Department of the Built Environment
Construction Management and Engineering

Providing location based health information using dynamic, aggregated and static urban data

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Version 5.3

Eindhoven, August 2021

Colophon

General

Title	Providing location based health information using dynamic, aggregated and static urban data
Defense Date	23-08-2021

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Preface

The impediment to action advances action.
What stands in the way becomes the way.

– Marcus Aurelius

This research is the culmination of two years of studies at the Construction Management and Engineering (CME) department of the University of Technology Eindhoven (TU/e). Besides being the ultimate test of all that I have learned in that time, it is also a combination of several topics I have found to be fascinating; health and data. Through this research I have tried to challenge myself as much as possible to create a practical, interesting and useful application which might be the basis for a healthier society in the future.

Obviously, as with all great challenges, this research could not have been completed without the help of some exceptional people. Firstly, I would like to express my gratitude towards my supervisors, especially Gamze and Miloš. Besides being able to assist me with expertise, knowledge and guidance, they were also able to make the graduation process very much enjoyable and spark my own enthusiasm, while always instilling in me a sense of autonomy. Without that type of assistance, I'm not sure the results would have been the same. Furthermore, I would like to thank my family for their support. Besides their support and interest, they were always first in line to test my theories and prototypes and always had the courage to give stern words of feedback when necessary. Keeping me with both feet on the ground and forcing me to be critical of my own ideas. Lastly, I would like to thank my girlfriend for putting up with my continual lectures about urban health, hexagons and programming, which I now realize must have been thoroughly boring. Besides these lectures, she was able to show an infinite amount of interest, for which I'm exceptionally grateful. In general, everyone involved in my academical, personal en professional development have (partially) formed me to who I am, and this research would not have been the same without them, thank you all.

I would like to invite you to read this thesis and draw your own conclusions on the topic I have investigated over the last six months. If you like to share your conclusions with me, feel free to contact me, and we can discuss our insights.

Sander de Meij

Summary

Providing location based health information using dynamic, aggregated and static urban data

The goal of this research was to create an efficient framework and method to provide Urban Health information for both short- and long-term decision-making making use of mobile sensors in combination with static data. A summarized list of 6 variables (Air Quality, Heat, Noise, Green Spaces, Walkability and Traffic Safety) was constructed to form the basis of the Urban Health Index (UHI). As both dynamic and static data are included in the UHI, a hexagonal grid is used to visualize the scores of each location. This grid combines the spatial resolutions of both data types, while ensuring high resolution information discovery. Moreover, end-user research showed that current use of location based applications is mostly concerned with finding optimal routes. However, respondents indicated that Urban Health information would mostly be used for the selection of optimal locations. Therefore, this was the basis for the application design proposed by this research. The application consists of three layers, each with a different function. The home page educates the user the UHI and its uses. The core of the application, is a map of the city (Eindhoven, the Netherlands) with the hexagonal grid layer projected on it. The goal of this part of the application is to explore the data on a more coarse level. Specific locations can be investigated further through the individual sub-index scores and historical progression of the UHI and relevant sub-indices. User-validation tests show that this format for showing Urban Health information is relatively effective, however, more research should be done on the indicators of Urban Health and their correlation to adverse health effects. Moreover, it should be investigated whether different categories of end-users have different requirements when using the dashboard. These requirements could lead to a new iteration of the proposed application and underlying methodology.

Keywords — Urban Health, Mobile Sensors, GIS, Dashboard, Data Visualization

1. Introduction

With the continuing urbanization rate, the topic of urban health has become more prevalent over the years and several aspects have been investigated in this regard, like the physical environment, the social environment and access to health and social services (Galea and Vlahov, 2005). Multiple (objective) variables are being considered in defining and measuring urban health, however, these variables are mostly considered statically (Leidelmeijer et al., 2014; Leitte et al., 2009). With this methodology, much insight can be gained in the relationship between health and urban aspects, however, it gives little insight into the real-time status of the physical environment and the impact it has, and often lacks high spatial resolution. As some variables of the urban environment can vary greatly during the day, this real-time data can provide additional insight for the end-user. For instance, looking at the way temperature differs during the day (diurnal temperature range), this

can have large effects on health and even mortality (Lim et al., 2012). In order to add value for the end-user and support decision-making with regard to Urban Health, an Urban Health Index (UHI) is proposed. The UHI is a combination of real-time sensor data and relevant static variables in order to gain a comprehensive insight. This study will explore the validity and added value of a real-time sensor network in order to gain insight into the urban situation of the city of Eindhoven, the Netherlands. The proposed application provides end-users the ability to base certain choices on Urban Health data.
Firstly, the theoretical background concerning possible Urban Health indicators will be explored. After which the methods used to create and visualize a comprehensive Urban Health Index (UHI) will be discussed. The results of these methods are discussed and the validity of the proposed design are shown. Lastly, a conclusion is drawn and possibilities for further research are mentioned.

2. Background

In order to define the concept of Urban Health, this research suggests that a definition of Urban Health can best be approached by investigating relevant indicators of Urban Health. A definition of a good indicator is given by (Briggs, 1999): an indicator must "meet the needs of their users, who are often not experts in the subject matter or the idiosyncrasies of the data, they must provide a relevant and meaningful summary of the conditions of interest. In order to satisfy the wider community — including those who might wish to challenge the message they give — they must be transparent, testable and scientifically sound. If they are to detect variation or change in the world they describe, they must be sensitive to real changes in the conditions they measure, yet robust enough not to be swamped by noise in — or minor differences in the source of — the data used. If they are actually to be developed and used, they must be cost-effective to compile and apply" (Briggs, 1999). Following this definition, the existing body of literature provides many possible indicators, most of which fit into either of three categories: climate, environment or social indicators (Galea and Vlahov, 2005). As this research is concerned with a practical method of providing Urban Health information, a selection is made among the found indicators, based on frequency in the literature, measurability and interpretability. First of the used indicators is humidity (Yang et al., 2017; Leitte et al., 2009; English et al., 2009; Schneider-Skalska, 2019). Humidity is mentioned to have a variety of adverse health effects in an urban setting. English et al. (2009) state that humidity might enhance the effects of temperature on inhabitant's health, advising to consider "apparent temperature, or the use of a heat index, which combines humidity and temperature, is important in looking at mortality effects" (English et al., 2009). Conversely, it has been suggested that air which is too dry (low humidity) aggravates the effect of particles and SO_2 in the air on chronic bronchitis (Leitte et al., 2009). Moreover, a frequently found indicator is temperature (Galea and Vlahov, 2005; Basu and Samet, 2002; Kjellstrom et al., 2007; English et al., 2009; Ebi et al., 2008; Braubach and Fairburn, 2010). The effect of temperature on health can be attributed to several aspects. Firstly, Kjellstrom et al. (2007) mention the effect of the Urban Heat Island (UHI) where the effect of heat waves are exacerbated in urban areas by lingering heat. Furthermore, "heat waves affect human health via heat stress, heath stroke, and death, as well as exacerbation of underlying conditions that can increase mortality. The frequency and intensity of heat events and heat-related deaths are projected to increase with climate change" (Ebi et al., 2008). Also, lingering heat in the nighttime might be of significance, as "physiologic recovery from daytime heat is hampered if temperatures during the night do not decrease sufficiently" (English et al., 2009). In addition, Lim et al. (2012) states that rapid temperature changes during the day are related to higher mortality levels. Besides these seemingly related indicators, urban noise is also found to be negatively related to health (Galea and Vlahov, 2005; Weaver et al., 2014; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010). The effects of noise have been argued to be both physical and cognitive. Physically, noise "increases the occurrence of hypertension and cardiovascular disease" (Basner et al., 2014), while also being the "main cause of environmental annoyance, and it negatively affects the quality of life of a large proportion of the population" (Clark and Stansfeld, 2007). This latter study also states that cognitive effects, "although modest, may be of importance given the number of people increasingly exposed to environmental noise and the chronic nature of exposure" (Clark and Stansfeld, 2007). These findings are underscored by Basner et al. (2014) as extended noise exposure might disturb sleep, cause daytime sleepiness and impairs cognitive performance in schoolchildren. Lastly, the indicator most frequently mentioned in existing research is Air Quality (Galea and Vlahov, 2005; Weaver et al., 2014; Leitte et al., 2009; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010; Briggs, 1999; English et al., 2009). The effects of air quality are mostly stated as being physical, like the increase of chronic bronchitis observed by Leitte et al. (2009), however, the economic effects of increased pollution are also quite severe. This has been thoroughly explored by Sullivan (2016).

Besides climate indicators, environmental indicators are also included in this research. First of these indicators is traffic safety or accidents (Hasselaar, 2021; Frumkin, 2002). Briggs (1999) reports in the name of the WHO: "Motor vehicle accidents continue to be a major cause of death and injury throughout the developed world, and are increasing in many developing countries." Related to the issue of traffic, is the walkability of certain areas (Galea and Vlahov, 2005; Kjellstrom et al., 2007). "A considerable body of research establishes that sprawl — as measured by low residential density, low employment density, low 'connectivity', and other indicators — is associated with less walking and bicycling and with more automobile travel than denser communities" (Frumkin, 2002). Therefore, it becomes clear that a sedentary lifestyle is indeed related to certain characteristics of the urban environment. In turn, "low levels of physical activity threaten health both directly and indirectly. A sedentary lifestyle is a well established risk factor for cardiovascular disease, stroke and all-cause mortality" (Frumkin, 2002). Supplementing the walkability of urban areas is the availability of green spaces (Krieger and Higgins, 2002; Frumkin, 2002). The effect of green spaces on health can be both physical and mental. As mentioned by Schneider-Skalska (2019), "abundant research on the influence of greenery, water and natural landscape on recovering from stress and intellectual fatigue shows that the role these factors play is absolutely invaluable." In addition, "lower percentage of natural area cover was correlated with deficits in viso-motoric development of children, as well as areas with lower natural area per capita had significantly higher values of childhood overweight" (Kabisch et al., 2016).

The mentioned indicators will be used in this research to construct one UHI in order to provide Urban Health information to the end-user. As has been mentioned, these indicators are selected for relevance and practicality, therefore, social indicators are not included in this research as they are often hard to measure and consider subjective variables.

3. Methodology

In order to transform the found indicators into useful information, several steps are proposed. Firstly, the requirements of the end-users need to be investigated, as these requirements form the basis for the system design. Secondly, the found indicators need formal definition which allow for the calculation of the UHI sub-indices. Lastly, the architecture of the system implementation needs to be defined.

3.1 End-user Research

In order to discover end-user preferences, a survey was spread among the public, without specific selection criteria. The survey returned 56 respondents, the results of which are discussed below.
To gain insight into current behavior concerning location-based applications, it was found that the most used application is Google Maps (n=49). Moreover, the current use of these applications is mostly concerned with routing: selecting the optimal route before, or during, a trip (n=46). This preference is underscored by the fact that respondents stated that their reason for using their current location-based application is because of the way routing is implemented (n=31).
When asked how they would use Urban Health information in this context, a clear difference to their current use-patterns was detected. For short-term decision-making, respondents stated that choosing the healthiest leisure locations was most preferred (n=43). Moreover, combined with the

option of selecting the most healthy travel destination, a total of 62 respondents prefer selecting healthy locations over the selection of healthy routes (n=13). Similar results were found with regard to long-term decision-making. Here, 36 respondents stated that their preferred use would be the selection of residence or other long-term location. Therefore, the proposed system and application will be concerned with the selection of healthy locations, instead of the selection of healthy routes.

3.2 UHI Definition

To define the UHI, each indicator stated previously is transformed into an index, based on found acceptable values. Firstly, Air Quality is based on the Common Air Quality Index (CAQI), defined by Elshout et al. (2012). This index includes values for Nitrogen Dioxide, PM2.5, PM10 and Carbon Monoxide. These values are considered with a one-hour average (or 24-hour average) and each have acceptable levels. As a final index score, the worst scoring variable is used, providing a score between zero and 100 (which will later be converted to a zero to one scale). Secondly, the temperature and humidity indicators are combined into a heat index (English et al., 2009). Heat (also known as apparent temperature) has been mentioned to have a significant impact on urban health and is therefore preferred over separate measures for humidity and temperature. The values for heat are transformed using a min-max normalization based on the minimum and maximum values found by Basu and Samet (2002). Thirdly, a noise index is proposed based on the suggested value of Héroux et al. (2020) in the name of the WHO. This research proposes a maximum daytime noise level of 53 dB, while nighttime values should be limited to 45 dB. This index is designed as a binary value, where a value of zero is returned when the suggested values are exceeded. Fourthly, green space values are also based on advice of the WHO. Where the minimal green space per inhabitant is set at 9 m^2, while an optimal area is set at 50 m^2 (Russo and Cirella, 2018). Similar to heat, this index is transformed using a min-max normalization based on these values, returning one for all values above 50 m^2, and zero for all values below 9 m^2 per inhabitant. Fifthly, traffic safety is based on the risk-analysis method described by Shah et al. (2018), where traffic risk is the road safety outcome divided by the total exposure. In this research, road safety outcome is set to the total amount of traffic accidents in the area, while exposure is set to the inhabitants of that area. Subtracting that value from one, returns the traffic safety of that area, where one indicates that no traffic accidents occur per inhabitant, while zero indicates that every inhabitant has been part of a traffic accident (on average). Lastly, walkability is proposed as a compounded indicator consisting of dwelling density, connectivity, land use mix, and net retail area (Leslie et al., 2007). Dwelling density is the number of dwellings per square kilometer in an area. Similarly, connectivity is measured by the amount of intersections per square kilometer. Net retail area is proposed to be the measure of actual retail area compared to the total retail parcel in the area. Suggesting that a larger unused parcel area is used for parking spaces. Considering land use mix, a measure of entropy with regard to different land use types is used. When the mix of these land use types is perfectly heterogeneous, a value of one is returned, while a perfectly homogeneous value returns zero. Net retail area describes how much of the retail plot is actually occupied by a shop. The combination of these compounding indicators try to measure how likely it is that walking is used as a mode of transportation over other modes, indicating healthy behavior in that area.
The final UHI is calculated by taking the average of all found sub-index scores. No weighting is used in this average, as this research suggests that all found indicators have equal importance in defining Urban Health.

3.3 System Design

To answer the question set in this research, an application is suggested which visualizes the proposed data effectively. This application follows a predetermined system to overcome the main challenges inherent to this subject, as well as the different data types. First, the previously described indicators have different underlying data types. This research proposes that mobile sensors add a new level of accuracy to Urban Health research (O'Keeffe et al., 2019), and therefore the high spatial resolution must be maintained as much as possible. However, some static data elements underlay the UHI, therefore, a compromise must be made. This is achieved by collecting the dynamic data points in a hexagonal grid, which also collects the static data elements. The mesh size of this grid still allows for the investigation of Urban Health with a rather high spatial resolution, while combining data with different resolutions. The proposed system will communicate this grid in a visualized manner, informing the end user on the gathered data. The process by which the data is gathered, processed and visualized follows several steps. Firstly, the data from the mobile sensors is gathered into a central database. As the static data is unchanging by definition, this only needs to be created and stored once, which can be done locally. The data processing is suggested to follow several sub-steps. First, check for each hexagon all the included data points which fall into the selected time frame. This time frame can be decided by the end-user, however, it is suggested to select the shortest possible time frame initially (one hour). Using the aggregated data points and the data inherent to that hexagon, each sub-index can be calculated for that hexagon. This information can be visualized in order to inform the end-user on the most recent Urban Health situation of the entire city. In order to inform end-users on the progression of Urban Health over a longer time period, the necessary data can also be collected within a longer time frame. The different visualization methods will be discussed in the next section.

4. Results

Implementing the methods described above, a prototype application is created following three distinct functions, these functions follow the background, end-user research, and methods described above. Firstly, the application educates the user on the relevant information to gain more insight in the calculation methods for the UHI and how to operate the application. As described above, Urban Health can be an unknown topic to the end-user, therefore, this function was included in the application to maximize information discovery possibilities through the application. The second function follows the hexagonal grid described in the previous section. This grid is projected onto a map of the city and allows the user to discover the healthiest location in the city. This research proposes that a color coding system is most suitable for displaying the hexagonal grid, as this allows for relatively easy discrimination between areas. Several functions are added in order to provide maximal utility. Firstly, the user can automatically select the best scoring location. While the proposed color coded system is appropriate for course discrimination between areas, exact comparisons can be cumbersome. Moreover, the user is able to filter the shown results based on personal preference. While the UHI is designed to give a comprehensive insight into Urban Health, individual users might be interested into different aspects of Urban Health based on personal situations. As mentioned, a differentiation is made between short- and long-term data, where the visualization function above is suited for short-term data. For long-term data, a user can select a location of interest which shows them the long-term data of that location. Firstly, the individual sub-indices of that area are shown. However, the most prevalent goal of this visualization is to show the progression of the UHI and relevant sub-indices over a longer time period. This is best done by visualizing a graph with multiple lines for the UHI and dynamic sub-indices. This enables the user to see the general trend of these indices and subtract relevant information from that graph.

The full prototype of this application can be viewed at urbanhealthindex.com. This version of the application is made as an iteration to the original after conducting a validation test among eight users. These users were asked to complete several tasks using the application. After each test, they were asked to rate both ease of use, and the usefulness of the information they gained in that task. This test has shown that the proposed system and implementation are experienced as a suitable method for informing users on Urban Health, using dynamic and static data. Overall, ease of use is rated with a 7.9, while the usefulness of information is rated an 8.2.

5. Conclusion & Discussion

This research has investigated the possibilities of real-time and static urban data, and how to use that data to provide urban health information for short- and long-term decision-making. Here, urban health was defined by several urban health indicators. As urban health is rather unknown subject to most inhabitants of cities, these indicators were chosen to provide more concrete information about this topic. Still, this research proposes that providing actual data on the performance of these indicators is not an effective way of communicating urban health information. Therefore, these indicators are translated into one comprehensive Urban Health Index (UHI). This index translates raw data on urban health indicator performance into an interpretable scale. This index is deemed to be a more effective tool to support decision-making of end-users.

In order to create this index, several important aspects were explored in this research. Firstly, both temporal and spatial resolution difference pose a challenge to creating one comprehensive overview of this type of data. As has been discussed, the static data elements are mostly collected on a neighborhood scale, while the dynamic data elements are collected as individual points. The goal of this research was to explore the advantages of dynamic data observed by mobile sensors, and therefore the high spatial resolution of this data should be maintained as much as possible. However, to compromise between these two resolutions, a grid structure is proposed in order to combine the different data elements. This grid can communicate the overall index, and the differing sub-indices, while maintaining a relatively high spatial resolution. Besides a spatial resolution difference, the data is also spread across time, therefore, a differentiation is proposed to show information across time. The main manner in which the index is communicated is using the most recent data, as this was shown to be among the most prevalent use cases proposed by end-user research. However, in order to also provide information to support long-term decision-making, an aggregation of information is also communicated over different time scales. Secondly, as has been briefly mentioned, the requirements of end-users has shown how this type of information would be used in location-based applications. While the current use of application based information is mostly concerned with route choice, urban health information would mostly be used for optimal location choice. Therefore, the proposed index and grid are designed to allow for optimal location choice, rather than creating optimal (healthy) routes.

This research describes an application which overcomes these challenges and provides several advantages over more traditional representations of urban health. As has been mentioned, most research into urban health is based on static data collection. This data gives much insight into urban health of certain locations and regarding certain indicators, however, more insight can be gained by extending this framework with the proposed dynamic data collection. Applying the proposed system, a holistic view of a city can be developed and problem areas regarding urban health can be located and targeted by end-users. These areas can be targeted by policymakers for development, or inhabitants as an instigator of residential relocation. In both cases, the system this research proposes allows for more exact decision-making with regard to urban health, making urban health a more prominent consideration within the decision process.
Moreover, implementing a working variant of the proposed system could be a basis of more research into urban health indicators as more exact relationships between urban health determinants and adverse health effects can be determined. As mentioned, the high spatial resolution is maintained in the system and therefore, problematic health outcomes can be deconstructed to more exact regions. This can be related to the urban health indicators of that area, allowing for more research to be done with regard to their relationship.

Relating back to the main question posed by this research, several answers can be given. Regarding the question of how real-time and static urban data can be used to provide urban health information for short- and long-term decision-making, it has become clear that an UHI combining different spatial and temporal resolutions is an effective way to communicate urban health information. Based on literature review, this index was constructed based on six different indicators: Air Quality, Heat, Noise, Green Spaces, Walkability and Traffic Safety. Different measurement and processing methods accompany these indicators, the results of which are combined into the final UHI. Moreover, end-user research has indicated that this index would mostly be used for the selection of optimal locations, which forms the basis of the results of this research. While the question was initially posed who the relevant end-users could be, this research has assumed a more general approach, surveying the public at large in order to form a general use case for this type of information. As has been discussed, the collection and merging of the data is mostly concerned with the differing spatial and temporal resolutions. This challenge can best be overcome by combining the data elements into one hexagonal grid, maintaining the high spatial resolution were possible. Lastly, the question was posed how this data can best be represented to the end-user. This research proposes the visualize the data differently based on the differing time scales. First, visualizing the most recent data (based on end-user research), while also allowing for more detailed visualization over larger time scales.

As has been mentioned, this system allows for a more exact exploration of the relationship between urban health indicators and adverse health effects. Therefore, future research could use this system to validate the predictive effectiveness of the proposed indicators. While the proposed indicators are based on the existing body of literature, a strong relationship between these indicators and health outcomes should be established. Moreover, additional indicators should be added where necessary. As the system is designed to allow for such changes, several iterations of the system could be compared to evolve the design further.

Besides the relationship between the proposed indicators and health outcomes, further development of the system could implement predictive elements making use of the increasingly growing field of machine learning. Implementing efficient algorithms to predict urban health developments in certain areas could assist end-users in making more informed decisions about the future. As an example, inhabitants can now choose to take the car because it is predicted to rain today, but the proposed system could tell them to take the bike when urban health is predicted to be good that day in the area. Such systems could also provide valuable information to policy-makers and urban developers, anticipating worsening urban health conditions and implementing interventions before adverse health effects occur.

Requirements provided by the end-user should inform further development of the system. This research initially set out to define different end-users, however, a more general approach was taken to define general end-user requirements. Therefore, further research should be done on the requirements of different end-user categories. This research has described possible differences between inhabitants and policy-makers, however, it should be determined how their requirements differ, if they differ at all. A suggestion would be that policy-makers are in need of more exact data, therefore, actual performance indicators could be provided to that end-user category. As an example, inhabitants could be informed by the Air Quality sub-index, while policymakers are informed by actual Carbon Monoxide, Particulate Matter and Nitrogen Dioxide levels. More in-depth research could indicate if such a difference is necessary and how this would influence the design of the system.

Finally, the sensor design principle should be investigated further. This research has shown the potential of such sensors, but has not gone into detail on the actual design of such sensors. Therefore, future research should indicate how such sensors can be realized in a cost-effective manner, also suiting the requirements set out in this research.

Samenvatting

Het verstrekken van op locatie gebaseerde gezondheidsinformatie, door middel van dynamische, verzamelde en statische stedelijke informatie

Het doel van dit onderzoek was om een efficiente methode te ontwikkelen om stedelijke gezondheidsinformatie te verstrekken ter ondersteuning van korte- en lange termijn besluitsvorming, gebruik makende van mobiele sensoren en statische data. Een lijst van zes variabelen (Luchtkwaliteit, Hitte, Lawaai, Groen, Beloopbaarheid en Verkeersveiligheid) is gevormd als de basis voor de Urban Health Index (UHI). Omdat zowel dynamische als statische data gebruikt worden in de UHI, word een zeshoekig raster gebruikt om de scores voor elke locatie te visualiseren. Dit raster combineerd de ruimtelijke resoluties van beide data types, terwijl een zo hoog mogelijke resolutie wordt behouden. Bovendien, laat eindgebruiker onderzoek zien het huidige gebruik van applicaties gebaseerd op locatie voornamelijk gericht is op het selecteren van optimale routes. Daarentegen geven respondenten aan dat zou stedelijke gezondheidsinformatie voornamelijk zouden gebruiken voor het selecteren van optimale locaties. Daarom vormt dit de basis voor de applicatie die dit onderzoek voorsteld. Deze applicatie bestaad uit drie lagen, elke met een specifieke functie. The home-page leert de gebruiken over de UHI en hoe deze te gebruiken is. Het centrale punt van de applicatie is een kaart van de stad (Eindhoven, Nederland) met het eerder genoemde raster hier op geprojecteerd. Het doel van dit deel van de applicatie is om de data te onderzoeken op een lagere resolutie. Specifieke locaties kunnen worden onderzocht door middel van de individuele sub-index scores en een historische progressie van de UHI en relevante sub-indexen. Validatie testen laten zien dat dit een relatief effectieve manier is om deze soort informatie te communiceren, echter moet er meer onderzoek gedaan worden naar de relatie tussen de indicatoren en gezondheidsrisico's. Verder moet het onderzocht worden of er verschillende eindgebruiker categoriëen zijn met verschillende voorkeuren. Deze voorkeuren kunnen leiden tot nieuwe iteraties van de voorgestelde applicatie en onderliggend systeem.

Keywords – Stedelijke gezondheid, Mobiele Sensoren, GIS, Dashboard, Data Visualisatie

1. Introductie

Gezien de aanhoudende verstedelijking word het thema van stedelijke gezondheid steeds belangrijker en zijn enkele aspecten van dit onderwerp al onderzocht, zoals de fysieke omgeving, de sociale omgeving en toegang tot gezondheidszorg en sociale ondersteuning (Galea and Vlahov, 2005). Meerdere variabelen worden overwogen in het definiëren en meten van stedelijke gezondheid, echter worden deze variabelen voornamelijk op een statische manier gebruikt (Leidelmeijer et al., 2014; Leitte et al., 2009). Met deze methode kan er veel geleerd worden over de relatie tussen gezondheid

en stedelijke aspecten, echter geeft het weinig inzicht in de real-time status van de fysieke omgeving en de impact dit heeft, bovendien ontbreekt het deze methode aan hoge ruimtelijke resolutie. Omdat sommige stedelijke variabelen sterk kunnen variëren gedurende de dag, kan real-time informatie extra inzichten creëren voor de eindgebruiker. Bijvoorbeeld, kijkende naar de manier waarop temperatuur kan veranderen gedurende de dag (diurnal temperature range), kan dit grote gevolgen hebben op de gezondheid en sterfte in een regio (Lim et al., 2012). Om deze toegevoegde waarde te bieden voor de eindgebruiker word in dit onderzoek een Urban Health Index (UHI) voorgesteld. De UHI is combinatie van real-time sensor data en relevante statische elementen, om een omvangrijk inzicht te geven in de stedelijke gezondheid. Dit onderzoek zal focussen op de manier waarop deze nieuwe methodologie gebruikt kan worden in Eindhoven (Nederland) en verondersteld dat deze informatie gebruikt kan worden door de eindgebruiker om bepaalde keuzes te ondersteunen.
Eerst zal de theoretische achtergrond over stedelijke gezondheid worden besproken. Daarna zal de methode gebruikt in dit onderzoek worden uitgelegd en tot slot de resultaten van het implementeren van deze methode.

