Developing Multi-scale Walkability Index Using Weather and Urban Environmental Data

Tong, Huiyi

Award date:
2023

Developing Multi-scale Walkability Index Using Weather and Urban Environmental Data

Huiyi Tong

Master's Thesis

General Information:

Name:	Huiyi Tong
Student ID:	1586076
University:	Eindhoven University of Technology
Faculty:	Built environment
Masters:	MSc Architecture, Building and Planning,
	Master-track Urban Systems and Real Estate (USRE)
Course Code:	7Z45M0
Study Load:	45 ETCS
Final Colloquium:	08/02/2023

Supervising Committee:

Bauke de Vries	Chair of the graduation committee	Eindhoven University of Technology
Qi Han	Main Supervisor	Eindhoven University of Technology
Aloys Borgers	Supervisor	Eindhoven University of Technology
Shahryar Sarabi	Supervisor	Eindhoven University of Technology

Table of Contents

Preface

This thesis is the result of a long period of hard work and a final project that is of great significance to me. I'm very glad that I chose to research this topic in the beginning and I have learnt a lot in the process. Improving the walkability of the footpaths to stimulate walking is important for every city, including those in my home country of China. In China, many cities have been trying to develop into pedestrian-friendly cities in recent years. Therefore, the research process on this topic not only satisfied my curiosity about walkability and urban data visualisation but also made me realise that the gains I made could help make my hometown a better place in the future. This makes me very excited and proud.

Throughout the graduation process, every difficulty has been a source of growth for me. Something can always be improved, but you have to enjoy the process. This has been deeply experienced me both in my Bachelor's studies in architectural design and in completing academic research projects at Masters level. I believe that each experience has enriched me academically and mentally.

The two years I spent in the Netherlands completing my Master's degree have been very valuable and I met many teachers and friends who helped me. I am grateful to Prof. de Vries for his patience in helping me with my study plan when I started at the university and was faced with the Corona lockdown. My final project supervisors, Qi and Aloys, were very attentive to me throughout the research process. They gave me valuable advice when I encountered challenges during the process. I am very grateful to Shah for giving me great encouragement when I was feeling frustrated. He not only provided a lot of guidance during my final project, but also provided a lot of insight into my future plans. Of course, I am also very grateful to all the participants who were invited to the online interview for this study and their willingness to help me even though it was close to the Christmas holidays. And to Lara, my final year study partner, for all the encouragement and companionship she gave me.

I would also like to express my gratitude to the 29th SERVICE board for taking care of me since I joined the SERVICE study association family and showing me the culture from the Netherlands. I will cherish this friendship. I would also like to thank my Chinese friends that I made during my study abroad, they made me feel at home. Finally, to my family, I would like to thank you for your understanding and companionship. Your support has allowed me to do what I want to do and have such a wonderful time. (Translation: 我非常感激我的家人对我的理解和陪伴，你们的支持使我能够做我想做的事情，并拥有如此美好的时光！)

Huiyi Tong (Cindy 童慧怡)

Summary

Walking can have a positive effect on health, transport, the economy and the environment (De Meij, 2021). Encouraging walking in cities can have a significant impact on sustainable urban development (Kamel, 2013). Many city managers and urban planners recognise that pedestrian friendliness is the key to success and have made decisions with the aim of encouraging walking. In the Netherlands, Utrecht has a pedestrian action plan and Amsterdam has a policy framework for "pedestrian spaces" (Duurzame mobiliteit - CROW, 2022). The discussion on how to encourage walking is promising. According to Duurzame mobiliteit - CROW (2022), making a city truly pedestrian-friendly requires measures in six main aspects, including the provision of viable, accessible, safe, comfortable and attractive routes and improvements at lower scales (districts, neighbourhoods, streets and footpaths themselves).

Improving the walkability of urban footpaths is therefore an important concern for city managers, urban planners and designers. In the academic field, researchers often set an index to represent the level of walkability to explore the indicators and the impact of walkability on other aspects such as the health of residents and the liveability of the community (Baobeid, Koç & Al-Ghamdi, 2013). Most defined walkability indexes (WI) are used to represent neighbourhood-scale walkability (Hall & Ram, 2018).

Based on the literature review, street connectivity, footpath cleanliness, footpath width, type of land use nearby the footpath, weather, crime rate, and streetscape aesthetics can all influence the walkability of the footpath (afiemanzelat, Emadi & Kamali, 2017). According to afiemanzelat, Emadi & Kamali (2017), indicators that affect walkability can be grouped into three categories: street conditions, function of the environment and personal comfort. Many of these subjective comfort indicators may change across situations, in contrast to those related to the characteristics of the streets. As a result, researchers tended to focus more on indicators related to street conditions and function of the environment to assess WI in a single situation during their research (Hall & Ram, 2018). However, the impact of personal comfort indicators on walkability should not be overlooked and can help bring research findings closer to reality (Hall & Ram, 2018). Existing studies assessing personal comfort indicators mainly used questionnaire surveys to obtain data, which may result in some comfort indicators not being effectively captured and data lacking generalisability (Hall & Ram, 2018). In fact, weather is an important factor in the personal comfort indicators, which has a direct impact on footpath conditions (De Arruda Campos et al., 2003). A well-equipped section of footpath may also cause inconvenience to pedestrians during extreme weather conditions, for example, when water accumulates on the ground. In addition, walkability may change when pedestrians are in different areas of the city, at different times of the day and under different weather conditions. Therefore, considering multiple categories of indicators to assess WI in different combinations of extreme weather conditions (scenarios) may help urban planners or designers to gain a more comprehensive understanding of the current situation in certain areas of the city.

Therefore, this research aims to help planners and designers to more fully and effectively identify problems in the city and propose effective solutions to encourage walking by assessing the walkability index (WI) at the footpath scale in Eindhoven under different weather scenarios. The WI represents the walkability potential of locations on the footpaths in the city under a particular scenario.

Firstly, by collecting urban environmental and weather data, 6 indicators in the 3 categories have been developed, and then additional two variables related to icy and smog conditions are added to assess WI (see Table 1). When developing the indicators, for the thermal comfort indicator 3 condition-based indicator scores are developed based on effect from shading on cold or hot days. For the water depth on the footpath, scores have been developed for 3 conditions based on rainfall level and snowfall conditions. For the ambient pollution indicator, scores have been developed for 2 conditions based on different times of the day. For the rest of the WI indicators scores has been defined for single condition.

Table 1: The identification *of* WI indicators and additional variables.

	Category		
	Personal comfort	Street condition	Function of environment
WI indicator	• Thermal comfort • Water depth on the footpath • Ambient pollution	• Street connectivity • Footpath width	• Nearby land use
Additional variable (penalty)	• Icy and slippery • Smog		

Next, four extreme weather scenarios have been selected from all possible scenarios to which one common weather scenario was added (see Table 2). After defining the scenarios for assessing the WI, the corresponding WI indicator outputs and additional variables are combined with equal weighting by default to assess the WI at the footpath scale for the selected scenarios. In order to facilitate a more comprehensive understanding of WI for urban planners and designers, the footpath-scale WI is also extended into hexagonal and neighbourhood level WI maps in the study. Lastly, three neighbourhoods have been selected for WI scenario analysis. By looking at the different levels of WI maps, it is possible to identify walkability-related problems in different scale areas in the three neighbourhoods and to derive which specific WI indicators contribute to a low or high WI.

Table 2: The final selection of scenarios for WI assessment.

Scenario	***Condition 1: Max/Min temperatures during the day***	***Condition 2: Weather***	***Condition 3: Time of the day***
1	Min temp <0 degree	Snow	Morning peak hour
2	Max temp >=25 degree	Sunny	Evening peak hour
3	Max temp >=25 degree	Violent rain	Evening peak hour
4	Max temp >=25 degree	Sunny	Off-peak hour
5	Max temp < 25 degree and min temp >=0 degree	Cloudy	Off-peak hour

Furthermore, a web viewer is created in this study to visualise the WI maps at the three scales and to enable urban planners or designers to interact with the WI maps to gain a better understanding of the walkability potential of the footpaths. During the validation phase, 4 students, teachers or professionals with a background in urban planning or design are invited to interact with the web viewer and conduct online interviews to gather feedback.

In conclusion, this study explores an objective way to develop indicators for the categories of street condition, function of environment and personal comfort and to combine them with equal weighting to assess the WI in multiple scenarios. The final results of the study can also be used in practice to help urban planners or designers more effectively identify walkability problems in specific areas by integrating footpath scale map into neighbourhood and hexagonal level maps and visualising them in a web viewer. In addition, this study also highlights some potential which can be used as a basis for future improvements. In future academic research or system expansion, a comparison of perceived walkability and objective assessment results of WI could be further explored to help establish a more comprehensive approach to WI assessment. In addition, WI maps could be developed as a plug-in for GIS software to enable urban planners or designers to use the data directly. Real-time data could also be introduced when assessing WI and forecasting WI system. On this basis it is even feasible to automatically generate the best WI route for the current weather conditions when pedestrians provide the start and end points of their journey. Such a system study could in the future be plugged into GPS systems to advise people in specific areas to optimise travel when extreme weather occurs.

Abstract

Encouraging walking as the main mode of transport in people's daily lives have distinct environmental, economic and personal health benefits. Street conditions, function of environment and personal comfort can all have influences on encouraging or discouraging walking. By identifying and quantifying indicators, a Walkability Index (WI) can be assessed to represent the walkability potential of the location on the footpath in the city. In the literature, the analysis of walkability potential at the footpath scale rather than the neighbourhood scale is lacking. Existing methods for developing personal comfort indicators and thus assessing WI mainly involve questionnaires rather than the objective ways. Moreover, the assessment of WI in multiple weather scenarios is often lacking. Therefore, it was decided to upgrade these considerations and incorporate them into a new GIS-based WI that was developed.

This study assessed WI at the footpath scale for four extreme weather and one common weather scenario by collecting urban environmental and weather data, combining six WI indicators from the categories of street condition, function of environment and personal comfort, with equal weighting by default. Two different types of neighbourhoods in the city were selected for analysis and comparison under the 5 scenarios, suggesting the high priority and enhancement needed in specific areas by urban planners or designers. The end result was also expanded into 50m size hexagonal and neighbourhood level WI maps. A web viewer was created to visualise WI maps combined with 3D city models and interactive functions to provide additional insights for urban planners or designers.

Keywords

Walkability, Walkability Index, Footpath, Extreme Weather, Urban Planning and Design, Weather Data, Urban Environmental Data

List of Figures

List of Tables

Chapter 1. Introduction

1.1 Research Context

Walking is an integral part of people's lives and urban activities. As a common mode of travel, increasing walking participation in regular activities could have a positive impact on health, transport, economy and the environment (De Meij, 2021). For decision-makers, walking should be encouraged and have a significant effect on sustainable urban development (Kamel, 2013). In practical cases, many Policy makers and urban planners make decisions with the aim of encouraging walking. According to Victoria State Government (2019) and Livin Spaces (2017), Melbourne and Barcelona as two influential cities are both working on an urban and regional design based on new concepts of pedestrian-friendly urban living. The Netherlands has also taken many initiatives to promote walking. For example, Utrecht published a pedestrian action plan and Amsterdam launched a policy framework for "pedestrian spaces" (Duurzame mobiliteit - CROW, 2022). It can be seen that by combining the multiple benefits of walking with the current urban trends, the discussion on how to encourage walking is promising.

For city decision-makers, encouraging walking and thus making a city pedestrian-friendly requires measures in six main aspects, including a focus on improvements in lower-scale areas (districts, neighbourhoods, streets and footpaths) and the provision of viable, accessible, safe, comfortable and attractive routes. For pedestrians, whether walking for commuting or leisure purposes, street conditions, the function of the environment and personal comfort all affect walkability (Rafiemanzelat, Emadi & Kamali, 2017). Street conditions include connectivity, pavement cleanliness, footway width, etc. The function of the environment includes nearby land use types, proximity to transport facilities, population density, etc. Personal comfort refers to the willingness to walk due to weather, crime rate, streetscape aesthetics, etc.

In order to better investigate the factors that influence walkability and the impact of walkability on other aspects such as the health of the inhabitants, the liveability and quality of life of the community and the long-term environmental, economic and social sustainability of the city (Baobeid, Koç & Al-Ghamdi, 2013), in the literature, researchers usually set an index representing the level of walkability as a dependent or intermediate variable. Most of the defined indices representing walkability are used to estimate neighbourhood density and amenity use (Hall & Ram, 2018). Thus, it's recommended by Hall and Ram (2018) that more supplementary measures of the physical activity environment should be considered to make the walkability index (WI) a more global indicator, particularly by increasing the emphasis on subjective comfort aspect of the indicator.

In fact, many of the subjective comfort indicators might change in different situations, as they have a more random nature of change. In contrast, built environment-related indicators are mainly related to the properties of the road. This may lead to a tendency for more researchers to focus more on the built environment-related indicators in the research process. However, perhaps these personal comfort variables could make the findings of the study more relevant to the reality of urban streets and could meet more demands in the future.

Among the personal comfort variables, the weather is an important factor and has a direct impact on pavement conditions. De Arruda Campos et al. (2003) explored the high importance of weather variables in influencing walkability on roads among 17 potential factors. Occasionally, a well-equipped section of footpath may deteriorate under extreme weather conditions. Therefore, looking at the walkability index in different conditions might help urban planners or designers to get a more comprehensive view of the current situation in certain areas of the city.

1.2 Research Motivation

Although there has been some discussion and assessment of the walkability index (WI) in a range of academic studies, most of these are limited to studies that are dominated by built environment characteristics and aim to estimate the overall density and amenity performance of neighbourhoods. In addition, the primary research method for many of these topics is the questionnaire approach.

Besides, the impact of weather changes on street walkability potential cannot be ignored and is sometimes dominant, especially in a country with varied weather conditions like the Netherland. The emergence of some unpredictable extreme weather may also lead people to avoid walking as a mode of travel. Therefore, paying more attention to the impact of weather variables on the walkability potential of footpaths can help identify potential problems in some areas under relatively extreme weather conditions and implement targeted measures.

In this case, the urban planner or designer will need to identify concerns about the urban street environment and walkability performance based on some relevant urban information data. When pedestrians are in different areas of the city, at different times of the day and in different weather conditions, walkability may change. Therefore, urban planners or designers need to know the walkability of the city in different contexts, especially in relative worse contexts, so that they can more accurately identify problems and suggest corresponding and effective urban planning or design measures.

1.3 Research Question

In this research, the walkability index (WI) represents the walkability potential of the location on the footpath in the city. The main target group is urban planners or designers. The main objective is to help planners and designers to identify more comprehensively and effectively the problems that exist in the city by providing the walkability potential on the footpath scale under several relative extreme weather scenarios, so that they can propose effective solutions to encourage walking in the city. Meanwhile, other groups of people could also benefit from the results of this study, such as Public Works and pedestrians. The final results in this project could help Public Works to gain insight into WI in different scenarios and at different scales and thus help them make decisions when setting up urban design projects. For pedestrians, understanding how WI performs in the neighbourhoods and streets in different scenarios could help them to make more appropriate route choice decisions. By using urban environmental and weather data, spatial characteristics (e.g., street connectivity) and weather-related indicators (e.g., thermal comfort) can be evaluated and quantified separately. Then, by combining indicators to assess WI on the footpath and visualise it to the end-user under different extreme environmental condition scenarios, they are able to have additional insight into the walkability potential in urban streets and the surrounding environment.

In line with the aim of this research, the following research questions could be formulated:

How to develop Walkability Index (WI) considering the influences of extreme weather scenarios for urban planners/designers' decision making?

Several sub questions could also be addressed:

What are the indicators selected for assessing the WI?

What type of data is needed and how to develop the indicators?

How to assess WI through the developed indicators?

How can WI be visualised to the urban planners/designers?

In this study, the subject of the research is the WI on the footpaths of Eindhoven in the Netherlands. WI will be estimated by combining a range of indicators regarding personal comfort, street conditions and function of the environment. The final result will show the WI information at different scales, in different dimensions and in several extreme weather scenarios in order to provide additional insight for urban planners or designers.

1.4 Scientific and societal relevance

In this research, the assessment of WI on footpaths in Eindhoven and the visualisation of WI and indicators can bring added value in terms of academic aspects. As mentioned previously, this study will assess the WI at the footpath scale by combining weather-related variables and built environment characteristics in different extreme weather scenarios. Therefore, it can have more practical value and can be more informative in academic research. For example, by comparing the results of WI at different locations on the footpath scale under different weather and time conditions, researchers can further analyse and identify a number of potential research topics worth discussing.

In the practice sector, it allows urban planners and designers to more objectively identify problems with the walkability of urban streets and areas, thus helping experts to analyse the problems more effectively and suggest measures. This can have a beneficial effect on the development of urban fabric and the living environment of the inhabitants.

And for Public Works, the multi-scenario assessment of WI can also help them know more about the walkability in the areas and set up urban design projects. In addition, it can bring an added value to the residents. When considering a new place to live, residents can choose a more walkable location by taking into account the walkability of the living environment under different weather conditions.

1.5 Reading Guide

The final output of this thesis will be a web viewer that will help urban planners or designers to identify urban concerns and propose solutions by visualising WI information at different scales, in different dimensions and in several extreme weather scenarios. Chapter 2 consists of a literature review. It will present information about walking as an active mode of travel, the assessment of walkability index (WI) and the potential indicators that influence walkability. Some research gaps can be observed from the literature review. Chapter 3 will explain the methodology behind the research design phases, and is therefore a guide to Chapter 4. In Chapter 4, the specific steps in the various phases of the study and the reasons for the definition of some thresholds will be specified. Chapter 5 will show the results of assessing the WI on the footpath scale in different scenarios, some analysis from the comparison of the WI within the same scenario and the web viewer created for the WI visualisation. Chapter 6 will describe the validation process and discuss some of the suggestions from the target group. Finally, conclusion and discussion are reached in Chapter 7 by answering the research questions, pointing out the limitations of this research project and making recommendations for subsequent research and tool development.

Chapter 2. Literature Review

In order to better understand the concept of walkability, this chapter will first explore the impact of walking as a travel mode in a number of aspects and what measures some cities undertake to encourage walking (Chapter 2.1). Then, a number of existing studies regarding walkability index definition and assessment will be investigated to provide a basis and reference for the systematic implementation of this study (Chapter 2.2). In addition, some possible indicators of walkability will be discussed in Chapter 2.3. In Chapter 2.4, the key findings and observed research gaps in the literature will be summarised.

2.1 Active Travel Mode: Walking

Walking is the basic mode of transport for people (Nuzir & Dewancker, 2016). All people who use other modes of transport, whether motorised or non-motorised, have to walk at some point in their journey. For example, walking is required to get to a public transport stop or to travel from a car park to a building. As can be seen, there is a continuous reliance on walking. However, with the emergence of the urban sprawl phenomenon, the development of the automobile is gradually reducing the popularity of walking in citizens' lives (Nuzir & Dewancker, 2016). This has also brought more carbon emissions and the extraction of fossil fuels, which has led to global environmental problems. As a result, encouraging walking is gradually becoming a popular topic of discussion and a recurring keyword in urban development strategies.

Encouraging walking could contribute to sustainable urban development. According to De Meij (2021), walking could reduce energy consumption and improve air quality from an environmental perspective. There are also individual, community, health and economic benefits from walking as a travel mode. According to Yang and Zhen (2020), encouraging walking is effective in reducing individual's BMI at a community level. Diehr and Hirsch (2010) also found that healthy, sedentary elderly people could benefit from a moderate increase in their walking. Having walking as part of the daily activity routine can also help to improve fitness and lower blood pressure (Shinkle & Teigen, 2008). In addition, walking can improve the mental health of pedestrians. Pedestrians move at a slower pace than motor vehicles, so they interact more with their surroundings (Nuzir & Dewancker, 2016). Hudda and Fruin (2018) also found that CO_2 concentrations would accumulate in vehicles with unopened windows, which would affect the driver's mental and physical status over time and cause safety problems. In contrast, the pedestrian environment is more conducive to air circulation. From an economic point of view, walking is less costly for individuals than driving a car, regardless of whether it is combined with other modes of transport (Shinkle & Teigen, 2008). On the other hand, studies showed that houses located close to bike paths or walking trails tend to sell faster and at a higher price, and areas with better access to amenities are more in demand (Shinkle & Teigen, 2008).

Many cities have proposed a variety of measures to encourage walking after learning about the benefits it offers as a mode of travel. Toronto, for example, has proposed an action plan to encourage walking that aims to establish the necessary policies, infrastructure and program elements to create a walking culture (Egan & Hyland, 2008). Measures include achieving a more intensive, mixed-use development pattern and developing an emissions reduction plan to support increased walking trips. In addition, the cities of Melbourne and Barcelona are also interested in becoming pedestrian-friendly cities (Victoria State Government, 2019; Livin Spaces, 2017). With many cities aiming to upgrade pedestrian infrastructure to improve street walkability to encourage people to choose walking as a mode of travel, it is important to understand the factors that influence walkability and to monitor the walkability of cities.

2.2 Walkability Index (WI)

The Walkability Index (WI) is usually developed and defined by researchers to indicate the walkability status of a particular area (De Courrèges et al., 2021). Therefore, the definition of the WI might vary from different studies and the way in which it is assessed depends on the purpose of the investigators. In the existing literature, WI generally referred to the walkability status of a community as a whole, rather than to street or smaller-scale performance. For the assessment of WI, Frank et al. (2005) and Quach et al. (2015) developed WI as a function of net residential density, street connectivity and land use diversity. A considerable amount of literature refers to the findings of this study.

There are a variety of approaches that can measure WI. For example, Habibian and Hosseinzadeh (2018) assessed WI by calculating population density, land diversity and design criteria based on a GIS database of the Rasht transport network, combining destination accessibility to illustrate the impact of travel purpose on WI and specifying it for three specific travel purposes (work, education and shopping). In this case, destination accessibility was determined by distance from the CBD (Habibian & Hosseinzadeh, 2018).

Lam et al. (2022) collected data on self-reported demographic characteristics and walking behaviour from 16,055 adult respondents, combined with calculations of seven subscales for three Euclidean buffers (150 m, 500 m and 1000 m around each 6-digit postcode location and for each administrative district in the GIS), and finally compared the associations between the index and walking outcomes and discussed which index primarily drove the correlations. Similarly, Golan et al. (2019) investigated the extent to which the WI reflects women's walking and which specific variables have the greatest impact on women's propensity to walk. The study combined a GIS-based calculation of 10 variables and asked the focus group about the ranking of variables to assess women's walkability index (Golan et al., 2019). In terms of GIS-based assessment methods, Tsiompras and Photis (2016) found the relative weighting of the four indicators in the hypothesis by conducting a Pan-Hellenic web-questionnaire among 871 respondents. It can be found that the purpose of a significant proportion of studies requiring assessment of WI includes exploring the level of relevance between assessment indicators and WI.

Kelly et al. (2011), on the other hand, specifically explored and compared methods for assessing the pedestrian environment and WI from a pedestrian perspective through different questionnaire formats. They included a computer-based instrument survey developed using stated preferences to determine the relative values of a range of factors in the pedestrian environment, these were identified in a combination of an extensive literature review and a survey of 2000 households (Kelly et al., 2011). In addition, a paper-based street questionnaire method was used, designed to investigate street surveys of values and attitudes towards different attributes of the pedestrian environment along the route (Kelly et al. 2011). The final method presented involved 20 walking interviews with 20 respondents. Respondents and researchers walked together along a predetermined route and conducted a "moving survey" to understand their real-life experiences while walking (Kelly et al., 2011). After assessing WI using these three methods, the research used case studies to demonstrate the advantages and disadvantages of using these different methods and to compare the results of urban walking routes (Kelly et al., 2011). In the end, the study showed that the three methods were somewhat complementary and provided different perspectives on walkability and different depths of understanding (Kelly et al. 2011).

As can be seen, most of the methods currently used to assess WI involve questionnaires. Whether in the weighting process of indicators or in the direct assessment of WI. However, the questionnaire approach might have the disadvantage of being too subjective and the results not being comprehensive. This approach might be better suited to the assessment of WI in a specific target population and in a specific regional context. Furthermore, the indicators formulated in these studies are all static and therefore only represent the static properties in the built environment of walking. However, different weather conditions may also have different effects on the walking environment.

2.3 Walkability Indicators

Walkability refers to the quality of walking conditions, including safety, comfort and convenience (Litman, 2022). It is often a composite indicator of the suitability of an environment for walking (De Courrèges et al., 2021). According to Rafiemanzelat, Emadi and Kamali (2017), the indicators that potentially affect walkability can be classified into street condition, function of environment and personal comfort. These three aspects can influence WI from various perspectives. So, a fair choice of indicators among these three categories can make the assessment of WI more comprehensive. In the existing studies, the choice of indicators, the way it is measured and the degree of influence may vary, depending on the location and objectives of the study. A list of potential indicators explored in the literature can be found in Table 3 in the end of Chapter 2.3.

2.3.1 Street condition indicators

Street condition indicators are mainly those that relate to the properties of the footway, where pedestrian preferred footway conditions may increase the willingness to walk and thus improve WI. According to De Arruda Campos et al. (2003), footway width and gradient have a high degree of importance in influencing WI. There is less variability in the methods used to measure these indicators. The remainder of the street condition indicators, such as pavement cleanliness and pedestrian crossing design, is relatively subjective in their measurement (Kelly et al., 2011; De Arruda Campos et al., 2003).

Street connectivity appears numerous times in the literature as a WI indicator and is considered to be one of the highest impact indicators (De Arruda Campos et al., 2003). However, very few studies on the evaluation of WI indicators refer to the measurement of street connectivity. In fact, there is more than one way to measure it. For example, Stangl (2015) used block size-based measures to reach conclusions in conjunction with assessing the extent of obstruction presented by blocks, while Koohsari et al. (2016) used the Space Syntax method to assess street connectivity. Dill (2004) evaluated various methods of measuring connectivity and stated that street density measurements require fewer calculations while computing link-node ratio or effective walking area requires more data and GIS knowledge.

2.3.2 Function of environment indicators

Environmental characteristics of the footpath belong to the function of environmental indicators, which can be represented by urban planning characteristics, population density or infrastructure deployment. In existing studies, researchers identified nearby land use types, proximity to transport facilities and population density as potential indicators of WI (Freeman et al., 2013; Knuiman et al., 2014; Pikora et al., 2003). De Arruda Campos et al. (2003) found that ground level activity can highly influence changes in WI, and neighbourhoods with relatively diverse functionality can effectively increase WI, which is likely to be related to safety and changes in population density. There might be a correlation between the environmental indicators, which needs to be taken into account when selecting the indicators for assessing WI.

2.3.3 Personal comfort indicators

Regarding personal comfort indicators, prior research validated the importance of personal comfort indicators on the impact of WI, but this category of indicators is usually not taken into account (Shammas and Escobar, 2019). This is probably because the personal comfort factor is relatively subjective and difficult to quantify. It includes weather, crime rate and streetscape aesthetics (Hall & Ram, 2018). However, this type of indicator can influence people’s willingness to walk significantly. For example, people might not prefer to walk in noisy or high-level air pollution road environments. Furthermore, the personal comfort indicators can change throughout the day, which in turn will add value to the visualisation of information and thus provide additional insight to end-users.

Table 3: Overview of potential WI indicators in literature

Category	Indicator	Reference
Personal comfort	Safety	Liao (2021); Kelly et al. (2011); Litman (2003); Pikora et al. (2003); Rafiemanzelat, Emadi & Kamali (2017).
	Streetscape aesthetics	Liao (2021); Pikora et al. (2003).
	Sense of place	Rafiemanzelat, Emadi & Kamali (2017).
	Weather: Rainfall	De Arruda Campos (2003); De Meij (2021); Clark, Scott & Yiannakoulias (2014); Delclòs-Alió et al. (2019).
	Weather: Thermal comfort	De Arruda Campos (2003); Clark, Scott & Yiannakoulias (2014); Labdaoui et al. (2021); Delclòs-Alió et al. (2019).
	Air pollution	De Arruda Campos (2003); Braubach & Fairburn (2010).
	Noise	Clark & Stansfeld (2007); Braubach & Fairburn (2010).
	Time of the day	De Arruda Campos (2003).
Street condition	Street connectivity	Liao (2021); Freeman et al. (2013); Hall & Ram (2018); Kelly et al. (2011); Knuiman et al. (2014); Lo (2009); Rafiemanzelat, Emadi & Kamali (2017); Ribeiro & Hoffimann (2018); Tsiompras & Photis (2017).
	Footway width	De Arruda Campos (2003); Abley et al. (2011); Lamour, Morelli & Marins (2019); Vichiensan & Nakamura (2021); Loo & Lam (2012).
	Footway slope	De Arruda Campos (2003).
	Pavement cleanliness	Kelly et al. (2011).
	Sidewalk accessibility	Lo (2009); Rafiemanzelat, Emadi & Kamali (2017); De Arruda Campos (2003).
	Pedestrian crossing design	De Arruda Campos (2003).
Function of environment	Population density	Freeman et al. (2013); Rafiemanzelat, Emadi & Kamali (2017); Ribeiro & Hoffimann (2018); Tsiompras & Photis (2017).
	Green space	De Meij (2021).
	Nearby land use types	Liao (2021); Freeman et al. (2013); Knuiman et al. (2014); Lo (2009); Rafiemanzelat, Emadi & Kamali (2017); De Arruda Campos (2003); Tsiompras & Photis (2017).
	Proximity to basic land uses	Tsiompras & Photis (2017).
	Public transport accessibility	Freeman et al. (2013); Hall & Ram (2018); Rafiemanzelat, Emadi & Kamali (2017); De Arruda Campos (2003).
	Facilities and services provision	Liao (2021); Pikora et al. (2003).
	Traffic signal phasing	De Arruda Campos (2003).
	Lighting	De Arruda Campos (2003).

Within this category, the weather indicators can influence WI to a certain extent, perhaps because it can affect not only the comfort of walking but also the conditions of the pavement directly. According to Clark, Scott and Yiannakoulias (2014), warmer seasons increase the likelihood of using walking as a mode of transport, while colder seasons decrease this likelihood. In Delclòs-Alió et al.'s study of Barcelona city (2019), it was found that temperature and rain can modify the impact of residential walkability on the walking activity of elderly people. Shammas and Escobar (2019) also found that shade on the footpath can improve the personal comfort of pedestrians during the hot summer days. Differences in WI between streets due to the weather indicator might be related to the combination of rainfall and street conditions (level of road flooding), thermal comfort and the level of air pollution.

2.4 Conclusion

To summarise the findings of Chapter 2, several aspects should be mentioned. Walking as an active mode of travel should be encouraged through a variety of measures. In addition to a number of pedestrian-friendly policies issued by the government, the overall performance of walkability at street and neighbourhood scale should be improved. Some of the low walkability streets should be given targeted attention. In some literature, the concept of walkability index (WI) is proposed to assess the overall walkability status of cities at the neighbourhood scale, but the analysis of walkability potential at the street scale is lacking. Besides, many of the existing methods for assessing WI involve questionnaires. Perhaps the introduction of questionnaires in the consideration of pedestrian personal comfort could be effective in obtaining subjective data and ranking results for the target population on indicators. However, the weather conditions of walking and the time of day can also have a dynamic effect on WI.

Although there are many academic studies dealing with WI, most of them focus on exploring the extent to which a variety of indicators influence WI. Furthermore, existing research focuses on the WI in a single scenario, probably because the indicators involved in assessing WI are characteristics of the built environment that are not altered by changes in time and weather.

Lastly, a review of studies related to potential walkability indicators suggests that there is still a gap in current studies that integrate personal comfort indicators. However, the impact of this type of indicator on WI would increase, because the urban street is full of interactions with pedestrians and the weather environment. Therefore, it is important to consider personal comfort indicators.

The literature review will directly influence the selection and definition of WI indicators in this study. Most indicators will be selected primarily based on the relevance and consensus of the literature, and personal comfort indicators will be considered. In this study, WI will be derived from different types of environmental indicators assessed to represent the walkability potential of specific locations on the footpaths in the city of Eindhoven. More variable WI indicators will be considered, combining multiple weather scenarios to assess WI. A detailed description of the WI indicators involved in this study will be presented in Chapter 4.

Chapter 3. Methodology

In this chapter, the phases of this study will be explained, along with the corresponding research methods. The chapter will also illustrate how the various research phases are integrated to answer the main research question and the sub questions.

3.1 Research Design

Throughout the research methodology, five phases can be identified based on the research objectives (see Figure 1). They include exploratory research, WI indicator preparation, WI assessment, visualisation of WI and validation. The exploratory research phase was already elaborated in the previous chapter. In this phase, the literature relating to walking as active travel mode, walkability index (WI) and walkability indicators were collected and discussed. A number of research gaps were identified. For example, the analysis of walkability potential at the footpath scale rather than the neighbourhood scale is lacking. Existing methods for developing personal comfort indicators and thus assessing WI mainly involve questionnaires rather than the objective ways. Moreover, the assessment of WI in multiple scenarios is often lacking. The research methodology involved in the rest of the phases includes different methods of data collection, methods of analysing indicators and WI and methods of visualisation to answer sub-questions. In addition, methods for validating the results will also be presented.

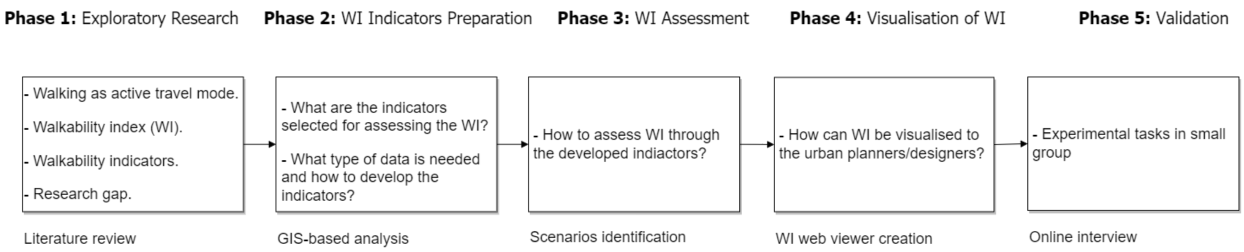


Figure 1. Research design phases

3.1.1 WI Indicators Preparation

This phase consists of the determination of WI indicators, the collection and development of the data required for each indicator. The selection of WI indicators will be based on the literature review and research objectives of this study. Several indicators within the categories of personal comfort, street condition and function of environment are used. This is to make the WI assessment more comprehensive and practical. In order to include indicators of personal comfort influenced by weather, different scenarios are explored under extreme conditions. The measurement of indicators can reflect the performance of the built environment in different locations in the city. The results and reasoning behind the selection of the specific WI indicators will be described in Chapter 4.

Once the WI indicators in this study are defined, all data should be collected. Generally, the output data of the indicators need to be based on one or more underlying data sources and analysed through different methods. According to ESRI (2022), a geographic information system (GIS) is a system that helps users create, manage and analyse all types of data by linking them to maps. It can integrate location data with descriptive information (ESRI, 2022). At this stage of the research, the required datasets from open data platforms can be linked to maps in GIS software so that the location and properties of the data can be visualised on a map for the subsequent WI indicator development process. The specific sources of data obtained for the indicators, the data collection process and the corresponding assumptions will be explained in Chapter 4.

