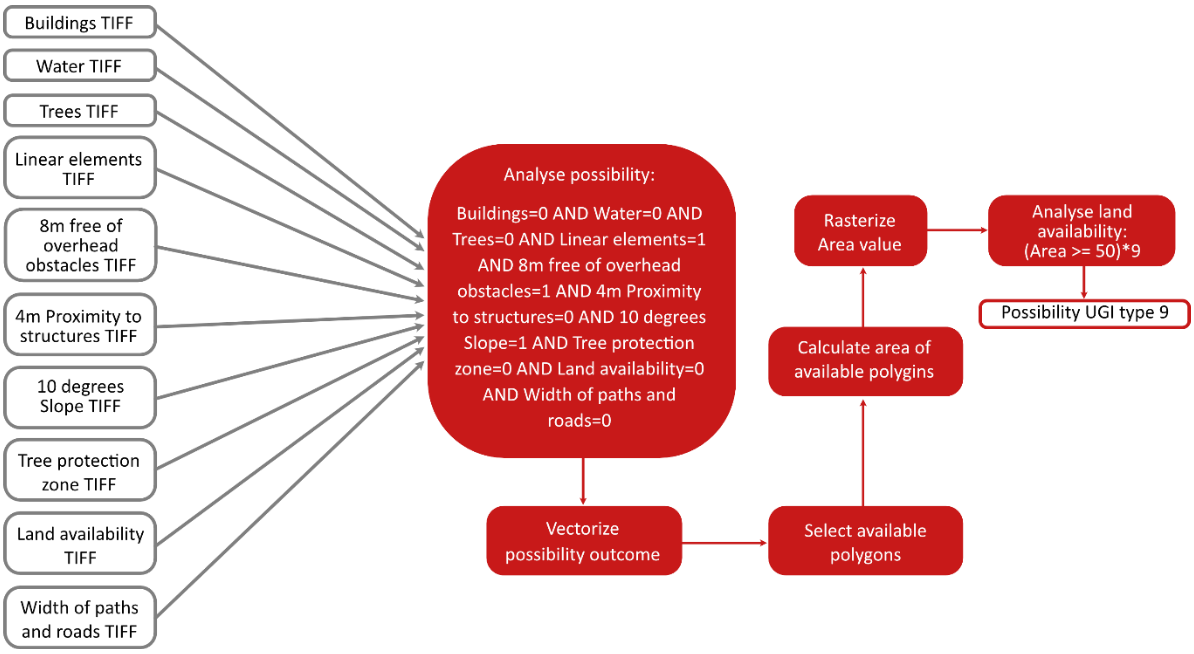


Figure 227: Possibility and land availability analyses UGI type 9

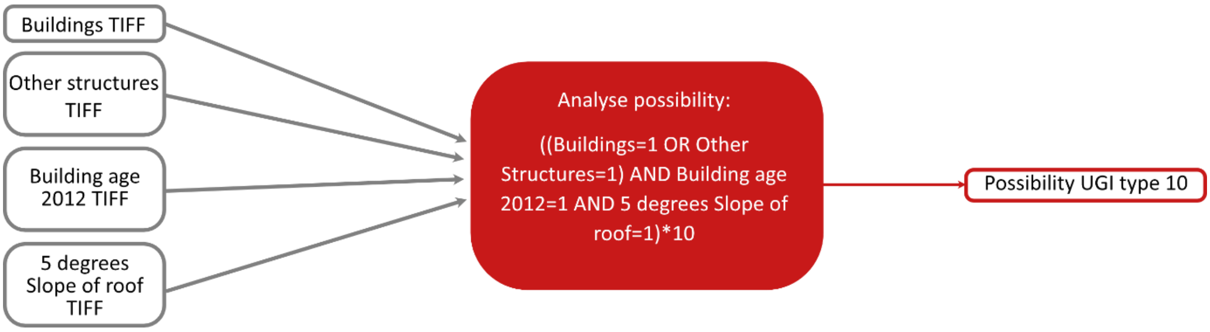


Figure 228: Possibility analysis UGI type 10

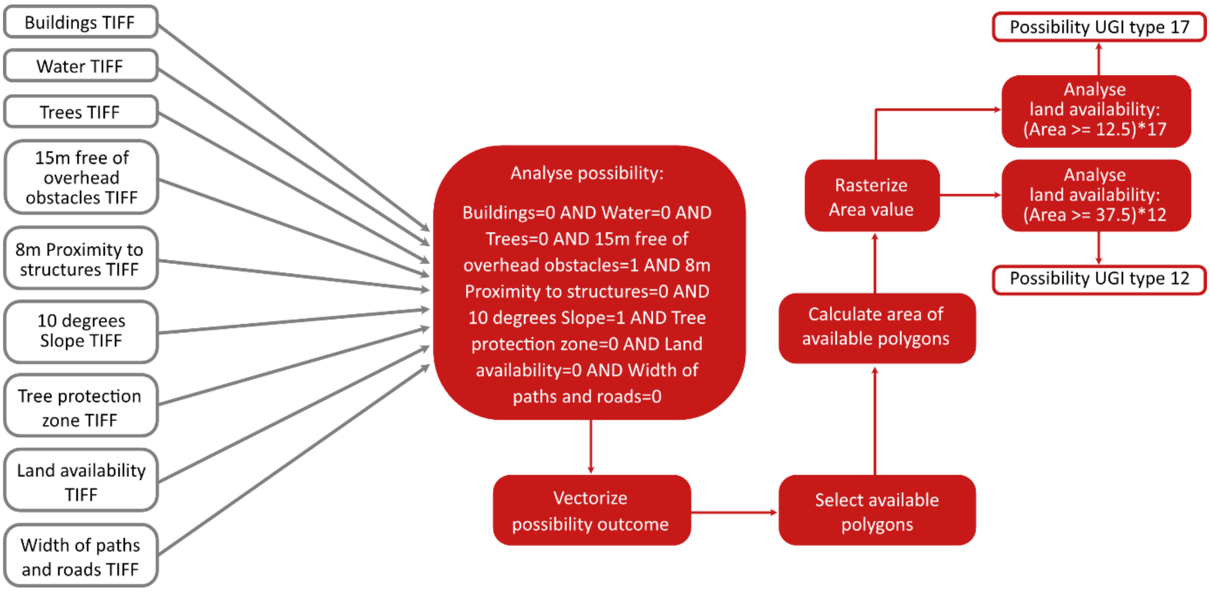


Figure 229: Possibility and land availability analyses UGI types 12 and 17

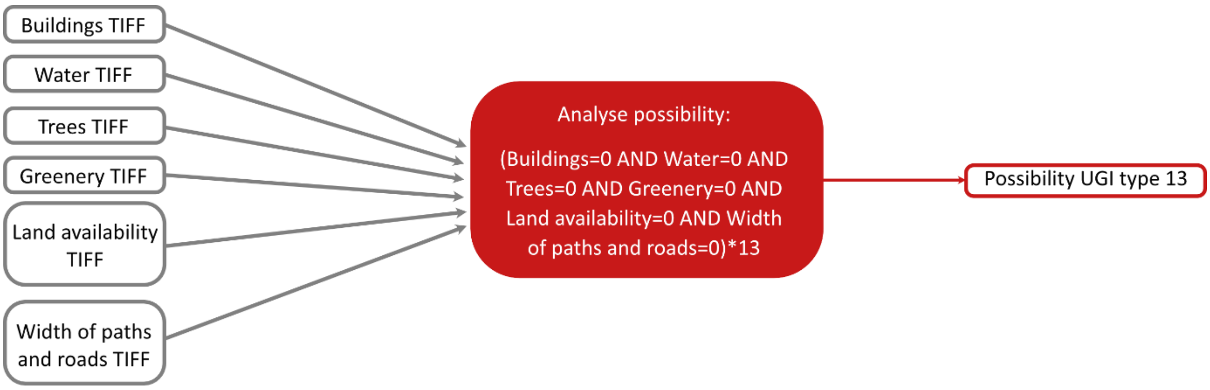


Figure 230: Possibility analysis UGI type 13