2. Achtergrond

Om het concept van stedelijke gezondheid te definiëren, gebruikt dit onderzoek indicatoren om stedelijke gezondheid te benaderen. Een definitie van een goede indicator word gegeven door (Briggs, 1999): een indicator moet "aan de eisen voldoen van de gebruiker, die vaak geen expert binnen het onderwerp of de eigenaardigheden van de data, en ze moeten een relevante en betekenisvolle samenvatting geven over de stand van zaken. Om aan de eisen te voldoen van de samenleving, inclusief hen die misschien de boodschap willen betwisten, moeten de indicatoren transparant, testbaar en wetenschappelijk onderbouwd zijn. Als men daadwerkelijke variaties wil ontdekken in de wereld die ze beschrijven, moeten ze gevoelig zijn voor werkelijke veranderingen, toch robuust genoeg niet te verdwijnen in ruis. Als ze daadwerkelijk gebruikt en ontwikkeld willen worden, moeten ze kosten efficiënt zijn in gebruik" (Briggs, 1999). Gezien deze definitie, kunnen er meerdere indicatoren worden ontdekt in de bestaande literatuur, welke in een van drie categorieën passen: klimaat, omgeving of sociale indicatoren (Galea and Vlahov, 2005). Gezien dit onderzoek gericht is op praktische toepassingen, is er een selectie gemaakt onder de gevonden indicatoren gebaseerd op gevonden frequentie, meetbaarheid en interpreteerbaarheid. De eerste van deze indicatoren is luchtvochtigheid (Yang et al., 2017; Leitte et al., 2009; English et al., 2009; Schneider-Skalska, 2019). Luchtvochtigheid word genoemd als de oorzaak van een verscheidenheid aan nadelige gezondheidseffecten in een stedelijke omgeving. English et al. (2009) noemen dan luchtvochtigheid de kans kan vergroten van temperature op inwoners' gezondheid, en adviseren daarom "schijnbare temperatuur, of het gebruik van een hitte-index, die luchtvochtigheid en temperature combineert, wat belangrijk is in relatie to sterfte" (English et al., 2009). Omgekeerd, word er ook gesuggereerd dat een lage luchtvochtigheid het effect van SO_2 deeltjes op chronische bronchitis kan verergeren (Leitte et al., 2009). Bovendien, is een vaak genoemde indicator temperatuur (Galea and Vlahov, 2005; Basu and Samet, 2002; Kjellstrom et al., 2007; English et al., 2009; Ebi et al., 2008; Braubach and Fairburn, 2010). Temperatuur kan meerdere effecten hebben op stedelijke gezondheid. Ten eerste, beschrijven (Kjellstrom et al., 2007) het effect van hitte-eilanden, waar het effect van een hitte gevolg erger is in stedelijke omgevingen omdat hitte meer blijft hangen. Verder, "beïnvloeden hittegolven de menselijke gezondheid door hitte stress, beroertes en sterfte, waar ook onderliggende aandoeningen worden verergerd. The frequentie en intensiteit van hitte momenten en hitte gerelateerde sterfte zal groeien door klimaat veranderingen" (Ebi et al., 2008). Ook is aanhoudende hitte gedurende de nacht belangrijk omdat "fysiologisch herstellen van dagelijkse hitte word beperkt als de temperatuur gedurende de nacht niet voldoende zakt" (English et al., 2009). Daarnaast, noemen Lim et al. (2012) dat snelle temperatuurschommelingen gedurende de dag zijn gerelateerd aan sterfte. Naast deze twee gerelateerde indicatoren, is een andere veel genoemde indicator lawaai (Galea and Vlahov, 2005; Weaver et al., 2014; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010). De effecten van lawaai worden geschetst als zowel fysiek als mentaal. Fysiek, "vergroot lawaai het voorkomen van hypertensie en hart- en vaatziekte” (Basner et al., 2014), terwijl lawaai ook ”de grootste oorzaak is van irritatie, en het een negatief effect heeft op een groot gedeelte van de populatie” (Clark and Stansfeld, 2007). Dit laatste onderzoek beschrijft ook de mentale effecten als ”hoewel bescheiden, kan het belangrijk zijn omdat een steeds groter wordende groep mensen word bloot gesteld aan omgevingslawaai en het vaak om chronische blootstelling gaat” (Clark and Stansfeld, 2007). Dit inzicht word gedeeld door Basner et al. (2014) en beschrijven hoe langdurige blootstelling slaap kan verstoren, slaperigheid kan veroorzaken en cognitieve prestaties kan verhinderen bij kinderen. Tot slot, de meest genoemde indicator is luchtkwaliteit (Galea and Vlahov, 2005; Weaver et al., 2014; Leitte et al., 2009; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010; Briggs, 1999; English et al., 2009). De effecten van slechte luchtkwaliteit worden vooral beschreven als fysiek, zoals het toenemen van chronische bronchitis Leitte et al. (2009), echter, zijn de economische gevolgen ook vrij ernstig zoals onderzocht door Sullivan (2016).

Naast klimaat indicatoren, worden omgevingsindicatoren ook meegenomen in dit onderzoek. De eerste van deze indicatoren is verkeersveiligheid (Hasselaar, 2021; Frumkin, 2002). (Briggs, 1999) omschrijft namens het WHO: ”Motor voertuig ongelukken blijven een grote oorzaak van sterfte en verwonding in eerstewereldlanden, en nemen toe in derdewereldlanden.” Gerelateerd aan verkeer, is de indicator van beloopbaarheid van bepaalde regio’s (Galea and Vlahov, 2005; Kjellstrom et al., 2007). ”Aanzienlijk onderzoek heeft bepaald dat stedelijke groet – gemeten door lage woondichtheid, lage werkdichtheid, lage verbindingsdichteid, en andere indicatoren - is gerelateerd met minder lopen en fietsen, en meer auto vervoer dan steden met hogere dichtheid” (Frumkin, 2002). Het is daarom duidelijk dat een inactieve levensstijl gerelateerd is aan bepaalde stedelijke factoren. Verder, ”heeft een inactieve levensstijl zowel directe als indirecte bedreigingen voor de gezondheid. Een inactieve levensstijl is een goed onderzochte risico factor voor hart- en vaatziekte, beroerte en algemene sterfte” (Frumkin, 2002). Een toevoeging aan beloopbaarheid, is de hoeveelheid beschikbaarheid van groen in een omgeving (Krieger and Higgins, 2002; Frumkin, 2002). De effecten van groen kunnen zowel fysiek als mentaal zijn. Zoals genoemd door Schneider-Skalska (2019), ”overvloedig onderzoek naar de invloed van groen, water en natuurlijk landschap op het herstellen van stress en intellectuele vermoeidheid laat zien dat de rol die deze factoren spelen waardevol is.” Bovendien, ”is een lager percentage of natuurlijk gebied gerelateerd aan een gebrek aan visueel-motorische ontwikkeling bij kinderen, evenals heeft een lager natuurlijk oppervlak per inwoner als gevolg een significant hoger percentage overgewicht bij jeugd” (Kabisch et al., 2016).

De genoemde indicatoren zullen worden gebruik om een UHI te creëren en stedelijke gezondheidsinformatie te voorzien aan de eindgebruiker. Zoals genoemd, zijn deze indicatoren geselecteerd op basis van relevantie en praktische waarde, daarom zijn sociale indicatoren niet genoemd. Deze indicatoren zijn vaak moeilijk te meten omdat ze subjectieve variabelen in kaart brengen.

3. Methodologie

Om de eerder beschreven indicatoren te transformeren in bruikbare informatie, stelt dit onderzoek enkele stappen voor. Ten eerste, worden de voorkeuren van de eindgebruiker onderzoek, omdat deze de basis vormen voor het voorgestelde systeem. Ten tweede, worden er formele definities geformuleerd voor de indicatoren wat het mogelijk maakt een UHI te creëren. Tot slot, word een structuur beschreven voor het implementeren van het systeem.

3.1 eindgebruiker Onderzoek

Om de voorkeuren van de eindgebruiker in kaart te brengen is er een enquête verspreid, zonder te selecteren voor specifieke doelgroepen. Deze enquête is ingevuld door 56 respondenten, waarvan de belangrijkste resultaten hier beschreven staan. Om zicht te krijgen in de manier waarop locatie-applicaties op dit moment gebruikt worden is men gevraagd wat hun meest gebruike applicatie is op dit moment, waarop het merendeel van de respondenten aangaf Google Maps te gebruiken (n=49). Bovendien, is hun gebruik vooral gericht op het selecteren van routes, zowel voor als tijdens hun reis (n=46). Deze conclusie word herhaald door het feit dat men aangeeft een voorkeur te hebben voor hun huidige applicatie omdat routes prettig worden geïmplementeerd (n=31). Wanneer men echter gevraagd word hoe ze stedelijke gezondheidsinformatie zouden gebruiken, word een duidelijk ander antwoord gegeven. Voor beslissingen op de korte termijn geeft men aan zij deze informatie vooral zouden gebruiken voor het kiezen van gezonde recreatie locaties (n=43). Gecombineerd met het kiezen van een gezonde reis locatie, geeft een totaal van 62 respondenten aan een voorkeur te hebben voor het kiezen van locaties, in contrast met het kiezen van een route. Vergelijkbare resultaten waren gevonden voor keuzes op de lange termijn. 36 respondenten gaven aan een voorkeur te hebben voor het selecteren van een locatie om te wonen of andere lange termijn locaties. Op basis van deze resultaten word verondersteld dat het voorgestelde systeem gericht moet zijn op het selecteren van locaties, in tegenstelling tot het kiezen van routes.

3.2 UHI Definitie

Om de UHI te definiëren word iedere indicator getransformeerd tot een index, gebaseerd op onderzochte acceptabele waardes. Ten eerste, word de luchtkwaliteit index gebaseerd op de Common Air Quality Index (CAQI), zoals beschreven door Elshout et al. (2012). Deze index is gevormd door waardes voor Stikstof Dioxide, PM2.5, PM10 en Koolstofmonoxide. Deze waardes worden gemeten met een gemiddelde per uur (of dag) en hebben verschillende toegestane waardes. De index score word bepaald door de slechts scorende variabele, en valt tussen nul en 100 (deze waarde word later geschaald tussen nul en een). Ten tweede, worden temperatuur en luchtvochtigheid gecombineerd tot de hitte-index (English et al., 2009). Hitte (ook wel schijnbare temperatuur genoemd) is eerder genoemd, en heeft een significante impact op stedelijke gezondheid en word daarom geprefereerd boven aparte indexen voor temperatuur en luchtvochtigheid. De gevonden waardes voor de hitte-index worden getransformeerd door een min-max normalisatie, gebaseerd op de minimale en maximale waardes gevonden door Basu and Samet (2002). Ten derde, word de lawaai-index gebaseerd op de waardes gevonden door Héroux et al. (2020) onder naam van de WHO. Dit onderzoek stelt dat een maximaal geluidsniveau gedurende de dag 53 dB is, terwijl een maximaal geluidsniveau gedurende de nacht 45 dB is. Deze index heeft een binaire vorm, waar een nulwaarde word gegeven wanneer de beschreven grens word overschreden. Ten vierde is de groen index ook gebaseerd op advies van deWHO. Hier, het minimale groen oppervlak per inwoner is vastgesteld op 9 m^2, terwijl een optimaal oppervlakte per inwoner 50 m^2 is (Russo and Cirella, 2018). Vergelijkbaar met de hitte-index, word de groen index getransformeerd met een min-max normalisatie gebaseerd op deze waardes, waar een maximale score word gegeven voor oppervlaktes boven 50 m^2 en een nulwaarde voor oppervlaktes onder 9 m^2. Ten vijfde, word de verkeersveiligheids-index gebaseerd op de risicoanalyse methode beschreven door Shah et al. (2018), waar verkeersrisico word gedefinieerd door het verkeersveiligheidsresultaat gedeeld door de totale blootstelling. In dit onderzoek is verkeersveiligheidsresultaat het aantal verkeersongelukken in een regio en blootstelling het aantal inwoners in die regio. Als deze waarde van een word afgetrokken, geeft dat de verkeersveiligheid in die regio. Bij een nulscore gebeuren er dus geen ongelukken per inwoner (gemiddeld), terwijl een score van een aangeeft dat iedere inwoner gemiddeld een ongeluk heeft. Tot slot, is de beloopbaarheid-index een samenstelling van vier variabele: woningdichtheid, verbindingsdichtheid, landgebruik combinatie en netto winkeloppervlakte (Leslie et al., 2007). Woningdichtheid word berekend door het aantal woningen per vierkante kilometer. Vergelijkbaar, is verbindingsdichtheid het aantal kruispunten per vierkante kilometer. Landgebruik combinatie word gemeten door de mate van entropie in relatie tot de verschillende landgebruik types. Wanner de mix van deze landgebruik types perfect heterogeen is, is dat een score van een, echter, wanneer deze mix perfect homogeen is is dat een nulscore. Netto winkeloppervlak meet hoeveel vierkante meter van het beschikbare stuk land bezet word door een winkel. De combinatie van deze sub-indicatoren meten in hoeverre deze regio aantrekkelijk is om in te lopen, wat een indicatie is van gezond reisgedrag.

De UHI is vervolgens berekend door het gemiddelde te nemen van de subindex scores. Deze subindexen worden ongewogen meegenomen in het gemiddelde, omdat dit onderzoek verondersteld dat ze een vergelijkbare invloed hebben op stedelijke gezondheid.

3.3 Systeem Ontwerp

Om de centrale vraag van dit onderzoek te beantwoorden, word een applicatie voorgesteld die voorgestelde data effectief kan visualiseren. Deze applicatie volgt een systeem dat is ontworpen om de belangrijkste uitdagingen inherent aan dit onderwerp en soort data te boven te komen. Ten eerste hebben de eerder beschreven indicatoren verschillende onderliggende data types. Dit onderzoek verondersteld dat mobiele sensoren een nieuw niveau van precisie toevoegen aan onderzoek binnen stedelijke gezondheid (O'Keeffe et al., 2019) en daarom moet de hoge ruimtelijke resolutie zoveel mogelijk worden behouden. Daarentegen, ligt er aan de basis van de UHI ook statische data met een lagere ruimtelijke resolutie, daarom moet er een compromis worden gemaakt. Dit wordt gedaan door de dynamische data punten te verzamelen in een zeshoekig raster dat ook het verzamelen van de statische data toelaat. De grootte van de zeshoeken behoud de mogelijkheid om stedelijke gezondheid te onderzoeken met een hogere ruimtelijke resolutie, terwijl de verschilde data typen gecombineerd worden. Het voorgestelde systeem zal dit raster visueel communiceren, wat de informatie overbrengt naar de eindgebruiker. Het proces waarmee de data wordt verzameld, verwerkt en gevisualiseerd volgt enkele stappen. Ten eerste worden allen data punten verzameld in een centrale database. Omdat de statische data, per definitie, onveranderlijk is, wordt deze een keer gecreëerd en (lokaal) opgeslagen. Hierna, word voor iedere zeshoek gecontroleerd welke data punten in deze zeshoek liggen en binnen de geselecteerde tijds periode vallen. Deze periode kan geselecteerd worden door de eindgebruiker, echter, suggereert dit onderzoek dat een zo kort mogelijke periode gebruikt word (een uur). Gebruik makende van de verzamelde data punten en data inherent aan de zeshoek kan de UHI worden berekend voor die zeshoek. Deze informatie kan vervolgens worden gebruikt op een visuele manier voor de eindgebruiker. Om de eindgebruiker te informeren over de progressie van de UHI over een langere periode, kan de nodige informatie ook worden verzameld over deze periode. De verschillende visualisaties worden besproken in de komende paragrafen.

4. Resultaat

De uitvoering van deze methode leidt tot drie functies, gebaseerd op de achtergrond, eindgebruiker onderzoek en beschreven methode. Ten eerste leert de eindgebruiker in de applicatie over het relevante informatie om meer inzicht te krijgen in de definities van de UHI en hoe de applicatie gebruikt kan worden. Zoals eerder genoemd, kan stedelijke gezondheid een onbekend begrip zijn voor eindgebruikers, daarom is deze functie toegevoegd aan de applicatie. De tweede functie is gericht op het visualisatie van het zeshoekige raster. Dit raster is geprojecteerd op een kaart van de stad en stelt de eindgebruiker in staat gezonde locaties in de stad te ontdekken. Dit onderzoek maakt gebruik van een kleurschema om de scores per zeshoek te visualiseren, wat makkelijk onderscheid tussen scores mogelijk maakt op grote schaal. Meerdere functies zijn hier aan toegevoegd om meer functionaliteit te brengen. Ten eerste, kan de eindgebruiker automatisch de best scorende locatie in de stad selecteren. Hoewel het kleurschema gebruikt kan worden om meerdere locaties te vergelijken, is deze methode ongeschikt voor het vinden van de absoluut beste waarde. Verder, is de eindgebruiker in staat de resultaten te filteren op basis van persoonlijke voorkeur. De UHI is ontworpen om een omvangrijke indicatie te geven van stedelijke gezondheid, kan het voorkomen dat eindgebruikers meer geïnteresseerd zijn in bepaalde aspecten van stedelijke gezondheid. Zoals eerder beschreven, word er onderscheid gemaakt tussen korte termijn en langetermijndata. Voor het onderzoeken van langetermijndata, kan de eindgebruiker een locatie selecteren. Hier worden de scores voor de subindexen weergegeven. Echter, is het belangrijkste aspect van deze functie het weergeve van de historische progressie van de UHI en relevante subindexen. Dit wordt gedaan door een tijdgrafiek die de eindgebruiker in staat stelt de belangrijkste trend te ontdekken.

Het volledige prototype van deze applicatie kan worden bekeken op urbanhealthindex.com. Deze versie van de applicatie is een tweede iteratie op basis van een validatie test met acht gebruikers. Deze gebruikers is gevraagd enkele opdrachten te volbrengen binnen de applicatie. Na iedere opdracht is hen gevraagd een gebruiksvriendelijkheid- en bruikbaarheidscore te geven. Deze test heeft laten zien dat de beschreven methode en applicatie een effectieve manier zijn om dit type data te communiceren met eindgebruikers. De gemiddelde gebruiksvriendelijk werd beoordeeld met een 7.9, terwijl bruikbaarheid werd beoordeeld met een 8.2.

5. Conclusie & Discussie

Dit onderzoek heeft de mogelijkheden van real-time en statische stedelijke data onderzocht, en hoe deze data gebruikt kan worden om stedelijke gezondheidsinformatie voor korte- en langetermijnbeslissingen te ondersteunen. In dit onderzoek, stedelijke gezondheid is gedefinieerd door enkele indicatoren. Omdat stedelijke gezondheid vaak een onbekend onderwerp is voor inwoners van steden, zijn deze indicatoren gekozen om meer concrete informatie te bieden over dit onderwerp. Verder, word er geconcludeerd dat het communiceren van pure data over prestatie van deze indicatoren een ineffectieve manier is om stedelijke gezondheid te communiceren met de eindgebruiker. Daarom zijn deze indicatoren getransformeerd tot een Urban Health Index (UHI). Deze index vertaald pure data naar een interpreteerbare schaal, en word daarom voorgesteld als een meer effectieve manier om besluitvorming te ondersteunen.

Om deze index te creëren zijn enkele belangrijke aspecten onderzocht. Ten eerste, het verschil in ruimtelijke en tijdelijke resolutie een uitdaging in het creëren van een overzicht met zulke verschillende data. Zoals eerder beschreven word de statische data voornamelijk verzameld op wijkniveau, terwijl de dynamische data als individuele data punten word verzameld. Het doel van dit onderzoek was om de toegevoegde waarde van mobiele sensoren te onderzoeken, en daarom moet de hoge ruimtelijke resolutie van deze data zoveel mogelijk worden behouden. Echter, als compromis tussen deze twee resoluties, word een raster structuur voorgesteld om meerdere data types te combineren. Dit raster kan de algemene index (en subindexen) communiceren met een relatief hoge ruimtelijke resolutie. Naast een verschil op ruimtelijk niveau, kan de data ook over verschillende periodes worden gevisualiseerd, daarom worden er ook verschillende methodes voorgesteld op dit niveau. De centrale manier waarop de UHI word gecommuniceerd is met de meest recente data (afgelopen uur), gezien dit een voorname reden voor gebruik was onder eindgebruiker onderzoek. Echter, om ook lange termijn besluitvorming te ondersteunen word de informatie ook gevisualiseerd over een langere periode. Verder, is gebleken uit eindgebruiker onderzoek dat men op locatie gebaseerde applicaties voornamelijk gebruikt voor het selecteren van optimale routes. Echter, zou men stedelijke gezondheidsinformatie liever gebruiken voor het selecteren van de optimale locatie, wat de basis vormt voor het resultaat van die onderzoek.

Dit onderzoek beschrijft een applicatie die deze uitdagingen overkomt en enkele voordelen heeft vergeleken met meer traditionele representaties van stedelijke gezondheid. Zoals genoemd, is het meeste onderzoek naar stedelijke gezondheid gebaseerd op statische data. Deze data geeft veel inzicht in stedelijke gezondheid op bepaalde locaties en indicator, echter kan er meer inzicht worden gekregen door het gebruik van dit voorgestelde systeem. Met dit systeem kan er meer holistisch beeld van de stad worden ontwikkeld en probleem gebieden kunnen worden gelokaliseerd door eindgebruikers. These gebieden kunnen worden verbeterd door beleidsmakers, of kunnen een beweegreden zijn voor inwoners om te verhuizen. In beide gevallen bied dit systeem een meer exacte manier voor besluitvorming over stedelijke gezondheid, wat dit onderwerp een belangrijker onderdeel maakt van de discussie rondom stedelijke aspecten.
Bovendien, wanneer een volledige versie van dit systeem word geïmplementeerd, kan het de basis vormen voor meer precies onderzoek naar de relatie tussen stedelijke gezondheidsindicatoren en gezondheidsrisico's. Door de hoge ruimtelijke resolutie kunnen probleem gebieden exacter worden onderzocht en worden verdeeld in kleinere gebieden.

Op de centrale vraag die dit onderzoek heeft geprobeerd te beantwoorden kunnen enkele antwoorden worden gegeven. Gezien de vraag hoe real-time en statische stedelijke gezondheidsdata gebruikt kan worden om korte- en lange termijn besluitvorming te ondersteunen, kan worden geconcludeerd dat een UHI die meerdere ruimtelijke en tijdelijk resoluties combineert een effectieve methode is. Deze index is samengesteld op de resultaten van onderzoek en bestaat uit: Luchtk-

waliteit, Hitte, Lawaai, Groen, Beloopbaarheid en Verkeersveiligheid. Verschillende metingen en processen gaan gepaard met deze indicatoren, waarvan de resultaten gecombineerd worden tot te uiteindelijke UHI. Bovendien, laat eindgebruiker onderzoek zien voornamelijk gebruikt zou worden voor het selecteren van optimale locaties, wat de basis vormt voor de resultaten van dit onderzoek. Hoewel dit onderzoek in eerste instantie onderzocht wie relevante eindgebruikers zouden kunnen zijn, is uiteindelijk een meer algemeen onderzoek gedaan waarin het algemene publiek is onderzocht om zo een standaard use-case te vormen. Zoals genoemd, vormt is het verzamelen en samenvoegen van de data vooral gelimiteerd door de verschillen in ruimtelijke en tijdelijke resolutie. Deze uitdaging kan best worden overkomen door de data te verzamelen in een (zeshoek) raster, wat de hoge ruimtelijke resolutie behoud. Tot slot heeft dit onderzoek een methode ontwikkeld om deze data te visualiseren ondanks verschillende tijd intervallen. Waar de meest recente data eerst word gevisualiseerd, en meer detail word geboden bij verder onderzoek door de eindgebruiker.
Eerder is voorgesteld dat dit systeem gebruikt kan worden om een de relatie tussen stedelijke aspecten en gezondheidsrisico's nauwkeuriger te onderzoeken. Daarom moet toekomstig onderzoek uitwijzen wat de nauwkeurigheid is van de op dit moment voorgestelde indicatoren. Hoewel deze indicatoren zijn gebaseerd op onderzoek, moet er een sterk verband tussen deze indicatoren en gezondheidsrisico's worden bewezen. Daarbij kunnen nieuwe indicatoren worden toegevoegd waar nodig, omdat het systeem modulair is ontworpen kunnen toekomstige iteraties extra waarde toevoegen.

Naast deze relatie tussen de indicatoren en gezondheidsrisico's, kan verdere ontwikkeling van dit systeem een voorspelling toevoegen gebruik makende van het steeds beter ontwikkelde machine learning algoritmes. Het implementeren van efficiënte algoritmes om stedelijke gezondheid te voorspellen in bepaalde gebieden kan de eindgebruiker assisteren in het maken van beslissingen verder in de toekomst. Als voorbeeld: gebruikers kunnen op dit moment besluiten met de auto te reizen omdat er regen voorspeld is. Met dit systeem zouden ze kunnen besluiten met de fiets te gaan, omdat de stedelijke gezondheid een hoge score heeft. Dit systeem kan ook waardevolle informatie bieden aan beleidsmakers en stedelijke ontwerpers, waar ze dalende stedelijke gezondheid kunnen anticiperen en aanpassingen kunnen doen voor de gezondheid van de inwoners beïnvloed wordt.

De voorkeuren van de eindgebruiker moeten de ontwikkeling van dit systeem bepalen in de toekomst. Dit onderzoek heeft een algemene voorkeuren onderzocht onder eindgebruikers, echter kan toekomstig onderzoek uitwijzen over er verschillende eindgebruiker categorieën zijn met verschillende voorkeuren. Dit onderzoek heeft mogelijke verschillen tussen inwoners en beleidsmakers aangekaart, maar toekomstig onderzoek moet aantonen hoe deze groepen exact verschillen. Een suggestie is dat beleidsmakers meer gebaad zijn bij exacte informatie en daarom liever precieze data hebben over indicator prestaties. Ze zouden bijvoorbeeld exacte Koolmonoxide waardes willen weten van een bepaalde regio, terwijl inwoners alleen de Luchtkwaliteit-index zouden gebruiken.

Tot slot, moet het sensorontwerp in meer detail worden uitgewerkt. Dit onderzoek heeft aangetoond dat mobiele sensoren grote potentie hebben, echter is er geen ontwerp voor zulke sensoren gemaakt. Daarom moet toekomstig onderzoek aantonen hoe zulke sensoren op een kostenefficiënte manier gemaakt kunnen worden, terwijl het voldoet aan de eisen van dat onderzoek.

Contents

List of Figures

List of Code

List of Tables

Acronyms

AHP Analytical Hierarchy Process. 12

AQI Air Quality Index. xxix, 25–28

CAQI Common Air Quality Index. x, xviii, xxix, 25–28

DTR Diurnal Temperature Change. 7

EU European Union. 27

GIS Geographic Information Systems. xxiii, xxix, 4, 5, 10, 12, 14–16, 33

GUI Graphic User Interface. 15

HFMD Hand, Food and Mouth Disease. 7

KPI Key Performance Indicator. 13

OSM OpenStreetMap. 34, 35

PII Personally Identifiable Information. 13

PPM Parts Per Million. 36

UHI Urban Health Index. vii–xiii, xv–xxi, xxv, xxvii, 3, 4, 15–17, 25, 29–33, 37, 42, 44–47, 49, 50, 52–57, 59, 60, 78

UHI Urban Heat Island. viii, xx, 7

WHO World Health Organization. ix, x, xvii, xviii, 5, 6, 8, 29, 31

Chapter 1

Introduction

With the continuing urbanization rate, the topic of urban health has become more prevalent over the years and several aspects have been investigated, like the physical environment, the social environment and access to health and social services (Galea and Vlahov, 2005). Multiple (objective) variables are being considered in defining and measuring urban health, however, these variables are mostly considered statically (Leidelmeijer et al., 2014; Leitte et al., 2009). With this methodology, much insight can be gained in the relationship between health and urban aspects, however, it gives little insight into the real-time status of the physical environment and the impact it has. As some variables of the urban environment can vary greatly during the day, this real-time data can provide additional insight for the end-user. For instance, looking at the way temperature differs during the day (diurnal temperature range), this can have large effects on health and even mortality (Lim et al., 2012). In order to add value for the end-user and support decision-making with regard to Urban Health, an Urban Health Index (UHI) is proposed. The UHI is a combination of real-time sensor data and relevant static variables in order to gain a comprehensive insight. This study will explore the validity and added value of a real-time sensor network in order to gain insight into the urban situation and provide end-users the ability to base certain choices on Urban Health data.

The main research question of this research is therefore:

How can real-time and static urban data be used to provide urban health information for short- and long term decision-making of end-users?

In addition to the main research question, 4 sub-questions complete the scope of this research:

What are the relevant indicators of Urban Health?

Who are the relevant end-users (and what are their needs)?

How can the different types of data be collected and merged into one Urban Health Index (UHI)?

How can the data be represented to the end-user?

With the answers to these questions, this research can add value to both residents and decision- and policymakers. For residents, a new variable can be added when making location choices in both the long- and short term. For instance, cycling can be done in the most healthy locations at that moment, while a person looking for a new home can choose for the healthiest location besides other considerations like price, area, and location. In addition, policymakers can pinpoint 'problem areas', where urban health seems to lack in comparison to other areas of the city. Areas where air pollution is rampant or where heath lingers in the summer months can be addressed more precisely due to the high resolution of the mobile sensors. Moreover, a more holistic view of the issue of urban health can be taken when all indicators of urban health are combined and objective comparisons can be made between neighborhoods, areas of even streets.