After using GIS tools to obtain data from the open data platform, WI indicators need to be developed based on the collected data in preparation for the WI assessment phase. In this process, the GIS analysis methods required for different indicators may vary. Particularly for weather-related indicators, which can have different effects on WI under different environmental conditions, it may be more effective to develop these indicators respectively in multiple conditions, for example different time periods for the thermal comfort indicator. Some GIS tools could be used to assist in the analysis of these types of data. For example, the "area solar radiation" tool could be used to analyse the different levels of solar radiation during a day in different seasons based on building height data and PET (Physiological Equivalent Temperature) data. This can provide a basis for the identification of scenarios in the phase of assessing WI. Also, taking into account the differences between units of measured indicators, their values need be normalised in order to be used as inputs in the subsequent WI assessment process. In this study, some WI indicators may have a positive or negative impact on the WI, therefore all developed WI indicators need to be normalised to a range of values from -1 to 0 or 0 to 1. During the data collection process, some missing values may be obtained. Therefore, when developing the WI indicators, the missing values are converted to value 0 by default so that they can still be combined with other indicators when assessing the WI.

In the development of WI indicators, it is sometimes useful to set thresholds based on literature findings to help analyse given data, for example, by setting optimal widths to help score all footpath widths in the city between 0 and 1. The specific process of developing each WI indicator selected in this study will be explained in Chapter 4. The overview of this research phase is shown in Figure 2.

Figure 2. Overview of WI indicators preparation phase

3.1.2 WI Assessment

When the WI indicators have been developed, the challenge of how to create scenarios and assess the WI in different scenario will be addressed. In the literature on evaluating WI, it is common to set a generic scenario and then assign weights to individual indicators in order to combine them and evaluate the value of WI. In many of the studies, researchers weigh all indicators equally (Shammas and Escobar, 2019). In other studies, for example, Giles-Corti et al. (2014) set the weight of street connectivity at twice the weight of the other indicators. In addition, some researchers chose to invite experts to assign relative weights to each indicator of the WI (Tsiompras & Photis, 2017). It can be noticed that not only is there a diversity in the selection of indicators, but the debate about the weighting of indicators also persists because new indicators for the WI are constantly being proposed.

In this study, the developed WI indicators should be able to represent the personal comfort or characteristics of the built environment in different locations of the city in multiple conditions. Therefore, when defining scenarios to assess WI, it is feasible to first set the conditions and the corresponding levels according to the weather-related WI indicators, so that all possible scenario combinations can be listed. Some thresholds need to be set based on the literature to determine how to label. For example, certain thresholds will be set for "winter conditions" or "heavy rain". More details on specific threshold settings will be given in Chapter 4. After the scenarios are listed, scenarios with extreme weather characteristics will be selected from all combinations according to the literature. Besides, some of combinations of weather characteristics that might bring hazard to walking environment should also be considered and listed. For example, some weather levels might bring extra impact due to the pollution from the traffic, thus influence the ambient pollution indicator. Moreover, to help urban planners and designers compare the difference in WI variation between the scenarios, a scenario with the most common weather conditions can be considered as a reference.

Based on the findings of extreme weather characteristics and interaction effects with built environment characteristics, the scenarios that will be involved during the WI assessment process can be filtered and identified. The specific WI indicator score will then also be determined for assessing WI in each scenario. In addition, some interactions effects of weather conditions may have additional negative effects on the WI, so a few additional variables (e.g., "smog”) are set to give penalties and included in the WI assessment phase. The equal weighting is decided as the default in the assessment of WI, and the GIS tool “weighted sum properties” will be used to help combine the weighted indicators to generate WI maps for different scenarios.

In addition, it is important to note that the resulting WI maps under multiple extreme environmental scenarios would show WI values at the scale of urban footpaths, including the urban streets with mixed traffic functions (e.g., residential streets). The overview of this phase is shown in Figure 3.

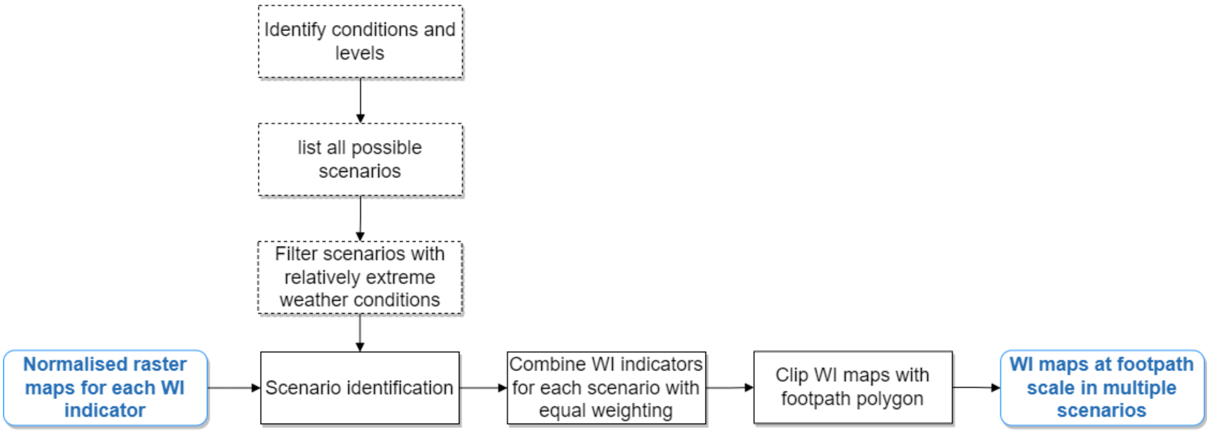


Figure 3. Overview of WI assessment phase

3.1.3 WI Visualisation

WI maps at the footpath scale can show WI score at specific locations on the footpath, but it lacks an overview map to show the overall level of WI within the city. Therefore, it is decided to generate WI maps at the neighbourhood scale and integrated into the 50m hexagonal grids based on existing WI maps at the footpath scale. For example, urban planners or designers can look at the overall performance of walkability at the neighbourhood scale to target and zoom in on specific neighbourhood for smaller scale analysis. The WI at hexagonal level is an intermediate scale of WI visualisation between footpath and neighbourhood scale to help urban planners or designers to more effectively target areas in specific neighbourhoods for problem identification and thus narrow down to the footpath scale to analyse specific problems.

When multiple scenarios of WI maps at footpath scale are generated, an interface is needed to convey the urban data in a more accessible way to the urban planner or designer. This research attempts to design a web viewer to visualise the generated WI maps and interpret the supplementary information. Figure 4 shows the contents included in the WI web viewer. End-users could then simply use the platform to play with the city maps and identify potential problem areas in order to propose more effective solutions.

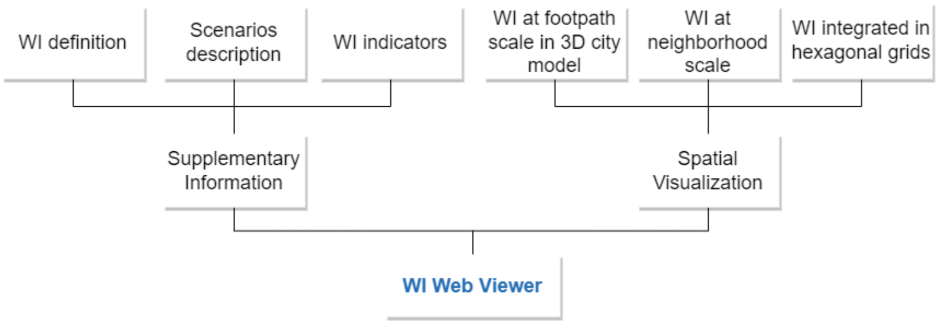


Figure 4. The contents included in the WI web viewer

For the visualisation of the WI at footpath scale, Shammas and Escobar (2019) visualised the WI in different colours on a map of Madrid city at 4 different times (see Figure 5). They estimated the WI by quantifying the indicators of noise, population, activities, connectivity and shade thereby focusing on the impact of comfort factors on WI. However, after urban planners or designers understand the walkability performance of a specific location based on footpath-scale WI maps, when identifying problems and proposing appropriate solutions they may wonder about additional built environment features, such as the height of surrounding buildings. It is therefore decided to use the 2022 OpenStreetMap 3D Buildings data to create a 3D base model of Eindhoven city. WI maps at footpath scale for different scenarios can then be combined with the 3D city model, which can provide urban planners or designers with a more comprehensive basis for environmental assessment.

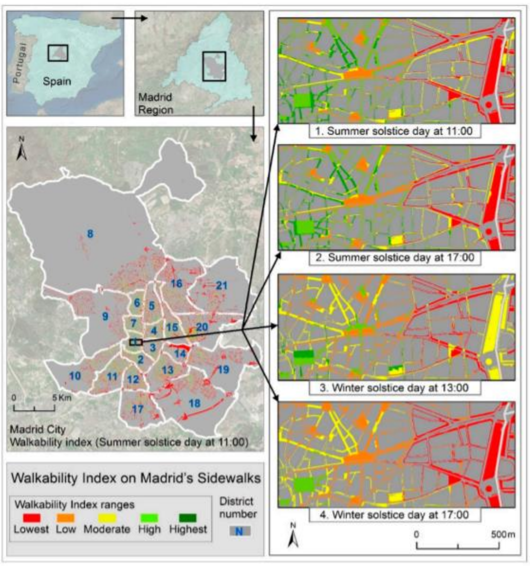


Figure 5. A 2D way of WI visualisation on the map of Madrid City (Shammas & Escobar, 2019)

As a tool to implement the web viewer, ArcGIS StoryMaps will be used in this project. According to ARCGIS (2022), ArcGIS StoryMaps is a web-based storytelling application that can be used without programming to help share maps in the context of narrative text and other multimedia content. In order to combine the footpath-scale WI maps for multiple scenarios with the 3D city model, this study utilises the ArcGIS web scene viewer tool. The generated models can be directly linked to the ArcGIS StoryMap for visualisation and allow end-user interaction. The overall design of the WI visualisation phase is shown in Figure 6.

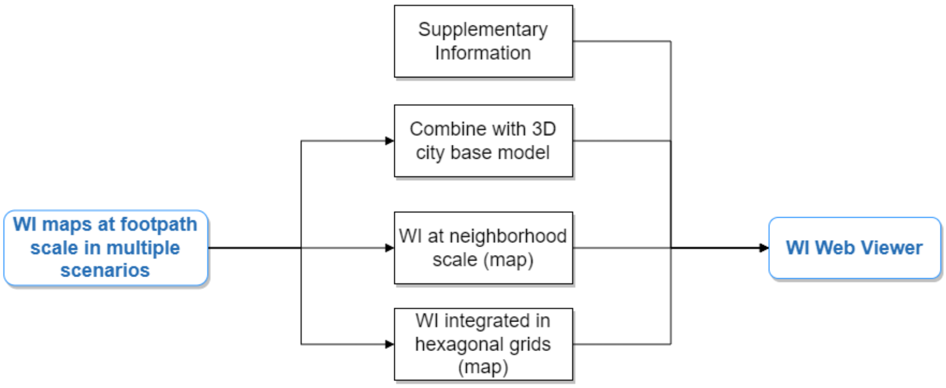


Figure 6. Overview of WI visualisation phase

3.1.4 Validation

After the web viewer with information visualisation is created, the validation phase allows for feedback to be collected by sharing the web viewer and inviting target group to participate. As the target group of this study is urban planners or designers, the validation process should primarily be aimed at this target group. Therefore, an urban designer, two Master students and a teacher from Eindhoven University of Technology with a background related to urban planning and design will be invited to participate in the validation process.

The validation process is mainly about the user's perception of using the web viewer based on the research objective. Basic information about the project and the access to the web viewer will be sent to the participants. Feedback can be collected by means of online interviews, containing some open questions and discussions regarding several topics:

- The assessment approach and importance of WI.
- Assessing and visualising WI in multiple extreme environmental scenarios.
- The methods of WI visualisation, including showing it on different scales and in different dimensions.
- The effectiveness of identifying potential area problems or finding potential areas for development based on WI.
- Suggestions for further expansion.
- User-friendliness and intuitiveness.

3.2 Conclusion

In summary, Chapter 3 introduced the 5 research phases, including exploratory research, WI indicator preparation, WI assessment, visualisation of WI and validation. Each phase can be used to answer the research questions in turn. At different phases, different research methods are also engaged.

The exploratory research phase focuses on conducting a literature review to help identify research gaps as well as enriching the supporting information relevant to the topic. The WI indicator preparation phase is to decide on the WI indicators, collect the required data and develop each indicator. The data collection and indicators development process will vary between different indicators.

The process of WI assessment includes the conditions definition, the listing and selection of scenarios. In addition, there is the process of summing WI indicators at default equal weights and generating WI maps at the footpath scale. The listing of scenarios is determined on the basis of weather conditions and levels. The selection of scenarios is based on whether the scenario is characterised by extreme weather conditions or may cause potential hazards to the pedestrian environment. A scenario with the most common weather condition in the Netherlands is also selected as a reference. A few additional variables are set to represent the interactions effects of weather conditions on the WI.

After assessing several extreme weather scenarios for the footpath-scale WI maps, the visualisation of the WI consists of a footpath-scale WI map in the 3D city model, the neighbourhood-scale WI map and an intermediate scale 50 m sized hexagonal grid map. In the end, a web viewer will be created to present all types of WI maps on the same interface and to facilitate user interaction with the final results. During the validation process, 4 participants representing the target group will be invited to use the web viewer and give some feedbacks through online interviews.

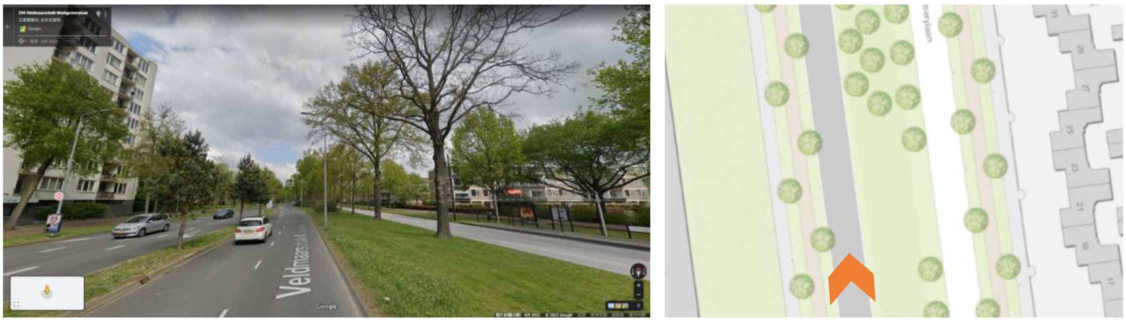
Chapter 4 will explain each step specifically based on the methods addressed in this chapter for each research phase.

Chapter 4. Implementation

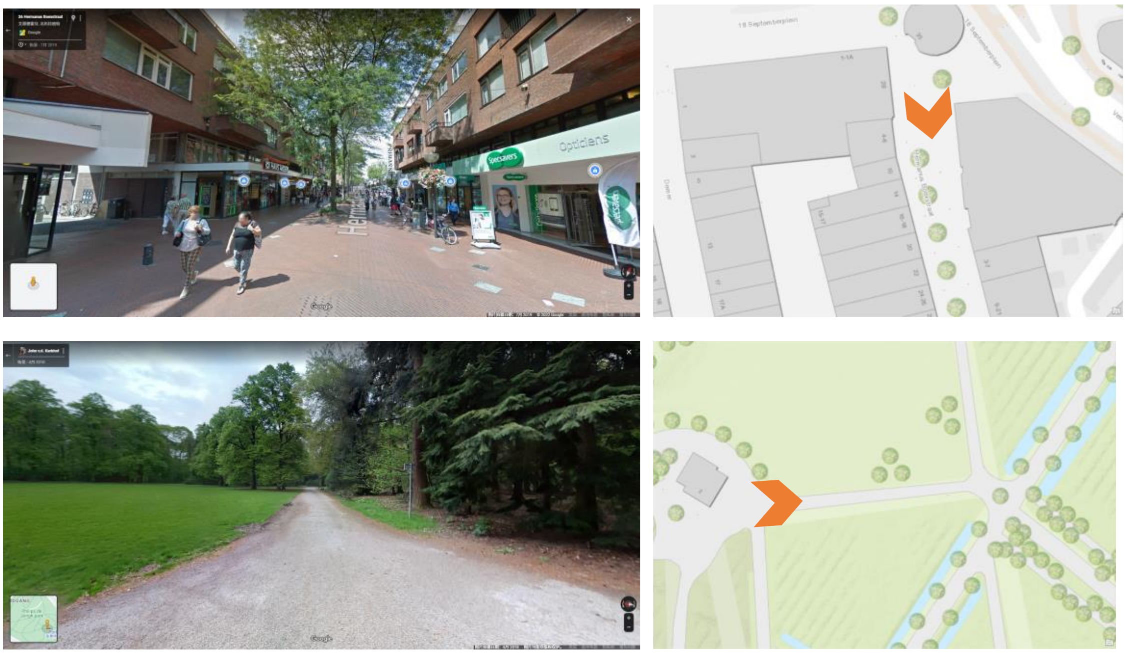
In the previous chapter, five research phases were introduced in the research design. In combination with the literature review and the objectives of this research, the general approach of each phase was decided and explained. This chapter will present the steps, methods and reasoning behind each phase of the study in a comprehensive and detailed manner. In the WI Indicator Preparation phase, the selection of WI indicators, the input data required for indicator development, the GIS tools involved in the indicator development process and the output data are explained more specifically. The WI Assessment phase shows the process of scenario creation and merging indicators to assess the WI. The WI visualisation phase outlines the content that will be displayed in the web viewer. More details of each phase will be elaborated in 4.1, 4.2 and 4.3.

It is important to note that the footpaths in this study refer to all possible footpaths within the city of Eindhoven. It consists of three main categories A, B and C (see Figure 7). Category A refers to most of the footpaths, which are on both sides of residential roads. Category B refers to footpaths on the two sides of the main roads, usually mixed with other transport mode, like motor vehicles, buses and bicycles. Category C refers to paths with single pavement that are used mainly or exclusively for pedestrians in shopping and green areas. This information can be used primarily to help develop footpath width indicators and query footpath polygons, which can be used to generate WI maps at the footpath scale. The specific uses of footpath information will be explained in this chapter.

Category A: residential road



Category B: main road



Category C: footpath in shopping and green area

For the right-side map: Light grey pavement represents footpath, red pavement represents cycling path.

Figure 7. Definition and classification of footpaths in this study (Google Map, 2022)

4.1 WI Indicators Preparation

Within this section, the first 2 sub research questions will be addressed. Namely: What are the indicators selected for assessing the WI? What type of data is needed and how to develop the indicators? Figure 8 shows the overview of this section and corresponding steps. In Chapter 4.1.1, 4.1.2 and 4.1.3, each step will be explained in detail.

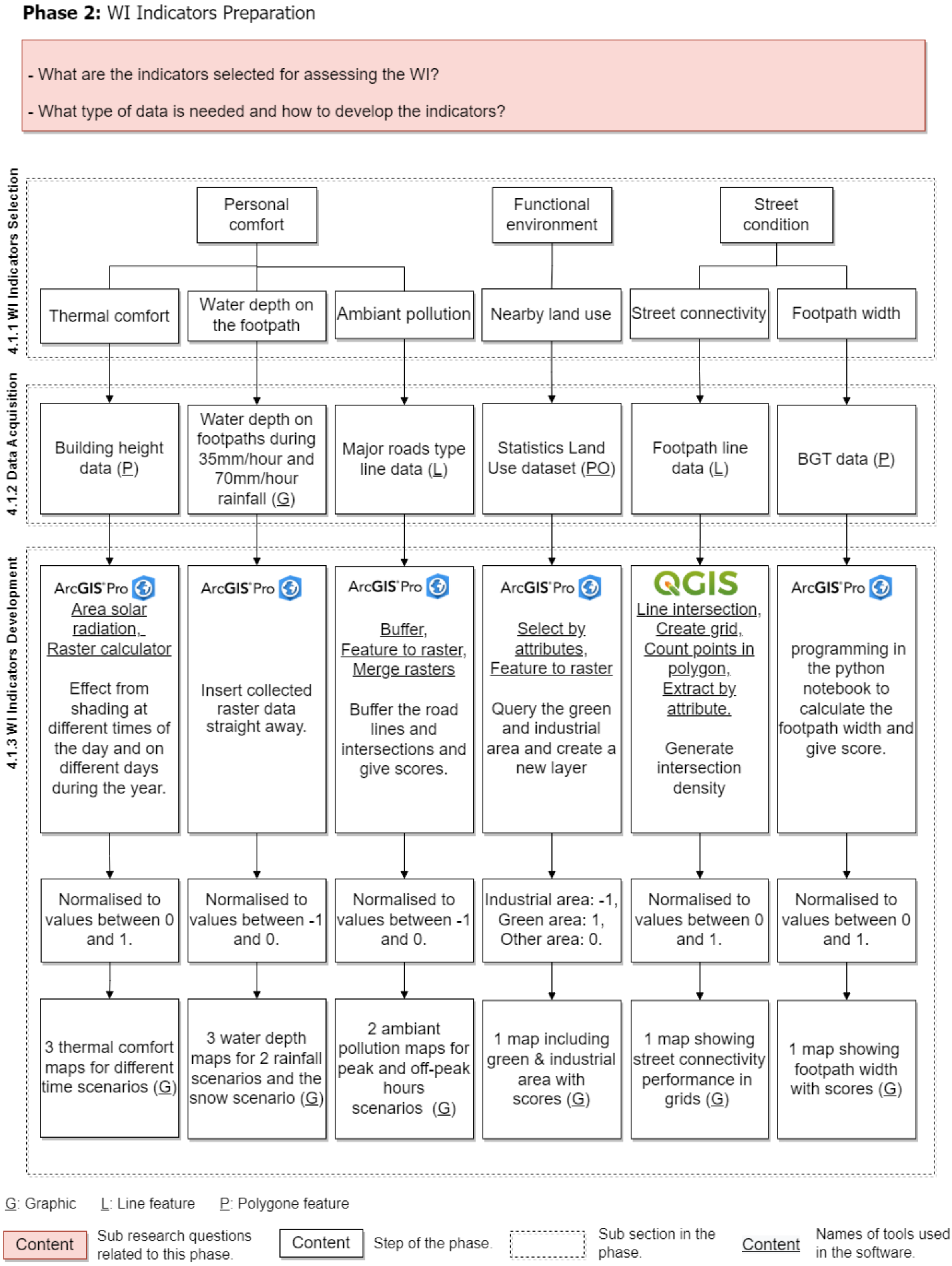


Figure 8. Overview of the steps in the WI indicators preparation phase.

4.1.1 WI Indicators Selection

The first step in preparing the WI indicators was to identify the indicators involved in this study. The process of selecting WI indicators should be combined with the literature review of potential WI indicators, the research objectives of this study and the urban context. For example, according to the literature review in Chapter 2.3, indicators related to street condition, function of environment and personal comfort are all potentially influencing the walkability of streets in different ways. Therefore, in order to make the assessed WI results more practical and comprehensive, indicators from all these categories should be taken into account.

For the choice of specific WI indicators, the selection was first be based on the most mentioned walking influence factors in the available literature, such as nearby land use types and street connectivity, which were considered to be well-tested. Footpath width was also considered to be an essential indicator for assessing the WI. Street connectivity affected walkability in a way that enhances street accessibility, whereas footpath width affected the convenience of walking. Within the personal comfort category, it could be seen in Chapter 2.3.3 that many studies showed that rainfall and thermal comfort were among the factors influencing walkability. According to Klimaateffectatlas (2018), severe precipitation over a short period of time can cause localised waterlogging in streets and squares in the Netherlands, while pavements in low-lying areas are highly susceptible to flooding. In addition, air pollution and noise can affect people's motivation to walk. Although there were also a number of potential indicators related to personal comfort that showed a strong influence on WI in the literature, most of them were more dependent on subjective factors and questionnaires needed to be used when measuring it. Given the limited time available and the limitations of obtaining this data directly, those indicators were not ultimately considered.

In order to clarify the framework and direction of the study more clearly, some assumptions about the selected WI indicators needed to be set. This could also help in the subsequent phases of the study to have a clearer and more rational elaboration. Table 4 provides a summary of the selected WI indicators and corresponding properties and assumptions in this study.

Table 4: Overview of the selected WI indicators in this research.

Indicator category	Name of indicator	Definition	Assumption	Effect on WI
Personal comfort	Thermal comfort	Thermal comfort based on level of shading at the location.	Only consider the effect from shading on cold or hot days.	On a sunny day, shading in hot weather and non – shading in cold weather bring positive effects.
	Water depth on the footpath	Impact of localised water accumulation on footpaths due to heavy precipitation over a short period of time.	Only consider heavy rain (rainfall level 70mm/2hr) and violent rain (rainfall level 140mm/2hr) situations.	Negative effect
	Ambient pollution	Impact of air and noise pollution on localised roads due to traffic flow.	Only consider the level of noise and air pollution in this indicator. Only consider the impact of traffic on noise and air pollution on primary and secondary roads.	Negative effect
Street condition	Street connectivity	Accessibility of footpaths.	Only consider the effect from the intersection density.	Positive effect
	Footpath width	The width of footpath.	Footpaths include double/single side pedestrian walkways on streets and streets with mixed functions (like residential streets).	Positive effect
Function of environment	Nearby land use	The effect of walking in a green or industrial area.	Only consider the built-up area. For the classification of land use only the green, industrial and other areas are considered.	Green area brings positive effect, industrial area brings negative effect.

4.1.2 Data Acquisition

After identifying the indicators involved in the assessment of the WI, the data collection needed to be carried out according to the definitions and assumptions set by this study for each indicator. As the indicators involved in the WI assessment were diverse and related to different aspects of the built environment and weather, the type of data to be collected and the identification of data sources needed to be implemented. The determination of the type of data to be collected should depend on the method of developing the indicator and the availability of the data required. The indicator development method will be further described in Chapter 4.1.3. The overview of data collected for each WI indicator and the corresponding data sources is shown in table 5.

Table 5: Overview of collected data and data sources for each WI indicator.

WI indicators	***Variable/static**	**Data collected**	**Data sources**
Thermal comfort	Variable (Different times during the day and on different days during the year)	Building height data (for analysing solar radiation effect)	Dataset: Basisregistratie Adressen en Gebouwen (BAG) from PDOK platform
Water depth on the footpath	Variable (2 rainfall levels)	Flood depth associated with short, severe precipitation (70mm/2hr and 140mm/2hr)	Dataset: Flood depth associated with short, severe precipitation, from Klimaateffectatlas platform
Ambient pollution	Variable (Peak time & off-peak time)	Major roads type line data (Including primary and secondary roads)	OpenStreetMap
Nearby land use	Static	Statistics Land Use dataset	Dataset: CBS Existing Landuse (INSPIRE harmonized) from PDOK platform
Street connectivity	Static	Footpath line data	OpenStreetMap
Footpath width	Static	Footpath polygon data	Dataset：Basisregistratie Grootschalige Topografie （BGT） from PDOK platform

** Variable/static means whether this WI indicator shows a single built environment performance or different performance in different conditions.*

Personal Comfort Indicators

For personal comfort indicators, which in this study mainly referred to weather-related indicators, the data collection and indicator development methods were relatively difficult and complex. In fact, the collection of weather-related data and methods mentioned in the existing studies were mainly used for the purpose of disaster management. Fan, Jiang and Mostafavi (2020) used real-time data from API and twitter data to extract timely information on local flood conditions and send it to infrastructure operators, rescue workers and residents to improve their ability to respond to disaster disruptions. Jongman et al. (2015) also used the Global Flood Detection System (GFDS) satellite flood signal, and flood-related Twitter activity data to explore early flood detection and rapid humanitarian response. For other types of weather data, the temperature-related information can be analysed by using Physiologically Equivalent Temperature (PET) data, which indicates how warm a person feels in a particular climatic situation (Klimaateffectatlas, 2015).

It seems that a suitable way to express weather indicators is to collect the data through a direct real-time data platform. In this research project, the first attempt to connect to the API to obtain weather data was unsuccessful due to the unavailability of the data. Therefore, it was decided to set up a few typical extreme weather conditions for the development of personal comfort indicators. During the data collection process, most of the WI indicators had some missing values in the data. Therefore, in order to prevent these missing values from causing problems in the WI assessment phase when other WI indicators are combined, it was decided to convert all missing values to 0 values by default.

Based on the definition and assumptions of the thermal comfort indicator, only the effect from shading was considered. Because shading may have the opposite effect on personal comfort during hot or cold days, the role of temperature is still relevant but will not be directly involved in the calculation of the indicator. Therefore, it was decided to collect the building height data (see Figure 9) from the open data platform PDOK (2022) to help analyse the solar radiation at various locations in the city on different days of the year and at different times of the day by using the tools in ArcGIS Pro. The details of the analysis can be found in Chapter 4.1.3.

Figure 9. The building height data viewed in ArcGIS Pro (PDOK, 2022)

The water depth data was collected from the Klimaateffectatlas platform (2018). This platform could provide the data regarding the flood depth on urban roads after a rainfall period of 70 mm and 140mm in two continuous hours in spring 2018 (see Figure 10 and Figure 11). This data enabled the analysis of the extent of road surface flooding for different levels of rainfall.

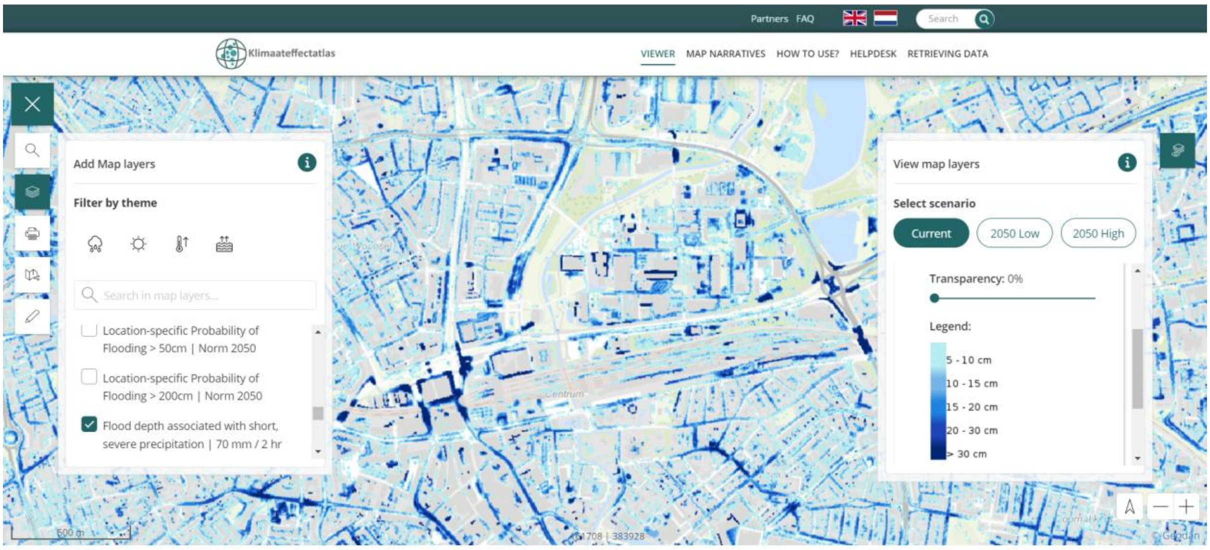


Figure 10. The water depth in road areas after a rainfall period of 70 mm in two continuous hours in spring 2018 (Klimaateffectatlas, 2018)

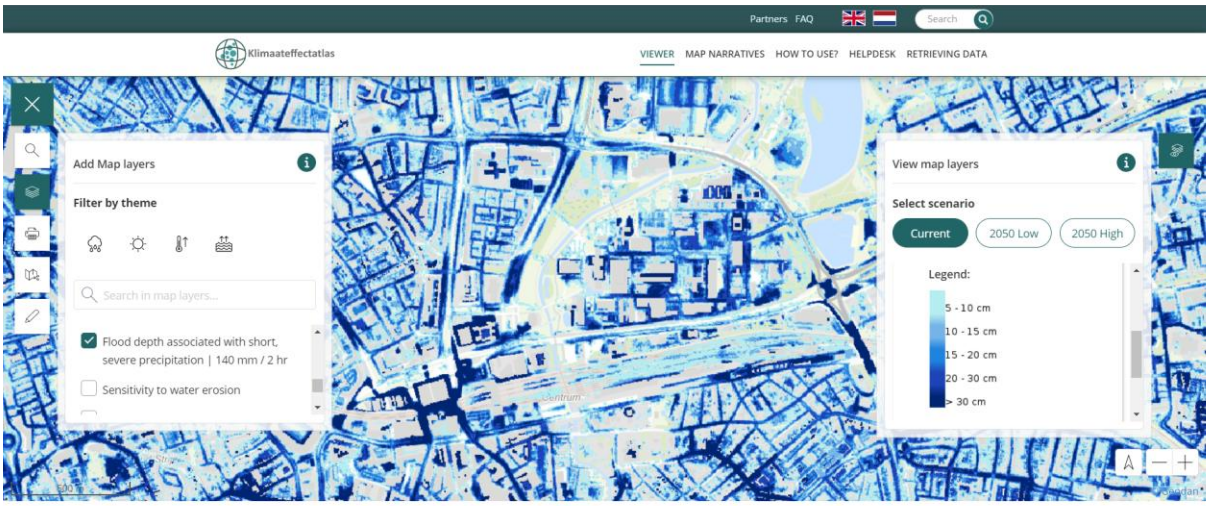


Figure 11. The water depth in road areas after a rainfall period of 140 mm in two continuous hours in spring 2018 (Klimaateffectatlas, 2018)

Based on the definition and assumptions of the ambient pollution indicator, this study only considered the effect of traffic on air pollution and noise in ambient pollution. Therefore, for the data collection, it was chosen to start with the city's major road location data, which was obtained from the OpenStreetMap road type data in QGIS software. In the process of indicator development, this data could be used to briefly analyse the impact of urban arterial traffic on ambient pollution at peak hour or off-peak hour, with the help of some literature findings. Chapter 4.1.3 will show more details of the analysis.

Street Condition Indicators

In this study, street connectivity and footpath width were decided as two of the indicators for WI assessment. In existing studies, there are various ways of measuring street connectivity. In this project it was decided to divide the city area into 50m size grids and calculate the density of intersections in each grid to represent the level of street connectivity. For this purpose, footpath line data needed to be obtained to generate the intersections. This could be extracted through OSM.

The footpath width calculated based on footpath polygon data which could be extracted from the De Basisregistratie Grootschalige Topografie (BGT) data. BGT data is a detailed large-scale base map (digital map) of the whole Netherlands, including the location registration of physical objects such as buildings, roads, water, railway lines, lands, etc (PDOK, 2022). The GIS-based calculation of the intersection density and the calculation of the footpath widths will be described in Chapter 4.1.3.