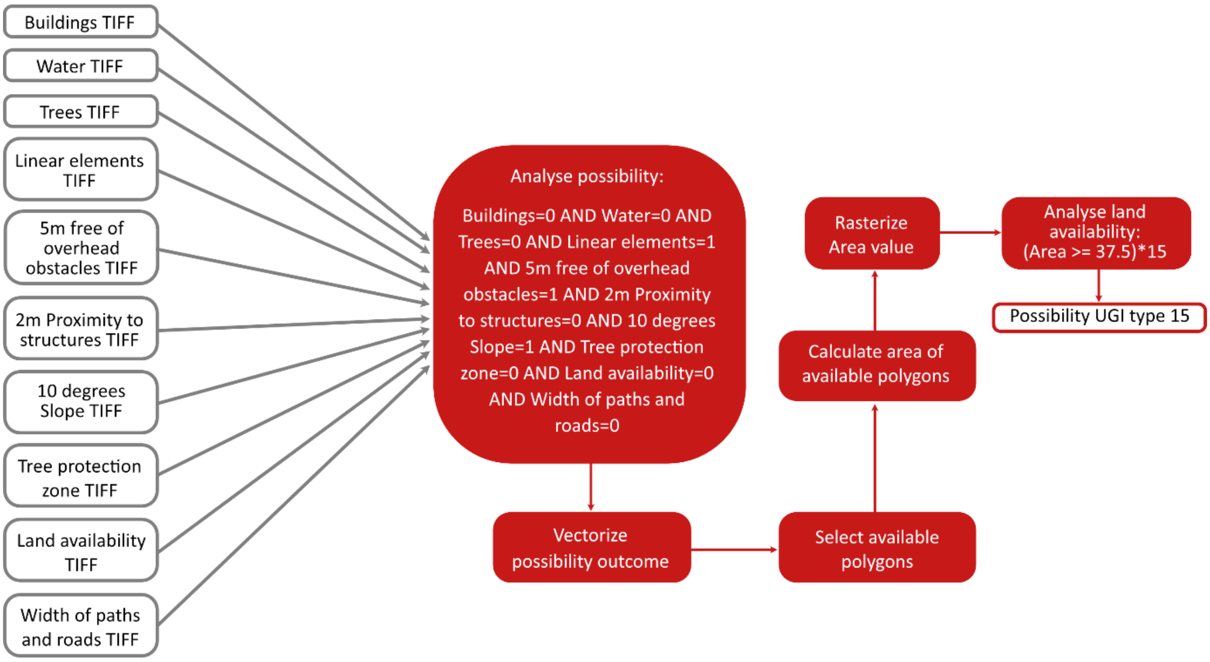


Figure 231: Possibility and land availability analyses UGI type 15

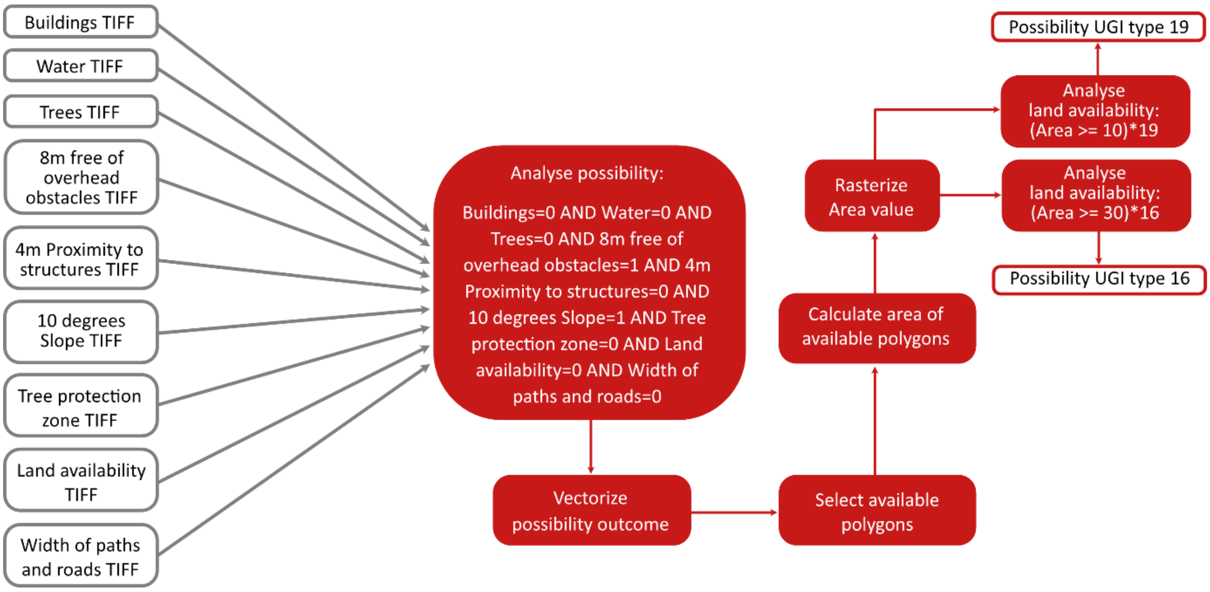


Figure 232: Possibility and land availability analyses UGI types 16 and 19

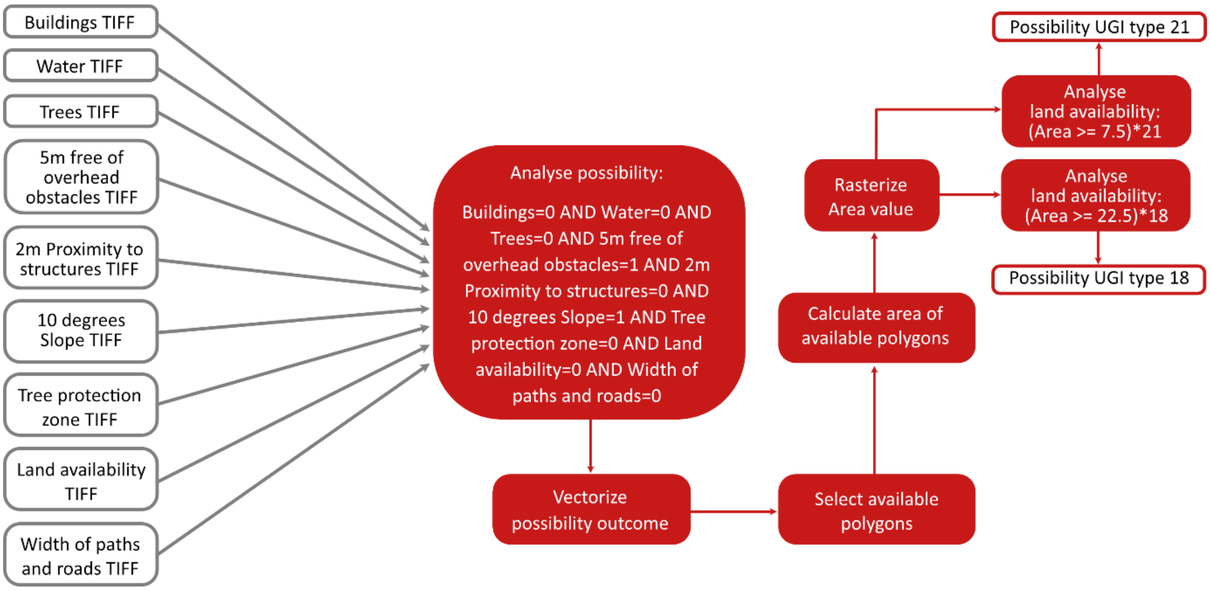


Figure 233: Possibility and land availability analyses UGI types 18 and 21

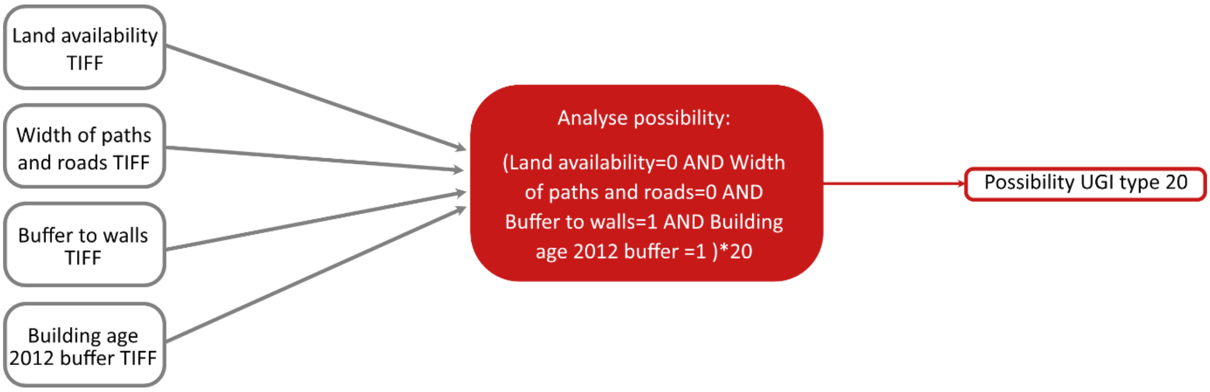


Figure 234: Possibility analysis UGI type 20