In order to show the added value of the proposed system, the city of Eindhoven (the Netherlands) will be used as an example. Eindhoven is a city with 235,000 inhabitants (Centraal Bureau voor de Statistiek, 2021) in the southern part of the Netherlands. The city provides a representative example, as it contains a wide range of neighborhood types and differing characteristics, which will be of importance for validating the proposed system.

This report starts with a literature review (Chapter 2) on possible indicators of urban health (Section 2.1) and how Geographic Information Systems (GIS) it can be used to support decision-making. Chapter 3 will go into detail on the needs of the end-user (Section 3.1) while also describing the methods in which the UHI will be calculated (Section 3.2). This Chapter will continue by describing the proposed system which will combine all previously mentioned considerations into one accessible application (Section 3.3) and how this application is implemented (Section 3.4). When the methods for applying the relevant information has been made clear, Chapter 4 will go into the final results of this research, which will be an application visualizing the relevant Urban Health information (Section 4.1). This application is validated once by a validation test (Section 4.2), after which the iterated final results is shown. Lastly, a conclusion will be drawn on how different types of Urban Health data can be provided to the end-user to support short- and long-term decision-making.

Chapter 2

Literature review

In order to understand the concept of Urban Health, several possible indicators of Urban Health will be explored in this chapter (section 2.1). Additionally, the added value of Geographic Information Systems (GIS) with regard to decision-making will be investigated in order to provide a basis for the suggested system implementation.

2.1 Urban Health Indicators

Before exploring different indicators with a relationship to urban health, the concept of an "indicator" should first be explained. The use of an indicator can be multiple, Briggs (1999) mentions several:

- to help monitor trends in the state of the environment, in order to identify potential risks to health;
- to monitor trends in health, resulting from exposures to environmental risk factors, in order to guide policy;
- to compare areas or countries in terms of their environmental health status, so as to help target action where it is most needed or to help allocate resources;
- to monitor and assess the effects of policies or other interventions on environmental health;
- to help raise awareness about environmental health issues across different stake-holder groups (including policy-makers, health practitioners, industry, the public, the media);
- to help investigate potential links between environment and health (e.g., as part of epidemiological studies), as a basis for informing health interventions and policy.

Furthermore, Briggs (1999) defines what a 'good' indicator must be and states that an indicator must 'meet the needs of their users, who are often not experts in the subject matter or the idiosyncrasies of the data, they must provide a relevant and meaningful summary of the conditions of interest. In order to satisfy the wider community — including those who might wish to challenge the message they give — they must be transparent, testable, and scientifically sound. If they are to detect variation or change in the world they describe, they must be sensitive to real changes in the conditions they measure, yet robust enough not to be swamped by noise in — or minor differences in the source of — the data used. If they are actually to be developed and used, they must be cost-effective to compile and apply' (Briggs, 1999). Weaver et al. (2014) draw similar conclusions in their report for the WHO, where the authors state that indicators should be: built on consensus, relevant, valid and reliable, sensitive to differences, clear specification and repeatable

In the remainder of this research, these aspects will be taken into account when selecting relevant indicators. Most indicators will be selected on the basis of relevance and consensus in the found literature, however, some might be discarded due to lack of clearness of the variables or complexity of measurement.

The existing body of literature on indicators of adverse Urban Health effects is quite extensive. Possible relevant indicators range from UV exposure (Briggs, 1999) to population density (Weaver et al., 2014). Therefore, it is useful to create some categories to divide possible indicators. These categories are based on the research of Galea and Vlahov (2005), however, some adjustments have been made to account for a more exact discrimination between indicators. Firstly, one might consider climate indicators, which are related to the climate in which a person lives, like pollution and noise. Secondly, a distinction can be made for environmental indicators related to Urban Health. These indicators are related to the physical (built) environment a person lives in, like green spaces and land use. The last category to distinguish indicators is the social category. These indicators are concerned with the social environment of a person, like feeling of connectedness and crime. Together, these three categories encompass an extensive list of indicators which are of importance regarding Urban Health. In the remainder of this Section, these categories will be discussed and the most frequently mentioned factors will be used for the system implementation.

2.1.1 Urban Climate Indicators

With regard to the urban climate some indicators appear in the literature frequently, however, some indicators are worth mentioning despite returning less frequently.

In an extensive report by the WHO (Briggs, 1999), several indicators of Urban Health were considered of importance. The report mentions that UV exposure poses a serious risk to health: "Adverse health effects include non-melanoma skin cancer, eye damage (including cataracts) and possible deleterious effects on the immune system" (Briggs, 1999). While the risks of extended UV exposure become clear in this report, further occurrences of this indicator in the literature are sparse. Therefore, this indicator won't be taken into consideration, as other indicators are considered to have a stronger link to urban health problems. Similarly, in the paper by English et al. (2009) an investigation was done into the possible impacts of climate change on human health. This research found that algae, wildfires, and pollen where a serious risk for inhabitants of the United States. In the same report, the authors state that "increases in heavy precipitation related to climate change and earlier regional snow melt and temperature variability raise risks of flooding and related community displacement and injuries" (English et al., 2009). A similar finding on extreme weather events was proposed by Ebi et al. (2008): "Directly, extreme weather events (including heat waves, floods, droughts, and windstorms) annually affect millions of people and cause billions of dollars of damages." Where English et al. (2009) mainly speak about storms and hurricanes, Ebi et al. (2008) are also concerned with extreme temperature events, which will be discussed later in this section. As most of these indicators are mostly infrequent in the literature or the result of different causes (English et al. (2009) state that the increase in pollen is due to an increase in CO_2 levels) these indicators will not be further investigated in this report.
An indicator which occurs relatively often in literature is quality of water supply (Weaver et al., 2014; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010; Briggs, 1999). This indicator is discussed mainly as an aspect of appropriate housing as stated by Krieger and Higgins (2002): "Features of substandard housing, including lack of safe drinking water, absence of hot water for washing, ineffective waste disposal, intrusion by disease vectors and inadequate food storage have long been identified as contributing to spread infectious disease." Similar conclusions were drawn by Hasselaar (2021) and Braubach and Fairburn (2010). The latter also stating that "the lack of a flush toilet for the private use of the household is still an issue for the lowest income population groups in the EU" (Braubach and Fairburn, 2010). As becomes clear from the presented literature and research, a lack of available water poses a real threat to health in the urban living environment. However, due to the nature of the indicator it will not be taken into account, as the measurement of "adequate" water sources would be outside the scope of this research and might not serve the purpose of the end-user group.

The previously mentioned indicator will thus not be used for further consideration in this report, however, several indicators have proven to be of influence on urban health and provide an opportunity for the scope of this research. First of which is humidity (Yang et al., 2017; Leitte et al., 2009; English et al., 2009; Schneider-Skalska, 2019). Humidity is mentioned to have a variety of adverse health effects in an urban setting. English et al. (2009) state that humidity might enhance the effects of temperature on inhabitant's health, advising to consider "apparent temperature, or the use of a heat index, which combines humidity and temperature, is important in looking at mortality effects" (English et al., 2009). Conversely, it has been suggested that air which is too dry (low humidity) aggravates the effect of particles and SO_2 in the air on chronic bronchitis (Leitte et al., 2009). Even more concretely, "a significant relationship between relative humidity and childhood Hand, Food and Mouth Disease (HFMD) was found, particularly children under five years old and urban children" (Yang et al., 2017). While relatively infrequent in the body of literature available, humidity will be taken into consideration in the system implementation of this report. As the indicator has some important combination effects with other variables, the effects might be profound. Additionally, in contrast with the previously mentioned water quality, this indicator is easy to assess and therefore suitable for further investigation.

Another indicator frequently appearing in the literature is the aspect of noise in urban settings (Galea and Vlahov, 2005; Weaver et al., 2014; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010). The effects of noise have been argued to be both physical and cognitive. Physically, noise "increases the occurrence of hypertension and cardiovascular disease" (Basner et al., 2014), while also being the "main cause of environmental annoyance, and it negatively affects the quality of life of a large proportion of the population" (Clark and Stansfeld, 2007). This latter study also states that cognitive effects, "although modest, may be of importance given the number of people increasingly exposed to environmental noise and the chronic nature of exposure" (Clark and Stansfeld, 2007). These findings are underscored by Basner et al. (2014) as extended noise exposure might disturb sleep, cause daytime sleepiness and impairs cognitive performance in schoolchildren. As the effects of extended noise exposure are significant, and the indicator allows for easy assessment in the urban environment, this indicator will also be further elaborated in this research.

Moving on to the next indicator in this category, a frequently occurring variable is temperature (Galea and Vlahov, 2005; Basu and Samet, 2002; Kjellstrom et al., 2007; English et al., 2009; Ebi et al., 2008; Braubach and Fairburn, 2010). The effect of temperature on health can be attributed to several aspects. Firstly, Kjellstrom et al. (2007) mention the effect of the Urban Heat Island (UHI) where the effect of heat waves are exacerbated in urban areas by lingering heat. Moreover, "heat waves affect human health via heat stress, heath stroke, and death, as well as exacerbation of underlying conditions that can increase mortality. The frequency and intensity of heat events and heat-related deaths are projected to increase with climate change" (Ebi et al., 2008). Also, lingering heat in the nighttime might be of significance, as "physiologic recovery from daytime heat is hampered if temperatures during the night do not decrease sufficiently" (English et al., 2009). In addition, Lim et al. (2012) states that rapid temperature changes during the day are related to higher mortality levels. While the effects are extensive, some groups of the population might be at more risk, Basu and Samet (2002) identifies the elderly (also more at risk from Diurnal Temperature Change (DTR)), infants, and persons of low socioeconomic status as potential high-risk groups with regard to higher ambient heat.

Related to the recent state of health in the world, temperature also seems to be correlated with the spreading of COVID-19. Bashir et al. (2020) found that both average temperature and minimum temperature are significantly correlated to this pandemic, which might provide decision makers with some additional information on the urban environment and the spreading of viruses.

As this indicator seems to account for a large part of urban health related issues, it will be taken into consideration in the remainder of this research.

The last indicator in this category has also been accounted for most often in the available literature, namely air quality or pollution (Galea and Vlahov, 2005; Weaver et al., 2014; Leitte et al., 2009; Krieger and Higgins, 2002; Hasselaar, 2021; Braubach and Fairburn, 2010; Briggs, 1999; English et al., 2009). The effects of air quality are mostly stated as being physical, like the increase of chronic bronchitis observed by Leitte et al. (2009), however, the economic effects of increased pollution are also quite severe. This has been thoroughly explored by Sullivan (2016), stating that "current economics research significantly underestimates the effects of air pollution, regardless of the outcome of interest" (Sullivan, 2016). Furthermore, the housing market might also be affected by increased level of pollution (Azmi et al., 2012). Due to the frequent occurrence in literature, severe health effects and prominence in urban situations, this indicator will also be taken into consideration for this research.

This concludes the climate indicators reviewed in this report. It is recognized that this summation is unlikely to be extensive, however, this literature review indicates that a certain trend is visible within the literature. This trend has been taken as the guideline for selecting the indicators used in this research. In the next Section, environmental indicators will be discussed similarly.

2.1.2 Environmental Indicators

Similarly to climate indicators, environmental indicators seem to have more and less prominent variables. Despite some indicators only returning sparsely in the literature, other indicators do return frequently but are unsuitable for this research. These will be discussed further in this section, the first part of this section will be dedicated to some less prominent indicators.

First of which is the indicator of recreational spaces (Krieger and Higgins, 2002). While similar to green spaces (which will be discussed in the second part of this section), this indicator is mentioned less frequently. Besides this, the essence of such indicators is similar, namely to promote healthy living in the neighborhood by active transportation such as walking or cycling. This aspect of healthy urban living will, however, be captured by other more prevalent indicators mentioned in the second part of this section. Other indicators mentioned by Galea and Vlahov (2005) are development density, aesthetic qualities and connectivity. As the author goes into little depth as to what the relationship is between these indicators and urban health, they will be considered outside the scope of this research. However, some elements will return in indicators in the second part of this section (connectivity, for instance, is related to walkability). Yet other aspect of the urban environment mentioned by Galea and Vlahov (2005) are also found by other authors, such as hazardous waste landfills (Braubach and Fairburn, 2010), scale of streets (Krieger and Higgins, 2002) and mixed land use (Weaver et al., 2014). Again, as little connection is made between these indicators and urban health and some of these indicators are hard to quantify within the scope of this research, they will be left out of consideration.

A recurring indicator in the literature, however, is traffic safety or accidents (Hasselaar, 2021; Frumkin, 2002). As Briggs (1999) reports in the name of the WHO: "Motor vehicle accidents continue to be a major cause of death and injury throughout the developed world, and are increasing in many developing countries." Stating clearly that vehicle accidents are still of influence to urban health, both in developed and developing countries. As this indicator is posed as a major cause of injury and death in urban settings and falls within the scope of this research due to good measurability, it will be taken into further consideration.

As has been mentioned before, physical activity or walkability is considered an important indicator of health in urban situations (Galea and Vlahov, 2005; Kjellstrom et al., 2007). "A considerable body of research establishes that sprawl — as measured by low residential density, low employment density, low 'connectivity', and other indicators — is associated with less walking and bicycling and with more automobile travel than denser communities" (Frumkin, 2002). Therefore, it becomes clear that a sedentary lifestyle is indeed related to certain characteristics of the urban environment. In turn, "low levels of physical activity threaten health both directly and indirectly. A sedentary lifestyle is a well established risk factor for cardiovascular disease, stroke and all-cause mortality" (Frumkin, 2002). While Kjellstrom et al. (2007) suggests that a more car-orientated lifestyle also implicates changes in "dietary patterns with increasing consumption of high-energy and high-fat 'fast foods'" (Kjellstrom et al., 2007). While a clear definition of what constitutes a walkable area will be given in Section 3.2, the indicator will be included into the research besides its relative complex nature.

Related to walkability is the availability of green spaces (Krieger and Higgins, 2002; Frumkin, 2002). The effect of green spaces on health can be both physical and mental. As mentioned by Schneider-Skalska (2019), "abundant research on the influence of greenery, water and natural landscape on recovering from stress and intellectual fatigue shows that the role these factors play is absolutely invaluable." However, "lower percentage of natural area cover was correlated with deficits in viso-motoric development of children, as well as areas with lower natural area per capita had significantly higher values of childhood overweight" (Kabisch et al., 2016). In contrast with the previously mentioned walkability, the amount of green spaces is clearly measurable in a defined area, however, a more concise measurement will be given in Section 3.2. As the effects of green spaces are indicated to be profound, and the measurability falls within the scope of this research, this indicator too will be included in the remainder of this research.

These indicators conclude the Section on the environmental influences on urban health. The next Section will consider the social aspects of the built environment.

2.1.3 Social Indicators

A definition of the social environment has been broadly defined as the "occupational structure, labor markets, social and economic processes, wealth, social, human, and health services, power relations, government, race relations, social inequality, cultural practices, the arts, religious institutions and practices, and beliefs about place and community" (Galea and Vlahov, 2005). This definition also shows the complexity and broadness of such possible indicators of urban health (while its relation also becomes clear). However, the main issue with such indicators with respect to this research is the measurability. Many of these indicators are subjective and therefore hard to quantify, therefore, they won't be used directly in the remainder of this research. However, as they represent a significant aspect of urban health, this Section will discuss several possible indicators for completeness.

Two indicators proposed by Galea and Vlahov (2005) are spatial segregation and social contagion. "Spatial segregation of different racial/ethnic and socioeconomic groups also may be an important determinant of health in cities. Many cities worldwide are highly segregated with multiple historical, logistical, and practical barriers to mixing social groups" (Galea and Vlahov, 2005). This study mainly stresses the effects of segregation on a lack of appropriate housing for certain groups of society. While access to health care services and lower social capital are also proposed as possible indicators of adverse health for socially segregated groups. Social contagion, however, relates to the way urban residents are influenced by the many closely related neighbors. Similar to biological transmission of diseases, Galea and Vlahov (2005) proposes that social ideas spread more rapidly in an urban context, which can have adverse health effects, for instance: "Several studies have provided both theoretical and empirical reasons to suggest that media representations of suicide could have some influence on a person's suicidality" (Galea and Vlahov, 2005).
Other social indicators of urban health are income (Weaver et al., 2014), socio-economic status (Krieger and Higgins, 2002) and crime or neighborhood safety (Braubach and Fairburn, 2010). While income is mentioned most often as a general predictor of health through various mechanisms, Galea and Vlahov (2005) mentions that "ecologic evidence has long suggested that countries with more egalitarian distribution of income have lower mortality rates." While many such mechanisms are also suggested by other studies like those of Weaver et al. (2014), without mentioning clear dynamics on how income is related to health this seems to have a clear and obvious relationship. Closely related is the aspect of socio-economic status, which is mentioned by Krieger and Higgins (2002) in the context of "inequitable distribution of substandard housing" for persons with lower socio-economic status. Less related to these indicators is the aspect of neighborhood safety, however, Braubach and Fairburn (2010) states that "the level and frequency of physical

activity in the residing population were affected by perceived safety in deprived neighborhoods (associated with litter, graffiti, etc.)". All in all, these indicators would represent a significant link to social health in an urban context.

A different aspect of social health related to the urban environment is that of social connectedness (Galea and Vlahov, 2005; Hasselaar, 2021; Schneider-Skalska, 2019). This aspect is mainly related to the aspect of social support in one's neighborhood and the level to which a person feels cohesion in the neighborhood. Influenced by many factors, Krieger and Higgins (2002) mentions that substandard housing in certain areas can "lead to social isolation because occupants are reluctant to invite guests into their homes. High-rise buildings may inhibit social interaction because they lack common spaces."

Lastly, a frequent aspect related to social well-being is population density (Weaver et al., 2014; Briggs, 1999). While this may have several effects on health, Galea and Vlahov (2005) mentions high population density with regard to fast spreading of contagious diseases. In contrast, (Schneider-Skalska, 2019) relate population density mainly to mental well-being and social cohesion. Therefore, it can be concluded that population density can influence social health through many mechanisms. While this indicator is not used directly in the proposed system, it is an indirect part of the proposed indicators.

This concludes the section on Urban Health indicators. The table below (Table 2.2) lists all indicators which have been discussed in this Chapter. The next section will go into more detail how GIS can be used to inform the end-user effectively about Urban Health

Indicator	**Category**	**References**
Pollution or Air Quality	Climate	Galea and Vlahov (2005); Weaver et al. (2014); Sullivan (2016); Azmi et al. (2012); Leitte et al. (2009); Krieger and Higgins (2002); Kjellstrom et al. (2007); English et al. (2009); Hasselaar (2021); Braubach and Fairburn (2010); Briggs (1999)
Temperature	Climate	Galea and Vlahov (2005); Lim et al. (2012); Basu and Samet (2002); Kjellstrom et al. (2007); English et al. (2009); Bashir et al. (2020); Ebi et al. (2008); Schneider-Skalska (2019)
Noise	Climate	Galea and Vlahov (2005); Weaver et al. (2014); Clark and Stansfeld (2007); Basner et al. (2014); Krieger and Higgins (2002); Hasselaar (2021); Braubach and Fairburn (2010)
Water Quality	Climate	Weaver et al. (2014); Krieger and Higgins (2002); Kjellstrom et al. (2007); Hasselaar (2021); Braubach and Fairburn (2010)
Green Spaces	Environment	Krieger and Higgins (2002); Kabisch et al. (2016); Frumkin (2002); Schneider-Skalska (2019)
Population Density	Social	Galea and Vlahov (2005); Weaver et al. (2014); Schneider-Skalska (2019); Briggs (1999)
Humidity	Climate	Yang et al. (2017); Leitte et al. (2009); English et al. (2009); Schneider-Skalska (2019)
Social Connection	Social	Galea and Vlahov (2005); Krieger and Higgins (2002); Hasselaar (2021)
Physical Activity or Walkability	Environment	Galea and Vlahov (2005); Kjellstrom et al. (2007); Frumkin (2002)
Traffic Safety	Environment	Frumkin (2002); Hasselaar (2021); Briggs (1999)
Mixed Land Use	Environment	Galea and Vlahov (2005); Weaver et al. (2014)
Scale of Streets	Environment	Galea and Vlahov (2005); Krieger and Higgins (2002)
Crime and Safety	Social	Galea and Vlahov (2005); Braubach and Fairburn (2010)
Hazardous Waste Landfill	Environment	Galea and Vlahov (2005); Braubach and Fairburn (2010)
Socio-economic Status	Social	Galea and Vlahov (2005); Krieger and Higgins (2002)
Income	Social	Weaver et al. (2014)
Extreme Weather	Climate	English et al. (2009); Ebi et al. (2008)
Development Density	Environment	Galea and Vlahov (2005)
Aesthetic Qualities	Environment	Galea and Vlahov (2005)
Connectivity	Environment	Galea and Vlahov (2005)
Social Contagion	Social	Galea and Vlahov (2005)
Spatial Segregation	Social	Galea and Vlahov (2005)
Recreational Spaces	Environment	Krieger and Higgins (2002)
Pollen	Climate	English et al. (2009)
Wildfires	Climate	English et al. (2009)
Algae	Climate	English et al. (2009)
UV Exposure	Climate	Briggs (1999)

Table 2.2: Overview of Urban Health Indicators

2.2 Geographic Information Systems (GIS) for decision-making

As the main research question of this report is how urban health information can be best provided to end-users, the manner in which this information needs to be provided needs to be investigated as well as the information itself. While previous Sections have investigated Urban Health indicators, this Section will go into more detail on what literature has found on effective decision-making using GIS.

Visual systems monitoring (smart) city performance are often called dashboards. A definition of such dashboards is provided by Jing et al. (2019): “a web-based interactive interface that is supported by a platform combining mapping, spatial analysis, and visualization with proven business intelligence tools.” This Section will go into detail on what makes a successful dashboard for monitoring and analyzing city performance for the end-user. Similar to Section 2.1, this Section is also divided into different categories. Firstly, aspects of the data related to the dashboard is discussed. This category is not necessarily concerned with the content of the data (which is discussed in previous Sections), however, with the structure and nature of the data. Secondly, the architecture of the dashboard is of importance. This category is concerned with the way in which the dashboard is set up. Lastly, the actual design of the dashboard is discussed. This category is concerned with how the user interacts with the dashboard and what form the dashboard should take.

2.2.1 Dashboard Data

A main concern when handling geospatial data is the fact that this data is often numerous and of great quantity. Li et al. (2016) define several challenges with regard to the extent of geospatial data and identify that “the development of efficient methods to display data integrated in the three dimensions of geographic and one dimension of continuous time” is one of the major challenges with regard to this type of data. Therefore, in order to successfully visualize geospatial data, data management should be as efficient as possible with regard to the goal of the dashboard.

In addition to efficient management of data, Smith and Salvendy (2005) suggests that “to make fact-based decisions, they [business leaders] need the right data, delivered reliably, in an easily accessed and perceivable form”. Focus in this definition is on the fact that the quality of the data is of great importance. As there are “concerns about data veracity and quality and how accurately (precision) and faithfully (fidelity) the data represent what they are meant to (especially when using samples and proxies), and how clean (error and gap free), untainted (bias free), and consistent (few discrepancies) the data are” (Kitchin and McArdle, 2017). These aspects have also been discussed with regard to the selection of proper indicators (section 2.1), however, it is worth mentioning that a dashboard is only as good as the data it visualizes. Different ways of ensuring data quality and correct indicators are provided by Nuradiansyah and Budi (2015) using Analytical Hierarchy Process (AHP), and Miola and Schiltz (2019) using different measuring processes.

Lastly, when data is managed efficiently and quality is ensured, the data should allow for the generation of new knowledge by the end-user (Kitchin and McArdle, 2017; Jankowski et al., 2001). Li et al. (2016) define knowledge discovery as “concerned with mining and extracting meaningful patterns and relationships from large data- sets that are valid, novel, useful and understandable”. Clearly related to the quality of the data, this aspect is more concerned with an inherent ability of the selected data to detect certain patterns or new information.

The previously mentioned aspects of dashboard design and structure will be used in Chapter 3 for the system design and implementation. As has been shown, appropriate data management and structure will add to the potency of the dashboard in several aspects.

2.2.2 Dashboard Architecture

Moving from the structure of the data, this Section will discuss the structure of dashboards. As has been discussed in the previous Section, dashboards and their data should be used in order to mine additional data (unknowable through the "raw" data). The architecture of the dashboard also plays a role in such regard. Research by Jing et al. (2019) describes several important architectural aspects of dashboards. Firstly, they define the concept of portability as "the provision of access to geospatial datasets and city performance Key Performance Indicator (KPI) data that can greatly help with understanding city performance". This concept relates to the fact that the data and eventual information should be accessible through multiple means and not confined to some medium or place. Secondly, the authors define interoperability as an important aspect to dashboard design. Interoperability refers to the fact that the dashboard should be able to communicate, act and interact with other systems in order to provide the end-user with the desired data and information. The authors name as an example the London CityDashboard (O'Brien et al., 2012) as an example "of heterogeneousness with various data, sensors, and users" (Jing et al., 2019). Lastly, the authors describe the aspect of scalability, which "refers to the ability to add and remove hardware (including computers and sensor devices), software modules, and graphic user interface (GUI) components for users without affecting the system availability." Similar aspects are described by Dameri (2017) and Li et al. (2016), however, these authors mostly describe the ability of dashboards to be able to scale to large data sets and computation without problems. This shows that the scalability of dashboards can be considered an important aspect for hardware, software and operational reasons where the user needs to be able to scale the dashboard to their preferences while not hampering the availability of the dashboard.

Another aspect of dashboard architecture has to do with ethics and privacy with regard to geospatial data. While dashboards for smart cities usually display aggregated and anonymous data, this does not necessarily mean that no thought should be given to ethical issue with regard to Personally Identifiable Information (PII). Kitchin (2016) identifies six aspects which should be considered in smart city applications. Firstly, "datafication, dataveillance and geosurveillance" refers to the fact "that people are now subject to much greater levels of intensified scrutiny as more and more aspects of their daily lives are captured as data." As mentioned before, data aggregation and anonymization should prevent this aspect of causing privacy infringements, however, this should be ensured in the architecture of the data application. Secondly, the author identifies "inferencing and predictive privacy harms" as a possible ethical issue using big urban data". Urban big data can generate inferences about an individual that are not directly encoded in a database but constitute what many would consider to be PII and which produce 'predictive privacy harms" (Kitchin, 2016). The author mentions examples of users being identified as frequenting certain places often and drawing conclusions from such behavior. Thirdly, "anonymization and re-identification" relates to a central problem using big data. Using certain algorithms, the reconstruction of PII using anonymized data set is possible in certain cases. Therefore, the architecture of the dashboard should prohibit this by design. Fourthly, Kitchin (2016) notes that "obfuscation and reduced control" of data is possible as smart city architecture can flow through many channels and thus the flow of the data can become impractical to track. This might cause problems in case of security breaches or other forms of data leaks. Therefore, the architecture of a dashboard system should be simple and easy to comprehend. Also, with the advent of big data gathering, "notice and consent" are hard to gather for inhabitants of certain areas. As an example, the gathering of traffic patterns usually requires no consent of the individuals being part of the pattern. In addition, with the increasing number of smart city applications, it would become onerous to gather consent on all (unknowing) participants. Therefore, the design of the dashboard application should take into account the possible unwilling participation of some people, while enabling information extraction for the end-user. The last element mentioned by Kitchin (2016) is the aspect of "data use, sharing and repurposing", as data is frequently shared between platforms it is again hard to track the flow of data and this might provide ethical issues if the data is shared without due consideration. The setup of a dashboard should take this into account, as by the very nature of such a dashboard the information is shared with others. A last point to be made, with regard to ethics regarding dashboard architecture, is the aspect of predictive harm. With a large set of data in an urban context, large areas could be predicatively targeted by many parties, which might be a cause for ethical consideration. One could imagine targeted commercial campaigns misusing the data provided by a smart city dashboard. Therefore, the architecture (and data) of such a dashboard should be set up to prevent unethical use.

This Section discussed the architectural aspects of a dashboard. Moreover, it discussed the ethical aspects which should be taken into consideration. The following Section will go into more detail on the actual design considerations for GIS dashboards

2.2.3 Dashboard Design

This last category discusses actual aspects of dashboard design. The design of dashboards is the actual interface between the end-user and the data, and therefore needs proper design to allow for information discovery.