Function of Environment Indicators

The Nearby land use indicator was mainly concerned with land use type data for specific areas of the city. The INSPIRE Land Use data set of the Netherlands contains such data. The PDOK open data platform (2022) could provide the Statistics Land Use data based on the topographical map of the Netherlands (BRT) and aerial photos of summer of 2015. In the indicator development phase, GIS-based information could be extracted from this data to obtain polygon information on industrial areas and green spaces. Chapter 4.1.3 will show more details of the indicator development process.

4.1.3 WI Indicators Development

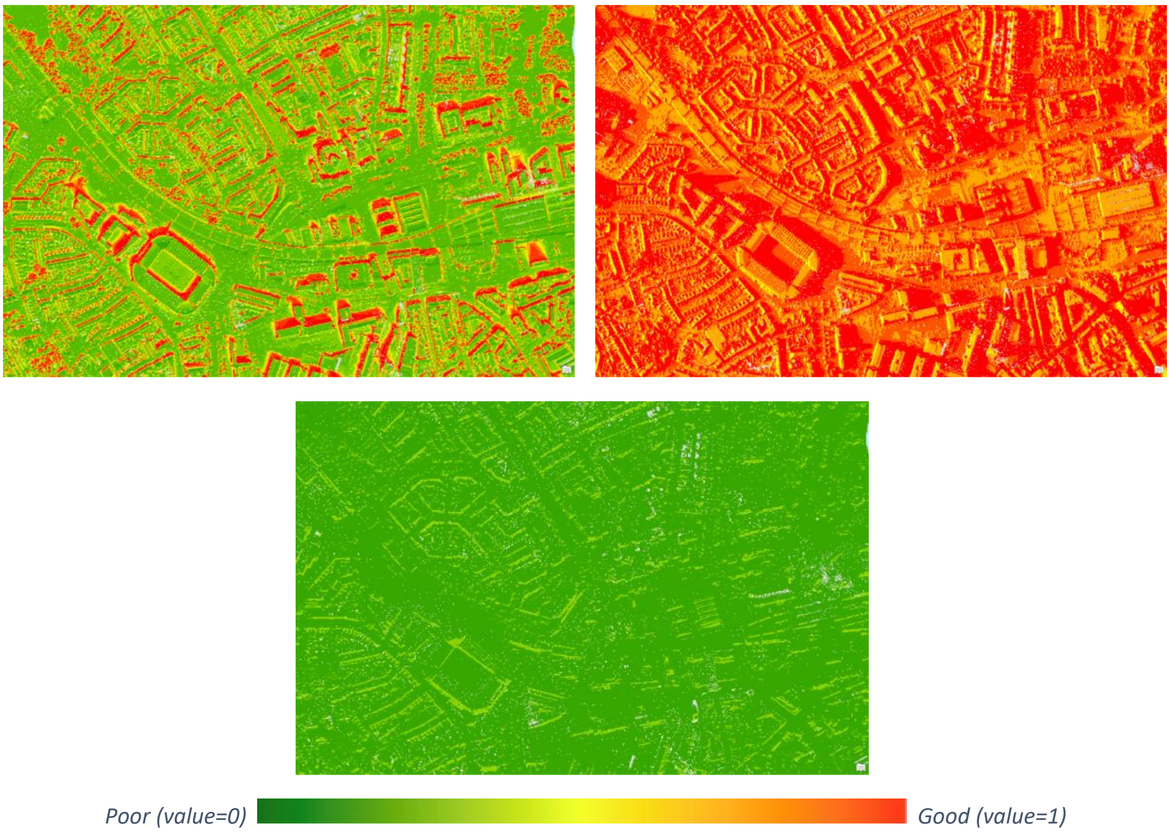
After the data required for the WI indicators was collected, each indicator had to be prepared and analysed based on the obtained data. The indicators were developed by using ArcGIS Pro or QGIS software. The coordinate system was standardized to Amersfoort / RD New – EPSG:28992. As different indicators involved different development methods, the development process for each indicator will be described separately below. An overview of how the final values and thresholds for each WI indicator were determined can be found in Appendix A.

Thermal Comfort Indicator

For the outdoor thermal comfort, physiological equivalent temperature (PET) is one of the indices that is usually used for the assessment (Deb and Alur, 2010). According to Klimaateffectatlas (2015) and De Nijs et al. (2019), the PET calculations were mainly based on solar radiation maps, surface types and statistical models made using the results of sensors. The calculation process didn't directly incorporate wind simulations, but rather made statistical correlations of wind effects in the statistical model (Klimaateffectatlas, 2015). Klok et al. (2019) highlighted the importance of shading in reducing heat stress in urban design when assessing thermally comfortable urban spaces in Amsterdam during the hot summer months. Measurements showed that PET were 12 to 22°C lower in spaces shaded by trees and buildings compared to sunlit areas (Klok etal., 2019). According to Nwanazia (2022), Since 1900, the worldwide temperature has risen by 0.8 degrees Celsius, but in the Netherlands this rise is estimated at 1.7 degrees Celsius, which is twice as fast as the world average. The importance of shading might therefore become increasingly important. The importance of sunshine in winter is similar to that of shade in summer, people prefer walking in the sun over shade in winter (Shammas and Escobar, 2019). Considering the importance of the shading effect in cold and hot weather and the limitations in data availability, the decision was to consider only the effect from shading on cold or hot days to represent the thermal comfort indicator. In this study, the thermal comfort indicator was developed based on solar radiation values.

Solar radiation can be generated based on building height data using the "area solar radiation" tool in ArcGIS Pro. Solar radiation varies from day to day and from moment to moment due to the time, sunlight angle and season. Therefore, in this study, it was decided to set several typical conditions, including summer day (representing very hot day) and winter day (representing very cold day) morning peak hour, evening peak hour and off-peak hour for generating solar radiation values by using the tool. Since the "area solar radiation" tool allows the selection of any day of the year and any time period to automatically generate a solar radiation map, this study defaults to the 10th and 220th day of the year for winter day and summer day respectively. The definition of peak hours refers to Boers from AutoWeek (2022), as 7:00 to 9:00 and 16:00 to 18:30. During the solar radiation generating process, it was found that the tool couldn't generate the solar radiation value under the winter day peak hour conditions probably as the sunlight hours are shorter during the winter days. Furthermore, when the temperature of the day is high, the temperature remains comfortable in the early morning, but gradually rises and reaches a peak as the intensity of sunlight increases, and the temperature begins to trend downwards around 5pm (Molenaar, 2019). Therefore, in terms of extreme weather condition, the shading effect was considered to be relevant after the morning peak on hot days. As there may be situations where there is no direct sunlight, but rather rain or cloudiness, the solar radiation effect would then be set to zero in the calculation of the thermal comfort indicator.

In the end, the thermal comfort indicator needs to be normalised between 0 and 1 (more desirable areas will have higher score) based on the overall maximum and minimum values by using the tool "raster calculator" in ArcGIS Pro. It should be noted that when the weather is very hot, the thermal comfort effect would be higher in the shading area, which means that in this case areas with higher solar radiation will have a lower indicator score. On the contrary, the effect would be higher in the area with direct sunlight during the cold weather, which means that areas with higher solar radiation will have a higher indicator score. Figure 12 shows the final output of thermal comfort indicator in three conditions.



Top left figure: summer day off-peak hour (10-12am). Top right figure: summer day evening peak hour (4-6pm).

Bottom figure: winter day off-peak hour (10-12am).

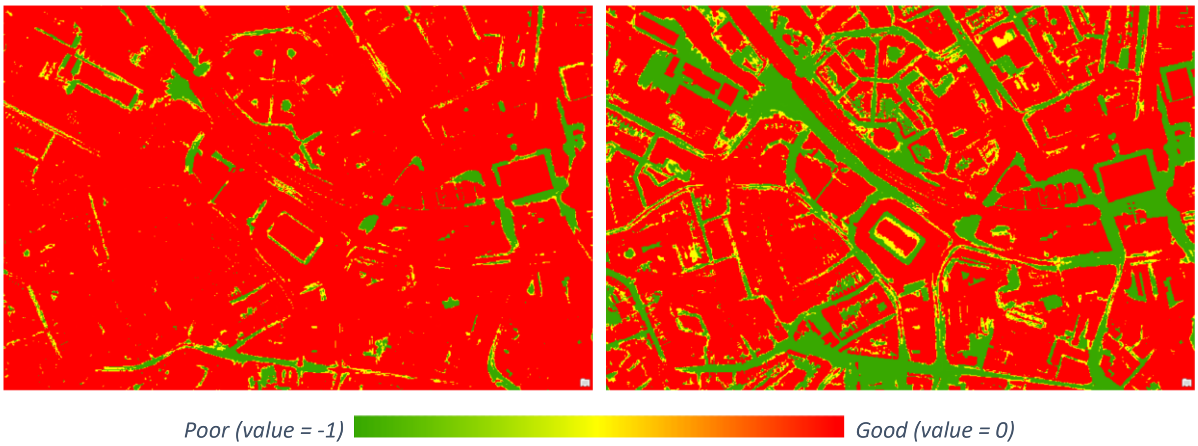
Figure 12. Thermal comfort indicator in 3 conditions.

Water Depth on the Footpath Indicator

The water depth indicator reflects the level of water accumulation in urban footpaths under the influence of continuous rainfall, which directly impacts the convenience of walking for pedestrians and the level of walkability in this condition.

In this study, the flood depth on urban roads caused by 2-hour period of 70mm and 140mm showers can be directly obtained from the Klimaateffectatlas (2018). According to Met office (2007), rain showers can be classified as "slight", "moderate", "heavy" or "violent" with accumulation rates of approximately 0 to 2 mm/hour, 2 to 10 mm/hour, 10 to 50 mm/hour, and >50 mm/hour. The data obtained therefore refers to the heavy and violent rainfall category, which will be discussed separately as conditions in this project.

Based on the flood depth data collected for two rainfall levels, the flood depth was already categorised into five classes from 5cm to over 30cm. Depending on the amount of rainfall, the area of puddles as well as the depth might vary. For example, at a rainfall of 70mm/2hr, the flood depth at a location on the footpath can reach 10cm, whereas at the same location after a rainfall of 140mm/2hr, the area of the puddle may increase and the depth may increase to 15cm. Lastly, the collected water depth data still needs to be normalised. It is worth noting that since this indicator has a negative impact on the WI, it should be normalised to a value between -1 and 0 to be involved in the WI assessment process. Figure 13 shows the developed water depth indicator raster maps for a rainfall period of 70 mm and 140mm in two continuous hours conditions. However, when the temperature is extremely low, snowfall may be incurred. For such extreme weather conditions, the level of water accumulation on urban footpaths is difficult to measure by the amount of rainfall or snowfall. Therefore, it was decided to give a constant -1 to the water depth indicator, thus generating a raster map with only one score covering the entire Eindhoven footpath areas. This could represent the worst circumstance and then be involved in the WI assessment.



Left: Water depth on the footpath in 70mm/2hr rainfall level.

Right: Water depth on the footpath in 140mm/2hr rainfall level.

Figure 13. Water depth on the footpath indicator in 2 conditions.

Ambient Pollution Indicator

As for the ambient pollution indicator, this study only considered the impact of traffic on noise and air pollution, but not the potential pollution caused by surrounding land use. In addition, there would be differences in pollution between street types due to differences in traffic flow. In this study, only the pollution effect on primary and secondary roads was considered and was estimated using the same methodology and threshold. Therefore, in evaluating this indicator, different buffer widths were created for primary and secondary roads and intersections based on two conditions, namely peak hour and off-peak hour. Then the buffer scores were assigned and overlaid on each other.

The OSM road type data and road lines can be obtained through QGIS. In this project, primary and secondary road lines were queried and used to create the buffer, and the intersection of road lines could be generated by using the "line intersection" tool. The buffer width was set differently between noise pollution and air pollution and between road lines and intersections, the exact threshold referred to in the literature. This is due to the fact that noise pollution caused by traffic generally affects a smaller distance range than air pollution. On the other hand, since cars remain in the intersection for a longer period of time than at each location on the road, the impact of pollutants from the intersection is relatively larger. Rose et al. (2009) attempted to develop and validate a new NO2 predictor on a traffic road and found that a buffer zone radius of 75 m predicted nitrogen dioxide most accurately. Wang et al. (2017) investigated the minute-scale variation of fine particulate matter (PM2.5) and carbon monoxide (CO) concentrations near a road intersection in Shanghai and found that the pollutant concentrations dropped sharply at 110 m near the intersection, with the maximum decay rate occurring at 500 m. For an investigation of the extent of noise pollution near roads, Calixto, Diniz and Zannin (2003) measured road traffic noise in Curitiba and chose to measure traffic noise at 25 m from the centre of the nearest road section to the observer. Alberola, Flindell and bullmore (2005), explored the significant impact of road noise within 30m of the location point relatively close to the junction, in a detailed comparison with the equivalent time histories within 45m and 70m.

Summarising the conclusions obtained in the existing relevant literature, the following thresholds were set for the development of the ambient pollution indicator in this project to build buffer for road lines and intersections (see Table 6).

Table 6: Thresholds identification for buffer creation of ambient pollution indicator.

	Intersection buffer	***Road buffer***	***Reference***
Noise pollution buffer	30m radius	25m radius	Alberola, Flindell & bullmore (2005); Diniz & Zannin (2003).
Air pollution buffer	110m radius	75m radius	Wang et al. (2017); Rose et al. (2009).

As it was decided to discuss both peak and off-peak conditions separately, in this indicator the two conditions would be created. This could reflect the potential for more noise or air pollution due to higher traffic volumes during peak hours. It was therefore decided to give each buffer the same score in the same condition for overlaying, but to set different scores between the conditions. It is important to note that when generating road buffers based on the road lines, there is an overlay of buffers at the intersection locations, so the road buffers at the intersection locations need to be dissolved before the scores are given (see Figure 14). An example of score accumulation in a typical road and intersection area is shown in Figure 15. If each buffer is given a score of -1, in a simple road area, the road has more pollution due to air pollution and noise, so the score is assumed to be -2. The area next to the road is still polluted but relatively less, so the score is -1. When the two roads cross each other, there is a double effect. The area where the 2 buffers intersect each other is scored as -2. The area where the 2 roads intersect each other is scored as -4. According to the weekly traffic congestion statistics by time of day provided by TomTom Traffic Index (2021), traffic congestion is approximately twice as high during peak hour as it is during off-peak hour. In this case, the score for each buffer was decided to be set to -1 during peak hours and -0.5 during off-peak hours. The summing of scores in different locations can be achieved with the raster function “merge rasters” in ArcGIS Pro. The sum of the scores still needs to be normalised. Similar to the water depth indicator, this indicator has a negative impact on WI and should therefore be normalised to a value between -1 and 0, with the value 0 representing areas not affected by ambient pollution. The results are shown in Figure 16.

Figure 14. An example of dissolving the overlayed road buffer at the intersection location

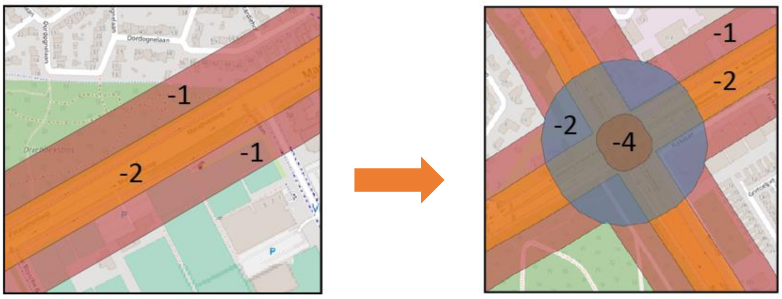
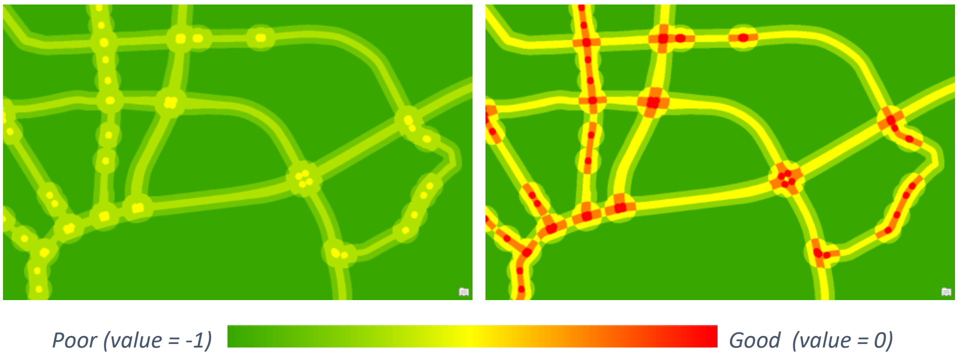


Figure 15. An example of score accumulation in a typical road and intersection area.



Left: Ambient pollution in off-peak hour. Right: Ambient pollution in peak hour.

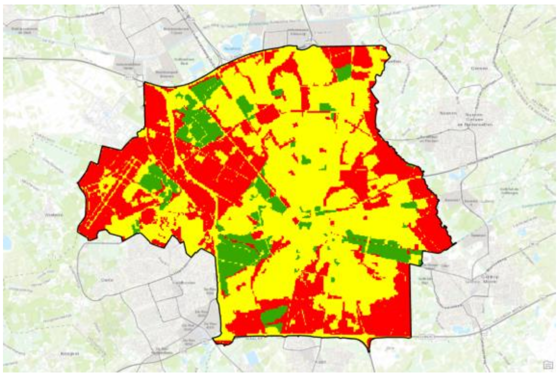
Figure 16. Ambient pollution indicator in 2 conditions.

Nearby Land Use Indicator

Some specific land use types can have an impact on the walkability of the surrounding footpaths. In this study, the nearby land use indicator represents the impact on walkability of the type of land use where the footpath is located. According to Kadali and Vedagiri (2015), pedestrian safety and comfort depends not only on traffic flow and road design elements, but also on different land use types, such as pedestrians being more comfortable in shopping areas than in industrial areas. Activities on industrial sites can create many potential problems, including noise, air and water pollution, and traffic congestion (Rahman and Szabó, 2021). Conversely, green spaces can provide many health benefits to citizens, such as promoting civic well-being through the enhancement of physical and mental health (Rahman and Szabó, 2021). Industrial and green spaces are considered to have a relatively greater impact on pedestrian walking comfort than other land use types. Therefore, only the influence of these two land use types was considered in this study as an indicator and thus involved in the assessment of WI.

Data on land use types in Eindhoven city can be collected from the open data platform and imported into QGIS. As the land use data is from 2015 CBS Existing Land use dataset, the land use type for some areas may now have been updated, resulting in inconsistencies with the data. Data types should be displayed as polygon. Then, the land use type needs to be queried for green area and industrial area. Green and industrial areas can be queried using the “select by attributes” tool in ArcGIS Pro and a new layer needs to be created with only these two land use types.

For the normalisation of this indicator, it was decided to set a score of 1 for the green area polygons and a score of -1 for the polygons representing industrial areas. The remaining land use areas were given the score of 0, which represented the default situation. Therefore, the final developed nearby land use indicator would then be a raster map of the areas with values of -1, 0 and 1 (see Figure 17).



Poor (value = -1) *Moderate (value = 0)* *Good (value = 1)*

Figure 17. Nearby land use indicator

Street Connectivity Indicator

The street connectivity was considered to be one of the most important indicators in the literature for assessing walkability. Moreover, more than one method is proposed for measuring street connectivity. Stangl (2015) proposed a block-size measure based on a “block section” to assess street connectivity by measuring the maximum distance between any two points on the perimeter of a block, or the area enclosed by a specified route network, to represent the extent of block obstruction in the environment (Stangl, 2015). Furthermore, Space Syntax is widely and intensively studied as a recognised method for assessing street connectivity. It captures street connectivity primarily by examining how proximate the streets are topologically to other streets in the network and how all streets in the network are connected to each other (Koohsari et al., 2016). In this case, the axes are like the human sight line, used to quantify the spatial network, and can be used to generate a “rational graph” by connecting to other adjacent axes, and then to quantify the number of direction changes that a person would have to move from that space to all other spaces by calculating the links in the network (Koohsari et al., 2016).

Street density measurement, as one of the common methods used for street connectivity, is often used when street connectivity is not the primary object of research (Dill, 2004). In this study it was decided to use this method to measure the street connectivity indicator. Street intersection density can be calculated with the help of QGIS. Firstly, the footpath lines can be queried using OSM road type data. Then, the “line intersection” tool can be used to generate all intersections of the footpath lines. In order to calculate the density, grids were created in the city to assist in the calculation by using the tool "create grid". In deciding on the size of the grids, this study referred to the 50m grid size defined by Frank et al. (2010) in their study of the walkability index at the neighbourhood scale. The coordinate reference system for the grid is set to be the same as the data layer. The development of the street connectivity indicator was then completed by simply counting the number of intersections in each grid by using the tool "count points in polygon" and "extract by attribute". The number of intersections in each 50m size grid is calculated as a grid score and normalised between 0 and 1. All footpath segments within the grid are given a grid score (see Figure 18).

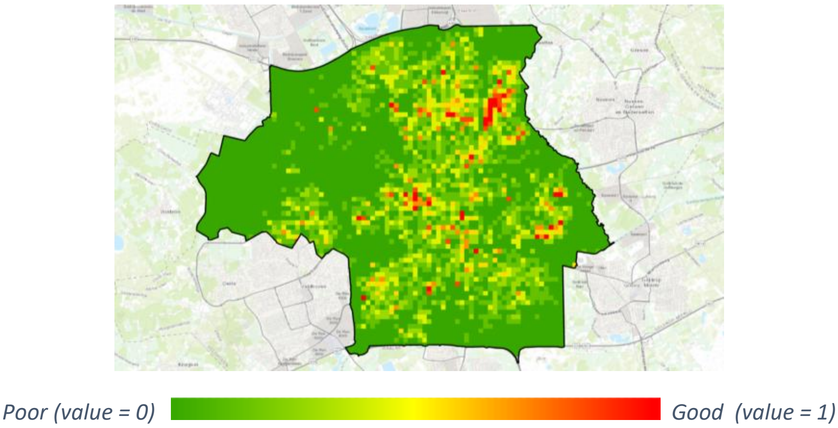


Figure 18. Street connectivity indicator.

Footpath Width Indicator

As an indicator to show the street condition, footpath width can influence the willingness of pedestrians to choose this route. According to Kim, Choi and Kim (2010), a number of studies indicate that narrow pavement width is one of the main reasons why people abandon walking and travel by car.

In this study, the calculation of the footpath width was based on the footpath polygon data. The data can be queried from the De Basisregistratie Grootschalige Topografie (BGT) data for the city of Eindhoven by using ArcGIS Pro software. The definition of footpaths and the categories were described at the beginning of this chapter.

Because the queried footpath polygon cannot automatically identify whether the footpath is on the two sides of residential road or in shopping area, it can only measure the width of the entire pavement. For example, in Figure 19, footpaths X and Y will be calculated and discussed as two different footpath widths respectively for residential road, while for footpath in shopping area the width refers to the two-way pavement (footpath width Z).

As for the determination of the method to calculate the footpath width, it was decided to use the method of programming in the python notebook of ArcGIS Pro to measure the width of each one-metre segment of footpath. The main steps in the software operation included dissolving the footpath polygons, creating lines from the polygons, generating points along the lines for each 1 metre section, generating Thiessen polygons from the points, setting scoring criteria based on the widths to give each 1 metre section a score. Figure 20 shows how to measure the width of the footpath on both sides of a typical residential road. The Python codes can be seen in Appendix A. Then, thresholds needed to be set based on the literature so that the width of each metre-long footpath could be scored individually.

Residential road *Footpath in shopping area*

Figure 19. Two examples to show the definition of the footpath width (Google Map, 2022).

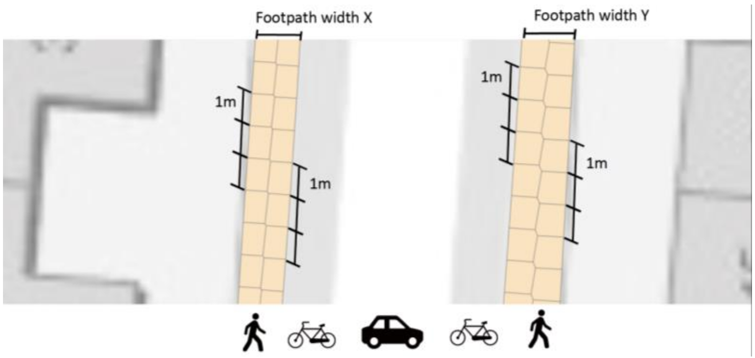


Figure 20. Process of measuring the footpath width in ArcGIS Pro.

In the guidelines for the design of accessible urban footpaths provided by Stadskantoor Zwolle (2022), for footpaths on both sides of the road at basic level, the minimum size of the footpath on each side should be no less than 1.5 metres (excluding kerbs). As explained earlier, this study did not discuss the calculation of footpath on the two sides of residential road and footpath in shopping area separately. In addition, the capacity demand between off-peak and peak periods was not considered. Therefore, taking into account the findings of the literature, it was decided to choose 1.5m as the width threshold for each side of the residential roads as well as for the shopping area pavement, and to give two scores (score 1 or 0) for different width values (see Table 7). Finally, the developed footpath width indicator can be presented as either 1 or 0 on a raster map (see Figure 21).

Table 7: Thresholds identification in this study for width of footpath and the corresponding score.

Width of footpath	***Score***
More than 1.5 meters (including 1.5m)	1
Below 1.5 meters	0

Figure 21. Footpath width indicator.

4.2 WI Assessment

After developing each WI indicator, it was possible to start combining them to assess the WI. This section describes the WI assessment phase in detail. The process and final results of this section therefore address the research question: How to assess WI through the developed indicators? Figure 22 provides an overview of the content and steps of this research phase. In Chapter 4.2.1 and 4.2.2, the contents of this overview will be explained in detail.

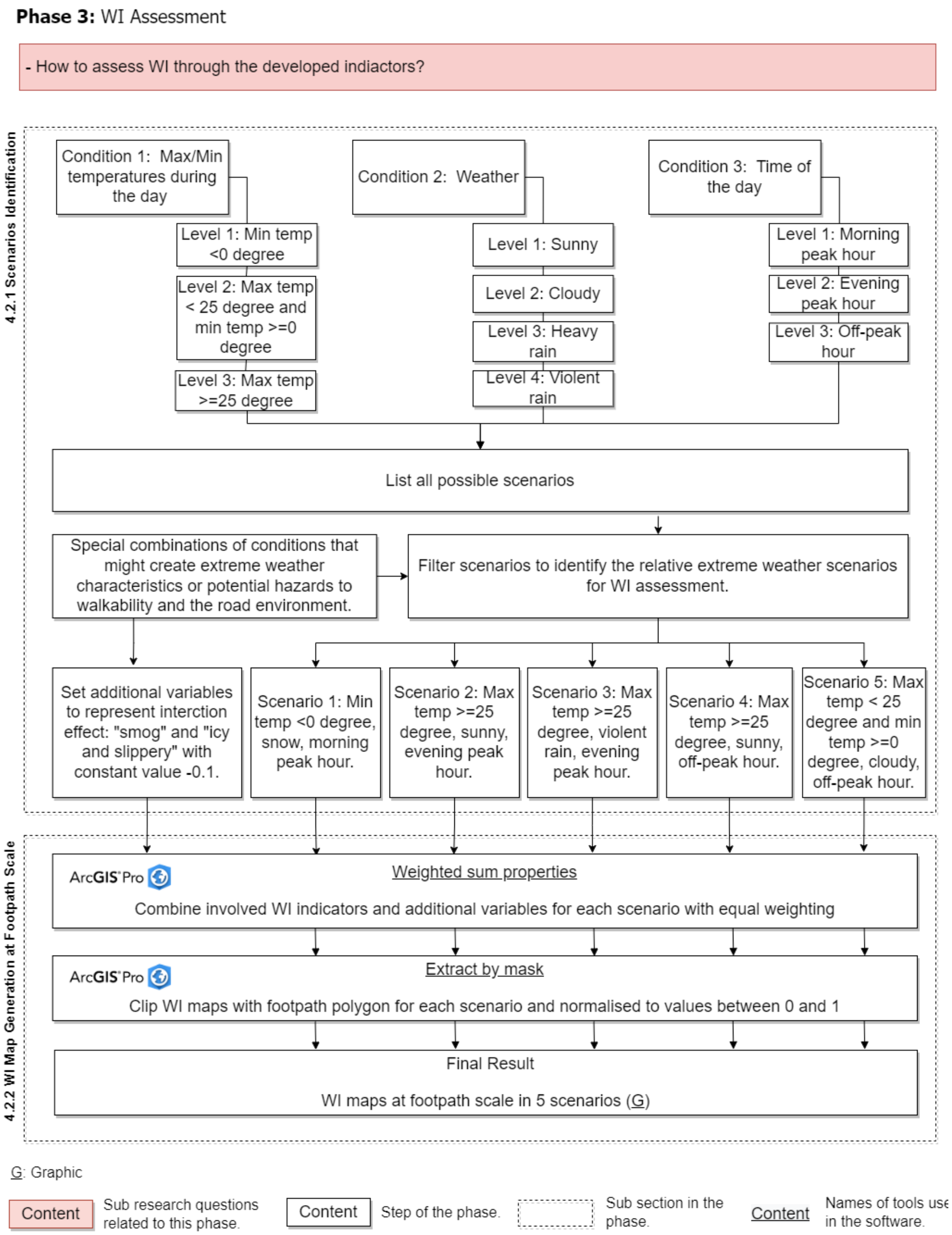


Figure 22. Overview of the involved steps in the WI assessment phase.

4.2.1 Scenario Identification

When all the WI indicators were developed, it was necessary to consider how to assess the WI in different scenarios. In accordance with the objectives of this project, the process of defining scenarios should be based on the indicators and the characteristics of extreme weather. Indicators can be combined into a final WI score in different scenarios.

For example, the thermal comfort indicator shows the effect of shading of the footpath depending on the season and time during the day. Thus, “summer day” and “winter day” can be used as one of the references for defining condition and then to help define scenarios. KNMI (2014) defined a summer day in the Netherlands as one with a maximum temperature of 25 degrees or more and a winter day as one with a minimum temperature below 0 degrees. Therefore, these thresholds can be used as a reference to define the weather conditions of the scenario in this project. In addition, the water depth on the footpath indicator can be assumed to have impact on the WI only when the weather is in heavy or violent rain. Different levels of rainfall (70mm/2hr or 140mm/2hr) can result in different levels of water depth on the footpath. Since ambient pollution describes the impact of air and noise pollution from traffic on the WI, it can be assumed that there are different levels of impact only at peak hour and off-peak hour. In summary, Table 8 shows the conditions and the corresponding levels involved in the definition of the scenarios in this study. All possible scenarios are listed in Appendix B according to the combination of conditions.

Table 8: The attribute and corresponding levels involved in the scenario identification process.

Name of the condition	***Level 1***	***Level 2***	***Level 3***	***Level 4***
Max/Min temperatures during the day	Min temp <0 degree	Max temp < 25 degree and min temp >=0 degree	Max temp >=25 degree	-----
Weather	Sunny	Cloudy	Heavy rain	Violent rain
*Time of the day	Morning peak hour	Evening peak hour	Off-peak hour	-----

** This means whether it is the period of the day when traffic congestion on the roads is at its highest.*

After all scenarios are listed, it is then necessary to select scenarios that are characterised by extreme weather or may have extreme weather potential. In fact, the potential for extreme weather conditions in the Netherlands is gradually increasing. The key numbers in KNMI’14-klimaatscenario’s showed that in 2050 summer temperatures will rise by 1-2.5 degrees, winter precipitation will increase by 3-17% and sea levels will rise by 15-40 cm (Leeson, 2022). According to Vasileiadou et al. (2013), climate change is expected to have an impact on the likelihood and duration of extreme weather occurrences, such as extreme precipitation, heat waves and extreme droughts. In conjunction with the defined condition and corresponding level, extremely hot or cold weather and long periods of heavy rainfall as extreme weather characteristics can negatively affect walkability. In addition, the interaction effect of several conditions might enhance the impact on walkability in a positive or negative way. For example, sunny weather can provide greater comfort to pedestrians if it is at a moderate temperature. However, when the temperature is excessive, sunny days might reduce the personal comfort of pedestrians. During the morning peak hours in winter, the potential for road icing can be greatly enhanced when temperatures are cooler and accompanied by rainfall (Koetse and Rietveld, 2009). Significant changes in ambient temperature also have a negative impact on human health as well as on air pollution (Kan et al., 2012). Traffic-related air pollutants can be relatively high at high temperature levels (Wu et al., 2013). Levels of some secondary air pollutants (e.g., O_3) are affected by temperature and tend to be higher in hot weather, while ozone causes a significant mortality risk (Kan et al., 2012). The probability of traffic congestion and disruption increases in the presence of low temperatures and rainfall, which also increases the amount of noise and air pollution generated on the road (Van Stralen, Calvert & Molin, 2015). Therefore, this study summarised these special combinations of conditions and the potential hazards to walkability and the road environment under the interaction effect in Table 9.

Table 9: Possible combinations of conditions that might cause extreme circumstances (*interaction effects).*

Condition 1	***Condition 2***	***Condition 3***	***Interaction effect***	***Source***
Min temp <0 degree	Heavy rain or Violent rain	Morning peak hour	This situation more likely to have fallen snow and icy roads. This may therefore lead to lower body temperatures as well as slippery road surfaces. In addition, the interaction effect might cause traffic congestion and increase traffic pollution.	Vasileiadou et al. (2013); Koetse and Rietveld (2009); Van Stralen, Calvert & Molin (2015); Sabir et al. (2011);
Max temp >=25 degree	Heavy rain or Violent rain	Peak hour	This situation can lead to more jaywalking and risky driving behaviour. In addition, in hot weather conditions, drivers are more likely to suffer from inattentive and reckless crossing behaviour.	Vasileiadou et al. (2013); Sabir et al. (2011); Zhai et al. (2019)
Max temp >=25 degree	Sunny	Peak hour	This situation might increase the pollution from the traffic and cause smog during the peak hours.	Kan et al. (2012); Wu et al. (2013); RIVM (2022).
Max temp >=25 degree	Sunny	Off-peak hour	During this time, the sunlight is more intense and can cause body temperature to be at its highest during the day, reducing personal comfort and risking heat stroke.	Vasileiadou et al. (2013); Wu et al. (2013); RIVM (2022); De Nijs et al. (2019).

Listing the interaction effect of conditions that can cause extreme weather characteristics can help in the WI assessment phase by filtering extreme weather scenarios and scenarios with potential footpath environmental hazards. In the filtering process, the scenario with the most common types of weather characteristics in the Netherlands is included to show how Eindhoven's footpaths behave in terms of WI during most of the year. According to Atkinson (2021), The climate type of the Netherlands is moderate maritime climate, with its proximity to the sea and flat topography making it tend to have cloudy and precipitation conditions. This scenario was created to allow urban planners or designers to better compare the difference in WI variation between the scenarios and to efficiently identify problems and propose solutions. Thus, the final selection of scenarios for the WI assessment is shown in Table 10.

Table 10: The final selection of scenarios for WI assessment.