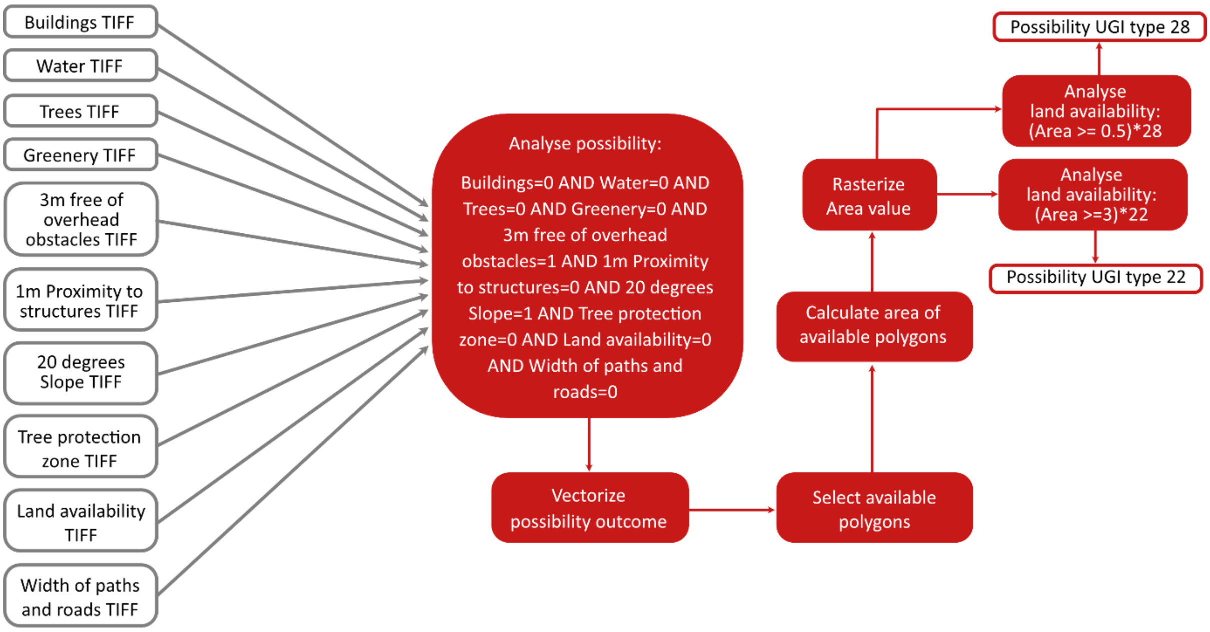


Figure 235: Possibility and land availability analyses UGI types 22 and 28

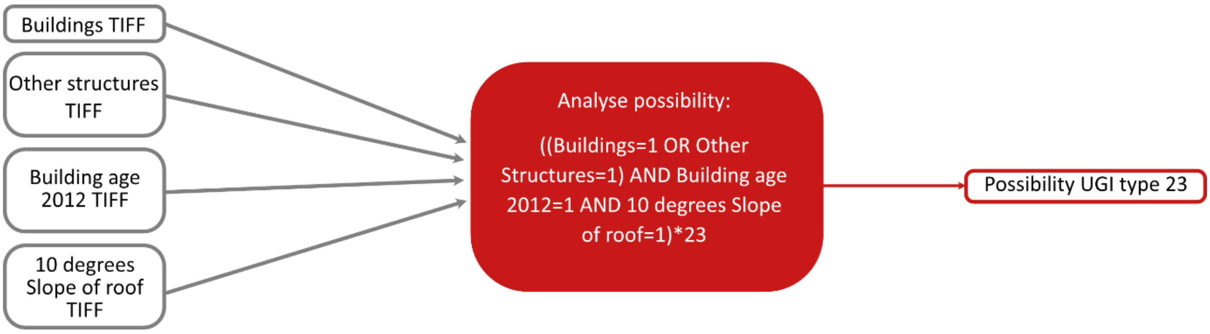


Figure 236: Possibility analysis UGI type 23

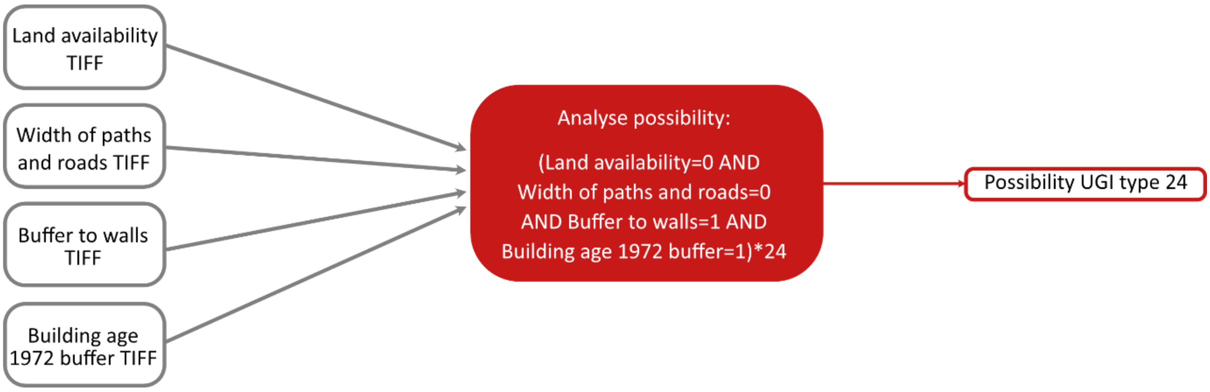


Figure 237: Possibility analysis UGI type 24

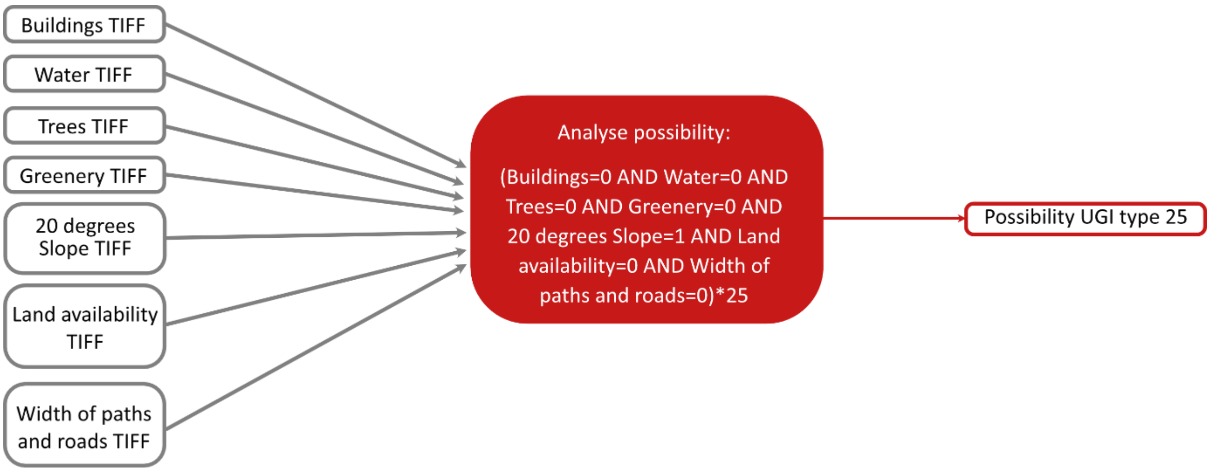


Figure 238: Possibility analysis UGI type 25

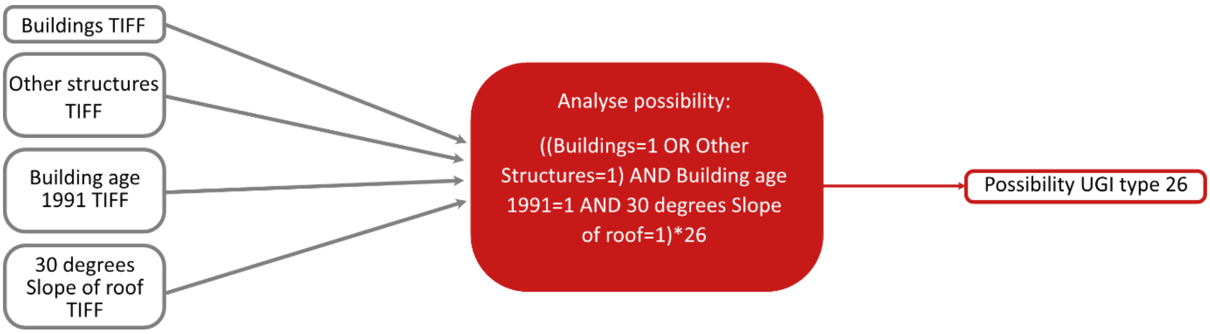