To allow for information discovery, it is suggested that a properly designed dashboard should be efficient (in space) (Smith and Salvendy, 2005; Few, 2015). Smith and Salvendy (2005) suggest to "use efficient visuals that combine multiple indicators in one space and provide some interactivity", while a similar conclusion is drawn by Few (2015): "there is at least one characteristic that describes almost all the information found in dashboards: it is abbreviated in the form of summaries or exceptions. This is because you cannot monitor at a glance the details needed to achieve your objectives." This relates to a second aspect in the definition of Few (2015), namely the fact that the dashboard should allow for the monitoring of data.
Jing et al. (2019) add that an integration with map context is also of importance when designing GIS dashboards, especially with regard to indicator data as is the case in this research. The author distinguishes between two types of dashboard design, "one-page" (as mentioned above) and "drilldown". The one-page approach is most useful for indicator dashboards "in which all indicators are laid out, allowing users to see them all at once" (Jing et al., 2019). When designing a dashboard which is in need of more views, the author advises creating multiple-linked views "that allows the user to work with various visualizations among multiple views, which is more effective than using views separately" (Jing et al., 2019). While this might be more efficient than separate views, Li et al. (2016) warn for "very busy displays" created through such multiple-linked views as it can lead to information overload: "It is important to note that human cognitive resources (such as the visual working memory that is critical in processing visual information; or spatial abilities which are critical for how well we can make sense of visualizations) are limited" (Li et al., 2016).

Besides the complexity of multiple views, the general complexity of a dashboard should also be taken into account (Li et al., 2016; Miola and Schiltz, 2019; Smith and Salvendy, 2005). As "dashboards have scientific utility because they seemingly translate the messiness and complexity of cities into rational, detailed, systematic ordered forms of knowledge" (Kitchin and McArdle, 2017), their goal should be to reduce complexity, not introduce new levels of complexity through their design. Therefore, Jing et al. (2019) advice to find "a balance between the complexity and media design".

The last element reoccurs most often in literature, and is the element of designing with the user requirements in mind (Miola and Schiltz, 2019; Kitchin and McArdle, 2017; Smith and Salvendy, 2005). It is the first design principle suggested by Jing et al. (2019), stating that the type of dashboard is in line with the user requirements. A similar sentiment is found by Few (2015): "An effective dashboard is the product not of cute gauges, meters and traffic lights, but rather of informed design: more science than art, more simplicity than dazzle. It is, above all else, about communication." Kitchin and McArdle (2017) stresses that very little user-testing is normally done on dashboard design, which "means that city dashboards provide a sub-optimal experience for users and their full utility is not being realized." The latter author also underscores that data and analytical literacy can not simply be assumed among the public (or even specialized user). Therefore, proper design, with the goals and needs of the end user in mind, is essential if the dashboard is to be used most optimally. A further research into these requirements will be done in Chapter 3, section 3.1.

This concludes the section on what elements should be taken into account while designing a dashboard using GIS for decision-making. A summary of all elements can be seen in Table 2.4. This table is also the conclusion of this Chapter, where the indicators for urban health have been explored and gathered in one Urban Health Index and an exploration has been made on the elements dictating proper dashboard design.

Design Principle	**Category**	**References**
Inline with user requirements	Design	Jing et al. (2019); Few (2015); Li et al. (2016); Miola and Schiltz (2019); Kitchin and McArdle (2017); Smith and Salvendy (2005)
Balance Complexity and Design	Design	Jing et al. (2019); Few (2015); Li et al. (2016); Miola and Schiltz (2019); Kitchin and McArdle (2017); Smith and Salvendy (2005)
Knowledge Discovery	Data	Li et al. (2016); Kitchin and McArdle (2017); Jankowski et al. (2001)
Scalability	Architecture	Jing et al. (2019); Dameri (2017); Li et al. (2016)
Choice of Indicators	Data	Nuradiansyah and Budi (2015); Miola and Schiltz (2019); Kitchin and McArdle (2017)
Multiple Linked View	Design	Li et al. (2016); Jankowski et al. (2001)
Graphic User Interface (GUI) style	Design	Jing et al. (2019); Nuradiansyah and Budi (2015)
Ethics	Architecture	Kitchin (2016); Kitchin and McArdle (2017)
Accessibility	Architecture	Kitchin and McArdle (2017); Smith and Salvendy (2005)
Data Quality	Data	Kitchin and McArdle (2017); Smith and Salvendy (2005)
Interoperability	Architecture	Jing et al. (2019)
Portability	Architecture	Jing et al. (2019)
Integration with Map Context	Design	Jing et al. (2019)
Monitoring	Design	Few (2015)
Data Efficient	Data	Li et al. (2016)
Space Efficient	Design	Few (2015)

Table 2.4: Overview of GIS Dashboard Design Principles

2.3 Conclusion

Summarizing the findings of Chapter 2, several aspects should be mentioned. Firstly, Section 2.1 showed that a multitude of Urban Health indicators can and should be considered within the context of this research, however, a selection has been made and consists of the following indicators:

- Air Quality
- Temperature
- Humidity
- Noise
- Green Spaces
- Walkability
- Traffic Safety

These indicators have been chosen for several reasons. First, these indicators reflect the most mentioned indicators found in the existing body of literature. This is taken as a proven foundation to build the UHI on, as these indicators are already properly researched. Second, some indicators were mentioned frequently, however, are judged to be impractical to include as they are hard to measure using the mobile sensor technique (i.e., water quality) or represent vaguely defined social concepts (i.e., social connectedness). Therefore, preference is given to concrete and measurable indicators which should give the UHI a meaningful and interpretable foundation. Lastly, some chosen indicators represent or depend on other mentioned indicators. For instance, Green Spaces, Walkability and Traffic Safety depend on population (density) and therefore are an indirect representation of the indicator. Moreover, Walkability is a complex indicator depending also on indicators like mixed land use, development density and connectivity. These considerations should result in an UHI which gives the end-user the necessary insight in the urban health situation to support decision-making over different time scales (short and long-term).

Besides relevant indicators for Urban Health, design principles for GIS dashboards were discussed in Section 2.2. This Section showed several aspects of dashboards within the categories of data, architecture, and design. An overview of the most important aspects of using GIS in a dashboard representation are summarized in Table 2.4.

The next Chapter will use these findings to research the end-user (Section 3.1), how the Urban Health Index (UHI) can be calculated (Section 3.2), how the system should be set up (Section 3.3) and eventually the actual systems' implementation method (Section 3.4).

Chapter 3

Application Architecture

This Chapter will translate the previously defined theory on the Urban Health Index (UHI) into a practical application which end-users can use in order to support decision-making. Therefore, end-user research is conducted first in order to get more insight into the current preferences of end-users with regard to location-based applications and how they envision the addition of health information to these applications. This research aspect will be elaborated in Section 3.1. Secondly, the previous findings on Urban Health indicators will be translated into a meaningful index in Section 3.2. Thirdly, the schematic design of the system will be explored in Section 3.3. In this Section, a conceptual overview of the application will be set out as a foundation for further implementation. Fourthly, the actual implementation methodology will be discussed in Section 3.4. In this section, the static elements defined in the previous Chapter will be collected and processed into a workable format in order to visualize the needed data meaningfully to the end-user. This process will be explained in detail in Section 3.4.1. Similarly, the process of collecting, storing and processing the dynamic data-elements will be discussed in Section 3.4.2. Section 3.4.3 will go into more detail on the technical basis of the application, which methods are used and how all different elements will be combined. Section 3.4.4 discussed the calculations made in order to translate the data into meaningful information. Finally, these calculations are used in Section 3.4.5 to visualize the information so the end-user can use for their intended use. An overview of how all elements of this research connect can be seen in Figure 3.1. The indicators discussed in Section 2.1 will be used in Section 3.2 to determine the actual UHI score of each individual location. Separately, the findings in Section 2.2 will be combined with the preferences and findings from the end-user research of Section 3.1, and used for the system design as described in Section 3.3. Finally, the system design will be combined with the UHI calculations to form the final implementation method for this application, which will be described in Section 3.4.

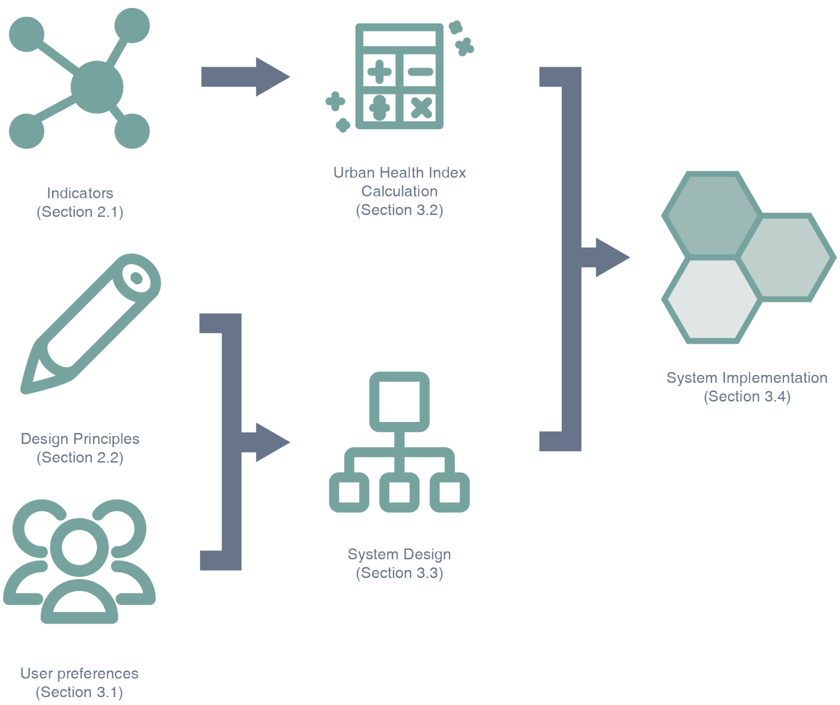

Figure 3.1: Overview of research design

3.1 End-user research

Before implementing the findings of Chapter 2, more insight is necessary on the possible end-users of the proposed application. In order to gain this insight, a survey was spread under a non-selected population. As the scope of possible end-user is limitless, no pre-selection was made under the respondents as all insights would give more insight into the preferences of the general audience. The following Section (Section 3.1.1) will go into detail on the survey and the intention of the survey questions. Section 3.1.2 will elaborate on the results and their possible interpretation.

3.1.1 Survey Design

The goal of this survey was to explore the way in which people currently use location-based applications and how they would envision the addition of health information into these applications. The survey aimed to uncover how current applications are effective in the way people use them, this would indicate how the newly proposed application can implement similar strategies. Besides this, the manner in which health would play a role in the use of location-based applications would indicate how the proposed application needs to be designed. The full survey can be found in Appendix A.

Firstly, the respondent was asked which application he or she uses most frequently. A preference for a certain application could indicate that that application has certain advantages. Later questions go into more detail with regard to the user's preferences using this application. This question was designed to introduce respondents to the theme of the survey before moving into the topic of health within this theme.

The second part of the survey, in which a small introduction is given to the topic of Urban Health and how this application aims to provide information. The second question of the survey asks respondents how they would use such information in the short-term. As will be discussed in Chapter 3.3, a separation is made between short-term and long-term use. These types of questions can be difficult for respondents to answer, as they need to imagine some unknown future state and application. However, it is the goal of this survey to discover the respondent's preference of this future state, therefore, these questions are included.

Part 3 of the survey goes into more detail on the current use of location-based applications. Firstly, the respondent is asked how he or she currently uses their preferred application from question 1. Secondly, the respondent is asked how their preferred application makes their preferred use of that application easy or hard. This combination of questions should indicate what the strengths and weaknesses are of certain applications, and what the newly proposed application could adapt or change in this regard. Lastly, the respondent is asked if he or she has any general comments about this subject. As multiple choice questions only give limited freedom in answering, this open question is designed to allow the respondent to provide any additional insights into the subject.

The last part of the survey is aimed at any further contact with the respondent.

3.1.2 Survey Results

This Section will go into detail on the results of the survey described in Section 3.1.1. The survey was spread among a random audience, where no pre-selection criteria were determined. This resulted in 56 respondents.

3.1.2.1 Location-based Application Preferences

Firstly, the most frequently used location-based applications are shown in Figure 3.2. The goal of this survey question was to investigate whether certain applications have clear advantages. As this Figure shows, a large majority of the respondents prefers the use of Google Maps (n=49), while car navigation is the least preferred location-based application (n=3). While this gives no immediate indications on why this is occurs, it shows that more attention should be paid to why Google Maps is preferred by 88% of the response base. Further questions should indicate if there is a clear difference between applications which can explain this preference. Moreover, further questions will be visualized per application, to see if responses differ largely per group.

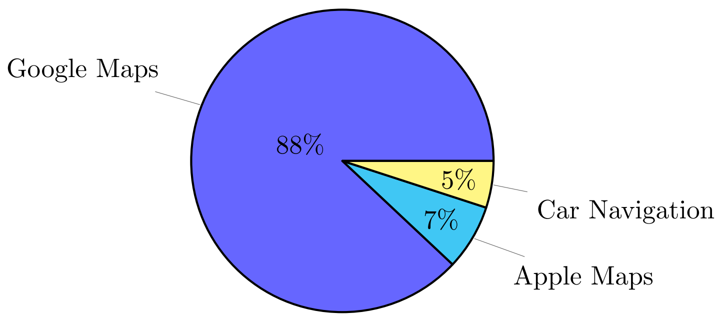

Figure 3.2: Most frequently used location-based applications

3.1.2.2 Current Use of Location-based Applications

In order to see how people currently use their preferred location-based applications, the respondents were asked about their current use. Figure 3.3 shows how the respondents use their preferred application, split per application group. The blue bars represent the percentages for the total respondent group, for example, in Figure 3.3 54% of the respondents chose option 1.

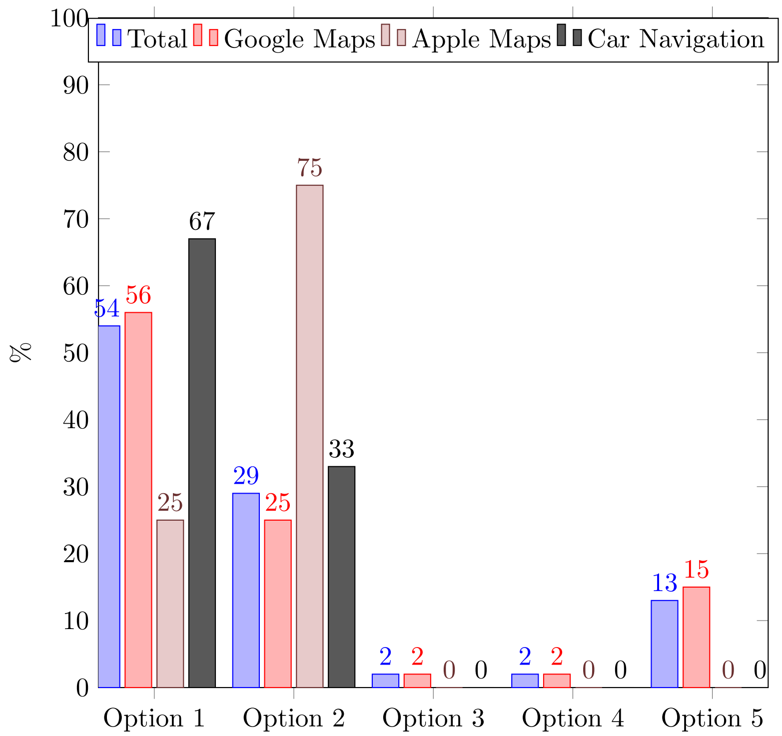

Figure 3.3: Current use of location-based applications per application

Option 1: selecting your route for travel destination / navigation (before a trip), Option 2: selecting your route for travel destination / navigation (during a trip), Option 3: looking up a location for other purpose than immediate travel (i.e. vacation), Option 4: looking up a shop or store location or other information about the store, Option 5: looking up a location for fun

The options in these graph represent the answer options provided to the respondents. They are listed below:

1. Selecting your route for travel destination / navigation (before a trip)
2. Selecting your route for travel destination / navigation (during a trip)
3. Looking up a location for other purpose than immediate travel (i.e., vacation)
4. Looking up a shop or store location or other information about the store
5. Looking up a location for fun

From this graph, it becomes clear that Option 1 and Option 2 are currently the most popular uses of location-based applications. Interestingly, users of car navigation have a bigger proportional preference for using their application before their trip compared to the total. Similarly, users of Apple Maps, have a larger proportional preference for using their application during their trip. However, from this graph it can be concluded that the most frequent use for location-based applications are related to choice of route, while looking up locations for fun (Option 5) has an auxiliary function. Looking up locations for other purposes than immediate travel (Option 3) and additional information (Option 4) seem very rare.

When asked to give a reason why this application has their preference, respondents gave answers in five categories:

	Category	Definition
1	Routing	The way routing is designed
2	Location Choice	The way location choice is implemented
3	Real-time Information	Availability of real-time and up-to-date information
4	Map Design	The actual design of the used map
5	General Ease of Use	Preference due to general ease of use, not considering other categories

Category 1 refers to a preference due to the way routing is designed in that application. One respondent states: "it [the application] makes it easy by showing possible routes and the time that it takes to travel". Category 2 indicates that the respondents uses the application because of the way location choice is implemented, for instance: "You can easily find stores which are part of a certain type of store (e.g., bike shop, grocery)". Further, the third category is related to the fact that information is updated in real-time or that the data is always up-to-date with the current urban situation: "It's [the application] constantly using up-to-date information, i.e., traffic jams or roadblocks, for selecting the best possible way to drive." The fourth category is concerned with the way in which the map of the application is designed regardless of the way it is used: "clear urban network with clear highlights of locations (such as amenities, street, green, etc.)." Lastly, the fifth category concerns a general ease of use: "Super easy User Interface, connected to calendar to suggest travel destinations, connected to contacts etc."

Looking at the results shown in Figure 3.4, it becomes clear that most respondents state they use their current location-based application because of the way routing is implemented. While users of car navigation indicate to have a preference for general ease of use, the remaining application groups show a strong preference for the way routing is implemented. Combined with the results from Figure 3.3, this would indicate that both Google Maps and Apple Maps implement features regarding routing which are attractive to users. Furthermore, a smaller segment of the respondents (17%, n=10) has indicated that they prefer their current location-based application due to the way location choice is implemented. Interestingly, all respondents who indicated location choice as a reason, belonged to the Google Maps user-group. Therefore, it could be concluded that the way Google Maps implements location choice is exemplary.

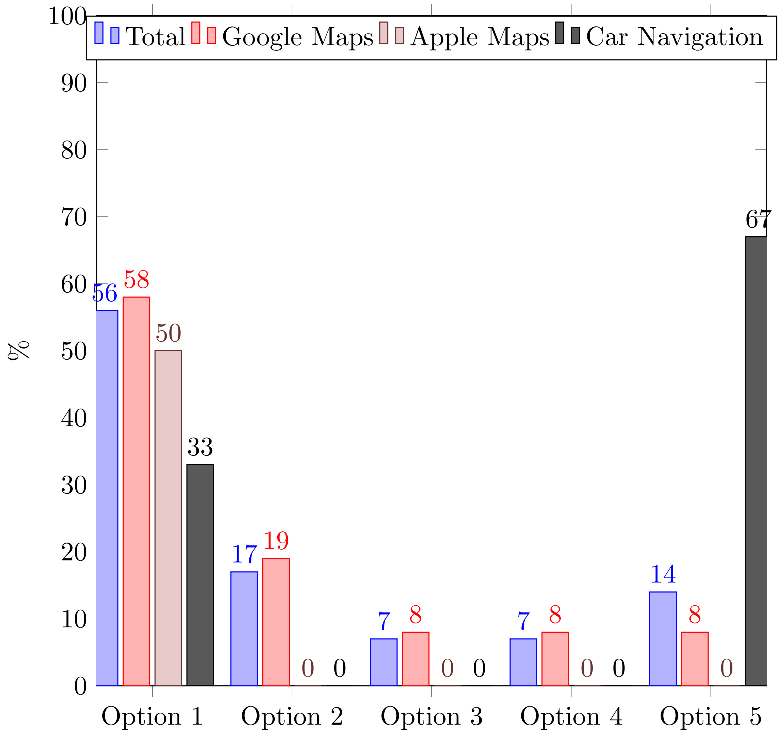

Figure 3.4: Stated preference reason of current location-based application

Option 1: Routing, Option 2: Location Choice , Option 3: Real-time Information, Option 4: Map Design, Option 5: General Ease of Use

3.1.2.3 Urban Health Index for Short-Term Decision Making

As has been mentioned in the previous Section, the remaining part of the survey asked respondents how they would incorporate health data in their use of location-based applications. Firstly, the respondents indicated how they would use such data in short-term decision-making. These results are shown in Figure 3.5. The options, again, represent the answer options presented to the respondents as listed below:

1. Selecting the healthiest travel destination (i.e., healthiest shopping location)
2. Selecting the healthiest travel route (daily travel
3. Choosing healthiest leisure locations (i.e., running)
4. I would not use this option for short-term decisions

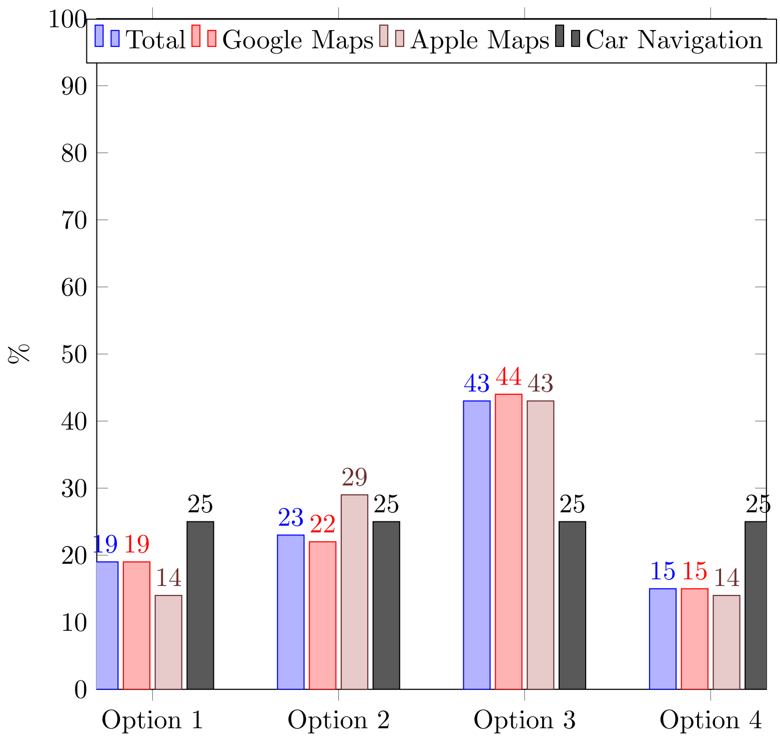

Figure 3.5: Urban Health Index preferences for short-term decision-making

Option 1: Selecting the healthiest travel destination (i.e. healthiest shopping location), Option 2: Selecting the healthiest travel route (daily travel), Option 3: Choosing healthiest leisure locations (i.e. running), Option 4: I would not use this option for short-term decisions

As can be seen in this graph, most respondents would use this data to look for the healthiest leisure locations in the short-term (Option 3). This seems a reasonable result, as leisure activities mostly require short-term decision-making and are conducted in the urban environment (i.e., “where can I go for a run now?”). Moreover, combining this option with Option 1 (selecting the healthiest travel destination), it becomes clear that respondents prefer choosing the healthiest travel location (combined 62%, n=52). In contrast, Option 2 (selecting healthiest travel route) has a smaller preference among the respondents (23%, n=19). This would indicate that people would use Urban Health information differently to how they are currently using their preferred location-based applications. As has become clear in the previous paragraph and Figure 3.3, respondents currently use their application mostly for routing, while this paragraph and Figure 3.5 would indicate that they would use Urban Health data mostly for location choice. However, some respondents indicated that they would not use this type of data for short-term decision-making (Option 4, 15% n=13).

3.1.2.4 Urban Health Index for Long-Term Decision Making

Lastly, respondents were asked to indicate their preferred use of Urban Health data for long-term decision-making. These results are shown in Figure 3.6. The provided answer options were:

1. Selecting healthiest travel destination (i.e., vacations)
2. Selecting residence or other long-term locations (i.e., living or working)
3. I would not use this option for long-term decisions

Most respondents indicated that they would use Urban Health data in the long term for choice of residence or other long-term locations (Option 2). While half as many indicated that they would use it for selecting travel destinations. More interestingly, compared to the previous paragraph, only a very small amount of respondents indicated that they would not use this type of data for long-term decision-making. This seems to indicate that a general preference exists among the respondents for using Urban Health data in long-term decision-making compared to short-term decision-making.

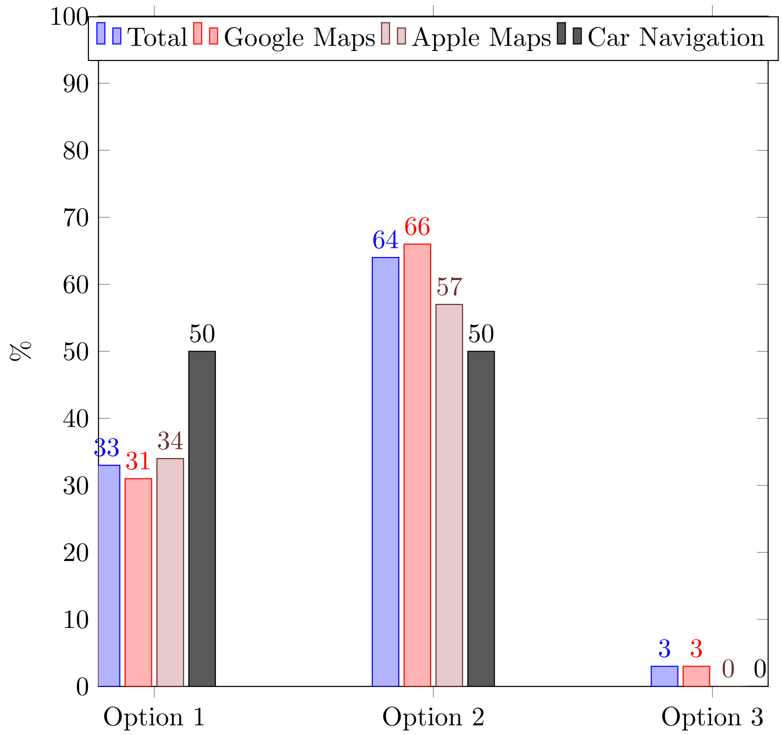

Figure 3.6: Urban Health Index preferences for long-term decision-making

Option 1: Selecting healthiest travel destination (i.e. vacations), Option 2: Selecting residence or other long-term locations (i.e. living or working), Option 3: I would not use this option for long-term decisions

3.1.2.5 Conclusion

Concluding, most respondents preferred the use of Google Maps as their current location-based application (Figure 3.2). Moreover, these applications where most frequently used in the context of routing (Figure 3.3). Including Urban Health, respondents report a preferred use for location choice with regard to short-term decision-making. Similarly, for long-term decision-making, respondents prefer the ability to choose residence or other long-term location.

Translating this to the proposed application, it seems that this application has a different purpose to currently used location-based applications, like Google Maps. Preferred use is currently mostly aimed at choosing optimal routes. However, the proposed application is aimed at choosing optimal locations. Attention should be paid to the manner in which Google Maps implements such applications, as it was marked as exemplary by respondents. The proposed application should therefore be designed to support location-choice based on Urban Health information, while not necessarily focusing on healthy route choice. Moreover, when designing a system that allows for healthy location choice, a differentiation should be made between short and long-term decisions. This difference should be based on the fact that in the short-term, respondents preferred to look for healthy leisure activities, while choice of residence was preferred in the long-term. These choices are of a fundamentally different nature, where leisure activity choice should be made quickly, choice of residence choices can be made with more consideration and time. Therefore, short-term decision-making should be supported by quick and easy use, while long-term decision-making should be supported by completeness of information and more in-depth analysis.

This concludes the Section on the preferences of end-users. The next Section will go into detail on the calculation method for the Urban Health Index (UHI).