Scenario	***Condition 1: Max/Min temperatures during the day***	***Condition 2: Weather***	***Condition 3: Time of the day***
1	Min temp <0 degree	Snow	Morning peak hour
2	Max temp >=25 degree	Sunny	Evening peak hour
3	Max temp >=25 degree	Violent rain	Evening peak hour
4	Max temp >=25 degree	Sunny	Off-peak hour
5	Max temp < 25 degree and min temp >=0 degree	Cloudy	Off-peak hour

The identification of scenarios can help define the indicators involved in assessing WI in each scenario. Since some WI indicators are variable, WI indicators may differ in different scenarios. For example, if the weather for the scenario is “sunny”, then the water depth on the footpath indicator is 0, the solar radiation values to be used for the thermal comfort indicator depends on the condition “Max/Min temperatures during the day” and “Time of the day”. It can be seen that the identified extreme weather scenarios with "sunny" conditions also contain high temperature condition. Therefore, the areas with higher solar radiation have lower thermal comfort score between 0 and 1. If the weather in the scenario is not 'sunny', the solar radiation value defaults to 0 and therefore the thermal comfort indicator defaults to 0 regardless of cold, medium or hot temperature conditions. For this setting, this study took a simplified approach applicable to these five extreme weather scenarios, which may not entirely represent real situation. As for the other weather conditions, if the weather in the scenario is “Heavy rain” or “Violent rain”, the water depth on the footpath indicator is equal to the water depth data at 70mm/2hr and 140mm/2hr precipitation respectively. In addition, in the scenario 1, the low temperature could lead to snowfall. Therefore, as explained in Chapter 4.1.3, the water depth indicator with a score of constant -1 would be involved in the WI assessment process.

Moreover, there are additional negative impacts on the WI due to the interaction effect of some weather conditions which should be taken into account. For example, when near-zero temperatures occur in conjunction with rain or snowfall, there is a risk of icy and slippery ground and might cause slip injuries (Hippi and Kangas, 2022). The negative impact of smog on pedestrians also should not be overlooked. According to West (2021), the main smog events are usually associated with heavy motor vehicle traffic, high temperatures, sunlight and calm winds. Studies have shown that the negative health effects of breathing smoggy air may outweigh any benefits from daily walking, with particularly severe health harms for the elderly (Dallas, 2017). Therefore, several constants representing interaction effects from specific scenarios could be included in the WI assessment phase. In this study, “Icy and slippery” and “smog” were set as two additional variables that had an interaction effect in scenarios 1 and 2 and affected WI negatively. Because of the difficulty in comparing the differences in degree between these interaction effects based on the literature, in this study, it was decided to use the same constant -0.1 on the raster map to reflect their negative impact when assessing the WI of scenarios 1 and 2. It is important to note that the “smog” additional variable only has effect in the air pollution buffer range. Table 11 illustrates the definition of the involved WI indicators (WII) and additional variables (AV) regarding each scenario. The specific calculation for each WI indicator can be found in Appendix A.

Table 11: Definition of the involved WI indicators (WII) and additional variable (AV) regarding each scenario.

Scenario	**WII 1: Thermal comfort**	**WII 2: Water depth on the footpath**	**WII 3: Ambient pollution**	**WII 4: Nearby land use**	**WII 5: Street connec tivity**	**WII 6: Footpath width**	**AV 1: Icy and Slippery (Within the whole city area)**	**AV 2: Smog (Within the air pollution buffer range)**
1: Min temp <0 degree, snow, during the morning peak hours.	0	-1	Betwee n -1 to 0	-1, 0 or 1	Betwe en 0 to 1	0 or 1	-0.1	0
2: Max temp >=25 degree, sunny, during the evening peak hours.	*Betwe en 0.64 to 1	0	Betwee n -1 to 0	-1, 0 or 1	Betwe en 0 to 1	0 or 1	0	-0.1
3: Max temp >=25 degree, volent rain, during the evening peak hours.	0	Betwee n -1 to 0	Betwee n -1 to 0	-1, 0 or 1	Betwe en 0 to 1	0 or 1	0	0
4: Max temp >=25 degree, sunny, during the off-peak hours.	Betwee n 0 to 1	0	Betwee n -0.5 to 0	-1, 0 or 1	Betwe en 0 to 1	0 or 1	0	0
5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.	0	0	Betwee n -0.5 to 0	-1, 0 or 1	Betwe en 0 to 1	0 or 1	0	0

** As the level of solar radiation varies from time to time, the value range of thermal comfort indicator for each time period is different, see Appendix A for details of the generation process.*

4.2.2 WI Map Generation at Footpath Level

After identifying the five scenarios to be discussed separately in the WI assessment and the WI indicators to be involved in the WI assessment process for each scenario, the required raster maps needed to be combined in ArcGIS Pro to obtain the WI values. All indicators were normalised between 0 and 1 or between -1 and 0 (when the indicator has a negative effect on the WI, such as water depth on the footpath and ambient pollution indicators), and higher values represent better performance.

The grid resolution of 2m was selected. If the WI indicator has no effect on the assessment of WI in the scenario, the indicator is equal to 0. Therefore, when assessing the WI for each scenario, the WI indicators and additional variables can be summed to obtain the WI value. In the output raster map, the WI would behave in a way that the higher the value, the better the walkability potential on the footpaths.

When combining the raster data from each WI indicator and additional variable to assess WI, each indicator additional variable will be given a default weight first, which is equal weight. When used by urban planners or designers, they can assign specific weights to each indicator based on their personal and academic experience, so that they can be used in the process of evaluating WI in the future when further developing web viewers and expanding the end-user type. The raster function "weighted sum properties" from ArcGIS Pro can help to combine the raster layers of involved WI indicators. After combing the indicators, a raster map with WI scores can be obtained for each scenario. An example can be found in Figure 23.

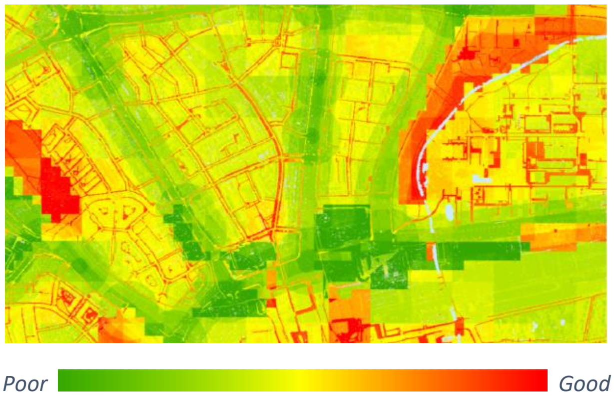


Figure 23. A raster map with WI score.

When the corresponding raster maps for all the required indicators and additional variables are finally combined, the combined raster map with WI values needed to be clipped with the Eindhoven footpath polygons to obtain a WI map at footpath scale, which is the final result of this study. The tool "extract by mask" in ArcGIS Pro could help to clip the raster map with Eindhoven footpath polygons. Figure 24 shows an example of a WI map for one scenario after clipping with the footpath polygon. Since the value range of the involved indicators varies between -1 and 1 when assessing WI, there would also be negative scores for the final assessed WI in the five extreme weather scenarios. Appendix E shows the WI maps at footpath scale for the city of Eindhoven in five scenarios (Figures E1 to E5). The final WI results for the five scenarios will be discussed in detail in Chapter 5.

Figure 24. Output WI map at footpath scale after clipping the raster map with footpath polygons in ArcGIS Pro.

4.3 WI Visualisation

In this section, the WI visualisation phase will be specifically introduced. The purpose of this phase is to help urban planners and designers to identify problems in the area from WI at different scales. The process of generating WI maps at different scales will be discussed, as well as the integration of footpath-scale WI maps with 3D city models. The details will be presented in Chapter 4.3.1. The creation of a web viewer to visualise all the information and the generated maps will be described in Chapter 4.3.2. The output of this phase can thus answer the research question: How can WI be visualised to the urban planners or designers? The content and steps of this research phase are outlined in Figure 25. In Chapter 4.3.1 and 4.3.2, the process of achieving each step will be elaborated specifically.

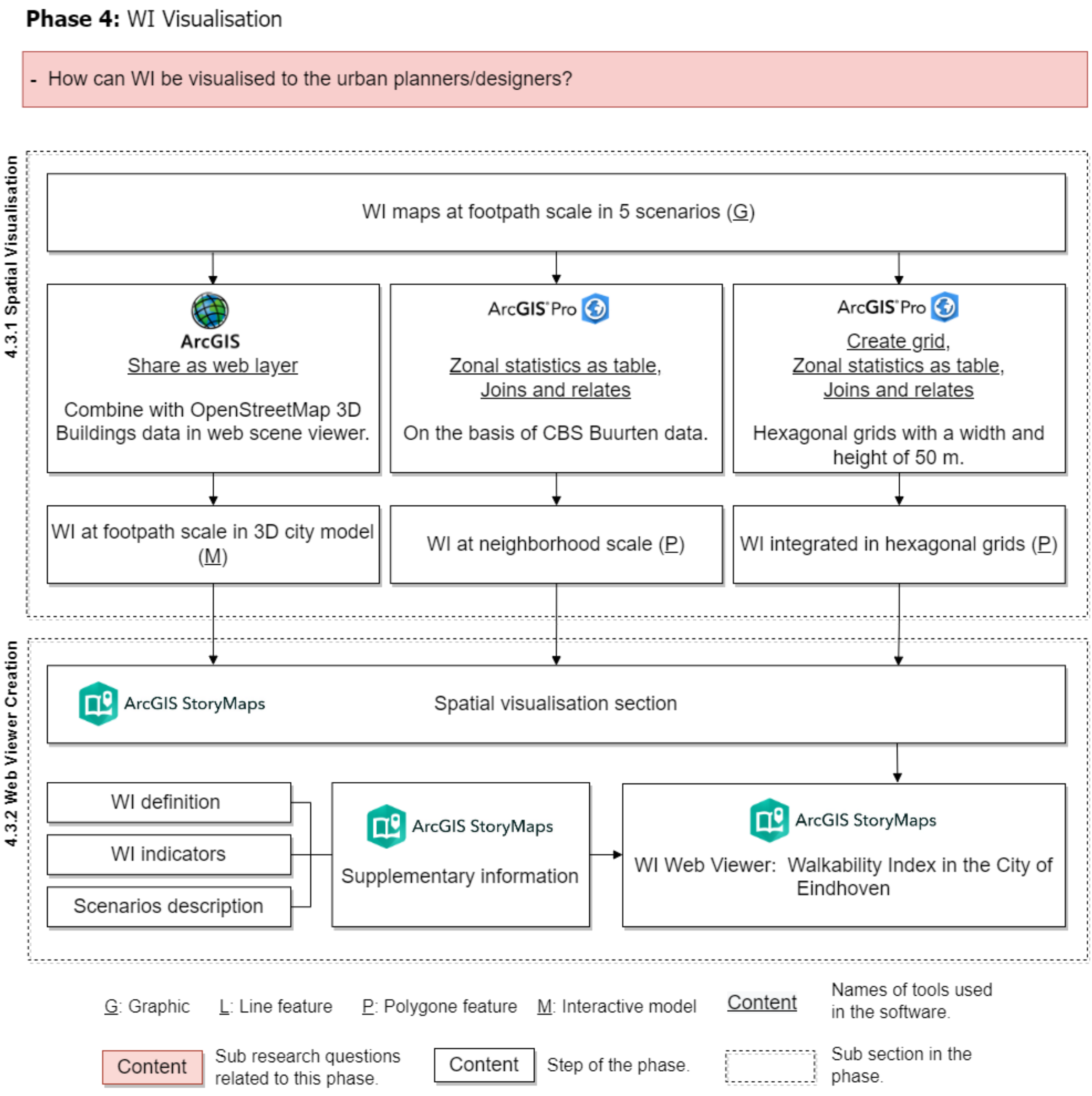


Figure 25. Overview of the contents and steps in the WI visualisation phase.

4.3.1 Spatial Visualisation

In the WI visualisation phase, WI maps at footpath scale were used as the basis for the development of different forms and scales of visualisation. Different ways of visualising the WI in the city can help urban planners, designers or Public Works of the city to understand the walkability from multiple perspectives, so that problems can be identified and measures proposed more quickly and effectively. Ways to visualise WI in this study include: showing WI map at footpath scale in 3D city model to allow interaction, WI at neighbourhood scale and WI integrated in hexagonal grids to visualise WI at an intermediate scale.

WI at Footpath Level in 3D City Model

The WI map at footpath scale provides a representation of the WI at specific locations on the footpath and a comparison of WI between locations within the scenario. Urban planners and designers can therefore know the walkability of a place, identify the problems of the area and propose solutions. When considering solutions to enhance the walkability of a footpath, they may expect additional information from the built environment, such as the height of surrounding buildings, to propose more appropriate solutions in conjunction with the footpath surroundings.

The building height information for Eindhoven can be obtained from the OpenStreetMap 3D Buildings data (ArcGIS, 2022) and added to the ArcGIS web scene viewer. The WI maps at the footpath scale for different scenarios can then be generated in ArcGIS Pro using the function “share as web layer” to the online ArcGIS map library, which can then be imported into ArcGIS web scene viewer to be combined with the base model (see Figure 26). As ArcGIS web scene viewer also has the function to set the angle of sunlight and weather, these can be set up according to each of the five scenarios to give a more realistic visualisation. The combined model allowed the end user to rotate, zoom in and zoom out.

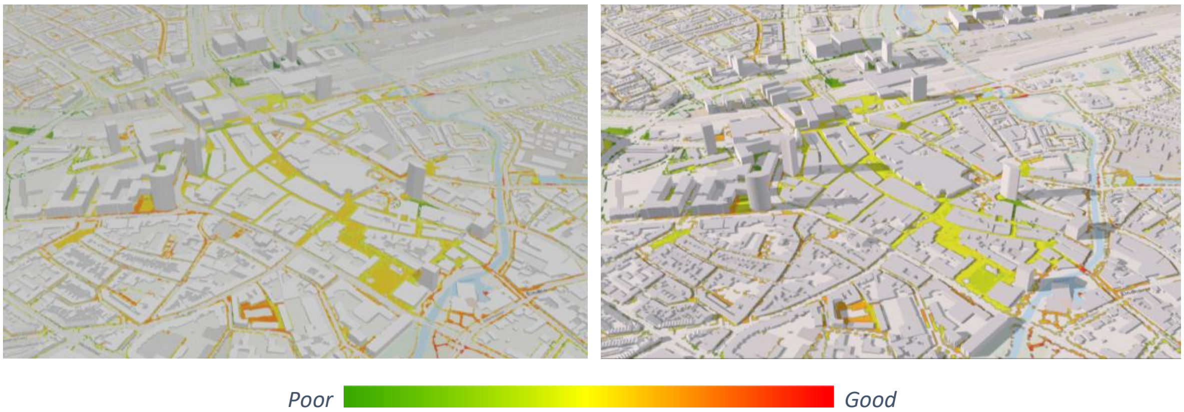


Figure 26. Examples of adding WI map at footpath scale to a 3D city model for 2 scenarios in ArcGIS web scene viewer.

WI at Neighbourhood Level

WI maps at the footpath scale can help urban planners or designers understand the WI of specific locations on the footpaths, allowing them to identify problems at the footpath scale and propose solutions. It is also important to understand the general walkability performance at the neighbourhood scale. This enables urban planners, designers or Public Works of the city to take an overview of WI in all neighbourhoods in the city and identify neighbourhoods and areas where walkability is weaker in different scenarios, so that they can target and narrow down to focus on the low WI of specific footpaths in the particular neighbourhoods.

The WI map at neighbourhood scale can be analysed on the basis of the footpath scale WI map with the support of ArcGIS Pro. First of all, the PDOK (2022) open data platform can provide access to the

"CBS Wijken en Buurten" data 2020 according to the municipality. Based on the geometry information of the Eindhoven neighbourhoods and the WI information of the footpaths, the tool "zonal statistics as table" can be used to assess the average level of WI within each neighbourhood. The WI values can then be joined to the attribute table of the neighbourhood's feature layer to achieve the visualisation of the WI at neighbourhood scale. The WI for each neighbourhood is therefore the average of the WI of all segments on the footpaths within that neighbourhood, that is, the average of all WI indicators over all segments on the footpaths in the neighbourhood.

The average WI in each neighbourhood needed to be calculated for each scenario, thus helping the target group to see the variation in walkability between neighbourhoods in each scenario. Figure 27 shows an example of the WI at neighbourhood scale in one scenario. The WI maps at neighbourhood scale for all scenarios will be presented in Chapter 5.2.

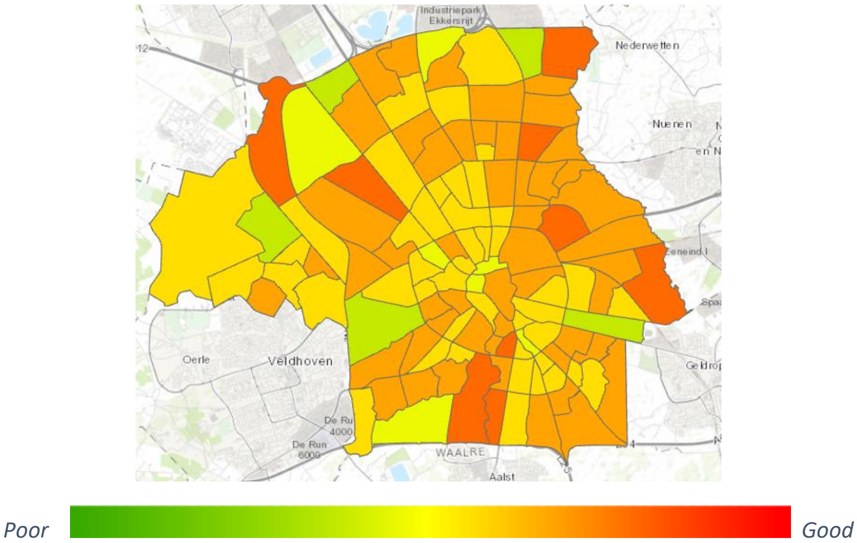


Figure 27. Example of generating WI at neighbourhood scale for 1 scenario

WI at Hexagonal Grid Level

As can be seen, the WI at neighbourhood scale shows the average performance of walkability in each neighbourhood, while the WI at footpath scale shows the WI of every segment of each footpath in the city. However, when urban planners, designers or the Public Works of the city understands the average WI of a neighbourhood and would like to dive deeper into a neighbourhood to see which areas have higher or lower WI, they may expect a scale between the neighbourhood and footpath to visualise WI. Therefore, it was decided to generate an intermediate scale WI map by integrating WI into hexagonal grids with a width and height of 50 meters. It would help the target group to more intuitively understand the WI variation between footpaths when exploring the WI within a neighbourhood, and then allow for targeted exploration of WI variation between segments on the footpaths. The approach for generating the WI maps at this scale is similar to the one used to generate WI maps at the neighbourhood scale. The tool "create grid" in QGIS was used first to create a base map with hexagonal grids covering the whole city. Then, by using the tool "zonal statistics as table" in ArcGIS Pro, the average level of WI within each hexagonal grid could be assessed. Similar to the WI maps at neighbourhood scale, the average WI values for each hexagonal grid were joined into the attribute table of the base map to visualise the WI in the hexagonal grid map (see Figure 28). The value in each hexagon is the average of the WI of all footpath segments within that hexagonal area. If there is no data for WI segments in the hexagon, then the hexagon becomes transparent. Similar to the neighbourhood-scale WI maps, the WI in each scenario is different and thus needs to be generated separately based on the corresponding footpath-scale WI maps. The WI maps integrated in hexagonal grids in all scenarios can be seen in Appendix D.

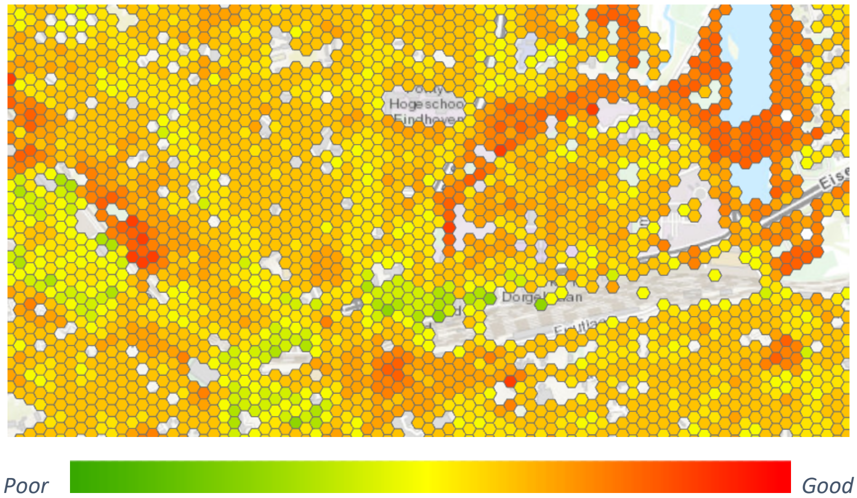


Figure 28. Example of generating WI integrated in hexagonal grids for 1 scenario

4.3.2 Web Viewer Creation

In order to better visualise this research and the different scales of WI maps to the target group and to enhance user interaction with the research output, it was decided to create a web viewer to integrate the indicators, the assessment and the visualisation of WI into a single platform. In the web viewer, not only the WI maps at footpath scale could be displayed in the 3D city model for the user to play with, but also the WI maps at neighbourhood scale and integrated in hexagonal grids could be clicked on by the user and show the WI of a specific neighbourhood or a grid within the neighbourhood. The platform was published and will be accessible via https://arcg.is/1LteaP to the target group. It can also be used as a potential tool for future development that allows information to be added and data to be updated. The process of creating the web viewer mainly involved the use of ArcGIS StoryMap. ArcGIS StoryMaps is a web-based storytelling application that allows to share the maps in the context of narrative text and other multimedia content (ESRI, 2022).

First of all, a "story" needed to be added to the ArcGIS StoryMap account, which is a blank page to add content to. The topic of the page was then defined as "Walkability Index in the City of Eindhoven" (see Figure 29). After setting the cover style and web layout, the content could then be filled in. For this study the visualisation in the web viewer consisted of two main parts: supplementary information and spatial visualisation. The process of creating specific content can be found in Appendix F.

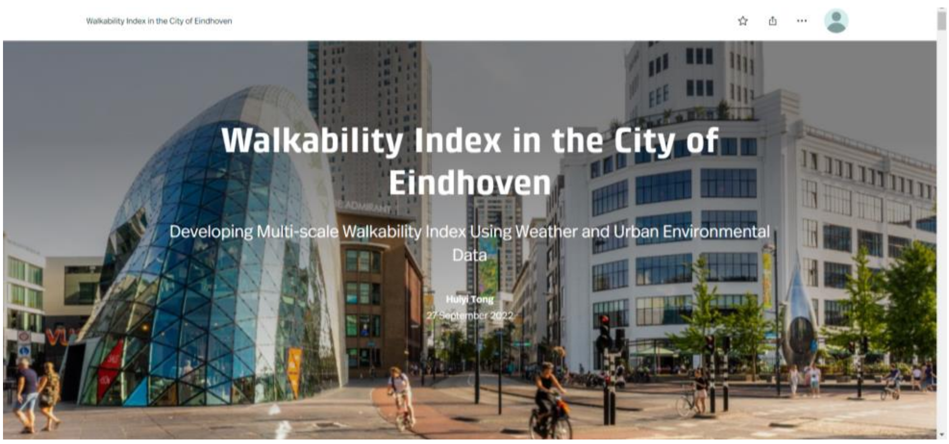


Figure 29. The cover page of the created web viewer

4.4 Conclusion

Overall, the implementation of the WI indicator preparation, WI assessment and WI visualisation research phases were described in Chapter 4. One or two sub-research questions were explored in depth in each phase, leading to the final result of WI maps at the footpath scale for five extreme weather scenarios.

During the WI indicator preparation phase, six WI indicators were selected for the WI assessment, including thermal comfort, water depth on the footpath, ambient pollution, nearby land use, street connectivity and footpath width indicator. The raw data for each indicator is available on several open data platforms and then needs to be processed or analysed separately in ArcGIS Pro or QGIS software. For the development of the variable indicators, it was decided to generate maps of the indicators in multiple conditions, thus retaining their variable properties and assisting in the scenario identification process during the WI assessment phase. Ultimately, each indicator was normalised to values between 0 and 1 or -1 and 0 prior to integrating them into one single WI.

The WI assessment phase consists of scenario identification and WI map generation at footpath scale. In order to identify valid and applicable extreme weather scenarios, three conditions were defined according to the research objectives and the WI indicators: Max/Min temperatures during the day, weather and time of the day. Corresponding to each condition there were three temperature levels (Min temp <0 degree, Max temp >= 25 degree and the situation in between), four weather levels (sunny, cloudy, heavy rain and violent rain) and three time periods (morning peak, evening peak and off-peak hours). Then all possible scenarios were listed based on condition and level. In the selection process, possible combinations of conditions that might be developed into extreme weather types by the interaction effect were found based on the literature, which helped to finally identify four relatively extreme weather scenarios and one the most common weather scenario in the Netherlands. Since some interaction effects have an additional impact on the WI, two additional variables “smog” and “icy and slippery” were set and given a constant -0.1 to include in the WI assessment phase. After identifying the scenarios, the WI indicators and additional variables contributing to the WI assessment for each scenario could be determined. The indicators and additional variables were combined with equal weights by default and clipped to footpath polygons to obtain WI maps at the footpath scale.

The WI visualisation phase is based on the extension of the WI maps on the footpath scale to the neighbourhood scale and WI integrated in hexagonal grids. This allowed urban planners, designers or the Public Works to see the performance of walkability as a whole and thus target the exploration of WI on areas and footpath segments. In addition, a web viewer was created to visualise the WI information in a user-friendly way on one platform, supporting the validation phase and providing possibilities for the future development of the tool. The final result of this study will be presented and described in Chapter 5.

Chapter 5. Scenario Analysis

In Chapter 4, the specific methods to implement the research phases were described, resulting in the generation of footpath-scale WI maps in five different extreme weather scenarios. Extensions were also made to visualise the neighbourhood-scale maps and WI integrated in the hexagonal grids. A web viewer was created to integrate all maps and enable interaction with the user. In this chapter, the final results of this research at footpath level will be first presented and 2 neighbourhoods will be selected and analysed in-depth (Chapter 5.1). In addition, the result at neighbourhood level will also be discussed in Chapter 5.2.

5.1 Result at Footpath Level

In the footpath scale map, WI scores were assigned to each footpath polygon in the city of Eindhoven under different extreme weather scenarios. The WI on footpaths can be compared between different extreme weather scenarios. As scenario five represents the most common weather scenario in the Netherlands, it was decided to start with the discussion of scenario five and find areas with low WI on the footpath. This will help urban planners or designers to give high priority to the enhancement of the urban environment in this area and to make targeted improvements. It is also important to focus on footpath areas that have high WI in Scenario 5 but low in the other four scenarios. Such areas indicate that although walkability levels are high in common weather scenarios, when extreme weather conditions occur, problems with walkability arise and therefore still need to be addressed by municipality or urban planners and designers. Scenario 1 has an overall low WI compared to the other scenarios. This is due to the fact that Scenario 1 consists of snowfall with low temperatures, this type of weather has an impact on all footpath areas in terms of walking comfort and also creates the risk of slippery roads. According to AlleCijfers (2022), the Aanschot district has the largest number of inhabitants, De Tempel is a neighbourhood located in the Aanschot district. Strijp-S is a neighbourhood and former industrial area, the area belonged to the electronics company Philips but the creative companies and residences have been established in the former industrial buildings since 2000 (Wikipedia, 2022). De Tempel and Strijp-S neighbourhoods were chosen to further define the target areas for analysis.

Residential neighbourhood: De Tempel

De Tempel neighbourhood is located in the northern part of Eindhoven and is surrounded by similar residential neighbourhoods, such as Woenselse Heide and Vlokhoven. Figure 30 shows the location of the De Temple neighbourhood, the 3D view and the results of the WI at footpath level in scenario 5. It can be seen that the southeast area of the neighbourhood has a lower WI, while the west area has a higher WI. This result was found to be similar in the other four scenarios. This is because the land use in the south-east area is an industrial area, there are some car repair shops, tyre and accessory shops, etc. The west side of the area is a green area and therefore scores higher on the land use indicator. Figure 31 shows the street views of the two areas.

For the comparison of the WI of other areas in different scenarios, it is necessary to zoom in to the footpath scale for a specific discussion. In order to show more clearly the WI in different scenarios and the scores of the WI indicators involved in the calculation, it was decided to select a 1m sized square segment A in the footpath area as an example. Segment A is located in the northern part of the De Temple neighbourhood, close to the main roads Tempellaan and Rode Kruislaan. Figure 32 shows a 3D map of the neighbourhood and a street view of where segment A is located. Table 12 presents the WI scores and value of each WI indicator at segment A under each scenario. The calculation of the thermal comfort and ambient pollution indicators values at segment A can be found in Appendix C.

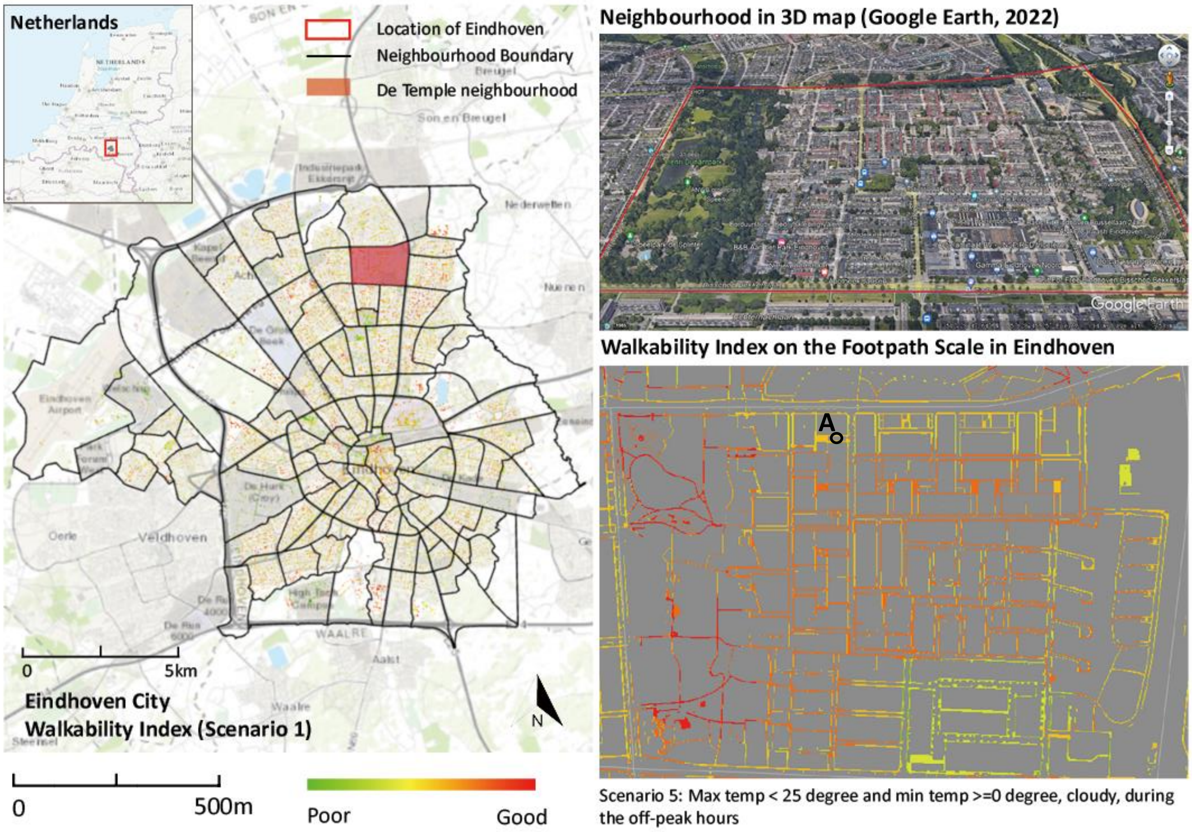


Figure 30. Location of De Tempel neighbourhood and WI at footpath scale in scenario 5 with the location of segment A

Figure 31. Street view of the south-eastern part of the neighbourhood with low WI scores (left) and the western part with high WI scores (right) (Google Earth, 2022).

Figure 32. 3D map of the area around segment A (left) and the street view with segment A's location (right) (Google Earth, 2022).

Table 12: Value of each WI indicator at segment A under each scenario.

Indicator value	Sc 1: Min temp <0 degree, snow, during the morning peak hours.	Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.	Sc 3: Max temp >=25 degree, violent rain, during the evening peak hours.	Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.	Sc 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.
WII 1: Thermal comfort (0 to 1)	0	0.76	0	0.16	0
WII 2: Water depth on the footpath (-1 to 0)	-1	0	-1	0	0
WII 3: Ambient pollution (-1 to 0)	-0.5	-0.5	-0.5	-0.25	-0.25
WII 4: Nearby land use (-1, 0 or 1)	0	0	0	0	0
WII 5: Street connectivity (0 to 1)	0.3	0.3	0.3	0.3	0.3
WII 6: Footpath width (0 to 1)	1	1	1	1	1
Additional variable (Icy or smog)	-0.1	-0.1	0	0	0
Walkability index (-3.1 to 4)	-0.3	1.46	-0.2	1.21	1.05

**WII: Walkability index indicator.*

According to Table 12, it can be seen that the WI is relatively low in the scenarios 1 and 3 with extreme weather conditions. This is mainly due to the reduced comfort level of pedestrians caused by snowfall or severe waterlogging conditions under high rainfall. Therefore, road drainage or potholes issues at this location need to be paid attention to. In addition, a main road is located a short distance to the north of Segment A, which could result in noise or air pollution. Although Segment A is not directly adjacent to the main road, it is still within the slight influence of pollution, and thus affects the WI. In addition, because segment A is in the air pollution buffer range, the smog has an additional negative impact on the WI in scenario 2. It can also be seen from Table 12 that the values of the thermal comfort indicators are different for scenarios 2 and 4. This is due to the lower position of the sun during the evening peak hours, resulting in a larger shadow area due to the housing surrounding segment A and the fact that the sunlight itself is less intense at this location than during off-peak hours. According to the street connectivity indicator score, the intersection density is relatively low in this area. For the future development of new residential projects, attention to improving street connectivity can effectively enhance the walkability of the area.

In order to compare the WI and each WI indicator between segment A and the surrounding area so that the overall level of walkability of the area around segment A can be seen, the WI and indicators in the area around segment A are shown in Table 13. Due to the fact that the northern side is a main road, this results in a generally lower WI in the northern part of the area than in the south, particularly in Scenarios 1 and 5. The WI results for scenarios 2, 3 and 4 are more complex due to the effect of water depth on footpaths and shading. In scenario 3, the footpath where segment A is located and the footpath to the west of the open space has a lower WI. This is mainly because these two footpaths are more heavily waterlogged during high rainfall events, resulting in poorer personal comfort. In scenario 2, a change in WI scores was observed on the north to south footpath to the south of the open space. This is due to the shade that is created on the east side of the housing during the evening peak hour in hot sunny weather, therefore increasing pedestrian comfort in this area and improving WI. These results suggest that although the level of walkability on these footpaths does not appear to be a problem in common weather conditions, when extreme weather conditions occur, the walkability potential of the areas needs to be focused on and improved. In addition, the north to south footpath to the north of the open space has lower WI scores in all five scenarios compared to the surrounding area. According to Table 13 it can be found that this is mainly because the width of the footpath in this area does not reach 1.5m, which affects the level of walkability.