Figure 239: Possibility analysis UGI type 26

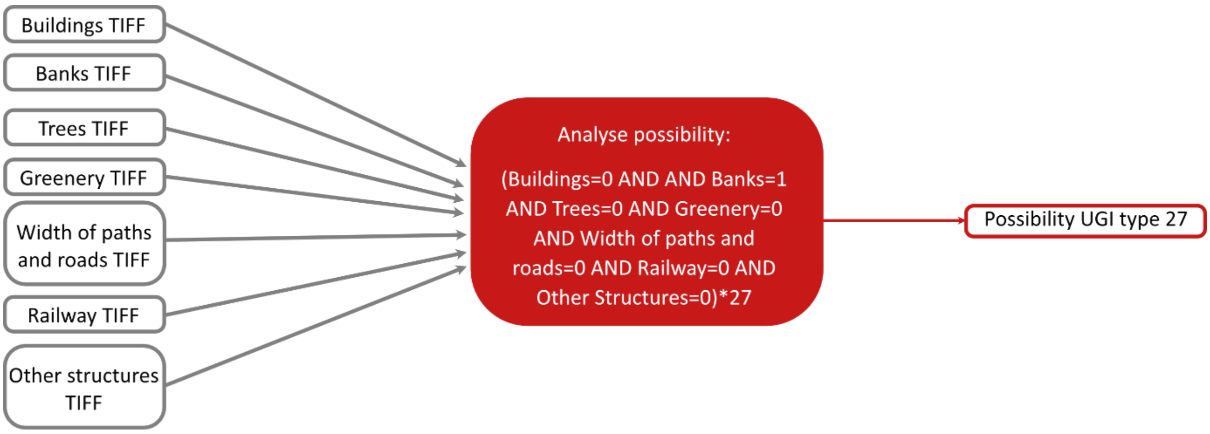


Figure 240: Possibility analysis UGI type 27

Appendix J – Weather input data table for HTC calculation

Table 20: The weather input data table

STN	YYYYMMDD	HH	DD	FH	FF	T	Q	U
344	20150701	1	100	30	30	195	0	60
344	20150701	2	90	30	30	184	0	65
344	20150701	3	90	20	20	180	0	66
344	20150701	4	100	30	30	178	2	69