3.2 Urban Health Index

Table 2.2 summarizes the indicators which could be used for the definition of an UHI. However, based on relevance in the literature, measurability and meaning a selection is made. This selection includes the following indicators: Air Quality, Heat (Temperature and Humidity), Sound, Green Spaces, Walkability and Traffic Safety. Moreover, in order to provide the end-user with usable information, these indicators should be abstracted and combined into an index. Such an index allows for the comparison of general Urban Health without the inspection of all individual indicators. As Weaver et al. (2014) defines it: "The UHI provides a flexible approach to selection, amalgamation, and presentation of health data. Its purpose is to furnish visual, graphical, and statistical insight into various health indicators and health determinants within particular geographic boundaries and health disparities with a focus on capturing intra-urban health disparities."
This section will go into detail for each selected indicator on how this indicator can and should be measured, how an index can be created and how a general index can be amalgamated from these individual sub-indices.

3.2.1 Air Quality

Air Quality can be considered a broad concept with many possible variables to be measured. Firstly, the assessment method of the U.S. Environmental Protection Agency (Air Quality Index (AQI)) will be considered. After which, the European version (Common Air Quality Index (CAQI)) will be discussed.

3.2.1.1 Air Quality Index (AQI)

This index ranges from 0 to 500, where 0 indicates good and 500 (or above) indicates hazardous, several intermediate levels are included based on the values of the variables. The AQI is build up from five different variables: Ozone (O_3), Particulate Matter ($PM_{2.5}$ and PM_{10}), Carbon Monoxide (CO), Sulfur Dioxide (SO_2) and Nitrogen Dioxide (NO_2). In section 2.1.1 the effects of Air Quality have been discussed, however, this report indicates which groups of society are most vulnerable to these variables. A summary is given in Table 3.1:

Variable	Sensitive Group
Ozone	People with lung disease, children, older adults, people who are active outdoors (including outdoor workers), people with certain genetic variants, and people with diets limited in certain nutrients are the groups most at risk
PM2.5	People with heart or lung disease, older adults, children, and people of lower socioeconomic status are the groups most at risk
PM10	People with heart or lung disease, older adults, children, and people of lower socioeconomic status are the groups most at risk
CO	People with heart disease is the group most at risk
NO2	People with asthma, children, and older adults are the groups most at risk
SO2	People with asthma, children, and older adults are the groups most at risk

Table 3.1: Sensitive groups regarding Air Quality (U.S. Environmental Protection Agency, 2018)

This Table indicates that these variables should indeed be taken into account while considering Air Quality. The U.S. Environmental Protection Agency (2018) describes a method for calculating the AQI. This calculation follows four steps:

1. Truncate the variables appropriately
2. Using a specific table (U.S. Environmental Protection Agency, 2018, Table 5) to find the two breakpoints
3. Using Equation 3.1, calculate the index of the specified pollutant (variable):

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}}(C_p - BP_{Lo}) + I_{Lo} \tag{3.1}$$

Where,

$I_p =$	the index for pollutant p
$C_p =$	the truncated concentration of pollutant p
$BP_{Hi} =$	the concentration breakpoint that is greater than or equal to C_p
$BP_{Lo} =$	the concentration breakpoint that is less than or equal to C_p
$I_{Hi} =$	the AQI value corresponding to BP_{Hi}
$I_{Lo} =$	the AQI value corresponding to BP_{Lo}

4. Round index to the nearest integer

Following these steps, an index for all mentioned variables can be calculated. The index also prescribes that in the case data is available on multiple variables, the highest index should be used as that variable is the "responsible pollutant".

Importantly, the time frame of these measurements should be considered, as they differ per variable. Firstly, Ozone, Sulfur Dioxide and Nitrogen Dioxide are represented by 1 hour averages. Secondly, Ozone and Carbon Monoxide are both also measured with an eight-hour average. Lastly, all particulate matter (PM2.5 and PM10) are measured using a 24-hour average. While these averages are used to report daily Air Quality, the authors also indicate that shorter intervals can be used in different situations which require real-time information (for instance during a fire).

3.2.1.2 Common Air Quality Index (CAQI)

While the CAQI is in some ways similar to the AQI, there are some important differences. Firstly, Elshout et al. (2012) stress the importance of different exposure times to pollutants in the air: "The different consequences of different exposure times poses an awkward communication problem. A health-based index meant to warn people for short-term exposure to adverse air quality is mainly in the good part of the index scale, indicating that air quality is not a problem. Though this could be true from the short-term exposure point of view, the long-term exposure (even to low levels of air pollution) is often worrisome." Therefore, the CAQI proposes three different time frames: hourly, daily and annually. The hourly and daily indices range from 0 to 100, where 0 is very low pollution and 100 is very high pollution. Conversely, the annual index can be higher than 1, which indicates that the EU standards were exceeded, equal to 1, which indicates that the average was according to the EU standard or lower than 1, which indicates that the average was better than the EU standard. Furthermore, the CAQI differentiates between traffic conditions and city background conditions. Where traffic conditions should be measured near roads and traffic situations and city background in a more urban environment. The difference in these aspects is in the variables they include (as can be seen in Table 3.2).

Type	**Pollutant Type**	**Variable**	**Time frame**
Traffic	Core Pollutants	NO_2	
		PM10	1h and 24h
	Pollutants	PM2.5	1h and 24h
		CO	
Urban Background	Core Pollutants	NO_2	
		PM10	1h and 24h
		O_3	
	Pollutants	PM2.5	1h and 24h
		CO	
		SO_2	

Table 3.2: Air Quality variables CAQI

Besides offering a more comprehensive framework for interpreting data in different time frames to the AQI, the CAQI is also easier to calculate. Where the AQI requires a formula and lookup-table, the CAQI has predefined values (in $\mu g/m^3$) which constitute the index class (for instance "very low") (Elshout et al., 2012, p.3). This makes the CAQI easier to implement and easier to interpret. A similar system is in place for the calculation of the annual indices, where all variables indicated in Table 3.2 have predetermined target values (Elshout et al., 2012, p.3). Similar to the AQI, however, is the fact that the highest index of the chosen variables is deemed most important and will reflect the index of Air Quality for that measurement period.
Furthermore, as has been mentioned before, the different time frames incorporated into the CAQI allow for more extensive interpretation and information gathering with regard to Air Quality. Also, the distinction between traffic conditions and urban conditions is particularly suitable for this research, as the goal of this research is to measure Air Quality exclusively in traffic conditions (the sensor will be mounted on vehicles after all). However, the traffic variant of the CAQI can be considered to be less extensive compared to the AQI. As can be seen in the comparison of Table 3.3 the proposed CAQI index does not include Sulfur Dioxide and Ozone, while the AQI does include these pollutants.

However, when comparing the two indexing methods, the more useful variant is the CAQI due to its different time frames, specific definition in traffic and interpretation. Therefore, this indexing method will be used for Air Quality in this research. The methods for measurements, data processing and representation will be further elaborated in Section 3.3 and Section 3.4.

3.2.2 Temperature & Humidity

Temperature in the urban environment can have severe adverse health effects, as has been discussed in section 2.1.1. However, the manner in which temperature is measured is of importance. Basu and Samet (2002) indicate that hearth disease and stroke was already significantly increased at temperatures higher than 16°C (60°F), while studies from Japan indicated that peak death induced by increased temperature occurred above 38°C (100°F).

AQI			CAQI (Traffic)		
Pollutants	Time Frame	Calculation Method	Pollutants	Time Frame	Calculation Method
Nitrogen Dioxide	1h	Look-up table	Nitrogen Dioxide	1h	Based on absolute concentration
PM2.5	8h	Formula	PM2.5	8h	
PM10	24h		PM10	24h	
Carbon Monoxide			Carbon Monoxide	Annually	
Sulfur Dioxide					
Ozone					

Table 3.3: Comparison AQI and CAQI

While these findings should be considered in this research, this does not give an indication on how to index temperature measurements in the urban environment. Furthermore, as English et al. (2009) indicate, apparent temperature plays an important role when considering temperature with regard to health. Apparent temperature is also known as the Heat Index, which combines relative humidity with temperature and is also connected to mortality effects (English et al., 2009). This can be related to the fact that higher humidity inhibits precipitation and the cooling of the body in higher ambient temperatures Therefore, the suggests the use of the Heat Index, which can be calculated by Equation 3.2.

$$HI = c_1 + C_2T + c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2 \tag{3.2}$$

Where,

HI =	Heat Index
T =	ambient temperature
R =	relative humidity
c_1 =	-8.78469475556
c_2 =	1.61139411
c_3 =	2.33854883889
c_4 =	-0.14611605
c_5 =	-0.012308094
c_6 =	-0.0164248277778
c_7 =	0.002211732
c_8 =	0.00072546
c_9 =	-0.000003582

The result of this calculation can be used to look up how “dangerous” that apparent temperature is. This is divided into four categories: caution, extreme caution, danger and extreme danger. Using the Heat Index in this way will give clear insight into the urban environment with regard to temperature and humidity.

3.2.3 Noise

In contrast to temperature, noise levels can fluctuate much more violently during the day (and night). Therefore, a different approach to temperature measurement should be taken, which is similar to the measurement of some pollutants mentioned in section 3.2.1. Due to the possibility of abrupt changes in noise level (for instance a passing bus), a moving average of the noise level measured in a certain region should be considered for providing information on noise levels.

Besides the measuring method, the noise level should also be determined. The WHO advises certain noise levels in their report (Héroux et al., 2020). This report advises noise levels for traffic noise, this research will make the assumption that this type of noise is most prevalent in an urban environment and of the highest importance with regard to urban health. The advice is to reduce daytime traffic noise to a level below 53 dB, while nighttime noise levels should be reduced below 45 dB (Héroux et al., 2020, p.49).

Therefore, this research will index noise levels in accordance to these suggested values (53 dB and 45 db) using a moving average to smooth out extreme values. The daytime value will be used for times between 06:00h and 23:00h, while the nighttime value will be used during the remaining times of the day. The noise index will therefore be binary, as it is either in accordance with the suggested values (1) or not (0). This binary value will later be used to generate an overarching UHI.

3.2.4 Green Spaces

Besides the climate indicators, also the environmental indicators will be indexed. While these types of indicators are more subjective interpretation, this research will try to quantify them satisfactorily. Therefore, it should be recognized that green spaces are not only related to urban health by their quantity, but also by their quality: “Urban planners, landscape architects and policymakers need to pay more attention to the quality of Urban Green Spaces and not only to the quantity” (Russo and Cirella, 2018). Besides this, the WHO also recognizes a certain minimum and advised value for green space per capita: “Research points to at least 9 m^2 of green space per individual, with an ideal Urban Green Space value of 50 m^2 per capita” (Russo and Cirella, 2018).

This research will, therefore, adhere to these values and index urban green space with regard to these values. The index will range from 0 (less than 9 m^2 per capita) to 1 (50 m^2 or more per capita). The values in between these minimum and maximum value will range accordingly, for instance, if there is 29.5 m^2 available per capita an index of 0.5 will be calculated.

3.2.5 Walkability

As has been mentioned in the previous Section, the environmental factors found in Section 2.1 are not always clear to define quantitatively. This is also the case for walkability as no clear definition is available. However, this section will be based on the research done by Leslie et al. (2007). The authors distinguish between 4 elements of importance in determining the walkability of a neighborhood:

1. Dwelling density (D)
2. Connectivity (C)
3. Land use mix (LUM)
4. Net area retail (NAR)

The dwelling density is simply defined as the number of dwellings per square kilometer. However, in order to allow for efficient summation in determining the walkability index, it will need to be normalized (range between 0 and 1). Therefore, a min-max normalization is used, as shown in Equation 3.3.

$$\text{Normalized Dwelling Density} = \frac{\text{Dwelling Density} - \text{Minimum Dwelling Density}}{\text{Maximum Dwelling Density} - \text{Minimum Dwelling Density}} \quad (3.3)$$

Connectivity is defined as the number of intersections per square kilometer. An intersection is defined as a crossing of at least 3 roads. Similar to the dwelling density, the connectivity measurement needs to normalized in order to allow for efficient summation, this process is shown in Equation 3.4.

$$\text{Normalized Connectivity} = \frac{\text{Connectivity} - \text{Minimum Connectivity}}{\text{Maximum Connectivity} - \text{Minimum Connectivity}} \tag{3.4}$$

Land use mix is defined by a slightly more complex calculation. The land use types taken into consideration are: residential, commercial, industrial, recreation, and other. In determining the land use mix, a measure of entropy is used as shown in Equation 3.5.

$$-\frac{\sum_k (p_k ln(p_k)}{ln(N)} \tag{3.5}$$

Where,

k =	category of land use
p =	proportion of the land area devoted to that specific land use k
N =	number of land use categories

This measure ranges between 0 and 1 per definition. 0 represents perfect homogeneity (only 1 land use type), while 1 represents perfect heterogeneity (all land use types are equally present).

Lastly, the measurement for net retail area is given by Equation 3.6.

$$\text{Net Retail Area} = \frac{\text{Gross Retail Area}}{\text{Total retail parcel area}} \tag{3.6}$$

Again, this measure ranges from 0 to 1, where 1 means that all the available land is used for actual shops and thus not devoted to other elements like car parks.

The overall walkability index is then calculated by Equation 3.7.

$$\text{Walkability Index} = \frac{D + C + LUM + NAR}{4} \tag{3.7}$$

This gives the walkability index the characteristic to range between 0 and 1, where 1 means perfect walkability and 0 the poorest possible walkability.

3.2.6 Traffic Safety

The last index to be defined is that of Traffic Safety. This index is based on the risk analysis proposed by Shah et al. (2018). The authors give an (initial) definition of traffic risk, represented by Equation 3.8:

$$\text{Risk} = \frac{\text{Road Safety Outcome}}{\text{Exposure}} \tag{3.8}$$

They provide that exposure has been calculated by varying data: passenger kilometers, population, number of registered vehicles. However, for this study the population per neighborhood will be used as exposure. This defines risk as the amount of traffic accidents per resident. If risk is 1, this means that (on average) every resident of that neighborhood has an accident. If risk is 0, no accidents occur. Again, this gives a rough estimation of traffic safety, as the concept is not directly quantifiable. In order to reflect the previously mentioned intuition that and UHI of 0 indicates the worst possible scenario, traffic safety (TS) is suggested to follow Equation 3.9.

$$\text{TS} = 1 - \text{Risk} \tag{3.9}$$

3.2.7 Defining the Urban Health Index

In order to combine all previously mentioned sub-indices, some adjustments should be made. As can be seen in Table 3.4, all sub-indices have differing ranges, which makes it hard to compare and combine these indices. Therefore, when necessary, all indices will be adjusted to range between 0 and 1. Furthermore, for some indices 1 indicates the worst possible situation, while for others this indicates the best possible situation. The overall UHI will use 0 for the worst situations and 1 for the best, therefore, all sub-indices will be adjusted for that (by subtracting the sub-index from one). For pollution, this gives Equation 3.10.

$$P_n = 1 - \frac{\text{P}}{100} \tag{3.10}$$

Where P_n is the variable assigned to the normalized pollution levels and P represents the measured pollution index as defined in section 3.2.1.2. As the pollution sub-index already ranged between 0 and 100, this alteration is only minor.

For the Heat index, a min-max normalization method leads to the formulation of Equation 3.11.

$$H = 1 - \frac{T - T_{min}}{T_{max} - T_{min}} \tag{3.11}$$

Where, H represents the normalized value of the heat index. Furthermore, T represents the measured apparent temperature which is limited to a range between 27°C and 58°C, meaning that all values below 27°C will be rounded up to 27°C and all values above 58°C will be rounded down to 58°C. This is done because the index has no specific meaning beyond this range, for instance: an apparent temperature of 20°C will receive the same index score (0) as an apparent temperature of 27°C (also 0). Accordingly, T_{min} and T_{max} are 27°C and 58°C respectively.

Regarding the noise, walkability and traffic safety indices, no alteration need to be made. Noise level is defined as a binary index and is thus either 0 or 1 by definition. Similarly, the walkability and traffic safety index are defined to range between 0 and 1 and therefore needs no further alteration.

Lastly, the green space index will use a similar method to the normalization defined above for Heat, which leads to the formulation of Equation 3.12.

$$GS_n = \frac{GS - GS_{min}}{GS_{max} - GS_{min}} \tag{3.12}$$

Where GS_n represents the normalized value for the green space index. Similarly, the measured green space value (GS) will be ranged between 50 m^2 and 9 m^2 for similar reasons defined above for the heat index. GS_{min} and GS_{max} will therefore be 9 m^2 and 50 m^2 respectively.

Combining these normalized indices into one over Urban Health Index (UHI), gives Equation 3.13:

$$\text{UHI} = \frac{P_n + H + N + GS_n + W + TS}{6} \tag{3.13}$$

As can be seen, equal weight is given to each sub-index, meaning that they are deemed equally important with respect to urban health. This method is consistent with the method prescribed by the WHO in their report on calculating UHI's (Weaver et al., 2014). Furthermore, the UHI ranges from 0, which is considered very poor, to 1, which is considered optimal, as this makes the UHI easier to interpret (i.e., an UHI of 1 is intuitively better than an UHI of 0.56).
As an example, let the pollution index be 0.47, heat index 0.96, noise index 1, green space index 0.76, walkability index 0.63 and the traffic safety index 0.34. This, in turn, gives the value provided by Equation 3.14.

$$\text{UHI} = 1 - \frac{0.47 + 0.96 + 1 + 0.76 + 0.63 + 0.34}{6} = 0.71 \tag{3.14}$$

Variable	Name	Worst	Bad	Average	Good	Best
P =	Pollution	>100	75-100	50-75	25-50	0-25
H =	Heat	>52-58	40 – 51	33 – 39	27-32	<27
N =	Noise	0				1
GS =	Green Spaces	<9	9 -23	23 – 36	36 – 50	>50
W =	Walkability	0	0 – 0.25	0.25 – 0.5	0.5-0.75	1
TS =	Traffic Safety	0	0 – 0.25	0.25 – 0.5	0.5-0.75	1

Table 3.4: Summary of sub-indices

Which can be considered a rather good score for this particular area. As can be seen, however, the individual score for traffic safety is rather low. This shows an inherent danger in reporting only the eventual UHI, as high values in many sub-indices can hide adverse health effects of a single sub-index. Therefore, it is advisable to also report the individual indices in some cases. This will be further discussed in Chapter 3, section 3.3.

This concludes the section defining the Urban Health Index (UHI), in the next Section the outline of the System Design is set out, after which the implementation of this design is discussed in more detail.

3.3 System Design

In order to achieve the functions determined in Section 3.1 a system is proposed. Section 3.4 will go into detail about the implementation of this design.

The system will be a location-based web application, therefore, an interactive map is proposed which will display the collected data described in Chapter 2. As the data is both dynamic, static and has several levels of spatial resolution, different data structures will be used. Firstly, the static data is mostly available on a neighborhood level, therefore, the preferred level of analysis for this type of data would be the neighborhood or city. However, the goal of this research is to provide Urban Health information with a high spatial resolution, as the data collected by mobile sensors can be analyzed with such a resolution (in contrast to the static data). Therefore, the static data will be aggregated into a hexagonal grid, which provides a compromise between the static and dynamic data resolutions described above. These hexagons will overlay the city of analysis (Eindhoven, the Netherlands) and will provide the end-user with the relevant Urban Health information. The sensor data, in contrast, will be recorded as data points which can be aggregated into the hexagonal grid. The process by which this will take place will be discussed in the remainder of this Section.
The hexagonal grid is preferred over a square grid for several reasons. Firstly, conceptually a hexagon has a low perimeter to area ratio, which should reduce edge effects. In squares, this effect could lead to a misrepresentation of data points at the edges of the squares. While, a circle has the optimal perimeter to area ratio, a hexagon is the closest shape which can be tiled across a surface. Moreover, in contrast to a square grid, all neighbors are equal in a hexagon. In a square grid, some neighbors touch an edge, while some touch a vertex. This effect doesn't appear in a hexagonal grid structure. Lastly, when this system is implemented over very large areas (i.e., countries) distortion is minimized. As the map projects a three-dimensional surface on a two-dimensional plane, some distortion occurs. This effect is more apparent in a square grid, which provides an additional advantage for the use of the hexagonal grid. It should be noted that a square grid could also provide informative results, as the mentioned effects are expected to be minimal. However, in order to provide a robust system, the hexagonal grid system is used.

Figure 3.7 below describes the process by which all the relevant data will be visualized. The design will include two different, but related, uses. Firstly, the most recent UHI will be displayed in order to enable short-term decision-making based on Urban Health information. However, as data is also collected in an historic context, data will also be displayed over a longer time period in order to support long-term decision-making. Examples of both long and short-term decision-making are respectively choosing a location for running and choosing the location of a new house. Both decision support-systems will be discussed below.

The first step in the system design (see Figure 3.7) is to record the sensor values for the relevant Urban Health indicators, as described in Section 3.2. These sensor values are combined into a new Datapoint (step 1.1). This collection of datapoints is a continual process and all data points are recorded to a central database, which allows for the querying of datapoints on several aspects (i.e., time of recording, UHI values or location). A similar process needs to be conducted for the Hexagonal grid (step 1.2). These hexagons will have attributes related to the indicators described in Section 3.2. While the collection of datapoints continues, the Hexagonal grid needs no (or little) updating, as the relevant indicators are unlikely to change regularly. Therefore, these steps only need to be conducted once and will not be collected in the database but stored on the host server, in contrast to the datapoints stored on an external database. Once the data is collected, it is processed, which constitutes different steps based on the time frame over which the data should be visualized. These different processes will be further discussed in Section 3.4.3. After processing the data, it can be aggregated into several visualizations (step 3). Firstly, a map will be visualized which gives an indication of the current UHI (step 4.2), conversely, data over a longer time-span will be visualized to inform the user on the historical context of their chosen location (step 4.1). Details regarding the exact methods used for aggregating and visualizing the data will be discussed in Section 3.4.5.

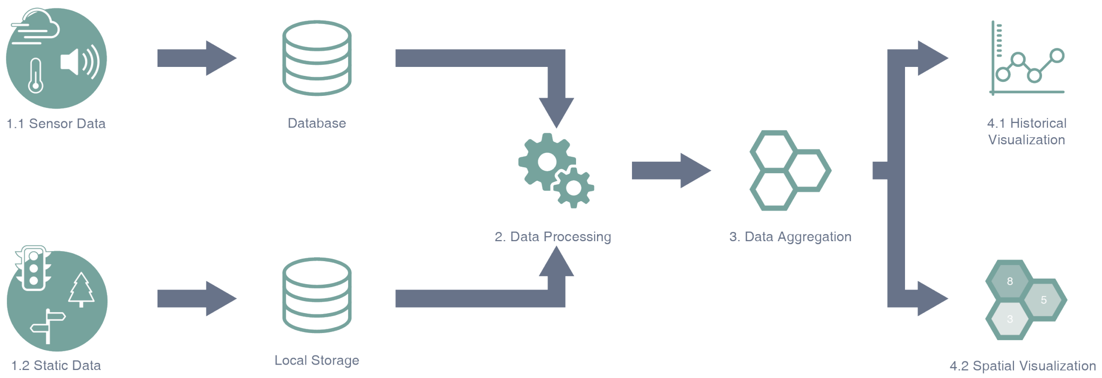

Figure 3.7: Overview of system design

3.4 System Implementation

As has been discussed in Section 3.3 the implementation of the proposed design entails several aspects. This Section will go into detail on the implementation of all aspects. Firstly, the creation of the Hexagonal grid will be discussed (Section 3.4.1). Secondly, a suggestion for adequate sensor design is made (Section 3.4.2). Thirdly, the calculation methods for the UHI will be detailed (Section 3.4.4). Lastly, the visualization of the data will be explained in Section 3.4.5.

3.4.1 Hexagonal Grid

The first step, in representing the suggested Urban Health data, is the creation of the previously discussed Hexagonal grid and its associated static data. The creation of this grid is done through several steps, all of which will be described below. The processing of this data is mostly done using Python and QGIS (QGIS, 2021). QGIS is an open-source GIS software, used to analyze and visualize geospatial data. Furthermore, several data elements from the open source OpenStreetMap (OSM) (OpenStreetMap-authors, 2021) will be used in addition to the data sources which will be mentioned.

1. As has been mentioned in Section 3.3, the level of analysis for the static data is mostly on a neighborhood level. Therefore, the municipal data on neighborhood definitions is used to aggregate the data in further steps. The `geoJSON` file (Gemeente Eindhoven, 2017) is loaded into QGIS. This file format (`geoJSON`) (Butler et al., 2016) is specifically chosen as it allows for data handling in several applications and is compatible with multiple visualization tools and web-applications.
2. The definitions provided in Section 3.2 indicate that several indicators are dependent on population numbers. Therefore, this data is added via a Python script. This script loops over the available neighborhoods and a data file containing population statistics (Centraal Bureau voor de Statistiek, 2020), if a match is found the population statistics are added to the file of the neighborhood definitions.
3. A similar method is used for the addition of green area. The data file used (Gemeente Eindhoven, 2021) is available through the municipality and is looped over in the same manner described in Step 2.
4. Moving on to the definition of traffic safety, the amount of traffic accidents per neighborhood needs to be aggregated. The data used for this analysis (Overheid.nl, 2015) details individual traffic accidents for the entire city. This data is loaded into QGIS together with the neighborhood data. As the neighborhood data describes a polygon and the traffic accidents are points, the vector analysis tool "count points in polygons" can be used. This tool adds a new attribute to the neighborhood data, which is a count of all traffic accidents in each polygon (hexagon).
5. The walkability indicator requires several elements, one of which is the amount of housing (Normalized Dwelling Density and Residential Land Use). In order to gather this data, OSM will be used and from this data source all buildings labeled as "residential" are queried, resulting in a polygon collection containing all residential buildings in the city of analysis. In order to determine the area of housing per hexagon, the "overlap analysis" QGIS tool is used. This tool measures the area of the input layer (polygon collection of residential buildings) per polygon of the output layer (neighborhood data) and adds this amount to the specific polygon. This results in an additional attribute in the neighborhood data containing the amount of residential buildings in square meters for each neighborhood.
6. The second element required for calculating the walkability sub-index is connectivity. Connectivity is defined as the amount of intersections per square kilometers. In order to determine this value, all roads are queried from OSM, these include all roads labeled as: Motorway, Primary, Secondary, Tertiary and Residential. With all roads available for analysis, several QGIS operations are executed. Firstly, all road types are merged ("merge vector layers") into one layer. These roads are then dissolved into one element, after which this element is transformed into one geometry ("multipart to singleparts"). On this geometry, the tool "line intersections" is used to determine the actual intersections in the city of analysis. As this results in multiple intersections being located several times, duplicate items are deleted. This results in a point for each intersection in the city. Similar to step 4, the points are counted for each polygon in the neighborhood data. This adds another attribute in the neighborhood data containing the amount of intersections in that neighborhood.
7. The third step in determining the walkability sub-index is calculating the land use mix. This calculation requires land use data for residential, commercial, industrial, and recreation areas (Section 3.2). As the residential area has been collected in Step 5, this is already part of the neighborhood data. OSM has no records of recreation areas, therefore these will be excluded from the calculation. For both commercial and industrial land uses, an identical method is used. Firstly, the area is queried from OSM, after which the "overlap analysis" (described in Step 5) is used. Conducting this for both land use types results in two new attributes in the neighborhood data, containing the land use areas in square meters.

8. The last step in determining the walkability sub-index is calculating the Net Retail Area, which is dependent on the Gross Retail Area and the total retail parcel area. Therefore, all buildings and land use areas labeled as “retail” are queried from OSM. For this calculation, only the buildings actually situated in retail land use areas need to be considered. Therefore, the building data is clipped to only include buildings situated in retail land use area. For both data files, an area attribute is calculated (as this calculation is done based on area). These area attributes are then added to a neighborhood data if the area is within that specific neighborhood (QGIS tool “join attributes by location”).
9. As all data elements regarding the calculation of the static data indices are collected, they need to aggregated into the previously discussed Hexagonal grid. This grid is created using the QGIS “create grid” tool. The grid is set to the extent of the city of analysis, and the hexagons have a width and height of 500 meters. As the grid is created for a rectangle cover in the city of analysis, some hexagons lay outside the city borders. Therefore, the centroid of each hexagon is determined (QGIS tool “centroids”), after which the centroids outside the city borders are clipped (QGIS tool “clip”). For each hexagon, the amount of centroids it includes is counted (QGIS tool ”count points in polygon”), which results in each hexagon having an attribute of either one or zero. One meaning it lays inside city borders, zero meaning it lays outside city borders. Therefore, all hexagons having a value of zero are deleted from the data set.
10. The last step in creating the Hexagonal grid is to transfer the neighborhood data to the hexagons. Again, the QGIS tool “join attributes by location” is implemented. This results in a Hexagonal grid containing all previously discussed data attributes. This grid is then exported in the `geoJSON` format for further use.