Table 13: Value of WI and each WI indicator around segment A under each scenario.

	Sc 1: Min temp <0 degree, snow, during the morning peak hours.	**Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.**	**Sc 3: Max temp >=25 degree, violent rain, during the evening peak hours.**	**Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.**	**Sc 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.**
WI (-3.1 to 4)					
WII 1: Thermal comfort (0 to 1)	0		0		0
WII 2: Water depth on the footpath (-1 to 0)	-1	0		0	0

WII 3: Ambient pollution (-1 to 0)		
WII 4: Nearby land use (-1, 0 or 1)	0	
WII 5: Street connectivity (0 to 1)		
WII 6: Footpath width (0 or 1)		
Legend	*Poor (Value=-3.1)*  *Good (Value=4)*	

Former industrial neighbourhood: Strijp-S

Strijp-S neighbourhood is located close to Eindhoven city centre. Because it used to be an industrial area and now some creative companies and residences have been established, the buildings are relatively high comparing with other neighbourhood. Figure 33 shows the location, a 3D map and the results of the WI at footpath level in scenario 5 of the Strijp-S neighbourhood. As can be seen, there are some large open spaces in the middle of the high building areas. The southern part of the neighbourhood has a lower WI, which is mainly due to the relatively low intersection density, resulting in a lower street connectivity indicator score.

The results for other areas of the WI vary between scenarios and therefore need to be scaled up for specific discussion. In a similar way to the analysis of the residential neighbourhood, a segment B was selected as an example in the footpath area for comparison and discussion in different scenarios. Segment B is located in the central part of the Strijp-S neighbourhood, it is surrounded by some tall buildings to the west and an open space to the east. Figure 34 shows a 3D map of the area around segment B and a street view of where segment B is located. The WI values and indicator score in each scenario can be seen in Table 14. The calculation of the thermal comfort indicator values at segment B can be found in Appendix C. As explained in Chapter 4.1.3, because the nearby land use indicator was developed based on the 2015 CBS Existing Land use dataset, part of this neighbourhood was still recorded as industrial area. But in fact, this area has now been redeveloped into residential and office areas (Wikipedia, 2022).

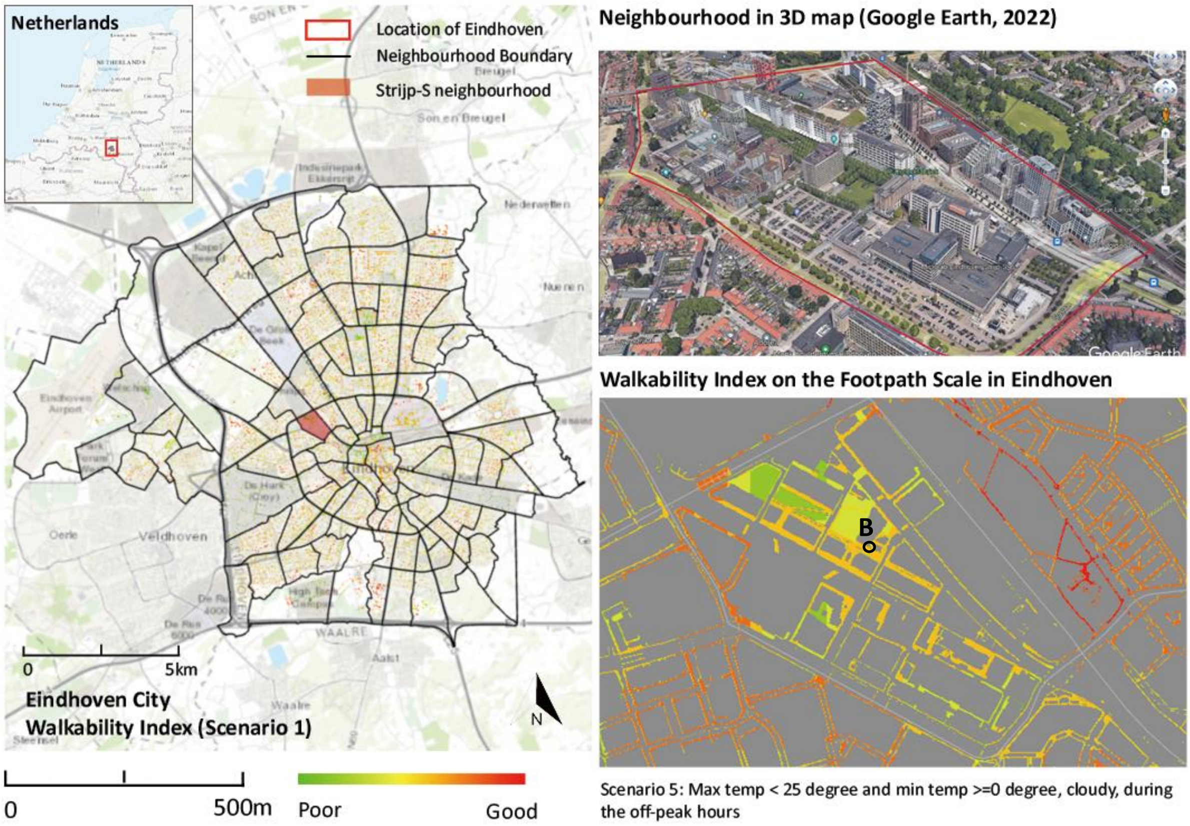


Figure 33. Location of Strijp-S neighbourhood and WI at footpath scale in scenario 5 with the location of segment B

Figure 34. 3D map of the area around segment B and the street view with segment B's location (Google Earth, 2022).

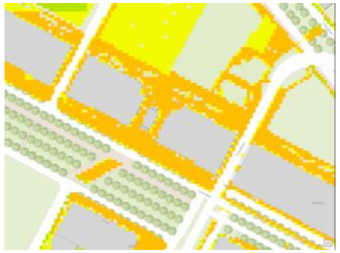
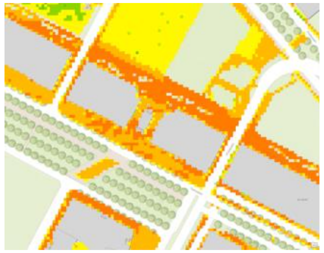
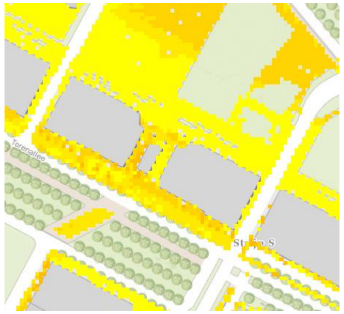
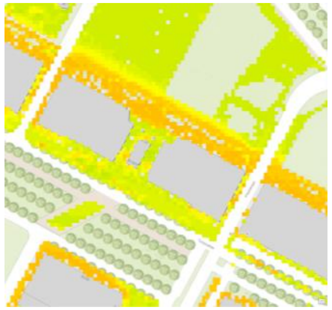
Table 14: Value of each WI indicator at segment B under each scenario.

Indicator value	Sc 1: Min temp <0 degree, snow, during the morning peak hours.	Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.	Sc 3: Max temp >=25 degree, violent rain, during the evening peak hours.	Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.	Sc 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.
WII 1: Thermal comfort (0 to 1)	0	0.78	0	0.7	0
WII 2: Water depth on the footpath (-1 to 0)	-1	0	-0.5	0	0
WII 3: Ambient pollution (-1 to 0)	0	0	0	0	0
WII 4: Nearby land use (-1, 0 or 1)	-1	-1	-1	-1	-1
WII 5: Street connectivity (0 to 1)	1	1	1	1	1
WII 6: Footpath width (0 to 1)	1	1	1	1	1
Additional variable (Icy or smog)	-0.1	-0.1	0	0	0
Walkability index (-3.1 to 4)	-0.1	1.68	0.5	1.7	1

**WII: Walkability index indicator.*

As can be seen from Table 14, scenarios 2 and 4 have relatively high WI. The tall buildings to the west of Segment B can create shadows for the footpath in hot and sunny weather, thus increasing the comfort level of pedestrians in this location. This location remains in shadow even at midday when the angle of sunlight is minimal. In addition, the water depth indicator scores for Scenario 3 show that this location is still moderately waterlogged during heavy rainfall, which can create inconvenience for walking. Therefore, target measures need to be taken by municipality, urban planners or designers in this case. The WI and indicators of the surrounding footpaths which cover segment B are shown in Table 15. As the buildings in the central area are generally taller, on sunny days when the temperature is higher, the footpaths on the north side of the buildings all produce a shading effect, resulting in a higher level of comfort. In addition, the problem of waterlogging in open space areas needs to be given attention in the high rainfall situations. The issue of road drainage or road potholes needs to be monitored.

Table 15: Value of WI and each WI indicator around segment B under each scenario.

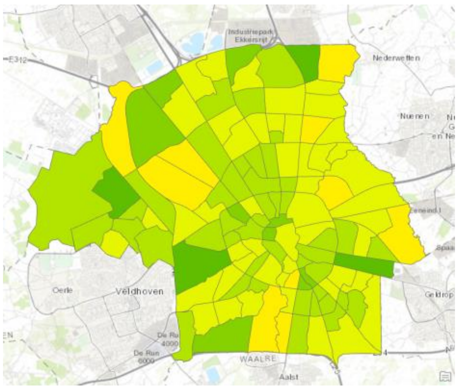
	Sc 1: Min temp <0 degree, snow, during the morning peak hours.	Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.	Sc 3: Max temp >=25 degree, violent rain, during the evening peak hours.	Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.	Sc 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.
WI (-3.1 to 4)					
WII 1: Thermal comfort (0 to 1)	0		0		0
WII 2: Water depth on the footpath (-1 to 0)	-1	0		0	0

WII 3: Ambient pollution (-1 to 0)	0	0
WII 4: Nearby land use (-1, 0 or 1)	-1	
WII 5: Street connectivity (0 to 1)		
WII 6: Footpath width (0 or 1)		
Legend	*Poor (Value=-3.1)*  *Good (Value=4)*	

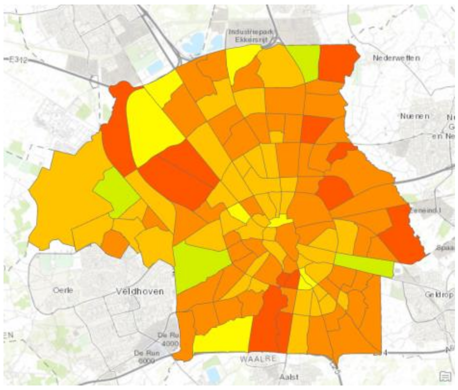
5.2 Result at Neighbourhood Level

The results at footpath level can help urban planners or designers to be aware of the WI at specific locations on the footpath and the scores for each indicator, enabling them to identify problems and suggest targeted solutions. Knowing the WI at a neighbourhood scale can help urban planners, designers or municipalities to get an overview of the WI for all neighbourhoods. From this they can narrow down for individual neighbourhoods and see the spatial layout in combination with the 50m sized hexagonal grid WI map and WI map at footpath level. By comparing the spatial layout under different extreme weather scenarios, it can help municipalities, urban planners or designers to better detect and propose solutions to improve walkability.

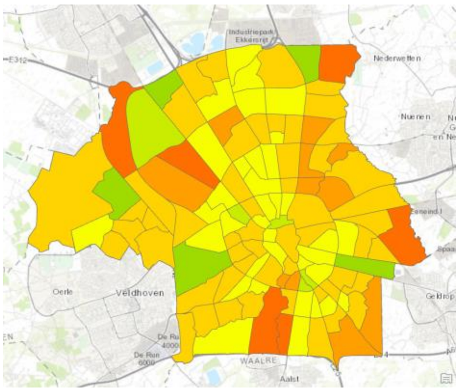
Figure 35 shows the results for WI at neighbourhood level in five scenarios. Similar to the analysis in Chapter 5.1, observations can be made starting with scenario five and compared to the other four extreme climate scenarios on a neighbourhood level. It can be seen that the neighbourhoods with higher WI are concentrated in the outskirts of the city of Eindhoven, particularly the neighbourhoods Bokt, Urkhoven, Gennep and BeA2 (See area C in Figure 35). This is due to the fact that these neighbourhoods are mainly covered by green areas and are the location of urban parks, resulting in high scores for the nearby land use indicator. In addition, due to the high tree cover, the shading effect is stronger and the thermal comfort indicator scores are higher, whilst ambient pollution is lower. In comparison, the Poeijers neighbourhood in the east of the city and the Mispelhoef neighbourhoods in the northwest near the airport have lower average WI scores (See area D in Figure 35). This is primarily driven by the fact that there is a high density of factory or storage buildings and material shops in the neighbourhoods. This results in a lower score for the nearby land use indicator. In addition, the average street connectivity of the area is low due to the large footprint of the factory buildings. When extreme weather occurs, these neighbourhoods can have new problems with walkability. For example, in hot and sunny weather, the thermal comfort scores are lower due to the low building height and low tree cover. It can also be seen from the WI of the two neighbourhoods in area D that the Mispelhoef neighbourhood has a relatively high average WI, which is mainly because it has some green areas in the western part of the neighbourhood. This neighbourhood therefore scores higher on the nearby land use indicator than the Poeijers neighbourhood.



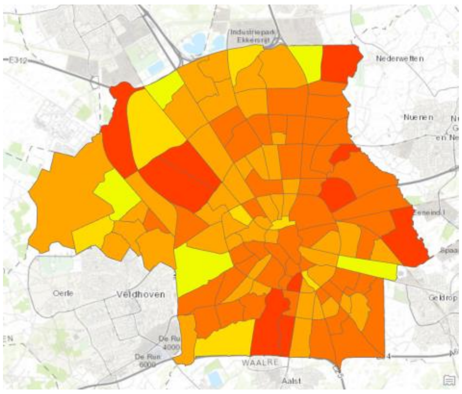
Scenario 1: Min temp <0 degree, snow, during the morning peak hours.



Scenario 2: Max temp >=25 degree, sunny, during the evening peak hours.

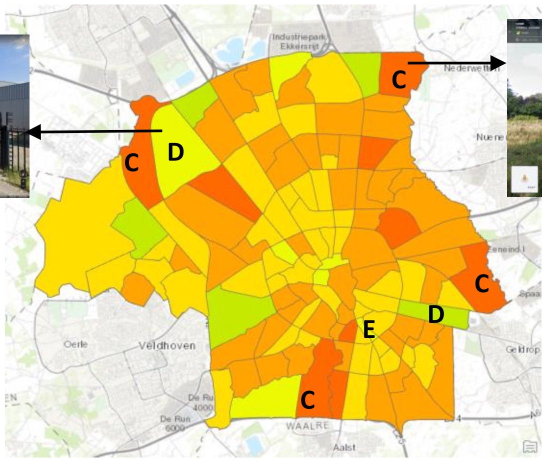


Scenario 3: Max temp >=25 degree, violent rain, during the evening peak hours.



Scenario 4: Scenario 4 (Sc 4): Max temp >=25 degree, sunny, during the off-peak hours.

Mispelhoef neighbourhood



Bokt neighbourhood

Scenario 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.

Poor (Value=-3.1)  *Good (Value=4)*

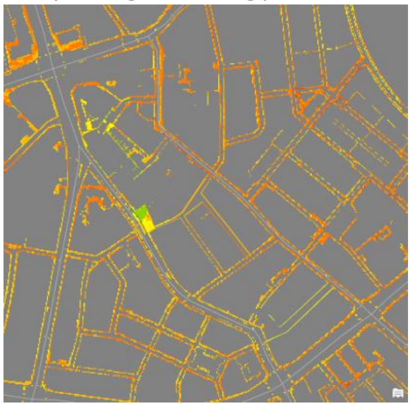
Figure 35. Result of WI at neighbourhood scale in 5 different extreme weather scenarios and Street views in Bokt neighbourhood and Mispelhoef neighbourhood (Google Map, 2022)

As the effect of greenfield and industrial areas on WI are absent, the WI scores of the other neighbourhoods need to be discussed more in terms of their spatial layout. For example, the Joriskwartier neighbourhood in the south-east of the city (See area E in Figure 35) has a very low WI score not only in Scenario 5, but also in Extreme Weather Scenarios 1 to 4. It was decided to carry out further analysis by checking the hexagonal grid WI maps and WI maps at footpath level for this neighbourhood (see Figure 36). Based on the hexagonal grid WI map for scenario 5, it can be seen that the western part of the neighbourhood has a low WI. The main reason for this is that the western side of the neighbourhood is adjacent to the main road Leenderweg. This results in the western part of the neighbourhood being affected by ambiance pollution from the main road, especially during the peak hours. In addition, the spatial layout of the WI maps at footpath level in Figure 36 suggests that the street connectivity of the neighbourhood is relatively low. This finding can be supported by the street connectivity indicator scores in this neighbourhood (see Figure 37). This is due to the fact that the housing type in this neighbourhood is mainly row houses. Continuous row houses would reduce the intersection density of the neighbourhood. Therefore, maybe more footpaths with small green spaces between housing could be considered in some new development projects in the neighbourhood, which could enhance the walkability potential of the neighbourhood.

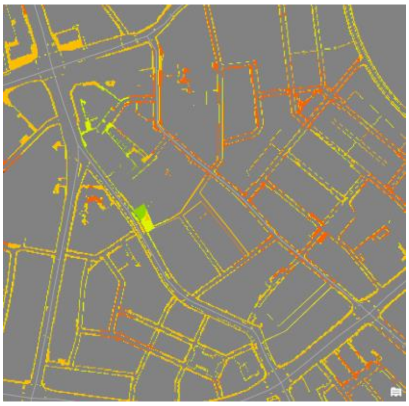
Scenario 1: Min temp <0 degree, snow, during the morning peak hours.

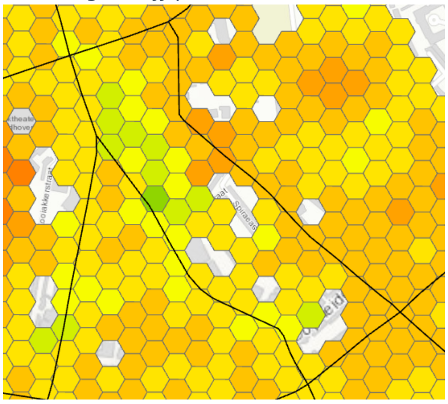
Scenario 2: Max temp >=25 degree, sunny, during the evening peak hours.

Scenario 3: Max temp >=25 degree, violent rain, during the evening peak



Scenario 4: Max temp >=25 degree, sunny, during the off-peak hours.

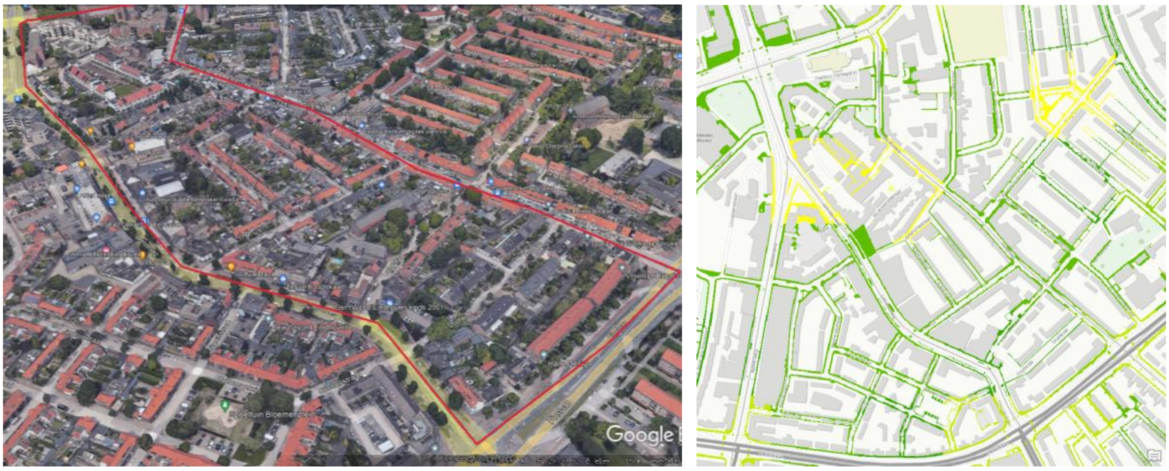




Scenario 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours

Poor (Value=-3.1)  *Good (Value=4)*

Figure 36. Result of WI at footpath level in Joriskwartier neighbourhood in 5 different extreme weather scenarios and the WI at hexagonal grid level in scenario 5



Poor Good

Figure 37. 3D map (left) and the street connectivity indicator score (right) of the Joriskwartier neighbourhood

In addition, when exploring other WI indicator scores, it was found that the width of the footpaths in between the row houses in the neighbourhood should be improved (see Figure 38). Interestingly, this is due to the street area occupied by parked cars and planting. The installation of greenery between the footpath and the motorway is an important way of enhancing the greenery of the neighbourhood and is promoted by the municipality. However, if such greenery would take up areas of the existing footpath, making it less wide than necessary, it would reduce the walkability of the area in terms of convenience. Therefore, when developing new projects, it may be important to be aware of the space taken up by greenery and parking on the road and to ensure the effective width of the footpath.

Poor (value = 0) Good (value = 1)

Figure 38. The street view in the Joriskwartier neighbourhood (left) and the footpath width indicator score of that location (Google Earth, 2022)

5.3 Conclusion

In Chapter 5, the WI results at footpath level and neighbourhood level were analysed and discussed regarding five different weather scenarios. In the analysis, it was found that different types of conclusions can be drawn from different scales of WI results. Therefore, it can help urban planners or designers to understand the walkability potential of the Eindhoven neighbourhoods and footpaths under different weather scenarios in different ways.

In the analysis of WI results at footpath level, firstly two different types of neighbourhoods De Tempel and Strijp-S were selected. A 1m sized square footpath segment was selected in each neighbourhood to show the WI and all indicators' scores. The value of WI and each WI indicator of the surrounding area under each scenario was also presented and discussed, allowing a better comparison of the segments with the surrounding locations and identifying issues of walkability at the footpath level. The analysis revealed that in the De Tempel neighbourhood attention should be paid to road drainage or potholes issues and ambient pollution from the northern main road, the shading, and footpath width. In a selected area of the Strijp-S community, it could be seen that due to the building height and the density of the buildings, the shading effect had a greater impact and there were also problems of moderate flooding during heavy rainfall in specific locations.

In the analysis of the WI result at neighbourhood level, the first step was to look at the overall WI difference between all neighbourhoods in the city of Eindhoven under five different weather scenarios. It was found that neighbourhoods with a higher proportion of green space had a higher overall WI score in all scenarios, while neighbourhoods with a high density of factory buildings had a lower overall WI score. In addition, some other neighbourhoods also have relatively low WI scores, not only in Scenario 5, but also in extreme weather Scenarios 1 to 4. The Joriskwartier neighbourhood was selected for further analysis and discussion. In conjunction with the review and analysis of the WI scores at footpath level and in hexagonal grids, it was found that several aspects should be paid attention to, including the impact of ambient pollution from the main road to the west, the low street connectivity due to the massive row houses, and the insufficient footpath width due to greenery and parking.

In the process of scenario analysis of WI at different scales, it can be concluded that the hexagonal grid WI map did not play an ideal role in the process of scenario analysis. This may be due to the fact that the hexagonal system covers the built-up area, resulting in it being less clear when demonstrating the WI of the footpath, which can have a negative impact on the helpfulness of the analysis results. However, when the hexagonal grids can be clicked on by the user and interacted with in the web viewer, the hexagonal grid WI map and the WI at neighbourhood level can then provide greater benefits. The validation phase will further validate the WI results at different scales in different weather scenarios by sharing the web viewer with the target group, which will be described in Chapter 6.

Chapter 6. Validation

In this chapter, the web viewer will be shared with the validation target group in order to test the assessed WI, informativeness and user-friendliness of the web viewer. By interacting with the web viewer, the target group can play with the 2D and 3D maps and express their opinions via an online interview. The validation test will be explained in detail in Chapter 6.1, including the questions that will be discussed during the online interview with the participants. Some interesting feedback will be discussed in Chapter 6.2. The participants will also be described.

6.1 Validation Test Design

In order to validate the results of WI and the application of WI in this study, a validation test was designed. The objective of this study is to help planners and designers to more comprehensively and effectively identify the problems of walkability in cities under different extreme weather scenarios, and thus to propose effective solutions to encourage walking in cities. Therefore, in the validation phase, the test participants were set to include an urban designer, two Master students and a teacher from Eindhoven University of Technology with a background related to urban planning and design.

The validation test can be divided into three sessions. First of all, the test taker received access to a web viewer (https://arcg.is/1LteaP) containing a general description of this study and WI results at different scales in 5 weather scenarios. The process of creating the web viewer and the specific information it contains can be found in Chapter 4.3.2. Nine questions were shared with the participants in advance, allowing them to prepare. In the second session, the participants could access the web viewer to get background information about the research, approach and introduction to WI maps at different scales. They can play with the 3D city model with WI at footpath scale and interact with the WI maps at neighbourhood level and hexagonal grid level. In the third session, an online interview would be organised with each participant and everyone will be invited to answer the questions (which had been shared with the participants in advance) to collect some of their opinions and suggestions. The questions asked are as follows:

- Do you think WI is important in urban planning and design? How?
- What do you think of the way of assessing WI in this study?
- What extreme weather scenarios do you think are important to assess WI?
- Do you think it is informative to visualise WI at three different scales?
- Do you think it is informative to visualise WI at footpath level in combination with a 3D city model?
- Do you think it is easy to identify potential problem areas or find potential development areas by checking the visualisation of WI at three different scales and five weather scenarios?
- Which scale do you think is more valuable to visualise WI? Is there anything missing?
- How user-friendly and intuitive is this way of visualising the WI?
- What would you suggest to further improve the WI, the visualisation and application of the WI?

The feedbacks collected in the end can be used to evaluate this study and can also provide recommendations and insights for subsequent research and web development.

6.2 Validation Result

After conducting online interviews with participants, a lot of valuable feedback was collected. Four participants were interviewed and their backgrounds were described as follows:

1. A TU/e Master student studying Urban System & Real Estate and Construction Management Engineering (USRE&CME) double degree program.
2. A TU/e Master student studying Urbanism.
3. A junior urban designer from a landscape architecture and urban planning firm.
4. An Assistant Professor at the department of the Built Environment at TU/e with a research focus on the healthy and social living environments.

The collected feedback from all participants will be discussed under the corresponding questions below.

- *Do you think WI is important in urban planning and design? How?*

In the feedback collected, all participants considered it very important to be aware of WI in urban planning or design projects. They thought that there is currently more focus on cars and how people commute rather than walkability, but it is important to understand how people walk in the area and whether the area is walkable. They also support the benefits of walking not only for the individual physically, but also for socialising and for mental health. In addition, finding footpaths that could be potentially dangerous (e.g., slippery) during the extreme weather conditions and showing some problems with the walkability of the area in extreme weather conditions could direct the attention of planners and designers so that they can figure out what they can do.

- *What do you think of the way of assessing WI in this study?*

Regarding the assessment of WI, a participant mentioned that it was interesting to take weather conditions into account, as indicators related to weather conditions were rarely used in the study, but rather facilities, lighting, etc. For the indicators to assess WI, the participants gave some suggestions. Apart from the current indicators, the wind effect was considered very important in the Netherlands and would like to be informed about. Depending on the wind direction and speed, walking in some areas can be very dangerous, such as around the corners of tall buildings. Street lighting were also mentioned to be important indicators affecting walkability. A participant was also interested in the extent to which the indicator influenced the WI. For example, the extent to which ambient pollution affects personal comfort in the real situation. This could be explored in more depth in the future studies.

- *What extreme weather scenarios do you think are important to assess WI?*

The participants agreed that thermal comfort and flooding are very important in the Dutch context, as urban heat islands can influence some areas to become very warm and a lot of rainy days can lead to flooding in some areas. It is also useful for urban design projects to understand the differences between peak and off-peak scenarios, as they can see changes in walkability during the day and then make improvements in spatial layout. A participant also felt that thunderstorms could also be dangerous in certain areas. For example, pedestrians may be more at risk if they are walking in the wild than in high-density areas.

- *Do you think it is informative to visualise WI at three different scales?*

The participants found all scales of WI to be informative. For different types of design projects, the preference for WI map might vary. The WI at footpath scale can help more to identify the problem in the certain area because it can show the difference of WI in a smaller scale. The WI map at neighbourhood scale might be more useful in terms of strategy development and overall policy. Hexagonal scale maps are perhaps more valuable to urban planners. However, navigation on a hexagonal level map can be difficult for people who do not know the city, as the streets and buildings are covered by hexagons. Therefore, it may be better to add a map with the current location, route and neighbourhood boundaries in one corner of the hexagonal map to help the user orientate themselves. A participant from the field of urban design also suggested adding some dots representing trees to the hexagonal map, which would show more information about the landscape.

- *Do you think it is informative to visualise WI at footpath level in combination with a 3D city model?*

Participants were excited to see the combination of WI maps and 3D city models. This combination can help end users to locate themselves more easily compared to 2D maps. It is also valuable for urban designers to see the integration with the buildings and the shadow projections of buildings. However, one participant suggested it would be more helpful to add the Street View feature, which allows the end user to feel like they are walking in the environment and physically experience what it is like to walk in the area. Adding more information, such as urban greenery, windows and openings in the building facades, would also be helpful for urban design projects.

- *Do you think it is easy to identify potential problem areas or find potential development areas by checking the visualisation of WI at three different scales and five weather scenarios?*

Participants believed that having three scales of maps in visualising the WI could assist urban planners, urban designers and architects working on projects at different scales in parallel. The different colours were represented by different WI levels and the three scales maps have the same legend, so people can compare easily. As for the 5 weather scenarios, the participants validated the comprehensiveness and commented that having a common weather scenario as a comparison is essential and valuable for preliminary research of the urban design projects.

- *Which scale do you think is more valuable to visualise WI? Is there anything missing?*

The participants answered their preferences for the different scales of the WI maps. It is interesting to note that more than one of them preferred the WI at hexagonal level. A participant who is a junior urban designer commented that the hexagonal level map shows a larger scale picture compared to the footpath scale and that it shows more detail compared to the neighbourhood scale. For urban designers, in some design projects, there is no need to provide as much detail as in the footpath scale, so the hexagonal level map is more universal from a dimensional point of view. In addition, in the web viewer it is possible to know the WI value of the area by clicking on each hexagon, whereas the WI map at footpath scale does not show the specific WI value but only the WI variation between areas. However, the hexagonal map still needs to be upgraded, for example by adding the location of trees. WI at footpath scale in 3D city model was also very popular among the participants. Not only do they think the 3D models look very attractive and professional, but the relations between footpaths, buildings and other roads are shown in a more intuitive way.

- *How user-friendly and intuitive is this way of visualising the WI?*

The use of a web viewer to visualise the WI was seen by the participants as a very attractive and useful way of doing this. By interacting with the web viewer, urban designers don't actually need to go directly to the site, but rather use virtual tools to do some prior investigation during the pre-design phase of a design project. The overall informativeness and interactivity of the web viewer was evaluated positively by the participants who found it to be a user-friendly way of presenting the indicators and WI related information at different scales. The participants also offered some specific advice to web viewers from the end-user's point of view. Firstly, a participant felt that it was not very clear on the web viewer how the location specific WI was assessed. It would be useful to explain more about the characteristics of the data collected and the process of assessing the WI indicators. In addition, most participants mentioned that it would be more beneficial if the WI indicator scores were displayed in addition to the WI results when users clicked on locations on the map. This would allow them to know the impact of each indicator on the location and thus be more effective in proposing specific solutions.

- *What would you suggest to further improve the WI, the visualisation and application of the WI?*

The participants provided some opinions and recommendations regarding the future development of the research and implementation of WI. In terms of applications in the working field, a participant who is a junior urban designer suggested converting the indicators and evaluated WI into data types that can be inserted directly into GIS software such as QGIS so that urban designers can work with them directly. Regarding the functional expansion of the WI, a participant proposed that in the future development of WI, the real-time data can be used and a GPS system can be created. For example, when people want to walk home and would like to choose a route with better WI instead of the quickest route, the GPS system can calculate and recommend the route which is safer in the current weather condition. An extreme weather alarm can also be developed and connected to the metrology institute of the Netherlands. When there is very poor WI throughout the area, a message can be sent to residents advising them to stay indoors. A link to a web viewer can also be included in the message so that residents can check the WI of their surroundings. In terms of future research directions, a participant suggested a possibility of incorporating interviews with pedestrians or questionnaires to obtain perceived walkability, which could then be combined with WI assessed in an objective way to compare the differences. It is also possible to obtain tracking data on pedestrians to analyse their walking behaviour, which may lead to some interesting conclusions.

The detailed validation results can be found in Appendix G, including summaries of the answers to each question corresponding to each participant. Feedback from participants from different backgrounds could not only validate the web viewer of this study, but also provide some new insights into the future development of WI.

6.3 Conclusion

In this chapter, the assessed WI, the informativeness and user-friendliness of the web viewer were assessed by the target group. Four participants with different backgrounds in the field of urban planning and design were invited and interviewed online.

During the validation process, the access to the web viewer and nine questions were shared with participants via email prior to the interviews. The online interviews allowed for the collection of extensive feedback related to the assessed WI, visualisations of the WI at three scales across five scenarios and comments on further development and functional expansion of the WI.

Based on the feedback collected, the participants agreed that WI is very important as it can inform urban planners and designers about the walkability of streets, neighbourhood and cities. The indicators related to weather conditions in this study are valuable to study, and some other indicators such as wind effects and street lighting are also important indicators in the Dutch context. They also suggested that in addition to showing the WI results on the map, the WI indicator scores could also be displayed, which would allow them to understand the impact of each indicator on the location and identify problems. The five scenarios identified in this study are very essential and the scenarios with common weather conditions contribute to the understanding of WI and to the comparison with other scenarios. The three different levels of WI and the combination with the 3D city model are very useful for urban planners, designers and architects in the pre-investigation phase of different types of projects. The hexagonal scale map was considered more versatile from a dimensional point of view for urban design projects. Although the hexagonal scale map is generated from the footpath scale map, and the footpath scale map is more useful in terms of informativeness, which is also important in urban design projects. However, in the web viewer, the hexagonal scale map can show the WI values for a specific area, whereas the WI map at footpath scale cannot. However, more information should be provided to help people navigate themselves more easily in the hexagonal level map. The combination of footpath level WI with a 3D model is also favoured as it not only visualises the relation between the footpath, the building and its surroundings, but also shows the shadow projections of the building. It would be more interesting if a Street View function could be added to this type of map so that the end user could walk through an area from a human perspective. For the future development of WI, it would be more useful if this data could be plugged into GIS software so that urban planners and designers could use it directly. The application could also be more beneficial to municipalities and residents by using real-time data to assess WI and create a GPS system. It can recommend routes with good WI and advise people to stay indoors when extreme conditions occur.