344	20150701	5	90	20	20	189	29	67
344	20150701	6	100	30	30	204	77	63
344	20150701	7	100	30	40	231	134	58
344	20150701	8	110	40	30	255	189	50
344	20150701	9	100	40	40	272	227	45
344	20150701	10	100	40	50	290	278	43
344	20150701	11	90	50	70	303	306	39
344	20150701	12	110	50	60	318	319	32
344	20150701	13	110	50	50	325	306	29
344	20150701	14	120	50	50	330	287	30
344	20150701	15	120	50	50	338	251	31
344	20150701	16	130	60	50	340	207	29
344	20150701	17	130	50	50	338	155	33
344	20150701	18	110	50	50	329	99	36
344	20150701	19	100	50	40	313	47	42
344	20150701	20	100	30	40	293	9	48
344	20150701	21	100	30	30	278	0	51
344	20150701	22	110	40	40	275	0	50
344	20150701	23	110	40	40	265	0	52
344	20150701	24	120	40	40	257	0	54
344	20150702	1	120	40	30	262	0	52
344	20150702	2	110	30	40	243	0	60
344	20150702	3	160	30	30	249	0	56
344	20150702	4	170	30	30	240	3	60
344	20150702	5	210	20	20	241	22	65
344	20150702	6	280	20	20	237	61	71
344	20150702	7	280	10	10	245	103	69

STN = Weather station number
YYYYMMDD = Date (Year, Month and Day)
HH = Hour (from 1 till 24)
DD = Wind direction in degrees
FH = Hourly mean wind speed in m/s
FF = Mean wind speed in m/s
T = Temperature at 1.5 m in °C
Q = Global radiation in J/cm^2
U = Relative atmospheric humidity at 1.5 m in percentages