As mentioned, the final result of this process is a data file in the `geoJSON` format. This data file contains a collection of hexagons, each with the attributes described in the process above. The standard format for a `geoJSON` feature collection can be seen in Listing B.1. The format for the Hexagonal grid, however, can be seen in Listing B.2. It contains a Feature Collection of polygons, where the properties contain all previously mentioned elements.

Several aspects of the format shown in Listing B.2 are noteworthy. Firstly, all elements regarding area are provided in square meters. Furthermore, in this example two elements are defined as `null`, this indicates that no area was found of this particular definition. As a definition of `null` provides some advantages over a definition of “0” in future use, these values are defined in such a manner. Moreover, lines 26, 31 and 33 (Listing B.2) indicate percentage values. Meaning, the percentage of that type of area with regard to the total area of the neighborhood. In this example, roughly 13% of the neighborhood is covered by buildings defined as “housing”. This concludes the collection and processing of the static urban data, the next section will go into more detail on how dynamic urban data will be collected, stored and processed.

3.4.2 Sensor Design

As the proposed application partly depends on dynamically collected sensor data, this section will give an overview of a possible sensor design. This design is based on the Raspberry Pi infrastructure, this system is accessible and would allow for easy adoption of a large fleet of sensors. However, it must be mentioned that not all sensors available for this infrastructure meet the requirements necessary for this application. Despite this, a possible prototype is suggested.

Firstly, in order to make on an overview of the proposed sensor (types), the units of measurement for each sub-index should be considered (Table 3.5).

Therefore, the used sensor types should be able to measure the relevant indicator in the correct unit of analysis or should be able to give a measurement which can be converted into this unit. Considering temperature and humidity, the Grove DHT11 sensor (Seeed, 2021d) is proposed. This sensor is capable of measuring both temperature and humidity with relatively high precision with

Indicator	**Unit**
Temperature	Celsius
Humidity	% (relative humidity)
Air Quality	
NO_2	$\mu g/m^3$
PM_{10}	$\mu g/m^3$
$PM_{2.5}$	$\mu g/m^3$
CO	$\mu g/m^3$
Noise	dB

Table 3.5: Unit of analysis for Urban Health indicators

the correct units. Further, considering an appropriate noise sensor, the Grove Analog Microphone (MEMS) sensor (Seeed, 2021a) is proposed. As the name suggest, this sensor only gives an analog output, which is unsuitable for this application. Therefore, this sensor would need to be calibrated to output the correct Decibel measurements. Section 3.2.3 has discussed the nature of the noise sub-index and therefore, the sensor can be calibrated to give a binary output when the measurement is above the set threshold. This would increase usability of this sensor, as a continual and exact output is unnecessary. Lastly, several aspects regarding air quality need to be measured. First of which are the particulate matter indicators for which the Nova SDS011 Laser sensor (Tinytronics, 2021) is proposed. This sensor is capable of sensing both PM_{10} and $PM_{2.5}$ with the correct unit of analysis. Considering Nitrogen Dioxide and Carbon Monoxide, an alternative sensor is proposed, the Grove Multichannel Gas Sensor (Seeed, 2021c). This sensor is capable of measuring a wide range of gasses, however, this sensor's output is given in Parts Per Million (PPM) and therefore the output would need to be converted to the given unit. Combining these sensors would give the user a sensor module capable of measuring all determined dynamic indicators of Urban Health.

Secondly, the measurement of the actual indicators, the setup of the sensors should also be mentioned. As the sensors would be attached to moving objects (vehicles), the location of the sensor should also be recorded. Therefore, a GPS module (Grove GPS Air530 (Seeed, 2021b)) needs to be included. Moreover, measurements should occur at a regular interval. As this research only gives a hypothetical overview of a sensor design, this interval should be tested in a real-world test. However, a 30-second interval should be appropriate, as this would provide an interval of roughly 250 meters assuming a speed of 30 km/h. As this distance is less than the proposed grid interval, this would result in multiple measurements per hexagon and therefore a rich data set to provide information to the end-user.

Lastly, the manner in which the collected data is shared with the application should be discussed. As will be discussed in Section 3.4.3, the application collects data from a central database. Therefore, the sensor modules will write the recorded data points directly to the database. Each data point will follow the structure as shown in Listing B.3. This structure shows that each data point is stored as a `geoJSON` file as a "point" type. The properties of each data point are separated into two categories: Index Variables and Time/Date. The time and date properties are included to allow for easy querying when implementing the application (Section 3.4). The Index Variables are again aggregated between the different sub-indices to create an orderly data structure. Each key will be ascribed to measured sensor value, for instance, the key "temperature" will be ascribed a value of 28°C.

This suggested prototype would allow for the necessary functions in order to provide the relevant information to the end-user. The next Section will go into more detail on how this data is used to provide this information to the end-user.

3.4.3 Application Architecture

Before discussing the calculations made in order to visualize the data, the basic architecture will be explained. Firstly, the main programming languages used in order to run the proposed application are JavaScript, HTML, and CSS. In order to run the application as a web-application, Node.js (Joyent, 2021) is used with an Express framework (StrongLoop and IBM, 2017). Node.js is described as "an asynchronous event-driven JavaScript runtime' and as 'designed to build scalable network applications" (Joyent, 2021), therefore it is deemed a good foundation for the proposed application. Furthermore, Express is described as "a minimal and flexible Node.js web application framework that provides a robust set of features for web and mobile applications" (StrongLoop and IBM, 2017), this is in accordance with the goals of the proposed application.

The Express framework is set up in a straightforward fashion, where every request is routed to a different web page. For instance, the request `http://urbanhealthindex.herokuapp.com/map/today` will be recognized by Express (if the application is online) and routed to the web page "/map", which will contain all the layout (HTML), styling (CSS) and functions (JavaScript) in order to visualize the necessary data.

Besides the application architecture, a database architecture is also used. For this application, the No-SQL (non-relational) database MongoDB Atlas (MongoDB, 2021) will be used. Firstly, a No-SQL database is used, as these types of databases don't require a predefined data structure. For this application, this means more flexibility in the storage of data points and possible grid structures. Moreover, MongoDB Atlas allows for easy access through Express and multiple query possibilities. The connection between the application and the database will be made using the Mongoose software package (MIT, 2021). This allows for queries, as can be seen in Listing B.4. This particular query will return all Datapoints where `properties.date.0` equals a predefined `year`, `properties.date.1` equals `month` and `properties.date.2` equals `day`. As has been discussed in Section 3.4.2, these properties equal the creation date of that particular data point. As `year`, `month` and `day` are defined as the current date, this query will return all data points created today. These data points can then be parsed to the web-page, in which these data points will be visualized (see Sections 3.4.4 and 3.4.5).

3.4.4 Urban Health Index Calculation

Before visualizing the previously defined datapoints and hexagonal grid, some additional calculations are required. As has been described in Section 3.4.1, and can be seen in Listing B.2, only the raw data is part of the hexagon data structure. Therefore, this data needs to be transformed into meaningful sub-indices using the methods described in Section 3.2. This section will go into more detail on the methods and data handling process used in this application.

As will be further elaborated in Section 3.4.5, the method used to visualize the data will make use of the Mapbox system (Mapbox, 2021). In order to load the data to this system, two elements are required. Firstly, the systems require a specification of the data type, as has been described in Section 3.4.1 the data is saved in a `geoJSON` format. Secondly, the data needs to be parsed, which will be the focus of this section. The first step in parsing the data is to load the Hexagonal grid data from the previously created `geoJSON` file in such a way that JavaScript can handle the data. An additional JavaScript package is used to do so, as can be seen in Listing B.5

In the remainder of this Section, the calculation methods for both static and dynamic variables will be discussed and how those variables will be used to determine the UHI for the entire city under investigation.

3.4.4.1 Static Variable Calculation

As can be seen in Listing B.5, the action of loading, processing and parsing the data is wrapped into one function named `loadData` and requires six arguments. These arguments will be further discussed in Section 3.4.5, however, they will allow the user to visualize the data to their own preferences. Furthermore, the `geoJSON` Hexagonal grid file is subtracted from the local directory and a function is used to ascribe this file to the `data` variable. As the data is now available, the sub-indices will be calculated. An overview of the steps regarding the static variables is given in Figure 3.8. This Figure shows three main steps for each individual hexagon, with several sub-steps regarding walkability. When all hexagons have been processed, the application moves on to calculate the dynamic variable scores. The process is shown in Listing B.6 in detail.

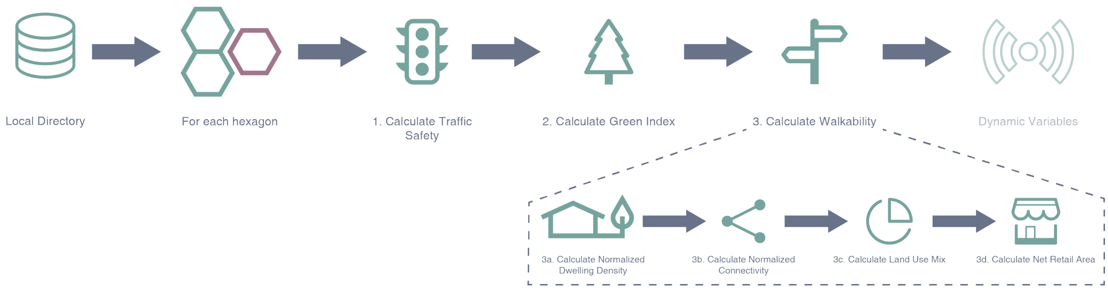

Figure 3.8: Overview of calculation of static indices

Firstly, two variables are set in order to identify each hexagon (`num`, Listing B.6 line 2) and calculate the best scoring hexagon (`window.best`, Listing B.6 line 3). These variables will be used further throughout the application.

Moreover, in order to determine the sub-indices for each individual hexagon, the application will loop over each feature of the `data` variable, as each hexagon is stored as a feature in this variable. For each loop, the feature will be referenced by the variable `f`. The application stores the results returned by the `trafficScore` function in the `trafScore` variable, which can be used later. A similar approach is used for every sub-index calculation described below. The `trafficScore` function is displayed in Figure 3.9. The input variables are displayed in the left column, while the output is displayed at the bottom. A diagram of the performed actions is given in the white rectangle. The exact code for the function can be seen in Listing B.7.

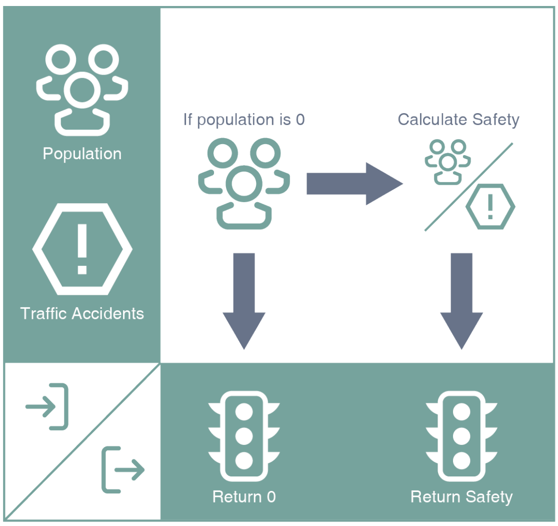

Figure 3.9: Function: Traffic Safety

This function expects two arguments, the amount of traffic accidents and the population of the area, which is in accordance with the definition given in Section 3.2.6. These values are stored in each individual hexagon, and will be accessed as can be seen in Listing B.6, line 12. This will be similar for subsequent calculations. If the population is exactly zero, this definition becomes irrelevant and therefore a score of zero is returned. However, in all other situations, the traffic safety of that area is calculated. If this score is lower than zero (i.e., the amount of accidents per resident is higher than one), a score of zero is returned. However, if a score higher than zero is calculated, this value is returned and ascribed to the `trafScore` variable previously mentioned.

The second sub-index calculation is green space (Listing B.6, lines 17 through 19). This function is shown in Figure 3.10, the corresponding code can be seen in Listing B.8. Similar to the calculation of Traffic Safety, the `greenSpaceScore` function expects two arguments: Green space area and the population of that area. As has been discussed in Section 3.2.4, the minimal amount of green space in an area has been set at 9 square meters per person, while the maximum (optimal) amount was determined at 50 square meters per person. These values are reflected by the two variables in the code snippet (lines 2 and 3). As these variables are relative to the population, this value is also calculated for this area, however, if the population is undefined (`null`) or zero, the green space sub-index becomes irrelevant and a score of zero is returned. If population is defined, however, the calculation for the green sub-index is made. If the relative green space area is lower than the minimal required area, a score of zero will be returned. Similarly, if the relative green space area is higher than the maximum required area, a score of one is returned. This corresponds to the explanation given in Section 3.2.4. However, if neither of these two situations occurs, the calculation is made and this value is then returned and ascribed to the `greenScore` variable (Listing B.6 line 17).

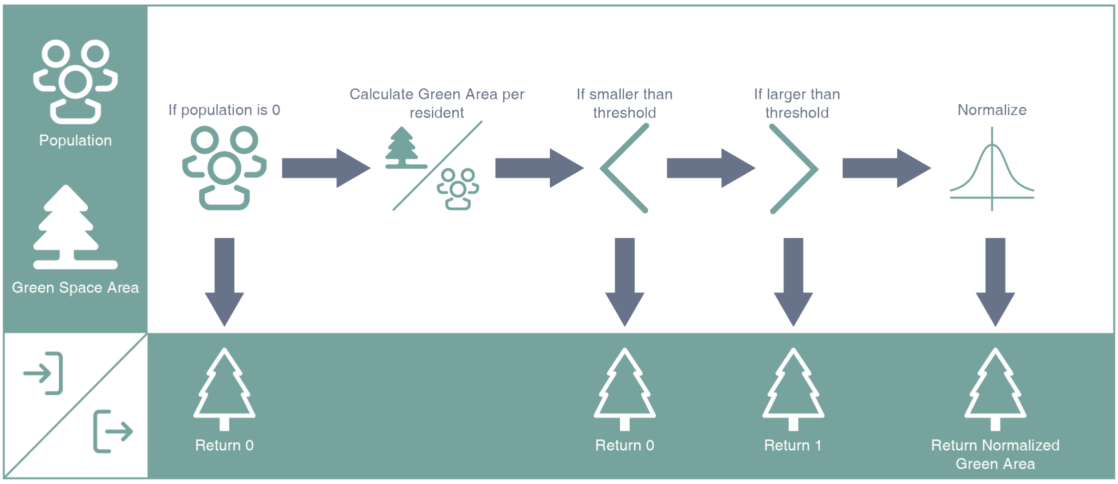

Figure 3.10: Function: Green Index

Lastly, the calculations are made for the walkability index. As this index is compounded from several smaller calculations, four functions will be discussed below. Firstly, the Normalized Dwelling Density is calculated (Listing B.6 line 23). This function is shown in Figure 3.11, the corresponding code can be found in Listing B.9. The definition given in Section 3.2.5 describes dwelling density as the amount of dwellings relative to the total area. However, as can be seen in Figure 3.11, this function only requires the dwelling density. As has been described in Section 3.4.1, each hexagon has an attribute `building_houses_pc` which is the percentage value of the amount of houses in that area, which fits the definition determined earlier. Further, the calculation normalizes this value by dividing by the largest occurring dwelling density in the data set (which is roughly 21.8 percent).

The second value to be determined is the normalized connectivity (Listing B.6, lines 25 through 28).

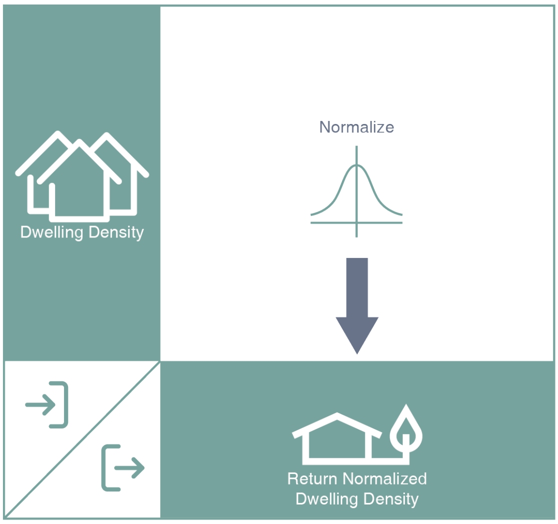

Figure 3.11: Function: Normalized Dwelling Density

This function expects two arguments: the amount of intersections and the total area. Similarly to the Normalized Dwelling Density, this calculation requires the maximum amount of intersections in order to determine the normalized value (line 2). After which the normalized amount of connections is determined (line 3) and the relative amount per square kilometer is returned (line 4 and 5) and ascribed to the `normConnect` variable (Listing B.6).

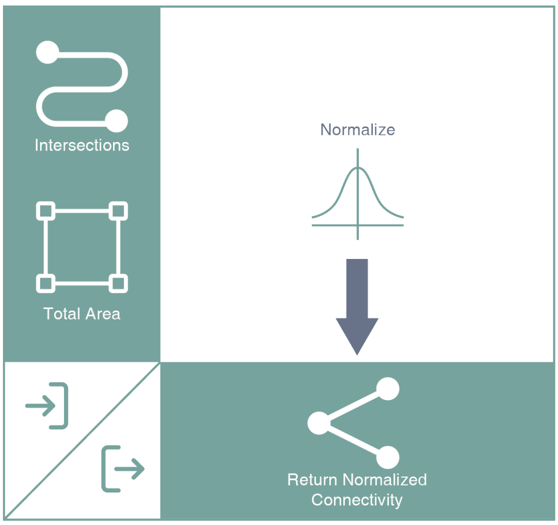

Figure 3.12: Function: Normalized Connectivity

Thirdly, the land use mix is calculated, using the formula provided in Section 3.2.5. In Listing B.6 lines 30 through 34 the relative land use percentages are first determined and added to an array. This array is then passed to the `lum` function shown in Figure 3.13, the corresponding code can be found in Listing B.11. Firstly, two variables are set in order to perform the calculation: the numerator of the variable and the constant `N`, which is equal to the amount of values in array `p` and will be the denominator of the equation. Subsequently, every value of array `p` is checked, if the value is zero, the numerator remains equal to its previous value. However, if the value is not equal to zero a calculation is made, which corresponds to the formula given in Section 3.2.5.

Lastly, the numerator is divided by `N` and inverted. This final value is returned and ascribed to the `landUseMix` variable.

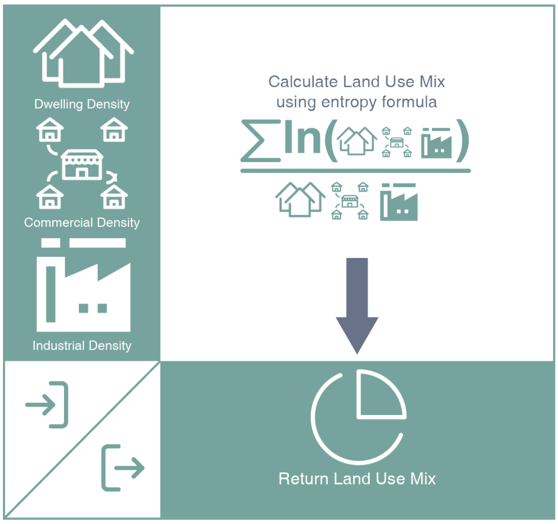

Figure 3.13: Function: Land Use Mix

The last calculation regarding walkability is for the determination of the Net Retail Area (Listing B.6, line 38 through 41). The `nra` function given below in Figure 3.14 (Listing B.12) expects two arguments: Gross Retail Area and the total area. Similarly to the calculations described above, if either of the two arguments provided is zero or undefined, a value of zero is returned. Otherwise, the Gross Area is divided by the total area, the result of which is returned and ascribed to the `netRetailArea` variable. Lastly, the average of all walkability calculations is determined (Listing B.6, lines 43 through 48) which is set as the final walkability score for that hexagon.

This concludes the calculation of all static variables of the hexagons. Which leads to the calculation of the dynamic variables determined by the measurements of the datapoints.

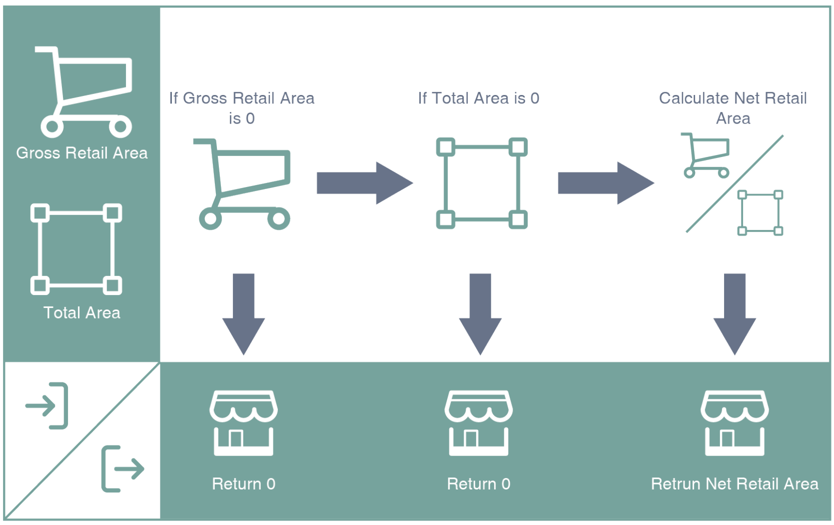

Figure 3.14: Function: Net Retail Area

3.4.4.2 Dynamic Variable Calculation

The process for determining the dynamic indices and the eventual UHI is described in Figure 3.15. The process describes several steps which will be discussed in more detail below

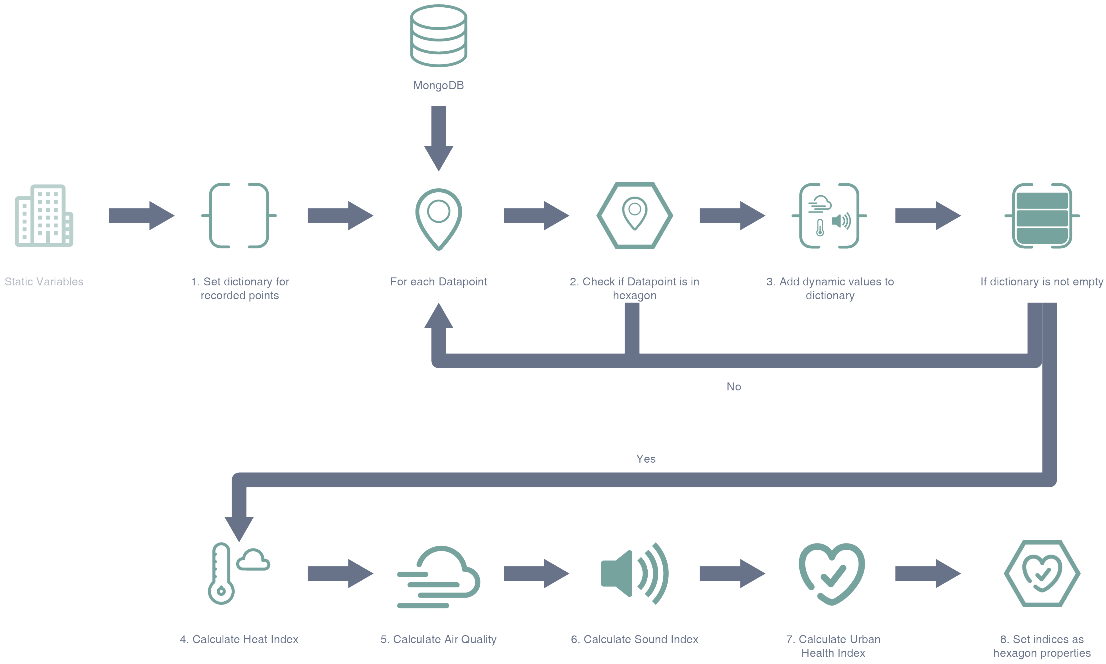

Figure 3.15: Overview of calculation of dynamic indices

Before checking which datapoints lay within the current hexagon under investigation, a dictionary is created to store the relevant values (step 1). This dictionary is shown in Listing B.13. This dictionary will store the values for each data point in the hexagon under investigation in order to calculate the average for the final calculation of the UHI.

This leads to the following step, in which the application loops over each data point parsed to the function (see Section 3.4.5) and checks if this data point lays within the current hexagon (Listing B.14 lines 2 through 5). This check is done by using the Turf (Turf, 2021) package, which enables the check described above. The function `booleanPointInPolygon` returns a Boolean which reflects whether the variable `point` (the data point) lays within the variable `poly` (the hexagon polygon). If this value is `True`, the application takes several additional steps. If it is `False`, it continues to the next data point. However, when the data point is within the bounds of the hexagon, the corresponding sensor data (see Section 3.4.2) is added to the dictionary (Listing B.14 lines 7 through 28).

After this step, all required information is available. As mentioned, Figure 3.15 (Listing B.15) describes the process of calculating the UHI of the hexagon. Firstly, it is checked whether the dictionary contains any data, if this is the case the UHI is calculated.

This is done by first calculating the Heat Index. As can be seen in Figure 3.16 (Listing B.16) this function expects two arguments: the ambient temperature and relative humidity. However, as shown in Listing B.15 lines 5 and 6, the average value for all recorded datapoints in this hexagon is passed in order to give the most representative depiction. This is done for all calculations regarding sensor data. For calculating the Heat Index, the formula given in Section 3.2.2 is used. However, if the calculated value is below 27 °C a score of one is returned, while a score of zero is returned when the calculated value is above 58 °C (Listing B.16 lines 21 through 25). In all other cases, the normalized Heat Index is returned (Listing B.16 line 26) and ascribed to the `heatScore` variable.

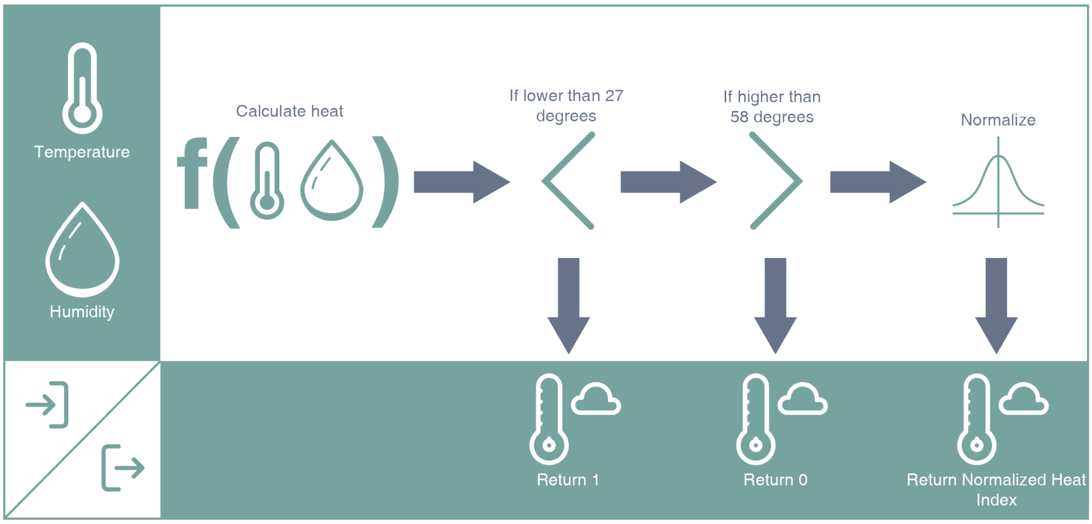

Figure 3.16: Function: Heat Index

The second index that needs to be calculated is the Air Quality index (Listing B.15). This function requires four arguments, which are each individual Air Quality measurement determined in Section 3.2.1. The calculation of the Air Quality Index is given in Figure 3.17 below, the corresponding code can be found in Listing B.17. It is worth restating how the Air Quality is calculated: an individual score is calculated for each marker (Nitrogen Dioxide, PM10, PM2.5 and Carbon Monoxide), and the highest of these scores is adopted as the Air Quality index. Each marker has different threshold values which are reflected in the calculation depicted in the Listing B.17, however, the calculation methods are the same for all input variables. The scores for each individual marker are calculated (Listing B.17 lines 6 through 44) after which these scores are compared to determine which is the highest (Listing B.17 lines 48 through 56). This value is returned and ascribed to the `aqScore` variable.