Chapter 7. Conclusion and Discussion

In this chapter, the research will be summarised and discussed based on the research process and results. The research will be summarised by answering the research questions and sub research questions. In Chapter 7.2, the limitations, potential for the improvement and recommendations for the future studies will be discussed.

7.1 Conclusion

By assessing the walkability index (WI) on footpaths in Eindhoven under several relatively extreme weather scenarios, the objective of this study was to help planners and designers to more comprehensively and effectively identify the walkability potential and problems on footpaths so that they can propose effective solutions to encourage walking in the city. In this context, the main question of this study was introduced: "How to develop Walkability Index (WI) considering the influences of extreme weather scenarios for urban planners/designers' decision making?" In order to answer this main research question, four additional sub-questions were formulated and answered individually through the implementation of corresponding research phases.

The questions "What are the indicators selected for assessing the WI?" and "What type of data is needed and how to develop the indicators?" were answered in the exploratory research and WI indicators preparation phase of the study. During the exploratory research phase, a literature review of walking, walkability index, walkability indicator and the current research gap was conducted to gain an understanding of the common WI indicators used in research (e.g., street connectivity) and methods of developing indicators. A lack of attention and quantitative methods for assessing WI at footpath scale in multiple scenarios and personal comfort indicators in current research were observed. Combining the information from the literature review and considering the availability of data, six indicators in the categories of personal comfort, street condition and function of environment were selected and defined. They are thermal comfort, water depth on the footpath, ambient pollution, street connectivity, footpath width and nearby land-use. In order to enable the assessment of WI in multiple extreme weather scenarios, it was decided to develop the personal comfort indicators (including thermal comfort, water depth on the footpath and ambient pollution) into variable indicators for multiple scenarios. During the data collection phase, the water depth on the footpath indicator was developed by direct data acquisition. The thermal comfort and ambient pollution indicators were developed using tools from ArcGIS Pro and QGIS and literature references to develop the acquired single scenario data into multiple scenario indicators. The static indicators street connectivity, footpath width and nearby land-use were developed using the tools in ArcGIS Pro and QGIS in conjunction with literature references. The final indicators were presented as raster maps with location specific data to facilitate the subsequent assessment of the WI in multiple extreme weather scenarios.

In the research phase WI assessment, the sub-research question "How to assess WI through the developed indicators?" was answered and the WI assessment process consisted of two main parts: scenario identification and indicator combination. First enumerate all scenario combinations by setting the conditions "Max/Min temperatures during the day", "weather" and "time of the day" and the corresponding levels (e.g., morning peak, evening peak and off-peak hours). The combinations of conditions that might develop into extreme weather situations were then filtered out according to the literature to help identify four relatively extreme weather scenarios (e.g., Max temp >=25 degree, sunny in the evening peak hour) and one common weather scenario for the Netherlands. Based on the five weather scenarios, the indicators involved in the WI assessment can be determined. In order to accommodate the interaction effects of some conditions on the WI, the additional variables "icy and slippery" and "smog" were set and given a penalty to be included in the WI assessment phase. By default, the indicators and additional variables were combined with equal weights and clipped to the footpath polygon to obtain a WI map at the footpath scale.

The generated WI maps at footpath scale were used in the WI visualisation research phase to help visualise information for the target group by converting the WI maps to other scales and creating a web viewer. This phase could answer the sub-research question "How can WI be visualised to the urban planners/designers?". The tools from ArcGIS Pro were used to convert WI maps at footpath scale into WI maps at 50m size hexagonal and neighbourhood levels, thus providing urban designers or planners with a multi-scale view of WI information. To enhance the interaction of the target group with the WI maps, a web viewer was created and visualised the three scales of WI maps for five weather scenarios. The web viewer was designed to integrate the WI map at footpath scale with the 3D city model and to provide pop-up information on the WI map at hexagonal and neighbourhood level. Four participants from different backgrounds in urban planning or design were invited and interviewed online, giving positive feedback on the system as well as suggestions for expansion. The feedback from the participants on the future development of the WI in terms of GIS software plug-ins and GPS systems also contribute to the future possibilities of the study.

Altogether, the following answer to the research question can be formulated: a walkability index (WI) can be developed by operationalizing indicators in the categories of street condition, function of environment and personal comfort, and then combining the indicators under extreme weather scenarios. Interaction between certain circumstances (e.g., traffic congestion) and extreme weather conditions on WI also need to be considered. The assessed WI scores can then be visualised at the footpath scale for comparison and analysis by urban planners and designers. To assist urban planners and designers in decision making, the WI on the footpath level can be extended to WI scores at the neighbourhood and hexagonal level and visualised in the web viewer.

As a result, this study demonstrates the inclusion of personal comfort indicators in the field of assessing walkability indexes and a method to assess WI in multiple weather scenarios. On the basis of this study, urban planners and designers can better capture the walkability potential of urban footpaths and thus efficiently identify problems in the areas. In the future development of this study, Public Works and pedestrians can also gain increasing benefits from the implementation of real-time data and GPS functionality.

7.2 Discussion and Recommendation

Throughout the process of this study, there were a number of findings that differed from expectations. For example, when WI maps at three scales were generated and scenario analysis was carried out, it was found that the WI map at hexagonal level did not play a desirable role in the analysis of the results. This is probably due to the fact that the neighbourhoods to be focused on are built-up areas, with only a few areas without footpaths. This would result in the hexagonal system covering the whole built-up area and therefore it is less clear when demonstrating the WI of the footpaths, which interferes with the process of analysing the results. However, in a web viewer, the hexagonal grid map can be zoomed in and out by the user and can be clicked on to bring up location specific information. This can increase the interactivity and provide additional benefits. This is also reflected in the validation phase. Participants mentioned that the WI at footpath scale could be more effective in helping to identify problems in the area as it could provide more information at a smaller scale. However, they found it very interactive and helpful to click through the hexagons and display the WI scores. It would be more beneficial to identify problems in the area if the WI indicator score could also be displayed.

A number of limitations can be identified in this study. Firstly, as there is no definitive list of indicators that affect walkability and the extent to which each indicator affects WI is inconsistent across studies, the full range of indicators could not be taken into account in the assessment of WI in this study. In addition, groups of pedestrians with different characteristics were not discussed in a categorised manner in this study. For example, elderly people may be more sensitive to weather indicators than younger people. Besides, the process of assessing WI in this study is not fully applicable to all types of cities due to differences in urban planning and the characteristics of the geographical environment. In terms of data collection, PET map for the winter scenario was not collected due to limitations in the existing data availability, and acquired land use data also had problems with being out of date. Moreover, as the footpath data collected had no attributes that defined the type of footpath (e.g., footpaths on both sides of residential roads and in shopping areas) when developing the footpath width indicator, the capacity demand was not considered in terms of separate scoring criteria for the different types of footpaths. Regarding the implementation of the thermal comfort indicator involved in the assessment of WI, only the effect on personal comfort due to solar radiation in very hot sunny weather was considered, but not the variation in thermal comfort during temperature changes. For example, in real situations, the thermal comfort indicator might increase as the temperature rises until a certain high temperature, and then it will decrease. Thus, this simplified setting leaves potential for improvement in terms of consistency with the actual situation. In the case of hexagonal-scale WI extended from footpath-scale WI, some hexagonal values may be based on only one or a few WI segments of data, which may make the map less trustworthy. Therefore, when using hexagonal maps, it is recommended that they be used as auxiliary maps in conjunction with other scales. On this point there is potential for improvement in future research.

For the development of the WI indicators and the assessment of the WI in this study, some methods can be improved and hopefully optimised in future related studies. For example, in the development of the ambient pollution indicator, assumptions were made regarding the values of the ambient pollution indicators based on the literature. The width of the pollution buffer of different types of streets should be investigated. In the development of the scoring rules, the scores could also be made more continuous. For example, a linear increase of the score from -1 to 0 could be considered for a distance of 0 m to 25 m from the road median. Similarly, when developing the footpath width indicator, a breakdown into more continuous scores could make the indicator more realistic. The wind effect, street lighting and street aesthetics influenced by the height and shape of buildings could be potential indicators in future studies evaluating the WI, resulting in additional social benefits. In assessing the WI, this study only considered the impact on the WI of the interaction effects icy and smog from extreme weather conditions. However, other interaction effects such as thunderstorms and hail still need to be considered. More discussion and reference to the literature is needed to quantify this effect.

The creation of the web viewer in this study could increase the practical relevance of the assessed WI and also provide ideas for future development of tools and platforms in related fields. In future extensions of the web viewer, the level of interaction with the end-user can be further improved. For example, urban designers or planners can customise the weighting of WI indicators based on their academic and practical experience, thus helping them to more precisely see the WI changes in different scenarios. In terms of information visualisation, a small map box could be added to the hexagonal level map to help users locate themselves more easily in the city. Adding a Street View function to the 3D map enables end-users to walk through an area and experience walkability from a human perspective.

For the potential development of WI-related research and applications, an assessment of perceived walkability can be added and compared to the results of an objective assessment of WI to help establish a more comprehensive methodology for assessing WI. Besides, the implementation of WI as a plug-in into GIS software could be considered, allowing urban planners or designers to work directly with the data. This would help the target group in a more professional way. In addition, the use of real time data could be introduced to explore a real time updating and forecasting system for WI. It could even be further explored to automatically generate the best WI routes that match the current weather conditions when pedestrians provide the start and end points of their journeys. Such a system could be investigated for future insertion into GPS systems. When extreme weather occurs, Public Works can also monitor the GPS system in real-time and advise people in critical areas to minimize their trips.

References

Abley, S., Turner, S., & Singh, R. (2011). Predicting Walkability. In *IPENZ Transportation Group Conference*. https://www.researchgate.net/profile/Shane-Turner-5/publication/335339674_Predicting_Walkability/links/5d5fb5a6299bf1f70b05e08d/Predicting-Walkability.pdf

AlleCijfers. (2022). *Héél véél informatie over Eindhoven.* https://allecijfers.nl/gemeente/eindhoven/

Arcgis. (2022). *OpenStreetMap 3D Buildings.* https://www.arcgis.com/home/item.html?id=ca0470dbbddb4db28bad74ed39949e25

Atkinson, K. (2021). Why does it rain so much in the Netherlands? *Dutchreview.* https://dutchreview.com/news/weather/why-does-it-rain-so-much-in-the-netherlands/

Baobeid, A., Koç, M. & Al-Ghamdi, S. (2013). Walkability and Its Relationships With Health, Sustainability, and Livability: Elements of Physical Environment and Evaluation Frameworks. *Smart and Sustainable Built Environment. 2*(3): 288-310. https://doi.org/10.3389/fbuil.2021.721218

Boers, J. (2022). *Zo ermijd je files en druk verkeer tijdens de spits*. Autoweek.nl. https://www.autoweek.nl/verkeer/zo-vermijd-je-files-en-druk-verkeer-tijdens-de-spits/

Braubach, M. & Fairburn, J. (2010). Social inequities in environmental risks associated with housing and residential location - A review of evidence. *European Journal of Public Health, 20*(1):36-42. DOI: 10.1093/eurpub/ckp221

Chan, S. Y., & Chau, C. K. (2019). Development of artificial neural network models for predicting thermal comfort evaluation in urban parks in summer and winter. *Building and Environment, 164*, 106364. https://doi.org/10.1016/j.buildenv.2019.106364

Clark, A., Scott, D. & Yiannakoulias, N. (2014). Examining the relationship between active travel, weather, and the built environment: a multilevel approach using a GPS-enhanced dataset. *Transportation, 41*(2):325-338. DOI:10.1007/s11116-013-9476-3

Clark, C. & Stansfeld, S. (2007). The Effect of Transportation Noise on Health and Cognitive Development: A Review of Recent Evidence. *International Journal of Comparative Psychology, 20:* 145-158.

Dallas, M. (2017). *Smoggy air may make daily walk a health hazard*. Cbsnews. https://www.cbsnews.com/news/smoggy-air-may-make-daily-walk-a-health-hazard/

De Arruda Campos, M., Chiaraida, A., Smith, A., Stonor, T. & Takamatsu, S. (2003). Towards a 'walkability index'. *Publisher: Association for European Transport (AET).* https://worldcat.org/isbn/0860503429

De Courrèges, A., Occelli, F., Muntaner, M., Amouyel, P., Meirhaeghe, A., & Dauchet, L. (2021). The relationship between neighbourhood walkability and cardiovascular risk factors in northern France. *Science of the Total Environment, 772,* 144877. https://doi.org/10.1016/j.scitotenv.2020.144877

De Meij, S. (2021). Providing location based health information using dynamic, aggregated and static urban data Science. *Eindhoven University of Technology Master Thesis.* https://ddwtue.nl/projects/2021-providing-location-based-health-information-using-dynamic-aggregated-and-static-urban-data/

De Nijs, T., Bosch, P., Brand, E., Heusinkveld, B., van der Hoeven, F., Jacobs, C., Klok, L., Kluck, J., Koekoek, A., Koopmans, S., van Nieuwaal, K., Ronda, R., & Steeneveld, G. (2019). *Ontwikkeling Standaard Stresstest Hitte.* Rivm.openrepository.com. http://hdl.handle.net/10029/623094

Deb, C., & Alur, R. (2010). The Significance of Physiological Equivalent Temperature (PET) in Outdoor Thermal Comfort Studies. *International Journal of Engineering Sciences and Technology, 2,* 2825-2828.

Delclòs-Alió, X., Marquet, O., Vich, G., Schipperijn, J., Zhang, K., Maciejewska, M., & Miralles-Guasch, C. (2020). Temperature and Rain Moderate the Effect of Neighborhood Walkability on Walking Time for Seniors in Barcelona. *International Journal of Environmental Research and Public Health, 17*(1), 14. https://doi.org/10.3390/ijerph17010014

Diehr, P., & Hirsch, C. (2010). Health Benefits of Increased Walking for Sedentary, Generally Healthy Older Adults: Using Longitudinal Data to Approximate an Intervention Trial. *The Journals of Gerontology, 65A* (9), 982–989. https://doi.org/10.1093/gerona/glq070

Dill, J. (2004). Measuring Network Connectivity for Bicycling and Walking. *Annual Meeting CD-ROM.* http://reconnectingamerica.org/assets/Uploads/TRB2004-001550.pdf

Duurzame mobiliteit - CROW. (2022). *Pedestrian.* https://www.crow.nl/duurzame-mobiliteit/home/systeemintegratie/voetganger/tips-voor-voetgangersvriendelijk-beleid

Egan, D. & Hyland, J. (2008). Toronto Walking Strategy: Putting Pedestrians First. In *the Urban Transportation Management Session of the 2008 Annual Conference of the Transportation Association of Canada.* http://www.bv.transports.gouv.qc.ca/mono/1023088/09_Techniques_gestion_circulation_routiere/05_Toronto_walking_strategy.pdf

ESRI (2022). *What is ArcGIS Urban*. https://doc.arcgis.com/en/urban/get-started/get-started-what-is-urban.htm

ESRI. (2022). *What is ArcGIS StoryMaps? — ArcGIS StoryMaps | Documentation.* https://doc.arcgis.com/en/arcgis-storymaps/get-started/what-is-arcgis-storymaps.htm

ESRI. (2022). *What is GIS? | Geographic Information System Mapping Technology.* https://www.esri.com/en-us/what-is-gis/overview

Fan, C., Jiang, Y. & Mostafavi, A. (2020). Social Sensing in Disaster City Digital Twin: Integrated Textual–Visual–Geo Framework for Situational Awareness during Built Environment Disruptions. *Journal of Management in Engineering, 36* (3). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000745

Frank, L. D., Sallis, J. F., Saelens, B. E., Leary, L., Cain, K., Conway, T. L., & Hess, P. M. (2009). The development of a walkability index: application to the Neighborhood Quality of Life Study. *British Journal of Sports Medicine, 44*(13), 924–933. https://doi.org/10.1136/bjsm.2009.058701

Frank, L. D., Schmid, T. L., Sallis, J. F., Chapman, J., & Saelens, B. E. (2005). Linking objectively measured physical activity with objectively measured urban form. *American Journal of Preventive Medicine, 28*(2), 117–125. https://doi.org/10.1016/j.amepre.2004.11.001

Freeman, L., Neckerman, K., Schwartz-Soicher, O., Quinn, J., Richards, C., Bader, M., Lovasi, G., Jack, D., Weiss, C., Konty, K., Arno, P., Viola, D., Kerker, B. & Rundle, A. (2013). Neighborhood walkability and active travel (walking and cycling) in New York City. *Journal of Urban Health, 90*(4):575-85. DOI: 10.1007/s11524-012-9758-7.

Giles-Corti, B., Mavoa, S., Eagleson, S., Davern, M., Roberts, R., & Badland, H. (2014). *How Walkable is Melbourne? The Development of a Transport Walkability Index for Metropolitan Melbourne. Place, Health and Liveability Research Program.* http://staging.auo.org.au/wp-content/uploads/2020/02/How-walkable-is-Melbourne-FINAL.pdf

Golan, Y., Henderson, J., Wilkinson, N. L., & Weverka, A. (2019). Gendered walkability: Building a daytime walkability index for women. *Journal of Transport and Land Use, 12*(1), 501–526. https://www.jstor.org/stable/26911279

Google Earth. (2022). *Google Earth.* https://earth.google.com

Google Map. (2022). *Google Maps.* https://www.google.com/maps

Habibian, M., & Hosseinzadeh, A. (2018). Walkability index across trip purposes. *Sustainable Cities and Society, 42*, 216–225. https://doi.org/10.1016/j.scs.2018.07.005

Hall, C. & Ram, Y. (2018). Walk score® and its potential contribution to the study of active transport and walkability: A critical and systematic review. *Transportation Research Part D: Transport and Environment, 61*(B): 310-324. https://doi.org/10.1016/j.trd.2017.12.018

Hippi, M., & Kangas, M. (2022). Impact of Weather on Pedestrians' Slip Risk. *International Journal of Environmental Research and Public Health, 19*(5), 3007. https://doi.org/10.3390/ijerph19053007

Hudda, N., & Fruin, S. A. (2018). Carbon dioxide accumulation inside vehicles: The effect of ventilation and driving conditions. *Science of the Total Environment, 610-611,* 1448–1456. https://doi.org/10.1016/j.scitotenv.2017.08.105

Jongman, B., Wagemaker, J., Romero, B. & De Perez, E. (2015). Early Flood Detection for Rapid Humanitarian Response: Harnessing Near Real-Time Satellite and Twitter Signals. *ISPRS International Journal of Geo-Information, 4*(4):2246-2266. https://doi.org/10.3390/ijgi4042246

Kadali, B. R., & Vedagiri, P. (2015). Evaluation of pedestrian crosswalk level of service (LOS) in perspective of type of land-use. *Transportation Research Part A: Policy and Practice, 73*, 113–124. https://doi.org/10.1016/j.tra.2015.01.009

Kamel, M. (2013). Encouraging walkability in GCC cities: smart urban solutions. *Smart and Sustainable Built Environment, 2*(3): 288-310. https://doi.org/10.1108/SASBE-03-2013-0015

Kan, H., Chen, R., & Tong, S. (2012). Ambient air pollution, climate change, and population health in China. *Environment International, 42*, 10–19. https://doi.org/10.1016/j.envint.2011.03.003

Kelly, C. E., Tight, M. R., Hodgson, F. C., & Page, M. W. (2011). A comparison of three methods for assessing the walkability of the pedestrian environment. *Journal of Transport Geography, 19*(6), 1500–1508. https://doi.org/10.1016/j.jtrangeo.2010.08.001

Kelly, C., Tight, M., Hodgson, F. & Page, M. (2011). A comparison of three methods for assessing the walkability of the pedestrian environment. *Journal of Transport Geography, 19*(6): 1500-1508. DOI: 10.1016/j.jtrangeo.2010.08.001

Kim, S., Choi, J., & Kim, Y. (2011). Determining the sidewalk pavement width by using pedestrian discomfort levels and movement characteristics. *KSCE Journal of Civil Engineering, 15*(5), 883–889. https://doi.org/10.1007/s12205-011-1173-1

Klimaateffectatlas. (2015). *Heat map - perceived temperature – Klimaateffectatlas.* https://www.klimaateffectatlas.nl/en/perceived-temperature-heat-map

Klimaateffectatlas. (2018). *Flood depth associated with short, severe precipitation - Klimaateffectatlas.* https://www.klimaateffectatlas.nl/en/flood-depth-associated-with-short-severe-precipitation

Klok, L., Rood, N., Kluck, J., & Kleerekoper, L. (2018). Assessment of thermally comfortable urban spaces in Amsterdam during hot summer days. *International Journal of Biometeorology, 63*(2), 129–141. https://doi.org/10.1007/s00484-018-1644-x

KNMI. (2014). KNMI'14: Climate Change scenarios for the 21st Century – A Netherlands perspective; by Bart van den Hurk, Peter Siegmund, Albert Klein Tank (Eds), Jisk Attema, Alexander Bakker, Jules Beersma, Janette Bessembinder, Reinout Boers, Theo Brandsma, Henk van den Brink, Sybren Drijfhout, Henk Eskes, Rein Haarsma, Wilco Hazeleger, Rudmer Jilderda, Caroline Katsman, Geert Lenderink, Jessica Loriaux, Erik van Meijgaard, Twan van Noije, Geert Jan van Oldenborgh, Frank Selten, Pier Siebesma, Andreas Sterl, Hylke de Vries, Michiel van Weele, Renske de Winter and Gerd-Jan van Zadelhoff. *Scientific Report WR2014-01, KNMI, De Bilt, The Netherlands.* www.climatescenarios.nl

Knuiman, M., Christian, H., Divitini, M., Foster, S., Bull, F., Badland, H. & Giles-Corti, B. (2014). A longitudinal analysis of the influence of the neighborhood built environment on walking for transportation: the RESIDE study. *American Journal of Epidemiol, 180*(5):453-61. DOI: 10.1093/aje/kwu171.

Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment, 14*(3), 205–221. https://doi.org/10.1016/j.trd.2008.12.004

Koohsari, M., Sugiyama, T., Mavoa, S., Villanueva, K., Badland, H., Giles-Corti, B. & Owen, N. (2016). Street network measures and adults' walking for transport: Application of space syntax. *Health & Place, 38:* 89-95.
https://doi.org/10.1016/j.healthplace.2015.12.009

Kwak, H.-Y., Ko, J., Lee, S., & Joh, C.-H. (2017). Identifying the correlation between rainfall, traffic flow performance and air pollution concentration in Seoul using a path analysis. *Transportation Research Procedia, 25,* 3552–3563.
https://doi.org/10.1016/j.trpro.2017.05.288

Labdaoui,K., Mazouz, S., Moeinaddini, M., Cools, M. & Teller, J. (2021). The Street Walkability and Thermal Comfort Index (SWTCI): A new assessment tool combining street design measurements and thermal comfort. *Science of The Total Environment, 795.*
https://doi.org/10.1016/j.scitotenv.2021.148663

Lam, T. M., Wang, Z., Vaartjes, I., Karssenberg, D., Ettema, D., Helbich, M., Timmermans, E. J., Frank, L. D., den Braver, N. R., Wagtendonk, A. J., Beulens, J. W. J., & Lakerveld, J. (2022). Development of an objectively measured walkability index for the Netherlands. *International Journal of Behavioral Nutrition and Physical Activity, 19*(1).
https://doi.org/10.1186/s12966-022-01270-8

Lamour, Q., Morelli, A. M., & Marins, K. R. de C. (2019). Improving walkability in a TOD context: Spatial strategies that enhance walking in the Belém neighbourhood, in São Paulo, Brazil. *Case Studies on Transport Policy, 7*(2), 280–292.
https://doi.org/10.1016/j.cstp.2019.03.005

Leeson, S. S. (2022). *Climate change is creating hotter days, says Dutch scientist.*
https://www.euractiv.com/section/energy-environment/news/climate-change-is-creating-hotter-days-says-dutch-scientist/

Liao, B. (2021). Walkability, Walking behavior, and Walking experiences: An analysis using virtual reality and revealed preferences approaches. *Research.tue.nl.* https://research.tue.nl/en/publications/walkability-walking-behavior-and-walking-experiences-an-analysis-

Litman, Todd. (2003). Economic Value of Walkability. *Transportation Research Record, 1828*, 3-11. DOI: 10.3141/1828-01.

Liu, W., Zhang, Y., & Deng, Q. (2016). The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate. *Energy and Buildings, 128,* 190–197. https://doi.org/10.1016/j.enbuild.2016.06.086

Livin Spaces. (2017). Walkable Cities: How Barcelona is Using Superblocks To Create Pedestrian-Friendly Cities. https://www.livinspaces.net/ls-tv/walkable-cities-how-barcelona-is-using-superblocks-to-create-pedestrian-friendly-cities/

Lo, R. (2009). Walkability: what is it? *Journal of Urbanism, 2*(2): 145-166. DOI: 10.1080/17549170903092867

Loo, B. P. Y., & Lam, W. W. Y. (2012). Geographic Accessibility around Health Care Facilities for Elderly Residents in Hong Kong: A Microscale Walkability Assessment. *Environment and Planning B: Planning and Design, 39*(4), 629–646. https://doi.org/10.1068/b36146

Met Office (2007). Fact Sheet No. 3: Water in the Atmosphere. *Crown Copyright.* https://web.archive.org/web/20120114162401/http://www.metoffice.gov.uk/media/pdf/4/1/No._03_-_Water_in_the_Atmosphere.pdf

Molenaar, R. (2019). *Hittestress en het heetste uur van de dag.* Alpenweerman. https://www.alpenweerman.nl/hittestress-en-het-heetste-uur-van-de-dag/

Nuzir, F. A., & Dewancker, B. J. (2016). Redefining Place for Walking: a Literature Review and Key-elements Conception. *Theoretical and Empirical Researches in Urban Management*, *11*(1), 59–76. http://www.jstor.org/stable/24873549

Oliver, L. N., Schuurman, N., & Hall, A. W. (2007). Comparing circular and network buffers to examine the influence of land use on walking for leisure and errands. *International Journal of Health Geographics, 6*(1), 41. https://doi.org/10.1186/1476-072x-6-41

PDOK. (2022). *Dataset: Key Register of Addresses and Buildings (BAG).* https://www.pdok.nl/introductie/-/article/cbs-existing-landuse-inspire-geharmoniseerd-

PDOK. (2022). *Dataset: Key Register of Large-Scale Topography (BGT).* https://www.pdok.nl/introductie/-/article/basisregistratie-grootschalige-topografie-bgt-

PDOK. (2022). *Introductie - PDOK.* https://www.pdok.nl/introductie/-/article/cbs-existing-landuse-inspire-geharmoniseerd-

Pikora, T., Giles-Corti, B., Bull, F., Jamrozik, K. & Donovan, R. (2003). Developing a framework for assessment of the environmental determinants of walking and cycling. *Social Science & Medicine, 56*(8): 1693-1703. https://doi.org/10.1016/S0277-9536(02)00163-6

Quach, A., Giovannelli, J., Chérot-Kornobis, N., Ciuchete, A., Clément, G., Matran, R., Amouyel, P., Edmé, J.-L., & Dauchet, L. (2015). Prevalence and underdiagnosis of airway obstruction among middle-aged adults in northern France: The ELISABET study 2011–2013. *Respiratory Medicine, 109*(12), 1553–1561. https://doi.org/10.1016/j.rmed.2015.10.012

Rafiemanzelat, R., Emadi, M. & Kamali, A. (2017). City sustainability: the influence of walkability on built environments. *Transportation Research Procedia, 24:* 97-104. https://doi.org/10.1016/j.trpro.2017.05.074

Rahman, Md. M., & Szabó, G. (2021). A Geospatial Approach to Measure Social Benefits in Urban Land Use Optimization Problem. *Land, 10*(12), 1398. https://doi.org/10.3390/land10121398

Ribeiro, A. & Hoffimann, E. (2018). Development of a Neighbourhood Walkability Index for Porto Metropolitan Area. How Strongly Is Walkability Associated with Walking for Transport? *International Journal of Environmental Research and Public Health, 15*(12): 2767. DOI: 10.3390/ijerph15122767.

RIVM. (2022). *National Heatwave Plan active as of 18 July and smog warning throughout the Netherlands | RIVM*. https://www.rivm.nl/en/news/national-heatwave-plan-active-as-of-18-july-and-smog-warning-throughout-netherlands

Sabir, M., Van Ommeren, J., Koetse, M., & Rietveld, P. (2010). Adverse Weather and Commuting Speed. *Networks and Spatial Economics, 11*(4), 701–712. https://doi.org/10.1007/s11067-010-9130-y

Shammas, T. & Escobar, F. (2019). Comfort and Time-Based Walkability Index Design: A GIS-Based Proposal. *International Journal of Environmental Research and Public Health, 16*(16):2850. https://doi.org/10.3390/ijerph16162850

Shinkle, D. & Teigen, A. (2019). Encouraging Bicycling and Walking the State Legislative Role. https://akpedbikealliance.files.wordpress.com/2009/11/ncsl_encouraging_bicycling_walking.pdf

Stadskantoor Zwolle. (2022). *Loopruimte voetpaden en trottoirs | Gemeente Zwolle.* https://www.zwolle.nl/loopruimte-voetpaden-en-trottoirs#

Stangl, P. (2015). Block size-based measures of street connectivity: A critical assessment and new approach. *2015 URBAN DESIGN International, 20*(1). DOI:10.1057/udi.2013.36

Tango, F. & Botta, M. (2013). Real-Time Detection System of Driver Distraction Using Machine Learning. *IEEE Transactions on Intelligent Transportation Systems, 14* (2): 894-905. DOI: 10.1109/TITS.2013.2247760

TomTom Traffic Index. (2021). *Eindhoven traffic report | TomTom Traffic Index.* Www.tomtom.com., https://www.tomtom.com/traffic-index/eindhoven-traffic/

Tsiompras, A. B., & Photis, Y. N. (2017). What matters when it comes to “Walk and the city”? Defining a weighted GIS-based walkability index. *Transportation Research Procedia, 24*, 523–530. https://doi.org/10.1016/j.trpro.2017.06.001

Van Stralen, W. J., Calvert, S. C., & Molin, E. J. (2015). The influence of adverse weather conditions on probability of congestion on Dutch motorways. *European Journal of Transport and Infrastructure Research, 15*(4). https://doi.org/10.18757/ejtir.2015.15.4.3093

Vasileiadou, E., Hisschemöller, M., Petersen, A. C., Hazeleger, W., Betgen, C., de Hoog, I., & Min, E. (2013). Adaptation to extreme weather: identifying different societal perspectives in the Netherlands. *Regional Environmental Change, 14*(1), 91–101. https://doi.org/10.1007/s10113-013-0460-4

Vichiensan, V., & Nakamura, K. (2021). Walkability Perception in Asian Cities: A Comparative Study in Bangkok and Nagoya. *Sustainability, 13*(12), 6825. https://doi.org/10.3390/su13126825

Victoria State Government. (2019). 20-Minute Neighbourhoods: Creating a more liveable Melbourne. https://www.planning.vic.gov.au/__data/assets/pdf_file/0031/428908/Creating-a-more-liveable-Melbourne.pdf

West, L. (2021). *The Causes and Effects of Smog.* Treehugger. https://www.treehugger.com/what-is-smog-causes-and-effects-1204194

Wikipedia. (2022). *Strijp-S*.Wikipedia. https://en.wikipedia.org/wiki/Strijp-S

Wu, S., Deng, F., Liu, Y., Shima, M., Niu, J., Huang, Q., & Guo, X. (2013). Temperature, traffic-related air pollution, and heart rate variability in a panel of healthy adults. *Environmental Research, 120*, 82–89. https://doi.org/10.1016/j.envres.2012.08.008

Yang, W., Zhen, X., & Zhou, S. (2021). How does neighborhood walkability affect obesity? The mediating role of commute mode. *Journal of Transport and Land Use, 14*(1), 737–759. https://doi.org/10.5198/jtlu.2021.1948

Zhai, X., Huang, H., Sze, N. N., Song, Z., & Hon, K. K. (2019). Diagnostic analysis of the effects of weather condition on pedestrian crash severity. *Accident Analysis & Prevention, 122*, 318–324. https://doi.org/10.1016/j.aap.2018.10.017

Appendix A. WI Indicators Preparation

An overview of how the final values and thresholds for each WI indicator were determined (more desirable areas will have higher values)

1. *Thermal comfort indicator (solar radiation in 3 conditions)*
   Method: Calculate the solar radiation values based on building height data (PDOK, 2022) by using "area solar radiation" tool in ArcGIS Pro. The generated solar radiation value depends on the shadows, the time of day and the day of the year.

Table 16. Overview of developing thermal comfort indicator values in 3 conditions

Condition	Generated solar radiation value range	***Thermal comfort indicator value range after normalisation (more desirable areas will have higher values)***
Summer day evening peak hour (4-6pm).	1.20 to 483.55	0.64 to 1 (areas with higher solar radiation will have a lower score)
Summer day off-peak hour (10-12am).	3.33 to 1350.91	0.0 to 1 (areas with higher solar radiation will have a lower score)
Winter day off-peak hour (10-12am).	0.54 to 220.00	0.0 to 0.16 (areas with higher solar radiation will have a higher score)

** Due to the large value range of generated solar radiation, the absolute minimum value of 0.0 after global normalisation is not equal to 0, but is approximated to 0.*

2. *Water depth on the footpath (Flood depths on the footpaths in 3 conditions)*
   Method: Directly obtained the flood depth data from the open data platform Klimaateffectatlas (2018) in 2 conditions. In rainfall weather, the different scores depend on the water depth and puddle area caused by the different rainfall levels. In snowy weather, a constant score of -1 is given to the entire footpath area.

Table 17. Overview of developing water depth on the footpath indicator values in 2 conditions

Condition	Water depth value range	***Water depth on the footpath indicator value range after normalisation***
70mm/2hr rainfall level	1 to 5 (*Classification of flood depths into five levels from 5 cm to over 30 cm)	-1 to 0
140mm/2hr rainfall level	1 to 5 (*Classification of flood depths into five levels from 5 cm to over 30 cm)	-1 to 0
Snow	-1	-1

** Areas of water depths between 5cm and 30cm exist in both conditions, this is because there are many areas throughout the city with potential for ponding under high rainfall and the areas that receive a score of 1 to 5 will vary under different rainfall levels.*

3. *Ambient pollution (effect from noise and air pollution in 2 conditions)*
   Method: Create buffers to represent effects from noise and air pollution on road and intersection areas. Give different scores to each buffer in different conditions and the scores of the buffers overlaid on each segment will be summed to represent the ambient pollution score for that location.

Table 18. Overview of threshold determination and scoring criteria

Pollution and area type	**Size of the buffer zone created around the midline/midpoint of the road/intersection area**	**Score given to buffer in peak hour condition**	**Score given to buffer in off-peak hour condition**	**Reference**
Air pollution on the road area	75m radius	-1	-0.5	Rose et al. (2009
Air pollution on the intersection area	110m radius	-1	-0.5	Wang et al., 2017
Noise pollution on the road area	25m radius	-1	-0.5	Alberola, Flindell & bullmore (2005).
Noise pollution on the intersection area	30m radius	-1	-0.5	Diniz & Zannin (2003).