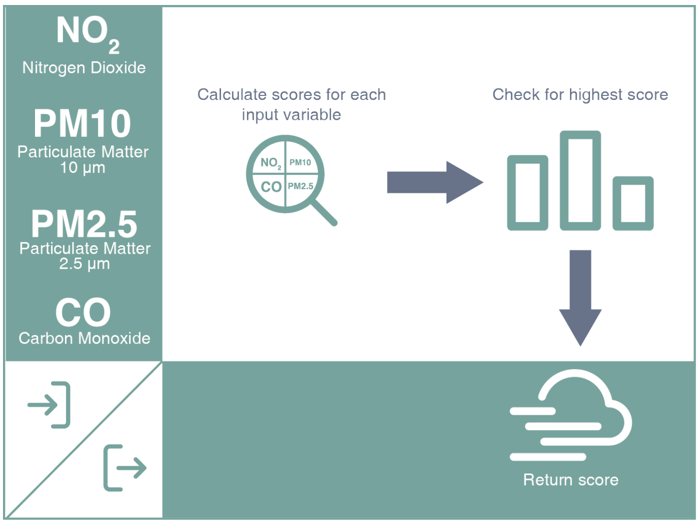

Figure 3.17: Function: Air Quality

The last index to be determined is the Sound Index (Listing B.15) line 16). This function expects one argument, which is the recorded sound value in decibels. Figure 3.18 (Listing B.18) shows the function for determining the Sound Index. The method used returns a score of zero if the recorded value is above the determined threshold (Section 3.2.3), and a value of one otherwise. This results in a binary value for the Sound Index.

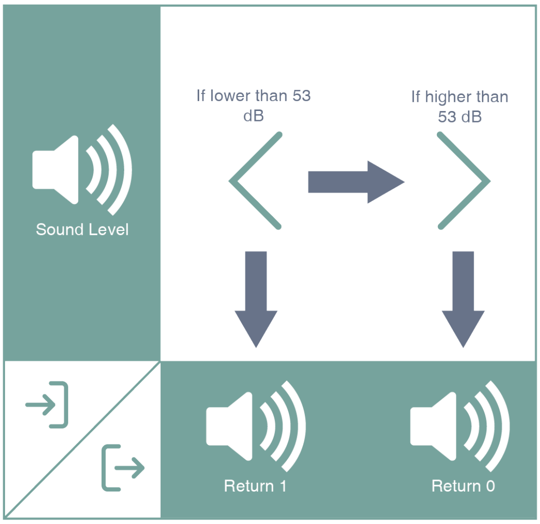

Figure 3.18: Function: Sound Index

Finally, the UHI will be calculated and attributed to the hexagon, as shown in Figure 3.19 (Listing B.19). First, the application checks which filters are selected. If a filter is selected, the value will be one, otherwise it will be zero (Listing B.19 lines 2 through 8). Then, the UHI is calculated for the hexagon in question, using the filter settings (Listing B.19 lines 11 through 18). Lastly, the sub-index scores are set to the properties of the hexagon as well as the UHI score.

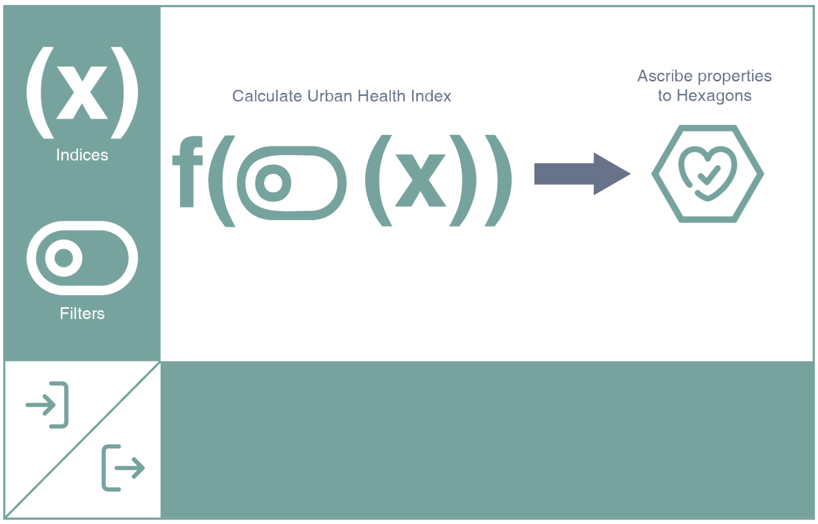

Figure 3.19: Function: Urban Health Index

This concludes the calculation methods used for determining the UHI and corresponding sub-indices. The following section will go into more detail how these values will be used to visualize the data in multiple ways.

3.4.5 Visualization

As can be seen in Figure 3.7, the previously determined data will be visualized in two ways. Firstly, the data from the most recent time period will be used to create a hexagonal grid visualization covering a map of the city. This informs the end-user of the UHI of every part of the city. Secondly, data from a chosen time period (month or year) will be used to inform the end-user of the progression of the UHI and its sub-indices over time. The method of generating the proposed visualizations is shown in Figure 3.20.

In order to realize these visualizations, several tools are used. Firstly, Mapbox (Mapbox, 2021) is used for the geospatial visualizations. Mapbox allows for a variety of geospatial visualization, which will be explained in this Section and in Chapter 4. Secondly, in order to visualize the progression of the UHI over time, Chart.js (Chart.js, 2021) will be used. This section will first elaborate on the method used for visualizing the map of the city and the accompanying functions, after which the historical data representation will be discussed.

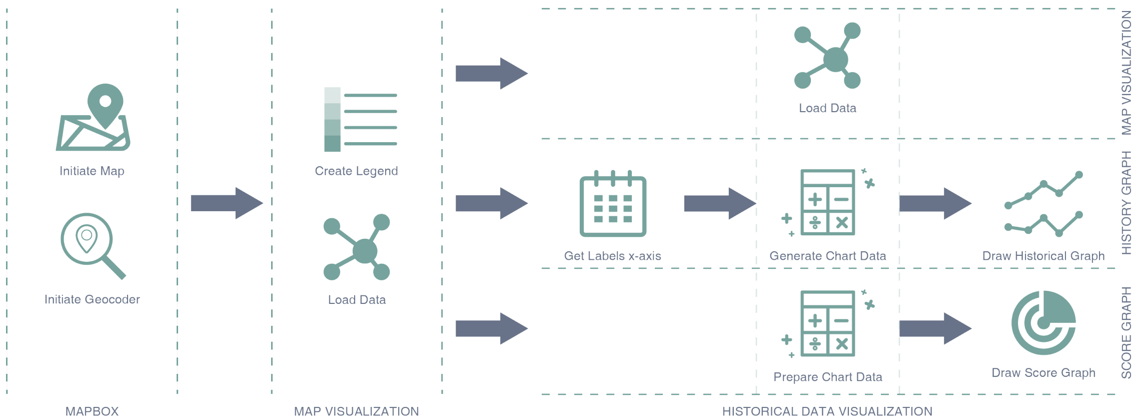

Figure 3.20: Overview of Visualization method

3.4.5.1 Map Visualization

As has been mentioned, Mapbox is used for all geospatial visualizations. The initialization of Mapbox, with several auxiliary functions, is shown in Listing B.20. Firstly, a new map is created with a specific style, center and zoom level. The results of these variables can be seen in Chapter 4. Secondly, the Mapbox client needs to be accessed in order to add a geocoder to the application. A geocoder allows the end-user to insert a location of their choice, which the map will recognize. In this application, the result of such a search query will be to show the location with a pin and to zoom in to that location. Lastly, to allow the end-user to control the map intuitively, some map controls (zoom, pan, scroll) are added.

The visualization of the map is triggered when the page tries to load the map (Listing B.21). This triggers two "functions". Firstly, the data is processed as described in Section 3.4.4. After which the legend for the map is created. This legend shows the color codes corresponding to each UHI score.
Besides loading the data, two elements should be further discussed. As has been discussed before, and as can be seen in Listing B.21, six filters are included in the calculation. The function of these filters is shown in Listing B.22. First, the appropriate input is selected, which is a checkbox the end-user can toggle if he/she wants to exclude (or include) that type of data from the visualization. When such a toggle occurs, the application removes all current layers and data sources from the map and checks whether the input is currently on (sub-index should be included) or off (sub-index should be excluded). Based on that information, the data is calculated again as has been described

in Section 3.4.4. The second element which is included in the loading of the data is the addition of a map source and a two map layers. The addition of a map source is a requirement set by Mapbox. These sources can be used for subsequent layers as input and visualization. In Listing B.23 it can be seen that the type is set to `geojson` (as discussed in Section 3.4.1) and the data element is set to the previously calculated data (Section 3.4.4). When this data source is available in Mapbox, the first layer is added. This layer uses the set color scheme to visualize the hexagonal grid based on the UHI score. As can be seen in Listing B.24, the `paint` variable is set to include the `colors` arrays, which is chosen to follow specifications set above. Furthermore, when the user hovers over a hexagon a red color is ascribed to that hexagon, which allows for easy selection of a location. The functionality with regard to the hover function is shown in Listing B.24 lines 36 through 60. As can be seen, the hover color is ascribed to the hexagon which ID matches the ID of the hexagons which is hovered over. A similar functionality is implemented for the opacity of the hexagons. As this layer only specifies the fill color of the hexagons, a second layer is added to visualize the outline (or border) of each hexagon. This layer is independent of the UHI score and therefore provides a uniform separation between each hexagon.

When the end-user has selected a location of interest, he/she can click on that location which shows a popup, which follows the logic shown in Listing B.25. This function uses a reverse-geocoder, which allows for the transformation of coordinates to location information like city, neighborhood, and street. This information, combined with the UHI score, is used to inform the end-user on the chosen location. Moreover, a link is provided to the historical data representation page, which will be discussed in the next Section.

3.4.5.2 Historical Data Visualization

As will be shown in Chapter 4, the historical data page shows several elements with regard to the chosen location. Firstly, a radar chart is shown, which provides the scores of each individual sub-index of the chosen location. Secondly, the chosen location is shown in more detail. Lastly, the historical progression of the UHI and relevant sub-indices is shown based on the chosen time period (month or year).

The visualization of the location is identical to the visualization method discussed in the previous Section, therefore, no further explanation will be given in this Section. To generate the historical graph, however, first the appropriate labels for the x-axis of the graph need to be generated. This processed exists of several steps, as can be seen in Listing B.26. The x-axis of the graph represent the dates on which the UHI have been recorded for the selected time period. Therefore, the current date and all dates on which data has been recorded need to be collected. Subsequently, for each date in the corresponding time period, the appropriate data is added as shown in Listing B.27. The Chart.js requires a data structure which includes an x-value (which is the date) and a y-value (which is the UHI or sub-index score). These values are added to the appropriate data array and used for the creation of the historical data graph (Listing B.27. The first step in this visualization is to select the appropriate element where the graph can be visualized. Then the previously created data and labels are used to format a data constant which conforms to the expected format of the Chart.js graph. This data constant expects the labels and a datasets array, which consists of dictionaries for each line which needs to be visualized in the line chart. In this application a line is created for each sub-index and the UHI, therefore, a dictionary is created for each of them. These dictionaries consist of variables related to visual aspects as well as the data which needs to be used. When the datasets array is prepared, the actual chart can be created. This chart includes a functionality to select a line for further investigation. The end-user can select a line by clicking on it, this will result in the line being highlighted to provide a more clear overview of its progression (Listing B.27, lines 63 through 123).

Similarly to the process above, the data for the radar score graph is prepared (Listing B.28). During the loading of the map visualization, the data corresponding to the selected location is stored and passed to the function creating the radar graph. This function sets the labels to the names of the sub-indices and the data to the data previously mentioned. This is passed to a new chart, which is then visualized (Chapter 4).

This concludes the Section on the visualization methods and thereby concludes Chapter 3. In this Chapter, the apparent preferences of end-users have been discussed (Section 3.1). After which a formal definition and calculation method for the UHI has been created (Section 3.2). These two elements were used for the design of the proposed system (Section 3.3), which implementation was discussed in Section 3.4. Chapter 4 will go into detail on the results of this methodology and how the visualizations turn out and relate to the previous findings.

Chapter 4

Application Results

This Chapter will show how the previously mentioned calculation and visualization methods result in a usable application, informing end-users on Urban Health information. The proposed application can be seen at urbanhealthindex.com. As can be seen in Figure 4.1, the application is separated into three distinct sections, each with a separate function. Most of these functions are discussed in the previous section, while the 'educate' function is an addition to inform the end-user on the theoretical background and instructions already discussed in this research. Therefore, Section 4.1.1 will show how the landing page of the application is used to educate the end-user on the theoretical background of the Urban Health Index (UHI) and how to use the application. Section 4.1.2 will show how the map mentioned in Section 3.4.5 and how the end-user can use this map for an initial exploration of the city or any specific location. Lastly, Section 4.1.3 will show the results of the previously mentioned historical data visualization and connected features. All options included in the proposed application can be found in Appendix D, the most important features will be discussed in more detail in the remainder of this Chapter.

In order to validate the effectiveness and usefulness of the application a validation test is conducted, which will be discussed in Section 4.2 after which the changes to the application made based on this test will be discussed (Section 4.2.3).

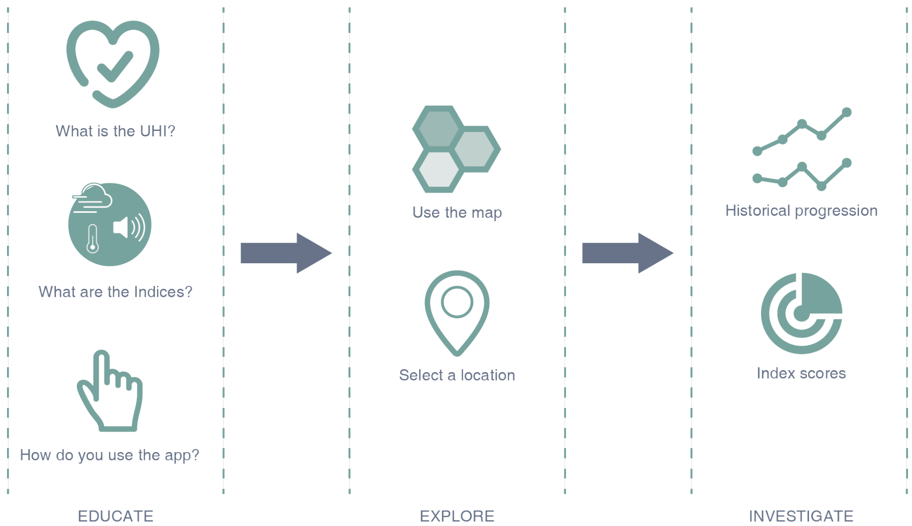

Figure 4.1: Overview of application structure

4.1 The Dashboard

4.1.1 Educate

The first element of the application is the landing page (Appendix D, Figure 1-5). This page is an "one-pager" which allows the user to scroll through all elements of information described below and link to different pages for more in-depth explanation of different topics. When a user decides to use the application, this is the page that is first shown. Therefore, the goal of this page is to educate the user on what the UHI is, and how he or she can use the application. For the more experienced user, an option is incorporated to move on to the exploration of the data. However, as can be seen in Figure 4.2, first a brief overview is given on what the UHI is, what types of data are used and what it can be used for (Figure 4.2, 2). This should give the end-user a good indication of what to expect from this application. Besides this function, the entire landing page has a navigation bar which allows for quick navigation over the page between topics (Figure 4.2, 1) and an option to move on to data exploration (Figure 4.2, 3).

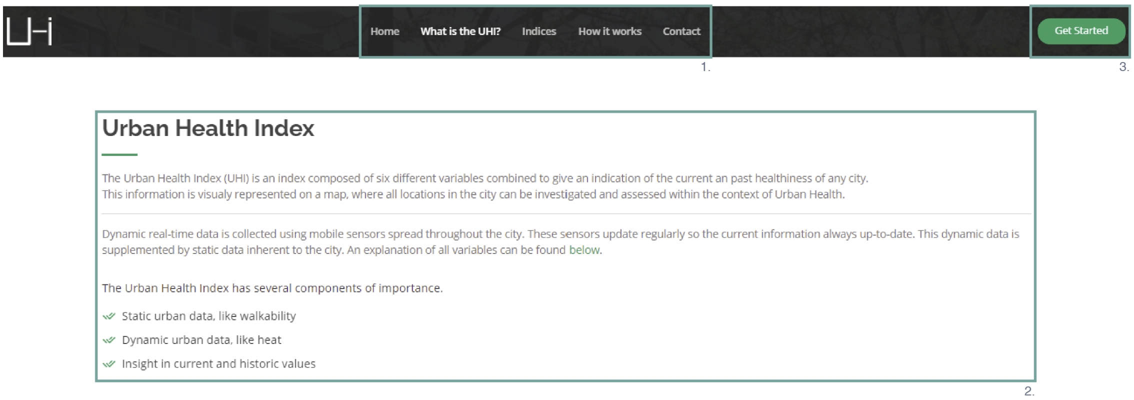

Figure 4.2: Informing the end-user on what the UHI is

The second element of the landing page is to educate the end-user on the different sub-indices composing the UHI, as can be seen in Figure 4.3. Firstly, the end-user is reminded that six different sub-indices are used and referred to a page which gives a brief overview of the overall calculation discussed in Section 3.2 (Figure 4.3, 1). The definitions for each individual sub-index are connected to the shown cards (Figure 4.3, 2). These cards refer the user to an explanation page as shown in Figure 4.3 (3). This explanation allows the end-user to understand the underlying definition of the UHI which could provide a more thorough understanding of the application. However, the application is designed to also inform users without this more extensive theoretical background.

The last function of the landing page is to inform the user on how to use the application (Figure 4.4). First, a brief explanation of the available functions is given (Figure 4.4, 1), which have been explained in Section 3.4.5 and will be further shown in Sections 4.1.2 and 4.1.3. Furthermore, the user is invited to start his or her exploration of Urban Health in the city (Figure 4.4, 2).

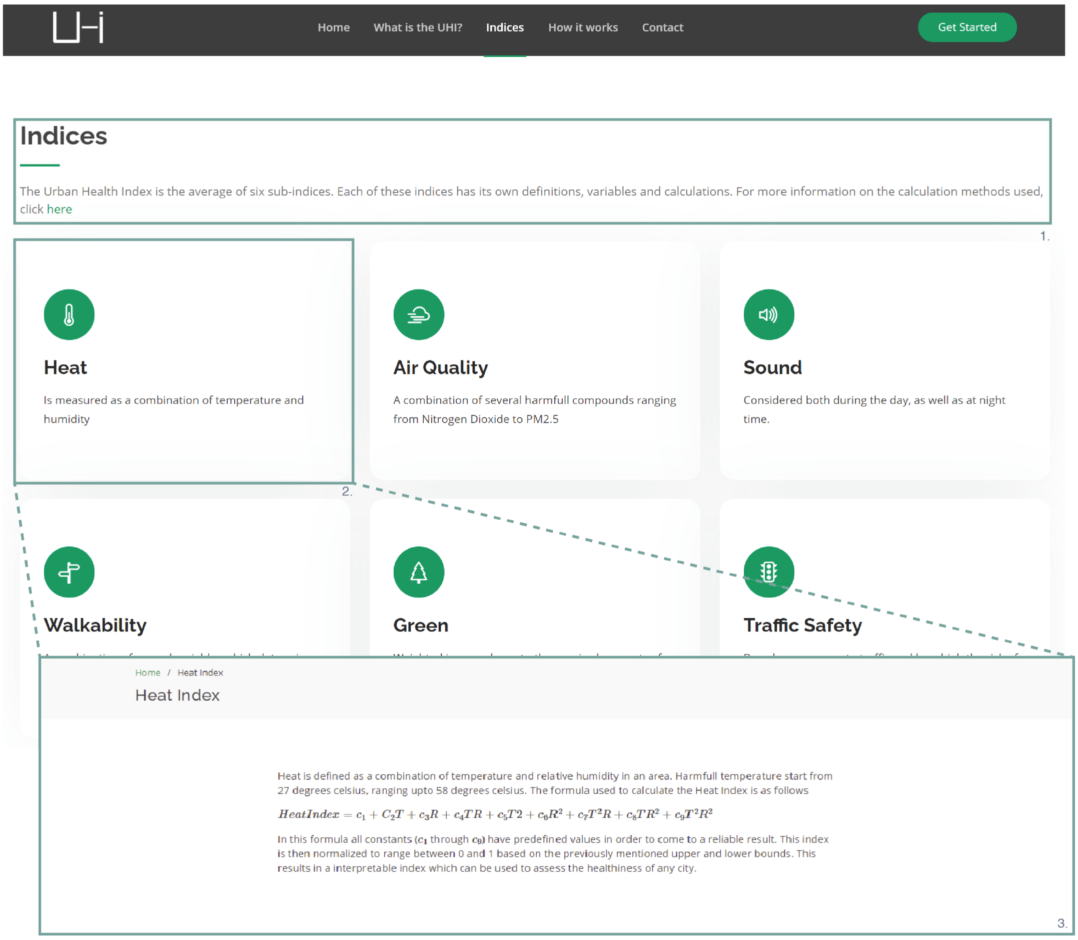

Figure 4.3: An explanation on the different sub-indices

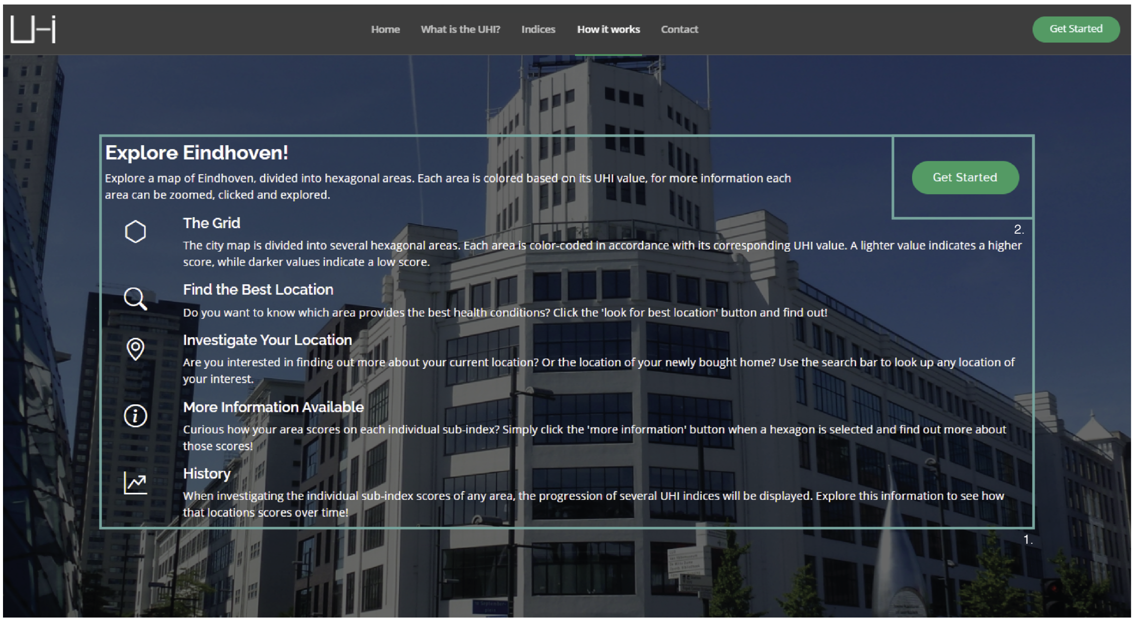

Figure 4.4: Instructions on how to use the application and which functions are available

4.1.2 Explore

When the user is familiar with the functions and methods employed by the application, he or she can start to explore the collected data (Appendix D, Figure 6-9). As has been discussed, this is firstly done through a hexagonal grid projected on a map of the city. This visualization method is shown in Figure 4.5, the corresponding functions will be explained in the remainder of this section.

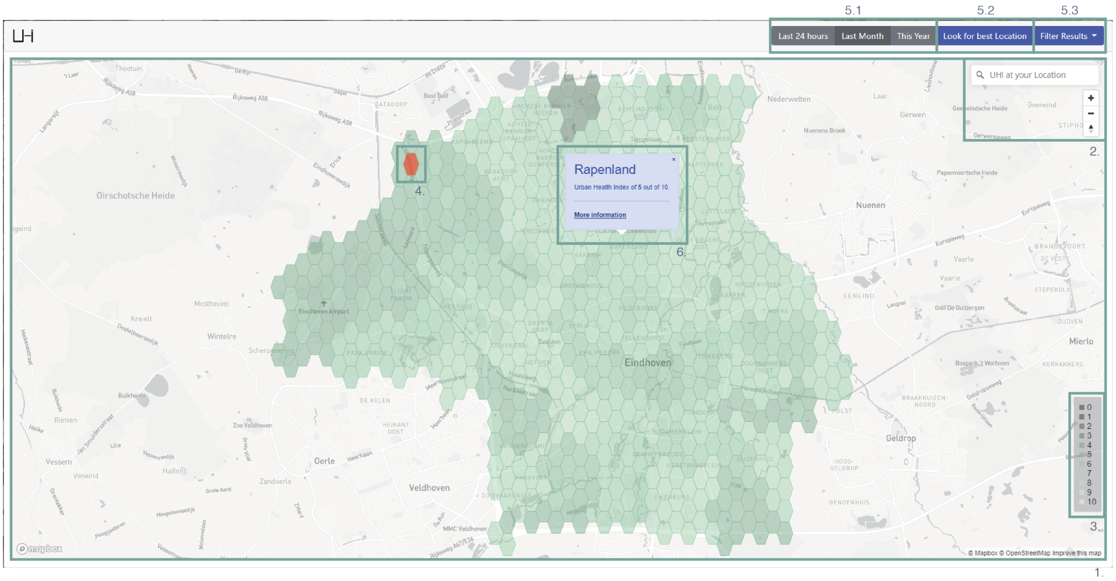

Figure 4.5: Visualization of data using the hexagonal grid

First, the map is rendered using a light color scheme (Figure 4.5, 1) as the focus of the visualization is on the grid and the underlying data. Within this map, two functionalities are added in order to allow for easy exploration of the data. The user can search for specific locations through the geocoder (Figure 4.5, 2), which zooms the map to that location. Furthermore, as the grid is color coded, an explanation of the colors is given by the legend (Figure 4.5, 3). The color scheme is designed to allow for an intuitive interpretation of the colors, however, the legend avoids confusion on which locations score better at first glance. As the user explores the map, he or she can hover over individual hexagons, which are highlighted by a different color (Figure 4.5, 4), to avoid the selection of the wrong location.

Besides the map, several functions are located in the top bar. The first of these functions is the selection of the time frame over which the data should be aggregated (Figure 4.5, 5.1). The standard time frame is all data from the last 24 hours, however, the user might be interested in the overall UHI of the last month or year. Furthermore, when no data is available from the last 24 hours, a notification is given (Figure 4.6) and the closest relevant time frame is chosen.

Figure 4.6: Notification informing the user on changed time frame due to missing data

Additionally, the user is able to search for the best possible location in the city (Figure 4.5, 5.2). This function zooms the map to the hexagon with the best UHI score and shows the relevant information (as in Figure 4.5, 6). As Section 3.1.2 has shown that end-users are mostly interested in selecting the healthiest location in the area, this function aims to meet those stated preferences.

The third option on the top bar has also been discussed in Section 3.4.5; the user is able to filter the shown data (Figure 4.5, 5.3). An example of such a filter selection is shown in Figure 4.7.