Table 19. Overview of developing ambient pollution indicator values in 2 conditions

Area type	**Distance from the midline/midpoint of the road/intersection area**	**Pollution type**	***Summed score in peak hour condition (score after normalisation)***	***Summed score in off-peak hour condition (score after normalisation)***
Primary or secondary road area	Less than 25m from the midline of the road area	Air plus noise pollution	-2 (-0.5)	-1 (-0.25)
Areas next to the primary or secondary road	Between 25m and 75m from the midline of the road area	Air pollution	-1 (-0.25)	-0.5 (-0.125)
Intersection area (2 roads crossing)	Less than 30m from the midpoint of the intersection area	Double effect of the road area	-4 (-1)	-2(-0.5)

4. *Nearby land use indicator (green area or industrial area)*
   Method: Give the scores to area according to different land use type.

Table 20. Overview of developing nearby land use indicator values

Area type	***score***	**Reference**
Green area	1	Rahman and Szabó (2021); Kadali and Vedagiri (2015)
Industrial area	-1	Rahman and Szabó (2021)
Other area	0	---

5. *Street connectivity indicator (intersection density)*
   Intersection density: the number of footpath intersections within a 50m size grid.

Method: The number of intersections in each 50m size grid is calculated as a grid score and normalised between 0 and 1. All footpath segments within the grid are given a grid score.

Table 21. Overview of developing street connectivity indicator values

Step number	Step description	Involved ArcGIS Pro tool	Reference
1	Generate the footpath intersection point based on the footpath line data	“line intersection”	OSM (2022)
2	Create 50m size grids throughout the city	“create grid”	Frank et al. (2010)
3	Count the number of intersection points in each grid	“count points in polygon” and “extract by attribute”	---
4	Normalise to values between 0 and 1 (the higher score the higher intersection density)	“raster calculator”	---

6. Footpath width indicator
   Method: Give the scores to every 1-meter footpath segment according to different width values.

Table 22. Overview of developing footpath width indicator values

Width of footpath	***Score***	**Reference**
More than 1.5 meters (including 1.5m)	1	Stadskantoor Zwolle (2022)
Below 1.5 meters	0	Stadskantoor Zwolle (2022)

Python codes for calculating the width of footpath and score evaluation based on the threshold:

```
import arcpy
import os
from arcpy.sa import *
arcpy.CheckOutExtension("3D")
arcpy.CheckOutExtension("Spatial")

Folder=r"D:\Master USRE\graduation project\indicator development\footpathwidth\fpw"
BGT=r"D:\Master USRE\graduation project\indicator development\BGT data\New\New\BGT_BBG.shp"
site_type_field="NBS_new"
verges='berm'
sidewalk='voetpad'
arcpy.management.MakeFeatureLayer(BGT, "BGT")
arcpy.management.SelectLayerByAttribute("BGT", "NEW_SELECTION", "NBS_new = 'voetpad'", None)

#Select sidewalks and verges
Neighbourhood_dir=r"D:\Master USRE\graduation project\indicator development\footpathwidth\fpwff"
os.makedirs(Neighbourhood_dir+r"\Width"+r"\BGT")
BGT_vector=Neighbourhood_dir+r"\Width"+r"\BGT"
arcpy.FeatureClassToFeatureClass_conversion("BGT", BGT_vector, "BGT")
BGT_vector_path = os.path.join(BGT_vector, "BGT.shp")

#Dissolve the polygons
os.makedirs(Neighbourhood_dir + r"\Width" +r"\BGT"+r"Dissolved")
BGT_dissoved=os.path.join(Neighbourhood_dir + r"\Width" +r"\BGT"+r"Dissolved","dissolved.shp")
arcpy.Dissolve_management(in_features=BGT_vector_path,out_feature_class=BGT_dissoved,
```

```
                    dissolve_field="", statistics_fields="", multi_part="MULTI_PART",
                    unsplit_lines="DISSOLVE_LINES")

    # Make lines from the polygons
    os.makedirs(Neighbourhood_dir + r"\Width" + r"\line")
    BGT_line = os.path.join(Neighbourhood_dir + r"\Width" + r"\line","line.shp")
    arcpy.PolygonToLine_management(in_features=BGT_dissoved,out_feature_class=BGT_line,neighbor_option="IDENTI
FY_NEIGHBORS")

    # Generate points along the line each 1 meter
    os.makedirs(Neighbourhood_dir + r"\Width" + r"\Points")
    BGT_point = os.path.join(Neighbourhood_dir + r"\Width" + r"\Points", "points.shp")
    arcpy.GeneratePointsAlongLines_management(Input_Features=BGT_line,Output_Feature_Class=BGT_point,Point_Pla
cement="DISTANCE", Distance="1 Meters", Percentage="",Include_End_Points="")

    # Generate Thiessen polyons from the points
    os.makedirs(Neighbourhood_dir + r"\Width" + r"\Tissen")
    Tissen = os.path.join(Neighbourhood_dir + r"\Width" + r"\Tissen", "Tissen.shp")
    arcpy.CreateThiessenPolygons_analysis(in_features=BGT_point,out_feature_class=Tissen,fields_to_copy="ONLY_FID")

    #Cliped the tissen polygon with boundries of the city
    Tissen_clip=os.path.join(Neighbourhood_dir + r"\Width" + r"\Tissen", "Tiss_c.shp")
    arcpy.Clip_analysis(in_features=Tissen,
    clip_features=BGT_vector_path,out_feature_class=Tissen_clip,cluster_tolerance="")

    # Calculate the area of polygons
    arcpy.AddField_management(in_table=Tissen_clip,     field_name="Area",     field_type="DOUBLE",
    field_precision="",field_scale="", field_length="", field_alias="",
                    field_is_nullable="NULLABLE",field_is_required="NON_REQUIRED", field_domain="")
    arcpy.CalculateField_management(in_table=Tissen_clip,     field="Area",
    expression="'!shape.area@squaremeters!'",expression_type="PYTHON_9.3", code_block="")
    os.makedirs(Neighbourhood_dir + r"\Width" + r"\Tissen"+r"\Tiss_BGT_join")
    Tissen_clip=os.path.join(Neighbourhood_dir + r"\Width" + r"\Tissen", "Tiss_c.shp")

    # Make a boolean raster from the areas considering the type of surface
    with arcpy.da.UpdateCursor(Tissen_clip,["Area_n","width"]) as wides:
      for wide in wides:
        if float(wide[0]) >= 0.75:
          wide[1] = 1
        else:
          wide[1]=0
        wides.updateRow(wide)

    # Make a raster from the polygon
    os.makedirs(Neighbourhood_dir + r"\Width" + r"\output102" +r"\True")
    NBS_width=os.path.join(Neighbourhood_dir+r"\Width"+r"\output101","width.tif")

arcpy.PolygonToRaster_conversion(in_features=Tissen_clip, value_field="width",
out_rasterdataset=NBS_width,cell_assignment="CELL_CENTER", priority_field="NONE", cellsize="1")
```

Appendix B. List of all possible scenarios

Table 23. List of all possible scenarios

Morning peak hour (C1) / Evening peak hour (C2) / Off-peak hour (C3)	Temperature: Min temp <0 degree (A1)	Temperature: Max temp < 25 degree and min temp >=0 degree (A2)	Temperature: Max temp >=25 degree (A3)
Weather: sunny (B1)	A1B1C1	A2B1C1	A3B1C1
Weather: Cloudy (B2)	A1B2C1	A2B2C1	A3B2C1
Weather: Heavy rain (B3)	A1B3C1	A2B3C1	A3B3C1
Weather: Violent rain (B4)	A1B4C1	A2B4C1	A3B4C1
Weather: sunny (B1)	A1B1C2	A2B1C2	A3B1C2
Weather: Cloudy (B2)	A1B2C2	A2B2C2	A3B2C2
Weather: Heavy rain (B3)	A1B3C2	A2B3C2	A3B3C2
Weather: Violent rain (B4)	A1B4C2	A2B4C2	A3B4C2
Weather: sunny (B1)	A1B1C3	A2B1C3	A3B1C3
Weather: Cloudy (B2)	A1B2C3	A2B2C3	A3B2C3
Weather: Heavy rain (B3)	A1B3C3	A2B3C3	A3B3C3
Weather: Violent rain (B4)	A1B4C3	A2B4C3	A3B4C3

Appendix C. The calculation of the WI indicator values at segment A and B

The calculation of the WI indicator values at segment A

WII 1: Thermal comfort indicator

Table 24. Calculation of thermal comfort indicator values at segment A in scenario 2 and 4

Extreme weather scenario	**Scenario for WI indicator development**	**Generated solar radiation value**	**Normalised solar radiation value between 0 to 1**	***Thermal comfort indicator value after normalisation (more desirable areas will have higher values)***
Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.	Summer day evening peak hour (4-6pm).	321.4	(321.4-0.54)/ (1350.91-0.54) =0.24	1-0.24=0.76
Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.	Summer day off-peak hour (10-12am).	1133.9	(1133.9-0.54)/ (1350.91-0.54) =0.84	1-0.84 =0.16

WII 3: Ambient pollution

Table 25. Location characteristics of segment A

	Located in ambient pollution indicator buffer zone	**Pollution type**
Segment A	In the 25m radius buffer	Air plus noise pollution

Table 26. Calculation of ambient pollution indicator values and smog additional variable at segment A

Extreme weather scenario	**Scenario for WI indicator development**	**Score given to each buffer**	***Summed score***	***Ambient pollution indicator value (score after normalisation)***	***Additional variable: smog (score given in the indicator buffer)***
Sc 1: Min temp <0 degree, snow, during the morning peak hours.	Peak hour	-1	-2	0.5	0
Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.	Peak hour	-1	-2	0.5	-0.1
Sc 3: Max temp >=25 degree, violent rain, during the evening peak hours.	Peak hour	-1	-2	0.5	0
Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.	Off-peak hour	-0.5	-1	0.25	0
Sc 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.	Off-peak hour	-0.5	-1	0.25	0

Additional variable: Icy and slippery

Table 27. Calculation of additional variable icy at segment A

Extreme weather scenario	***Additional variable: icy (score in the whole city area)***
Sc 1: Min temp <0 degree, snow, during the morning peak hours.	-0.1

The calculation of the WI indicator values at segment B

WII 1: Thermal comfort indicator

Table 28. Calculation of thermal comfort indicator values at segment B in scenario 2 and 4

Extreme weather scenario	**Scenario for WI indicator development**	**Generated solar radiation value**	**Normalised solar radiation value between 0 to 1**	***Thermal comfort indicator value after normalisation (more desirable areas will have higher values)***
Sc 2: Max temp >=25 degree, sunny, during the evening peak hours.	Summer day evening peak hour (4-6pm).	293.5	(293.5-0.54)/ (1350.91-0.54) =0.22	1-0.22=0.78
Sc 4: Max temp >=25 degree, sunny, during the off-peak hours.	Summer day off-peak hour (10-12am).	406.4	(406.4-0.54)/ (1350.91-0.54) =0.3	1-0.3=0.7

Additional variable: Icy and slippery

Table 29. Calculation of additional variable icy at segment B

Extreme weather scenario	***Additional variable: icy (score in the whole city area)***
Sc 1: Min temp <0 degree, snow, during the morning peak hours.	-0.1

Appendix D. Maps of WI integrated in hexagonal grids in 5 extreme weather scenarios

Scenario 1: Min temp <0 degree, snow, during the morning peak hours.

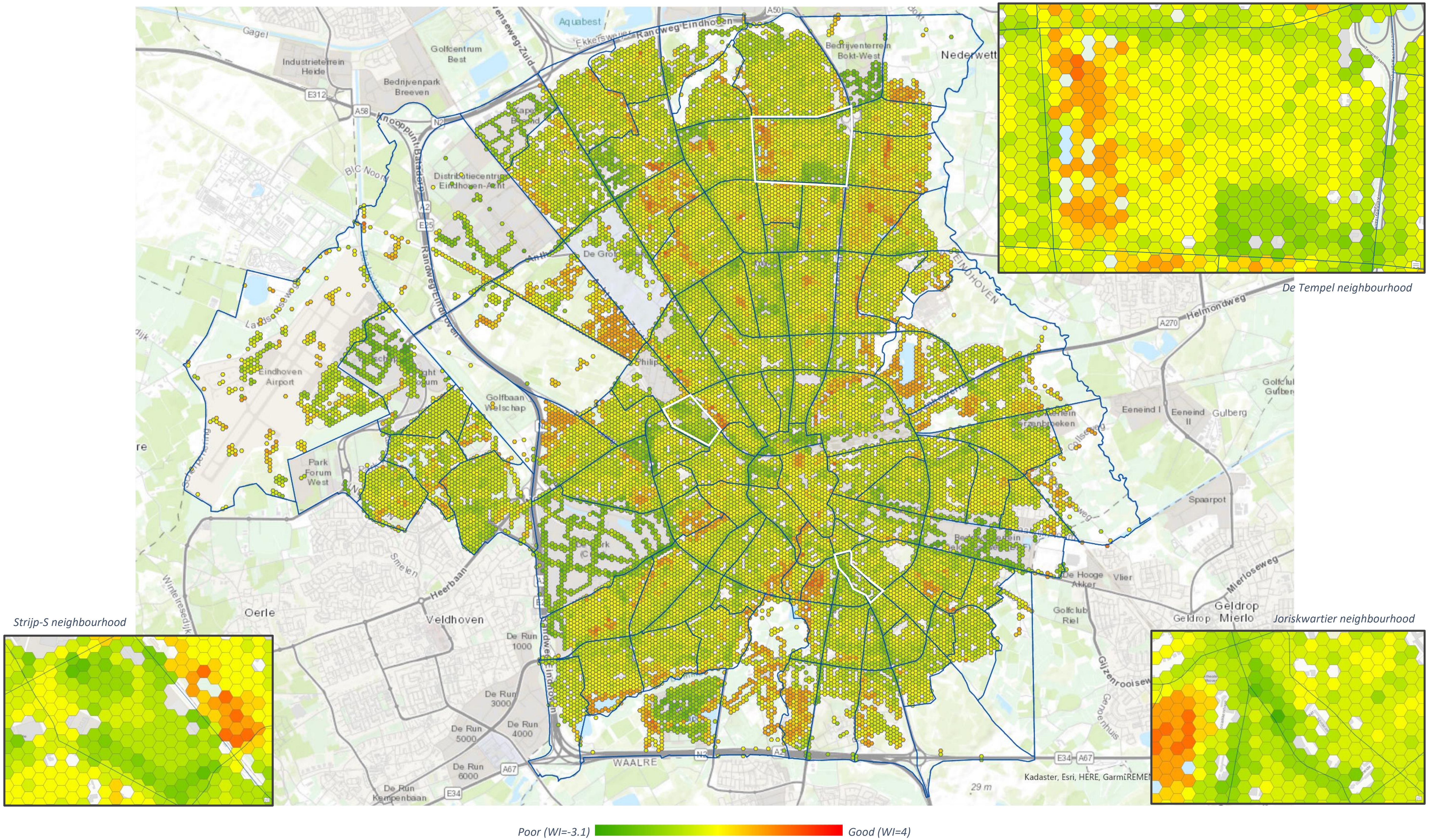


Figure 39. WI at hexagonal level for Scenario 1

Scenario 2: Max temp >=25 degree, sunny, during the evening peak hours.

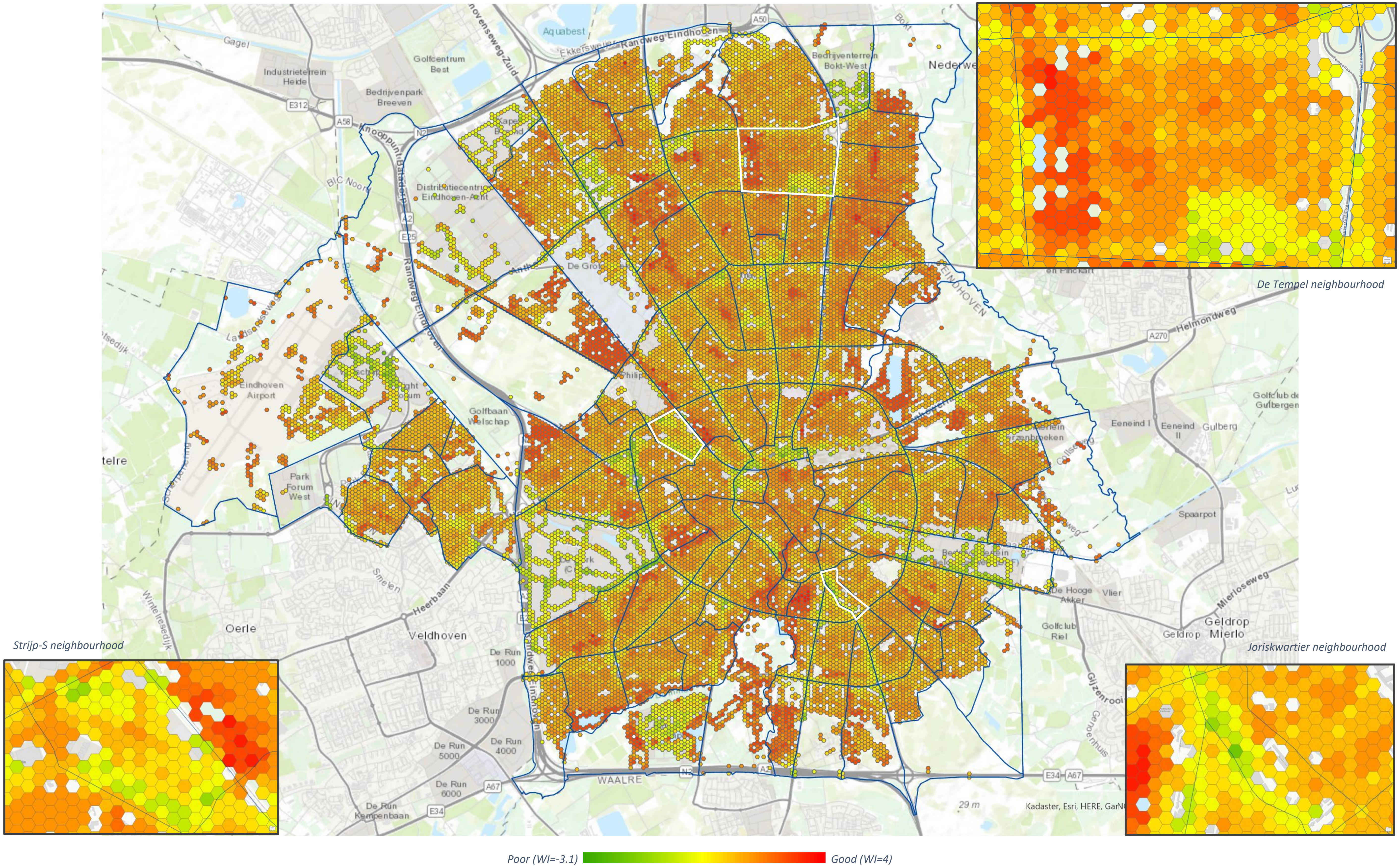
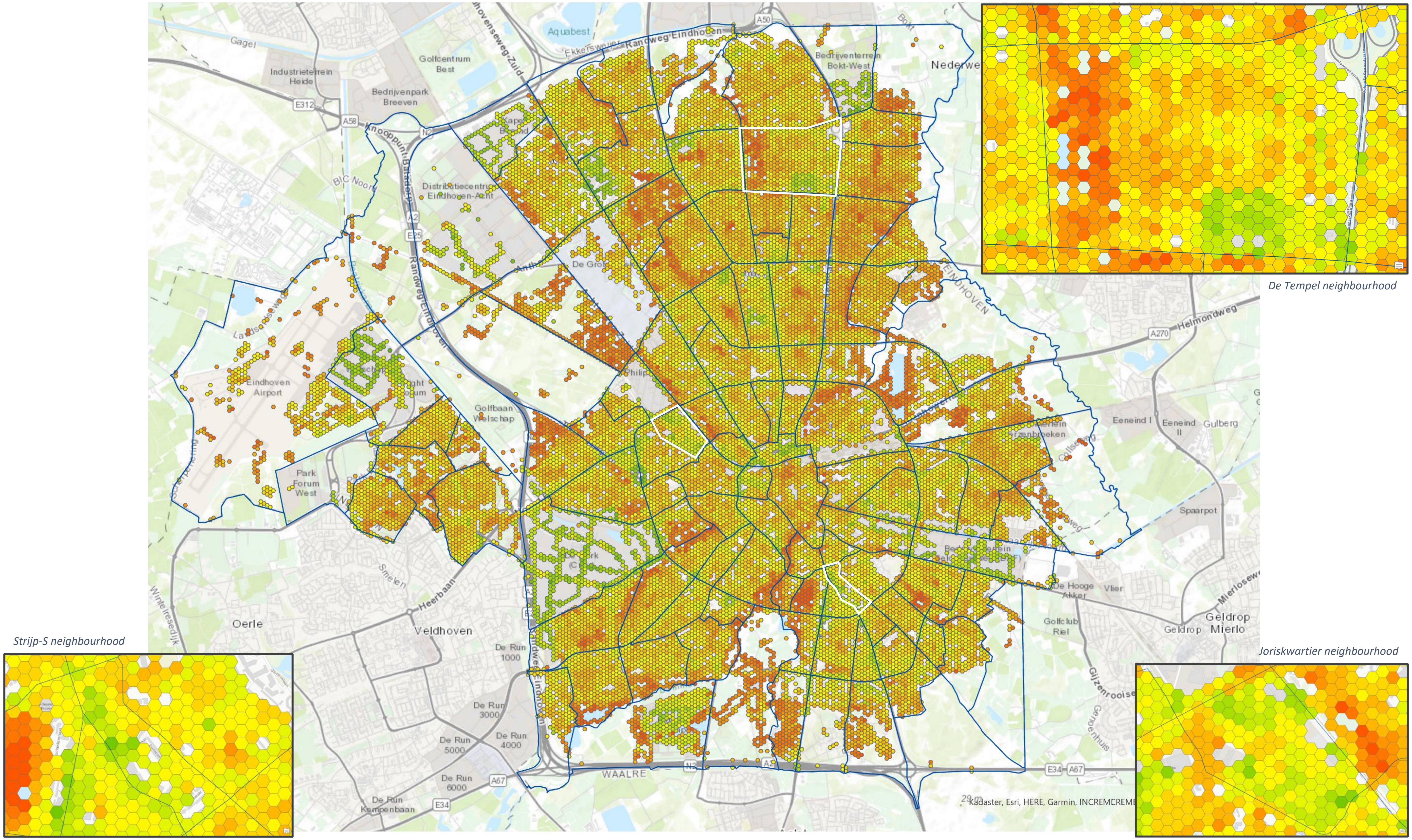


Figure 40. WI at hexagonal level for Scenario 2

Scenario 3: Max temp >=25 degree, violent rain, during the evening peak hours.



Poor (WI=-3.1) Good (WI=4)

Figure 41. WI at hexagonal level for Scenario 3

Scenario 4: Max temp >=25 degree, sunny, during the off-peak hours.

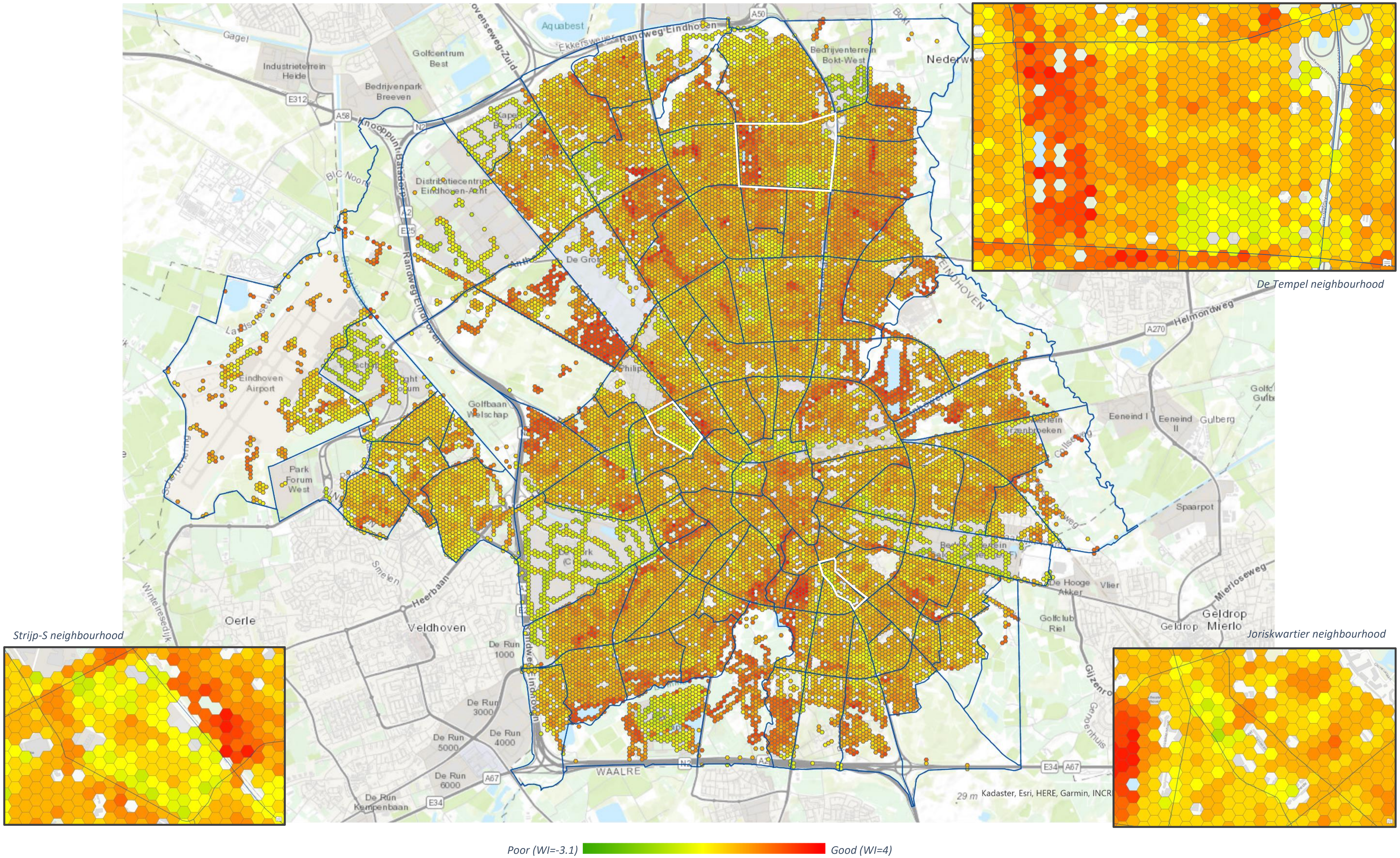


Figure 42. WI at hexagonal level for Scenario 4

Scenario 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.

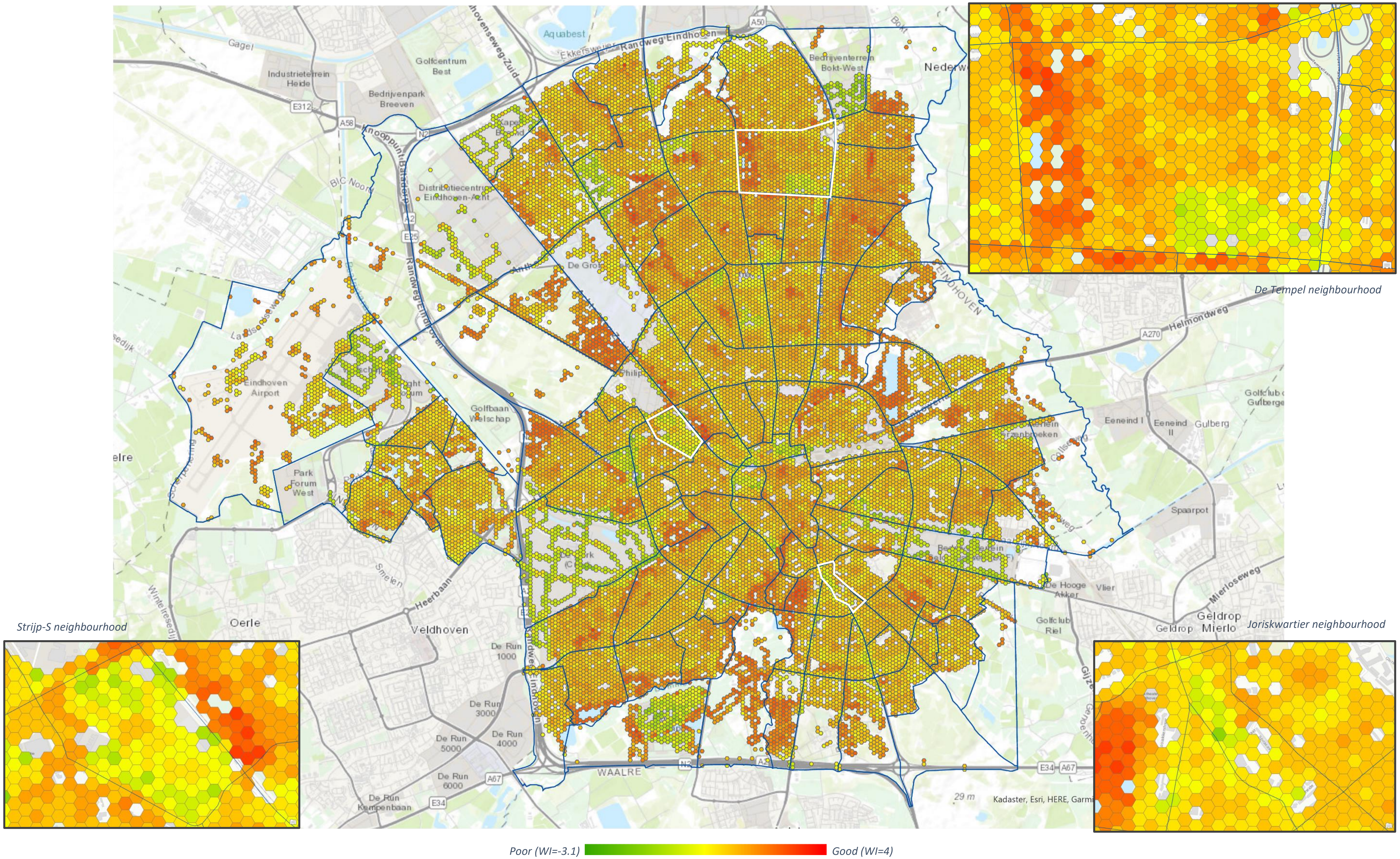
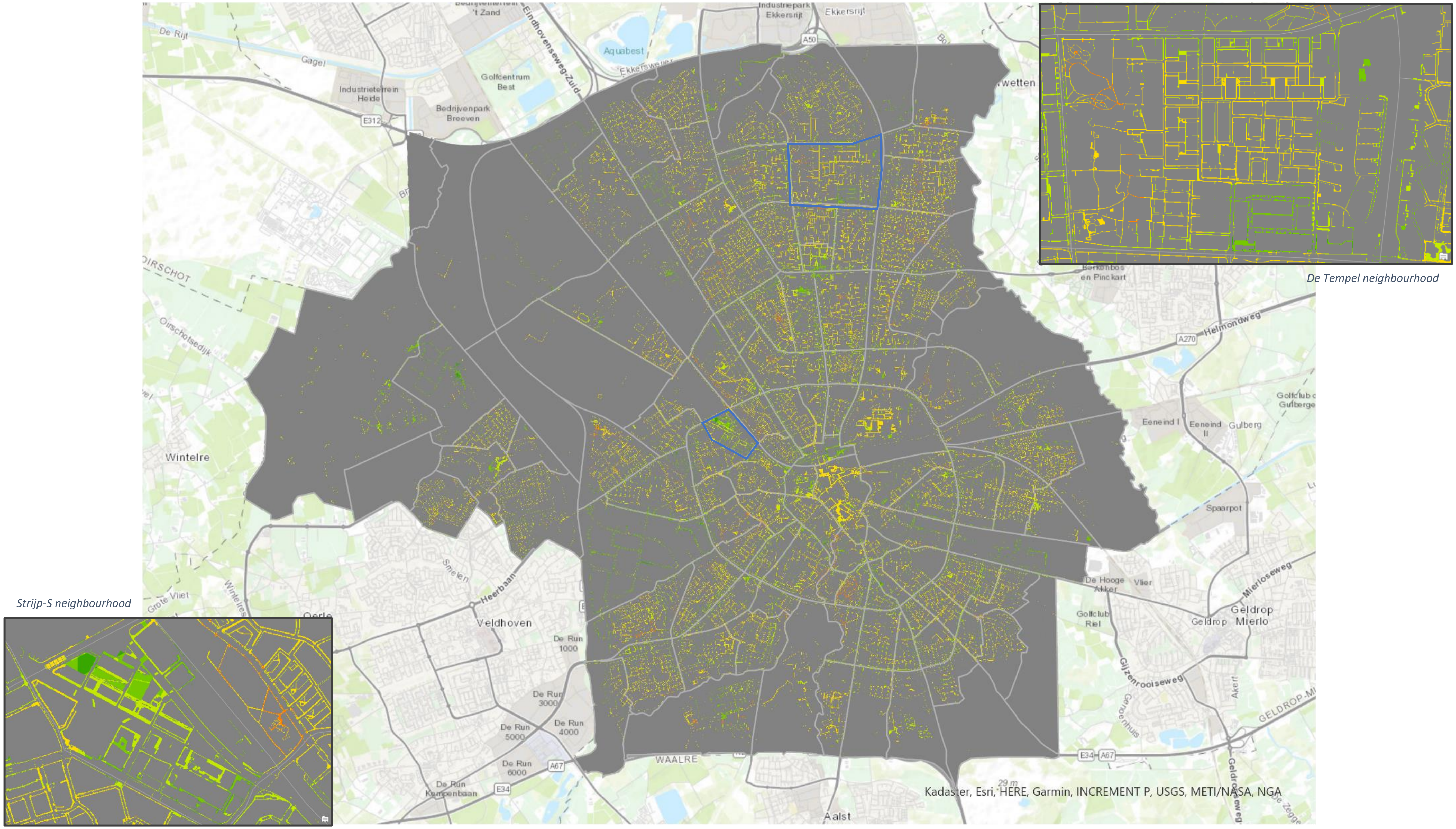


Figure 43. WI at hexagonal level for Scenario 5

Appendix E. Maps of WI at footpath scale in 5 extreme weather scenarios

Scenario 1: Min temp <0 degree, snow, during the morning peak hours.



De Tempel neighbourhood

Strijp-S neighbourhood

Poor (WI=-3.1) — *Good (WI=4)*

Figure 44. WI at footpath scale for Scenario 1

Scenario 2: Max temp >=25 degree, sunny, during the evening peak hours.

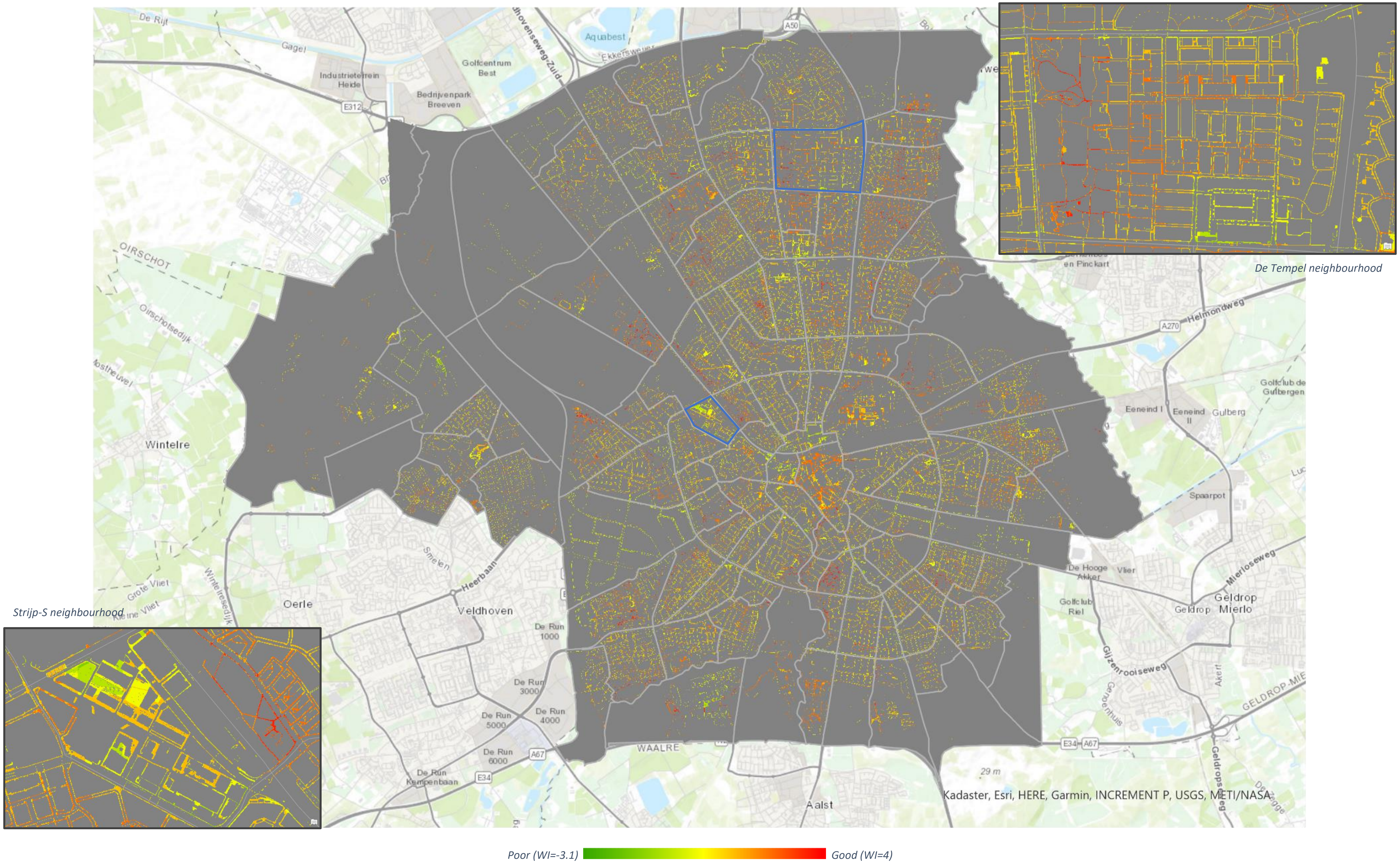
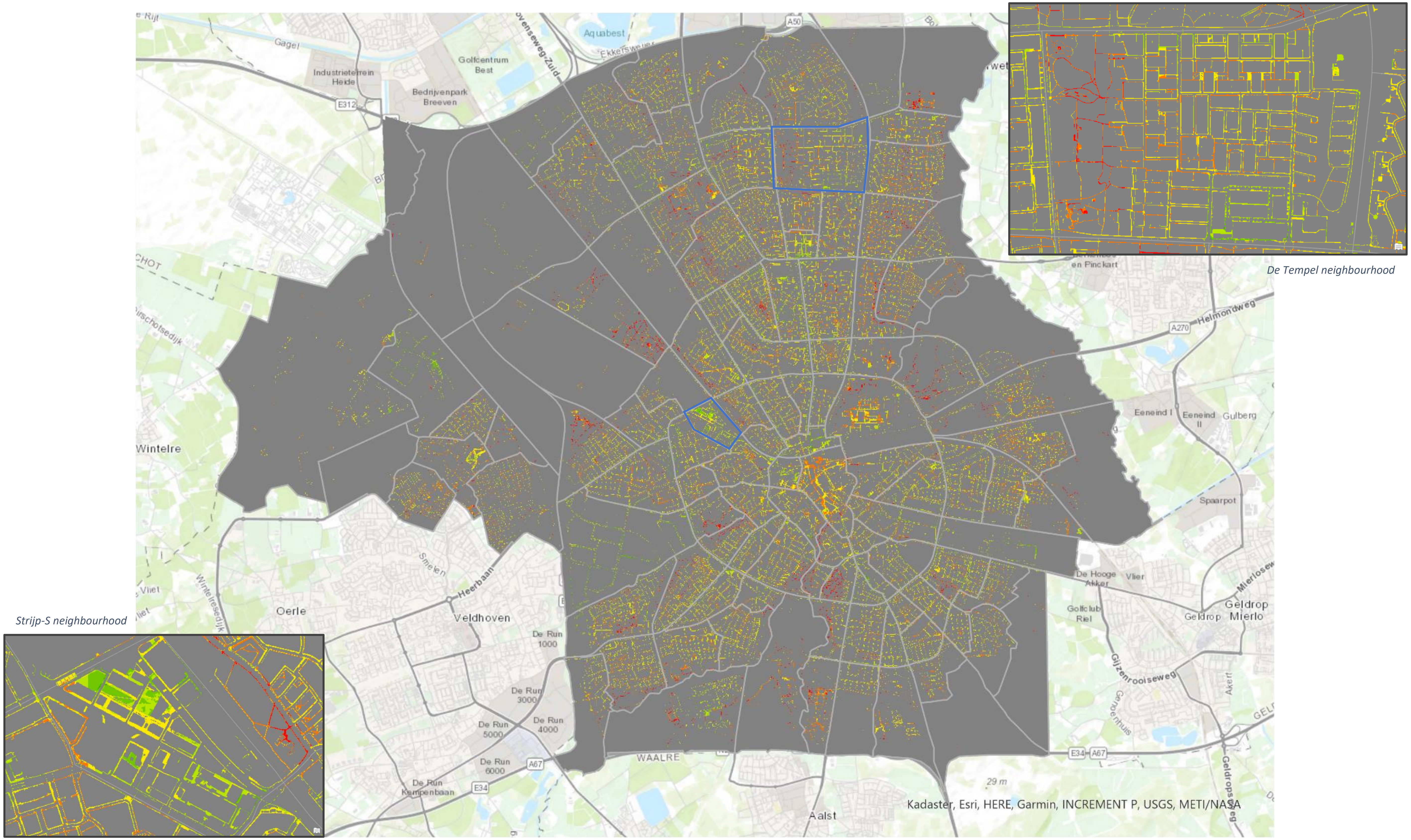


Figure 45. WI at footpath scale for Scenario 2

Scenario 3: Max temp >=25 degree, violent rain, during the evening peak hours.



Poor (WI=-3.1) — *Good (WI=4)*

Figure 46. WI at footpath scale for Scenario 3

Scenario 4: Max temp >=25 degree, sunny, during the off-peak hours.

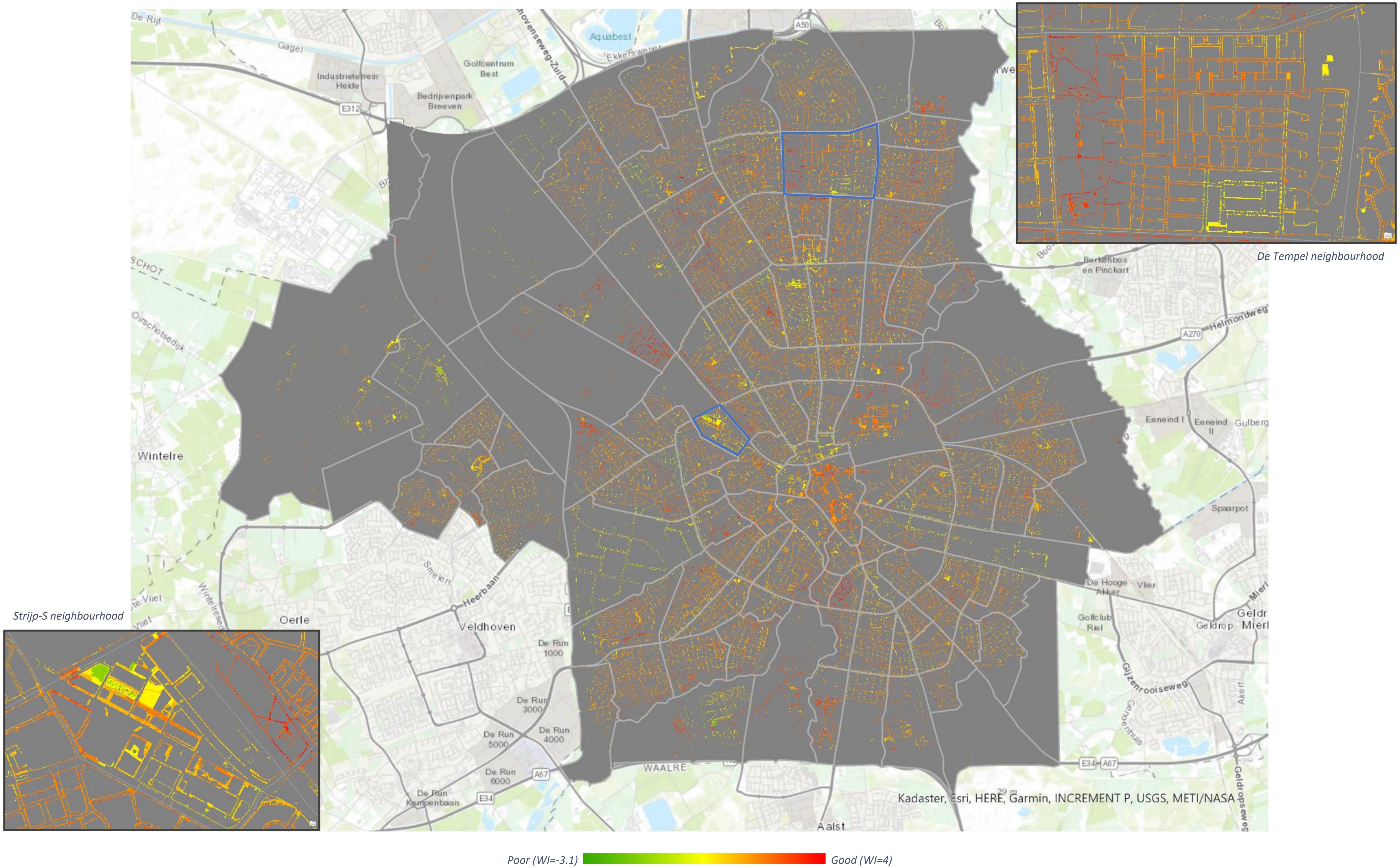


Figure 47. WI at footpath scale for Scenario 4

Scenario 5: Max temp < 25 degree and min temp >=0 degree, cloudy, during the off-peak hours.

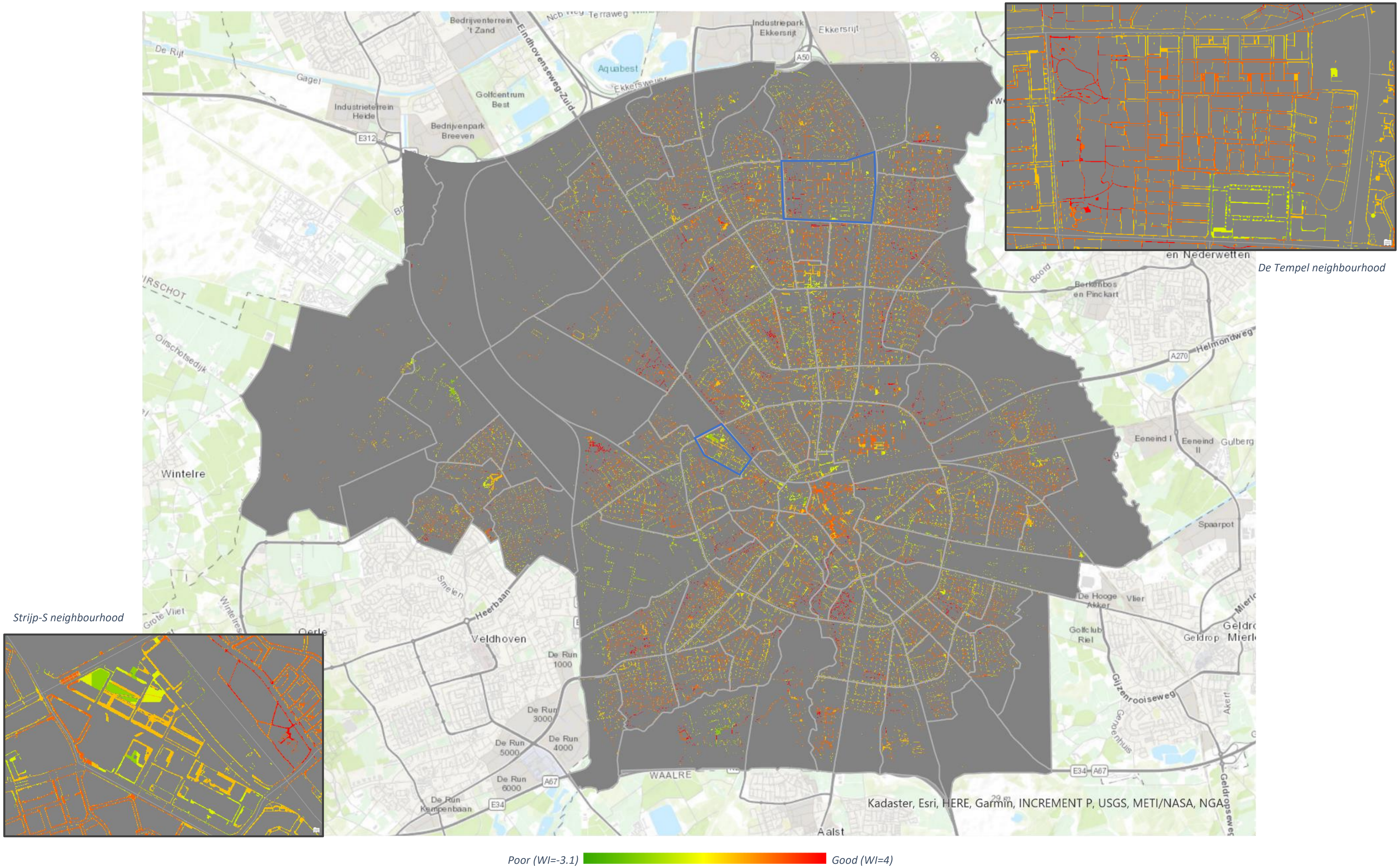


Figure 48. WI at footpath scale for Scenario 5

Appendix F. Content in the web viewer and process of creating them

Supplementary Information

The supplementary information is used to introduce the research context of the study, the research objectives and some background information to assist with the WI visualisation. The order in which the information is presented follows the order of the research phases. The main sections included are as follows.

- Introduction of the research context Eindhoven City.
- Definition of WI.
- Objective of this research.
- Definition and classification of footpath in this study.
- Explanation of the WI assessment process (including WI indicators and scenarios identification).
- Explanation of the WI visualisation in 3 different scales.

These sections can be inserted into the web viewer as text, tables or images using the "add content block" function. The position, font size and shape of each block can be set independently. Figure 49 shows the research context, definition of the WI and research objective sections in the web viewer.

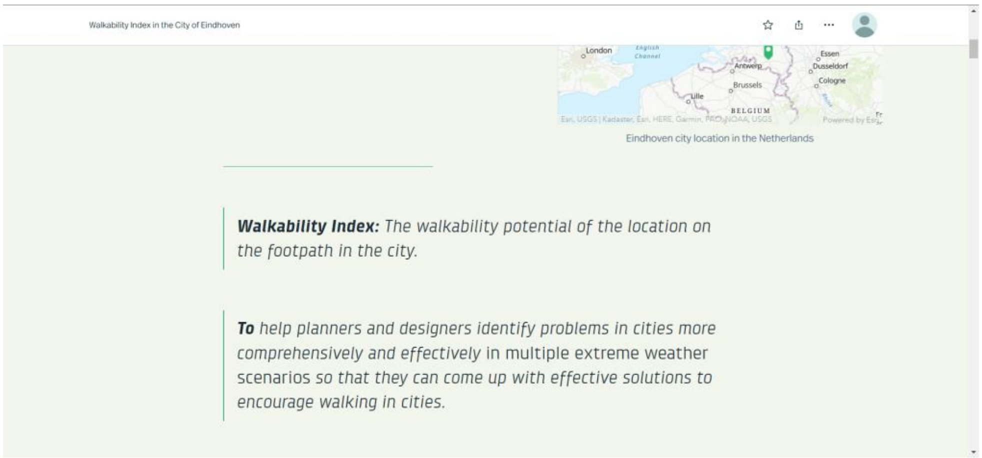


Figure 49. The research context, definition of the WI and research objective sections in the web viewer.

Spatial Visualization

After introducing all the supplementary information, the generated WI maps at three scales for multiple extreme weather scenarios can be displayed. The three scales of WI maps were divided into three sections in descending order of scale, including WI at neighbourhood scale, WI integrated in hexagonal grids and WI at footpath scale as described in 4.3.1.

In order to visualise the WI maps in different scenarios in a more user-friendly way, it was decided to add an immersive content block to switch between scenarios in a "slideshow" or "sidecar" manner. The “slideshow” is a full-screen, media-focused layout with minimal accompanying text, which is considered to be more suitable for displaying WI at footpath scale. As the target group might need to play with the model and see the walkability performance on the footpath. Users can manually switch maps to see the WI at footpath scale in different scenarios, but cannot click on a footpath segment to see the WI score. The “sidecar” is an immersive block with media panel and narrative panel, which is thought to be more appropriate for displaying the remaining two scales of WI maps. As the target group might prefer to see the map as a whole to decide which areas to explore in depth. Users can switch between scenarios by scrolling down the page and can also click on neighbourhood polygons or hexagonal grids to see the WI scores and compare them across different scenarios. Figure 50 shows the visualisation of the WI at neighbourhood scale, hexagonal scale and footpath scale in the web viewer.

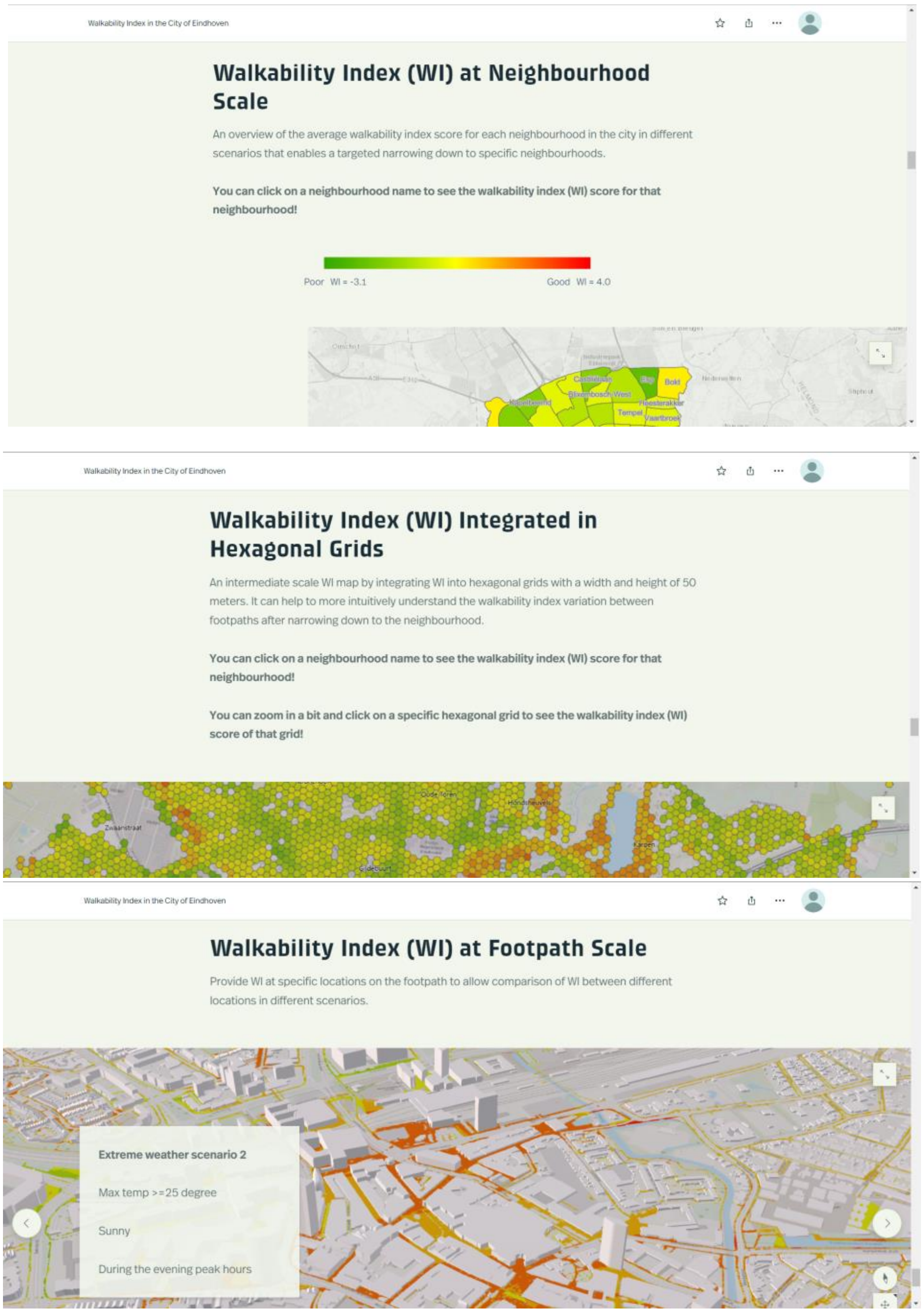


Figure 50. Visualisation of the WI at neighbourhood scale, hexagonal scale and footpath scale in the web viewer.

Appendix G. Validation results: Answers from the online interview for each question

- **Do you think WI is important in urban planning and design? How?**

A TU/e Master student studying USRE&CME: I think WI is important, especially if it can help to find the routes that might be more dangerous for pedestrian to walk on during the extreme weather situations.

A TU/e Master student studying Urbanism: I think it's very important, because currently there is little attention given to walkability. More attention is paid to the cars and how people can commute. But it's important to see how people walk and if this area is walkable for urban design field.

A junior urban designer from a landscape architecture and urban planning firm: Yeah, especially if you can visualize the WI. Showing it with colors make the WI really easy to understand comparing with showing it in Excel or scientific research papers for example. During the prior stage of the design project like sketch design process, you don't really need to go to the location straight away. You can do some prior investigation using the virtual tools.

An Assistant Professor at the department of the Built Environment at TU/e: It is important. Walkability has positive effect not only on walking but also it can create chances for people to go outside and meet other people, so it has several health benefits. Therefore, it is important to stimulate walking and we still need to do more research into how we can stimulate it in different ways, and which element in the built environment can contribute to walkability.

- **What do you think of the way of assessing WI in this study?**

A TU/e Master student studying USRE&CME: There's a lot of different ways to calculate it and I think it's interesting the way you've taken weather conditions into account, I've never seen that before. I have seen many studies that consider indicators including facilities, lighting, etc., but have not considered weather conditions.

A TU/e Master student studying Urbanism: I think for the WI indicators you've covered all aspects broadly, including personal comfort, functional environment, etc. For the land use indicator, you could extend it to residential or commercial areas, but that's a more detailed approach.

A junior urban designer from a landscape architecture and urban planning firm: The data looks really convincing, so I think it could be useful in the future. For the WI indicator, I think it would be useful to add wind speed, as there are usually strong winds in the Netherlands. For example, near the Phillips Museum there is an intersection of two streets, which creates a wind tunnel, and there is wind in the wind tunnel all the time, especially during heavy rain. It is really not recommended to go there in these weather conditions.

An Assistant Professor at the department of the Built Environment at TU/e: It's a quantitively and objective way to measure WI, which is quite useful and important. On the other hand, comfort does matter, but I wonder to what extent environmental pollution really affects the willingness to walk. I think this point could perhaps be explored in more depth.

- **What extreme weather scenarios do you think are important to assess WI?**

A TU/e Master student studying USRE&CME: Heat is quite important. Urban Heat Island cause some areas to become very warm. Another interesting factor is the wind. Depending on the wind direction, there are areas that can be quite dangerous, like around the corners of tall buildings. Thunderstorms can also be interesting. The closer you are to other buildings, the safer you are, but if you are walking in the wilderness, it can be more dangerous than in high density areas. Street lighting may be important. For example, if it's cloudy and there's a storm, it will be dark and you won't really be able to see very well.

A TU/e Master student studying Urbanism: I think it is quite important to have common weather conditions because it makes it easier to make comparisons. Also, heavy rain conditions are important because in the Netherlands it is usually rainy. Peak hour conditions are relatively more important because you can see how the walking capacity changes during the day, for example.

A junior urban designer from a landscape architecture and urban planning firm: I think that for the Netherlands the hot weather in summer is painful. Also, heavy rain and windy weather can be quite useful to emphasize. I was also thinking about hail, but I would say it is quite rare.

An Assistant Professor at the department of the Built Environment at TU/e: Snow is not common in the Netherlands, but it does limit people's willingness to walk (there was snowfall on the day of the interview). Also, in my opinion, greenery and shade are very important.

- **Do you think it is informative to visualise WI at three different scales?**

A TU/e Master student studying USRE&CME: Yes, three models are good because it does make people more aware of their environment. So usually on a map you have to know where you are, whereas if you have a three-dimensional model, people recognise their environment and their location much more quickly.

A TU/e Master student studying Urbanism: Yes, it is useful to have different scales. However, I think the neighbourhood and footpath levels are much more informative. The hexagonal level is a bit difficult to zoom in on, move around and navigate. Perhaps for different fields people find informativeness in different ways. For example, perhaps an urban planner would find neighbourhood and hexagonal scales more informative, while an urban designer would use neighbourhood and footpath scales more often.

A junior urban designer from a landscape architecture and urban planning firm: Yes, I think it depends on which scale you need in your project. Different scales are useful for different types of projects. But for me, I would suggest adding the tree in hexagonal scale and then you can see it when you zoom in. You can add it as dots or something like that, without going into too much detail.

An Assistant Professor at the department of the Built Environment at TU/e: They are all very good. Different scales can be applied to different target groups. I think for individuals a smaller scale would be more useful, whereas a neighborhood scale might be useful in terms of strategy development and overall policy, but not so much for design. For design, the footpath scale would be more valuable because it's difficult to design at the full neighborhood scale. For urban planners, perhaps a hexagonal level would be more helpful.

- **Do you think it is informative to visualise WI at footpath level in combination with a 3D city model?**

A TU/e Master student studying USRE&CME: Yes, it shows exactly where you live and how WI is on the footpath. It would be easier to navigate your specific location in the 3D model if there could be an overview map in the corner showing where you are in the map and which neighbourhood you are in. This could help the scale of the 3D map to be more informative.

A TU/e Master student studying Urbanism: Absolutely. First of all, I can position myself more accurately in a 3D city model than in a 2D map. When you design something, the integration with the buildings is very important and the shading is also very helpful to show. The 3D model also looks very attractive and professional. It is also much more interactive.

A junior urban designer from a landscape architecture and urban planning firm: I am a fan of 3D models. I think it looks very nice and is much easier to understand. Because from a human point of view you can only see the shape of the buildings, but when you look at the city from a higher altitude you can see the projection of the shadows of the buildings. Maybe it would be nice to have windows and openings on the facade.

An Assistant Professor at the department of the Built Environment at TU/e: Absolutely. This can be useful for all target groups, even for individuals and policy makers, to help them navigate themselves more easily.

- **Do you think it is easy to identify potential problem areas or find potential development areas by checking the visualisation of WI at three different scales and five weather scenarios?**

A TU/e Master student studying USRE&CME: Definitely. Using different scales, scenarios and colours can give a good view of the WI situation in these areas. The problems then can be identified more effectively.

A TU/e Master student studying Urbanism: Yeah. Five scenarios are sufficient to show the WI in different scenarios. From these three scales, you can easily see that the WI is better in the city centre. You can also find the WI of the project area to help analyse the design context. So, I think it can really help with urban design projects.

A junior urban designer from a landscape architecture and urban planning firm: Yes, it's quite easy to understand because you have different colours representing different levels and you have the same legend for different maps so people can easily compare. WI is visualised on the map and the information is clickable so you don't need to read all the descriptions to understand what's happening there. The weather is also visible on the 3D map and you can see the rain and snow. So, it's quite understandable and you can zoom in or out if you want. For the scenarios, I would say that 5 is more than enough. Otherwise, it can get a bit confusing when you put a lot of different models and scenarios together.

An Assistant Professor at the department of the Built Environment at TU/e: Yes. Smaller scales are more useful for defining problems in different areas because you can see the differences within a neighborhood. In particular by checking the footpath scale map and the 5 scenarios you can see the WI differences between locations which can help find the problem.

- **Which scale do you think is more valuable to visualise WI? Is there anything missing?**

A TU/e Master student studying USRE&CME: I think personally, I like the one with the hexagon the best. Because it's not quite as detailed as the 3D model, but you can tell it's the street that runs through the area and is more walkable. Also, it looks beautiful with the colouring and the pictures created. But if people don't know the city, a 3D map would be best. For the hexagonal map, I don't see a street view, so I'm not sure which of these hexagons covers my house. It might be interesting to attach a Street View to the 3D model. You would feel like you were really in the 3D model, walking through the city to see if these areas are good or bad. You could create a 360-degree view and they could turn around and see what it would be like to stand there. I believe you can do this in ArcGIS, there is a VR function that makes you feel like you're walking through this environment you've created.

A TU/e Master student studying Urbanism: I don't think anything is missing, I think the 3D city model is more valuable. Because from there you can really see the relation to the buildings and other streets.

But maybe for urban planners they prefer the scale of the neighbourhoods because they can see the overall WI of the area and find regional problems.

A junior urban designer from a landscape architecture and urban planning firm: I prefer the hexagonal scale because it is more universal and you can use it in more situations. It shows a bigger picture compared to a 3D model and it shows more detail compared to a neighbourhood scale. For urban designers, in some cases, there is no need to provide as much detail as with the footpath scale. But architects may prefer to have more zooming options. Also, I like the feature of clicking on the hexagon to show the WI score, by looking at the pavement scale map I can't see the WI score at the specific location. I don't think there is anything missing because it makes the figure more confusing. So, I wouldn't say you need to have something in between, but just work on top of the map scale you already have.

An Assistant Professor at the department of the Built Environment at TU/e: Personally, I prefer the footpath scale. It provides more information and shows the information in more detail at the footpath level. Perhaps it would be more helpful to include urban greenery and trees in the maps.

- **How user-friendly and intuitive is this way of visualising the WI?**

A TU/e Master student studying USRE&CME: I think it's very simple and that's a good thing. You just scroll down to show the different maps and the different scenarios. People can drag the map around to see the different areas, it's very clear. So, I think it's a very clear way to show your results. It's definitely intuitive and I think everyone would be very comfortable using it. It would be clearer if you could explain in more detail in the first part of the website how you collected these location-based data.

A TU/e Master student studying Urbanism: The web viewer is very interactive and I can click on the map and see relevant information. I think the way the WI is displayed in colour is very intuitive. However, I found that you use red for good levels and green for poor levels. In the field of urban design, we usually use green to represent something positive. So, I personally found it a bit difficult to read your map.

A junior urban designer from a landscape architecture and urban planning firm: I think it's very user-friendly, you don't feel like you're doing something scientific. You don't need that much related knowledge; people can look at the map to see the walkability performance. Maybe it would be good to have neighborhood boundaries on a hexagonal scale map so it can be easier to navigate. Because now you can see the names of the areas, but you might lose some of the detail.

An Assistant Professor at the department of the Built Environment at TU/e: It is very user-friendly and easy to understand. The way of visualizing the different levels of WI through different colors is very intuitive and the function that you can click on hexagons and neighborhoods to see the information is interactive.

- **What would you suggest to further improve the WI, the visualisation and application of the WI?**

A TU/e Master student studying USRE&CME: When I look at the map, I only know that the WI for each area is good or bad or a level in between, but I don't know exactly why. It can be helpful if you click on an area that shows green and then there is a pop-up window telling you why it is green. For example, it will show that the WI is low because the area is hot or flooded. Alternatively, it could be implemented to click on an area and then have a pop-up window stating the indicator score and how the WI is calculated, which would be even better. For applications, you could also use it for GPS systems. When someone wants to walk home, they could choose a route with good WI (safer) rather than the fastest route. This system might also allow people to understand that in certain weather conditions they should just stay inside because it becomes dangerous outside. So, if the whole area around you is very low WI and there is a snowstorm, then they can know that it is better to stay inside. You can also connect it to the Metrology Institute in the Netherlands and they can send a message to people to stay at home. In the message you can include a link to tell people to look at what the Walkability Index will be in their surrounding area. As a result, people can make the decision to leave the house or stay indoors.

A TU/e Master student studying Urbanism: For the visualisation of the WI in the web viewer, when I click on the map, I can only see the result of the WI, but not the process that led to this result. Therefore, it might be better to show the calculated results or indicator scores when I click on the locations. This could help the urban planner or designer to understand directly the problems in the area and come up with specific solutions that correspond to the indicators. It would be even more valuable to see which indicator has what impact on which neighbourhood or footpath. For the application of WI, I believe there are many more uses that can be made of it. For example, I am currently working on my graduation project related to public space and quality of life and I can already see how your results might help my project. Because you use three categories of indicators to keep it broad, many people from different fields can use it.

A junior urban designer from a landscape architecture and urban planning firm: Perhaps the inclusion of trees in the medium scale would be good. From the perspective of the website, it looks good. I think the projection of the shadows is also important because when I do landscaping, I want to know what the shadows look like. Shadows are also quite important for the whole atmosphere of the city. I'd also like to know what the soil looks like there, but that's too much detail for this type of website and I think that's a different field. Also, it would be nice to be able to import the data you have from the online version into QGIS, or just import the maps as images so that urban designers can work with it. This would be more professional for urban planners or designers.

An Assistant Professor at the department of the Built Environment at TU/e: Firstly, trees and urban greenery could be added to the map. Perhaps in a future study you could interview people or ask them to do some questionnaires in order to see the perceived walkability. In that way you could combine it with the WI assessed in an objective way and see if there is a big difference. Then you can see what indicators you are missing and what is very important to walkability. Alternatively, perhaps you could try to get tracking data on pedestrians to see their walking behavior and which footpath they prefer, which might lead to some interesting conclusions.