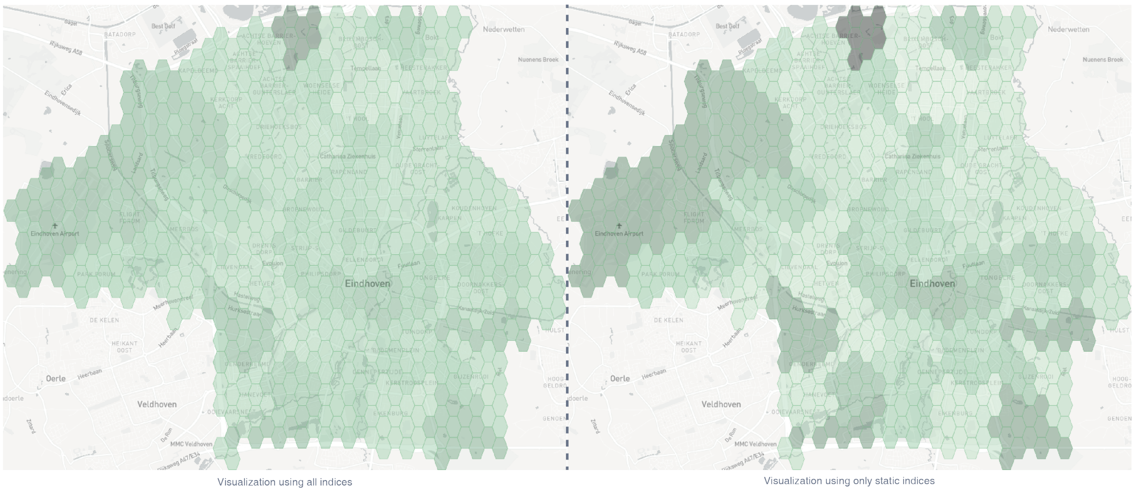

Figure 4.7: Comparison between visualization using all indices (left) and static indices (right)

Lastly, when the user has selected a location of interest, a popup is shown with some additional information. First, the name of the neighborhood is shown. Secondly, the exact UHI score (ranging from 1 until 10) is provided. Lastly, the user is prompted to investigate further by using the 'more information' link. This link leads to the historical progression of that area and is the subject of the next section.

4.1.3 Investigate

As the user has chosen a location to investigate in more detail (Appendix D, Figure 10), the first part of this page is shown in Figure 4.8. As can be seen, this page includes several functions. First, the name of the selected neighborhood is displayed (Figure 4.8, 1.1), while the user is also able to return to the original map (Figure 4.8, 1.2). Moreover, as has become clear in Section 3.1.2, users prefer the use of current location-based applications due to their implementation of routing options. As has been concluded before, this application will therefore focus on the selection of locations. Figure 4.8 (1.2) shows that the applications allows the user to create a route in Google Maps, from their current location to the selected hexagon location. This combines the proposed goal of this application with the best practices from current location-based applications.

The second element of this visualization is the map showing the chosen location in more detail. This allows the user to refer back to the location of their choice and connects the previously discussed visualization (Section 4.1.2) to the current data representation. Finally, the UHI is displayed in more detail. The graph shown in Figure 4.8 (3) shows the score of the current location based on the selected time frame, as well as the scores of the individual sub-indices. In this example, it becomes clear that this location scores rather high on Green, Traffic Safety, Sound and Air Quality, while the Heat Index scores very poorly. This allows the end-user to further investigate the data and draw more in-depth conclusions. In this example, the user might be concerned about the Heat Index and look for a different location with a better Heat score. Conversely, the user might not be concerned about the Heat Index and chose this location to go for a run.

The second part of this page is devoted to the representation of historical data regarding the UHI and corresponding dynamic sub-indices. Figure 4.9 shows the general visualization for historical data.

As can be seen in this Figure, the label of the graph shows the users which time period is selected

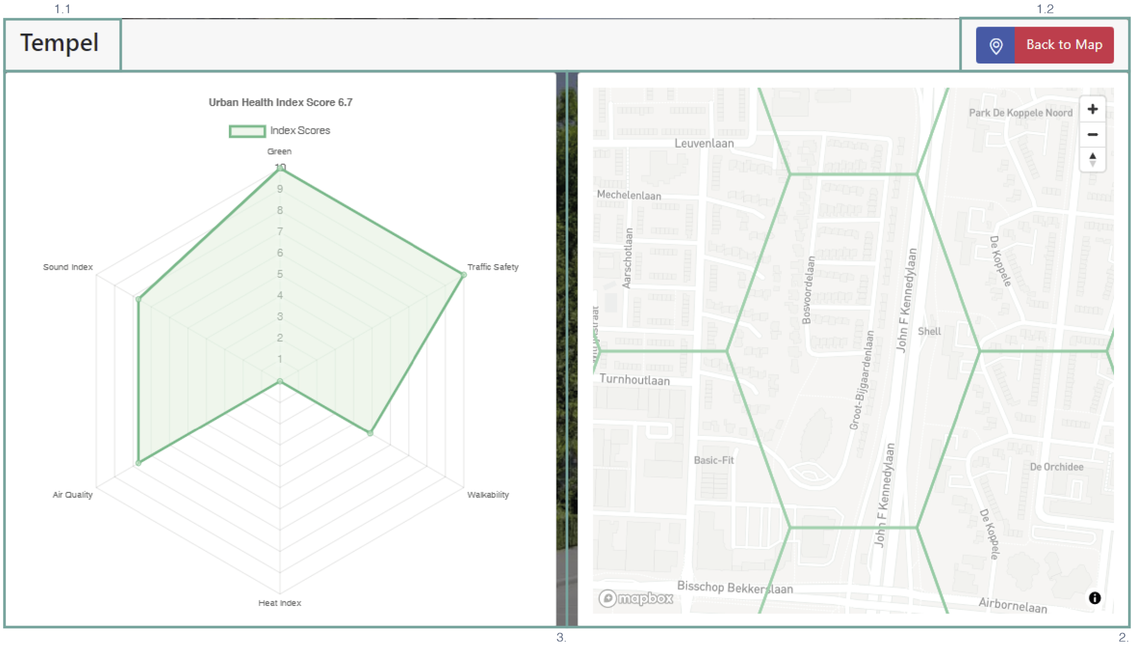

Figure 4.8: UHI and location of selected hexagon

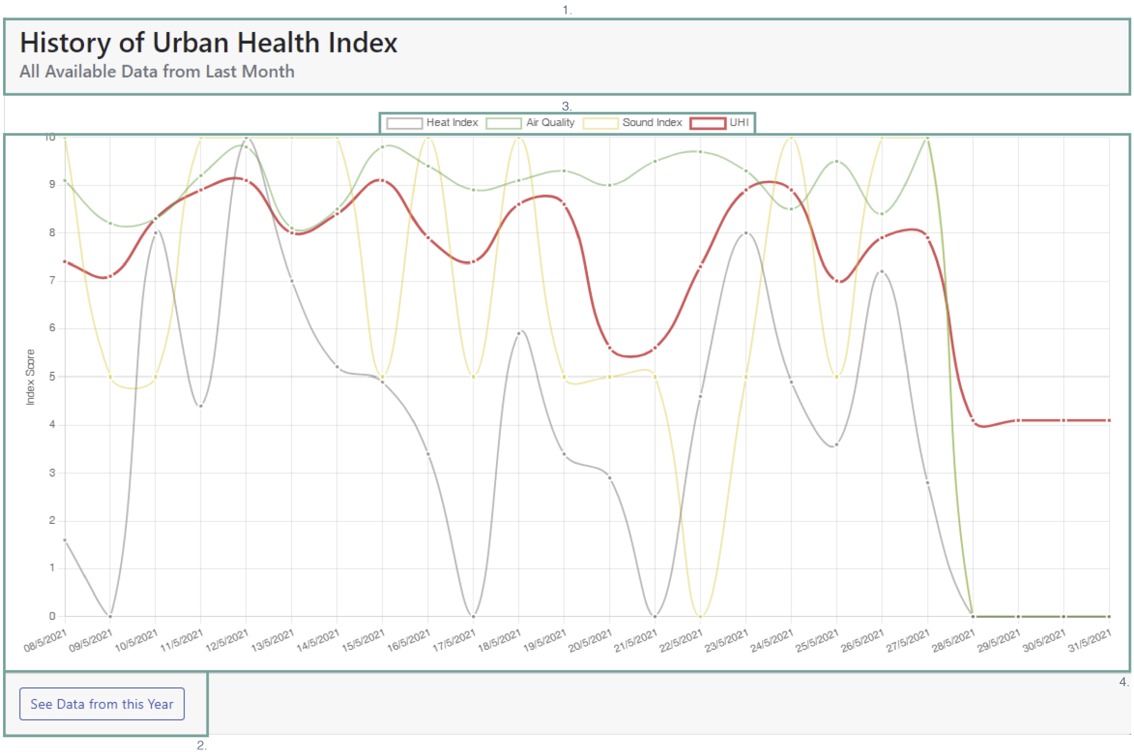

Figure 4.9: Historical data of UHI and dynamic sub-indices

(Figure 4.9, 1). Furthermore, if the user decides to change their chosen time frame, this can be done by the corresponding button (Figure 4.9, 2). This button will show all the available data from this year. The graph itself consists of two elements. Firstly, the legend shows which sub-indices are included and has a dynamic function (Figure 4.9, 3). When a sub-index is toggled in the legend, that sub-index will be removed from the graph (Figure 4.10, right). As the data can become unclear and tangled, this option allows for more exact information discovery by focusing on specific sub-indices where necessary. The graph itself consists of four lines representing the sub-indices and UHI in accordance with the legend (Figure 4.9, 4). The UHI is shown more prominently as to focus of the application is on the overall index.

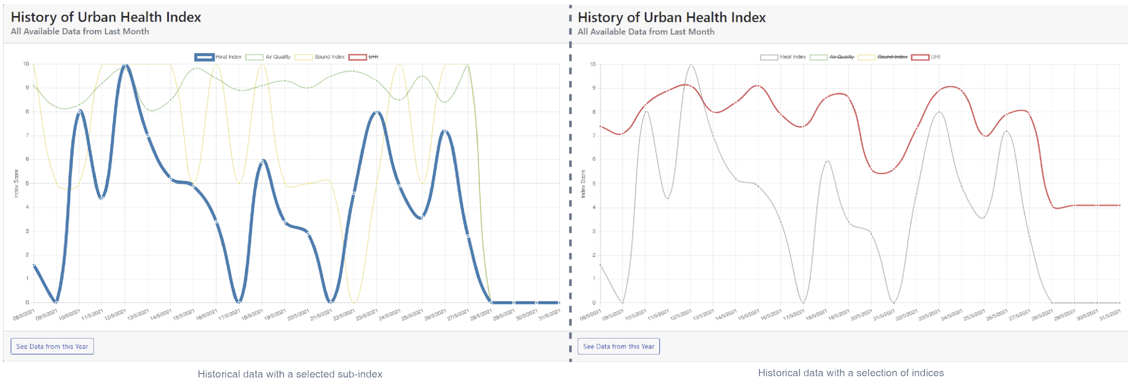

Figure 4.10: Comparison of different selection method for historical data graph

Figure 4.10 shows different applications of the historical data graph. The left image shows how a specific sub-index can be selected and highlighted in order to better investigate the progression of that sub-index. Furthermore, the right image shows a situation in which the user has toggled several sub-indices, which leaves only the Heat Index and the UHI. This scenario allows the user to compare the sub-index to the overall UHI and as can be seen, the UHI generally scores higher than the Heat index. For the user this might indicate that this location isn't ideal for him as the user is looking for a location where the Heat index consistently scores high.

This concludes this Section on the results. This Section has focused on the results of the previously described methodology and how the application is designed to assist the end-user in their search for information. The next Section will show how end-users experience the application and what alterations are made based on their experience.

4.2 Validation of Dashboard Usability

4.2.1 Validation Test Design

In order to validate whether the previously described application is both easy to use and provides the necessary information, a validation test is used.

This test is set up according to a specific scenario (Appendix C). The participant is asked to imagine that he or she is currently interested in Urban Health information, both in the short- and long-term. As previous research (Section 3.1) has shown that user are generally interested in Urban Health information, the participant is asked in this test to set aside personal (dis)interest in this topic. The validation test is divided into several smaller tasks, these tasks are designed to use most of the application's functions and guide the participant through different sections and directions through the application. These tasks are posed as questions, which the participant is able to answer through the application. When a task is completed, the participant is asked to rate the ease of use and the validity of the information gathered within the context of the application. For instance, how useful is background information on the calculation of the Heat index. The questions which were asked are listed below:

1. Can you explain what the UHI is?
2. Which six indices are used for the calculation of the UHI
3. Can you look up the best scoring location?
4. What is the UHI score of this location?
5. What are the sub-index scores for that location?
6. What was the UHI score on 23 May?
7. Can you make a comparison of only the UHI and Heat Index?
8. How is the Heat Index calculated?
9. Can you look up the best scoring location again, but without the Heat Index?

As Figure 4.1 shows, the application is designed with three underlying principles, which are also reflected in the design of the validation test. Tasks 1, 2 and 8 are to be completed on the home page and are therefore designed to validate how well the education principle is designed and how useful this information is to the participant. Secondly, questions 3, 4 and 9 are to be completed using the map and are therefore a test of the exploration principle. Thirdly, the investigation function is tested with questions 5,6 and 7. When the participant has tested the historical data representation he or she is asked to go back to the home page, in order to test ease of navigation through the application, as this requires several steps back. Finally, the participant is asked to perform a more complex operation by using the filter option, which tests a more in-depth aspect of exploration of the data.

When the participant has rated all individual aspects of the application, the participant is asked to give one overall rating of ease of use and usefulness of the data. During the entire test, the participant is free to give any comments and remarks with regard to the design and data. These scores and remarks are aggregated to see how well each individual aspect of the application is understood and how valid those aspects are in the context of Urban Health information. These results will be given below.

4.2.2 Validation Results

The previously described test was conducted with eight participants. Some of these respondents were familiar with the concept proposed in this research, while others were new to the concept. Each participant was asked to complete the task individually while only given the tasks to complete, no further assistance was given. The average scores are shown in Table 4.1.

	Ease of Use	**Usefulness of Information**
Educate (Home Page)	7.8	6.9
Explore (Map)	9	8.3
Investigate (History)	7.8	7.5

Table 4.1: Average Validation Test score per application aspect

Furthermore, participants were asked to give an overall rating of the application, which is shown in Table 4.2

Ease of Use	**Usefulness of Information**
7.9	8.2

Table 4.2: Average Validation Test for complete Application

Generally, these scores show that both the ease of use and usefulness of the provided information is well-received by the participants. Table 4.1 shows that the exploration aspect of the application is particularly easy to use, while providing the most useful information. Conversely, the home page is less easy to use, while the information provided there is of less importance to the participants.

This could indicate that the users of this type of information are simply interested in exploring the data, without educating themselves on the theoretical background.

Besides the average scores, the scores of each individual task (as described in Section 4.2.1) also provide useful information. These scores are shown in Tables 4.3 and 4.4, where Table 4.3 shows the scores related to ease of use while Table 4.4 shows how useful the participants found the information related to that task.

	Participant								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Avg.**
1	10	10	10	8	10	10	10	9	9.6
2	10	10	10	9	9	7	8	4	8.4
3	9	10	10	9	8	2	10	8	8.3
4	10	10	10	10	10	10	10	10	10
5	10	10	8	7	9	10	10	9	9.1
6	10	10	9	9	10	9	7	9	9.1
7	3	7	0	5	8	8	8	3	5.3
8	7	5	0	5	3	8	8	0	4.5
9	10	10	9	9	8	8	8	9	8.9

Table 4.3: Ease of Use Scores per Task for each Participant

	Participant								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Avg.**
1	10	9	7	7	10	3	6	4	7
2	10	10	4	8	9	8	8	6	7.9
3	10	6	4	9	7	8	9	9	7.8
4	10	10	8	9	8.5	10	6	3	8.1
5	10	10	7	8	7	10	9	6	8.4
6	8	5	5	6	7	6	8	8	6.6
7	10	7	5	4	8.5	8	10	8	7.6
8	3	8	6	3	5.5	8	10	3	7.6
9	10	9	8	9	9	9	10	9	9.1

Table 4.4: Usefulness of Information per Task for each Participant

Regarding the ease of use, these results show that task 7 in particular was a bottleneck in the use of the application. This tasked required the user to move from the History page (Investigate) to the Home Page (Educate) and open the 'Heat' page. Firstly, it was unclear for most participants how they could navigate through the application. The designed path requires the user to first select to move back to the map, after which the user can click on the UHI icon to move back to the Home Page. Neither of these two steps were obvious to the participants. Secondly, the user needs to click on the title of the 'Heat' card (Figure 4.4) to move to the information page of the Heat sub-index. This was also unclear to the participants, as they expected the entire card to be a link to this page.

Investigating Table 4.4, it becomes clear that tasks 1 and 6 are least useful to the participants. Task 1 asks the participants to look up some basic information on the UHI. While participants mentioned that this information could be useful, they found that the currently provided information wasn't very useful to them and that they would prefer to use the application instead of reading this information. Interestingly, task 6 asks the participants to look up the UHI of a specific date on the History page. This functionality was the result of the end-user survey, as the ability to see the historical trend of data was a frequently stated use of this type of information. This conflicting result could be explained by the fact that participants weren't particularly interested in information of a particular day, but more on the general trend. This would indicate that the Historical data is relevant to the user, however, information of specific dates is irrelevant.

The results of this test was cause for some small design iterations of the application. These changes will be discussed in the next Section.

4.2.3 Design Iteration

The previous Section has shown that the main issue participants had with the application was concerned with the navigation from the History page to the Home Page. This has led to several design changes. Firstly, when the user chooses the 'more information' option in the Map (Figure 4.5, 6) a new tab is opened with the History page. Previously, this would open the History page in the same window. With this new addition, the user is able to switch between the Map and History page more easily, or even have them open side-by-side. Moreover, some alterations have been made to the header of the Map (Figure 4.5, 5). These changes can be seen in Figure 4.11.

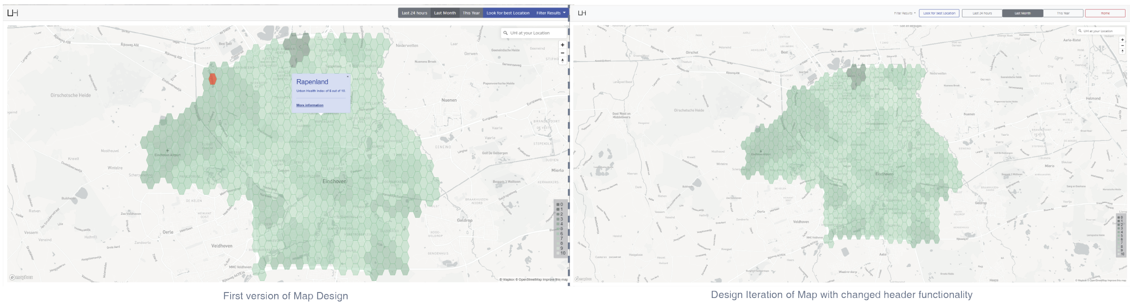

Figure 4.11: Comparison between Map Design Iterations

As can be seen, the option to find and filter results have been separated from the other options in the header, as some participants had trouble finding or distinguishing this button. This creates more room to the right of the time-frame selection buttons, which is filled by a new button which allows the user to move back to the home page. This should make navigation throughout the application more intuitive for the user. As the application should also be usable on mobile formats, the header of the map now collapses into a menu when viewed on mobile.

Lastly, has been mentioned previously, the option to read more on the calculation of the sub-indices (Figure 4.4) has been changed to make the whole card a link to this page. These alterations make the application more accessible and easy to use for the end-user.

Chapter 5

Conclusion

This research has investigated the possibilities of real-time and static urban data, and how to use that data to provide urban health information for short- and long-term decision-making. Here, urban health was defined by several urban health indicators, as given in Table 2.2. As urban health is rather unknown subject to most inhabitants of cities, these indicators were chosen to provide more concrete information about this topic. Still, this research proposes that providing actual data on the performance of these indicators is not an effective way of communicating urban health information. Therefore, these indicators are translated into one comprehensive Urban Health Index (UHI). This index translates raw data on urban health indicator performance into an interpretable scale. This index is deemed to be a more effective tool to support decision-making of end-users.

In order to create this index, several important aspects were explored in this research. Firstly, both temporal and spatial resolution difference pose a challenge to creating one comprehensive overview of this type of data. As has been discussed, the static data elements are mostly collected on a neighborhood scale, while the dynamic data elements are collected as individual points. The goal of this research was to explore the advantages of dynamic data observed by mobile sensors, and therefore the high spatial resolution of this data should be maintained as much as possible. However, to compromise between these two resolutions, a grid structure is proposed in order to combine the different data elements. This grid can communicate the overall index, and the differing sub-indices, while maintaining a relatively high spatial resolution. Besides a spatial resolution difference, the data is also spread across time, therefore, a differentiation is proposed to show information across time. The main manner in which the index is communicated is using the most recent data, as this was shown to be among the most prevalent use cases proposed by end-user research. However, in order to also provide information to support long-term decision-making, an aggregation of information is also communicated over different time scales. Secondly, as has been briefly mentioned, the requirements of end-users has shown how this type of information would be used in location-based applications. While the current use of application based information is mostly concerned with route choice, urban health information would mostly be used for optimal location choice. Therefore, the proposed index and grid are designed to allow for optimal location choice, rather than creating optimal (healthy) routes.

This research describes an application which overcomes these challenges and provides several advantages over more traditional representations of urban health. As has been mentioned, most research into urban health is based on static data collection. This data gives much insight into urban health of certain locations and regarding certain indicators, however, more insight can be gained by extending this framework with the proposed dynamic data collection. Applying the proposed system, a holistic view of a city can be developed and problem areas regarding urban health can be located and targeted by end-users. These areas can be targeted by policymakers for development, or inhabitants as an instigator of residential relocation. In both cases, the system

this research proposes allows for more exact decision-making with regard to urban health, making urban health a more prominent consideration within the decision process.
Moreover, implementing a working variant of the proposed system could be a basis of more research into urban health indicators as more exact relationships between urban health determinants and adverse health effects can be determined. As mentioned, the high spatial resolution is maintained in the system and therefore, problematic health outcomes can be deconstructed to more exact regions. This can be related to the urban health indicators of that area, allowing for more research to be done with regard to their relationship.

Relating back to the questions posed in Chapter 1 several answers can be given. Regarding the question of how real-time and static urban data can be used to provide urban health information for short- and long-term decision-making, it has become clear that an UHI combining different spatial and temporal resolutions is an effective way to communicate urban health information. Based on literature review, this index was constructed based on six different indicators: Air Quality, Heat, Noise, Green Spaces, Walkability and Traffic Safety. Different measurement and processing methods accompany these indicators, the results of which are combined into the final UHI. Moreover, end-user research has indicated that this index would mostly be used for the selection of optimal locations, which forms the basis of this research. While the question was initially posed who the relevant end-users could be, this research has assumed a more general approach, surveying the public at large in order to form a general use case for this type of information. As has been discussed, the collection and merging of the data is mostly concerned with the differing spatial and temporal resolutions. This challenge can best be overcome by combining the data elements into one hexagonal grid, maintaining the high spatial resolution were possible. Lastly, the question was posed how this data can best be represented to the end-user. This research proposes the visualize the data differently based on the differing time scales. First, visualizing the most recent data (based on end-user research), while also allowing for more detailed visualization over larger time scales.

5.1 Discussion and Recommendations

As has been mentioned, this system allows for a more exact exploration of the relationship between urban health indicators and adverse health effects. Therefore, future research could use this system to validate the predictive effectiveness of the proposed indicators. While the proposed indicators are based on the existing body of literature, a strong relationship between these indicators and health outcomes should be established. Moreover, additional indicators should be added where necessary. As the system is designed to allow for such changes, several iterations of the system could be compared to evolve the design further.

Besides the relationship between the proposed indicators and health outcomes, further development of the system could implement predictive elements making use of the increasingly growing field of machine learning. Implementing efficient algorithms to predict urban health developments in certain areas could assist end-users in making more informed decisions about the future. As an example, inhabitants can now choose to take the car because it is predicted to rain today, but the proposed system could tell them to take the bike when urban health is predicted to be good that day in the area. Such systems could also provide valuable information to policy-makers and urban developers, anticipating worsening urban health conditions and implementing interventions before adverse health effects occur.

Requirements provided by the end-user should inform further development of the system. This research initially set out to define different end-users, however, a more general approach was taken to define general end-user requirements. Therefore, further research should be done on the requirements of different end-user categories. This research has described possible differences between inhabitants and policy-makers, however, it should be determined how their requirements differ, if they differ at all. A suggestion would be that policy-makers are in need of more exact data, therefore, actual performance indicators could be provided to that end-user category. As an example, inhabitants could be informed by the Air Quality sub-index, while policymakers are informed by actual Carbon Monoxide, Particulate Matter and Nitrogen Dioxide levels. More in-depth research could indicate if such a difference is necessary and how this would influence the design of the system.

Finally, the sensor design principle should be investigated further. This research has shown the potential of such sensors, but has not gone into detail on the actual design of such sensors. Therefore, future research should indicate how such sensors can be realized in a cost-effective manner, also suiting the requirements set out in this research.

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Appendix A

Survey

A.1 Survey for Scientific Research: Providing location based health information using dynamic, aggregated and static urban data

Welcome to this survey! You are asked to take part in a scientific study in the form of filling out a survey. Participation is voluntary. Participation requires your written consent. Before you decide whether you want to participate in this study, you will be given an explanation about what the study involves. Please read the information in the subject information form (click the link below) and ask the investigator for an explanation if you have any questions. You may also discuss or distribute it with your partner, friends or family. The aim of this study is to learn how people use location-based applications and how people would use health information in such applications. This information is used to gain insight into the users' needs. The study is performed by student Sander Rob de Meij from the Faculty of the Built Environment, Eindhoven University of Technology under the supervision of Dr. G.Z. Dane and Msc. M. Viktorovic, MSc. Answering the questions will take you approximately 15 minutes. Thank you in advance for your time, and please don't hesitate to contact us if you have any questions or concerns about the survey. **Principal researcher:** Sander Rob de Meij, e-mail: s.r.d.meij@student.tue.nl , Department of the Built Environment, Eindhoven University of Technology **Supervision:** Prof. dr. ir. B. (Bauke) de Vries, Dr. G.Z. (Gamze) Dane, M. (Miloš) Viktorović, MSc **Informed Consent Form** Study: Providing location based health information using dynamic, aggregated and static urban data By participating in this study, I agree to the following:

- I have read the subject information form. I was also able to ask questions. My questions have been answered to my satisfaction. I had enough time to decide whether to participate.
- I know that participation is voluntary. I know that I may decide at any time not to participate after all or to withdraw from the study. I do not need to give a reason for this.
- I want to participate in this study voluntarily
- we will ask you to fill in a questionnaire in which data is collected
- we will collect personal data through questionnaires and in order to contact and communicate with you; the personal data is collected anonymized and cannot traced back to you directly
- we will collect, store, and analyze the data to answer the research questions in this study.

There are 8 questions in this survey.

A.1.1 Location Based Applications

Q1. Which of the following applications do you use most frequently? Please choose only one of the following:

- Google Maps
- Apple Maps
- Bing Maps
- Waze
- Car Navigation
- Other

A.1.2 Urban Health Information

Imagine that your preferred location based application can provide you with information about healthy locations. For instance, you would be able to see the current Air Quality, Temperature and Humidity of a location of your interest, or see the amount of green spaces in a neighborhood. Similarly, you would be able to see the progression of Temperature over the last month or the Sound levels during the night time of a specific location. Using such an application (with similar functions), what would you use this application for?

Q2. What would you use this option for in the short-term? Please choose all that apply:

- Selecting the healthiest travel destination (i.e. healthiest shopping location)
- Selecting the healthiest travel route (daily travel)
- Choosing healthiest leisure locations (i.e. running)
- I would not use this option for short-term decisions
- Other

Q3. What would you use this option for in the long-term? Please choose all that apply:

- Selecting healthiest travel destination (i.e. vacations)
- Selecting residence or other long-term locations (i.e. living or working)
- I would not use this option for long-term decisions
- Other

A.1.3 Application Goal

Q4. What is currently your most frequent goal while using 'answer from Q1'?

- Please choose only one of the following:
- selecting your route for travel destination / navigation (before a trip)
- selecting your route for travel destination / navigation (during a trip)
- looking up a location for other purpose than immediate travel (i.e. vacation)
- looking up a shop or store location or other information about the store
- looking up a location for fun

- assisting in long-term decisions (i.e. searching for potential new living location)
- Other

Q5. How does 'answer from Q1' make 'answer from Q4' easy/hard?

Q6. Do have any suggestion or other comments about this topic?

A.1.4 End of Survey

Thank you for participating in this survey. If you have any questions or suggestions, please let me know at s.r.d.meij@student.tue.nl

Q7. Would you like receive the end result of this project? Or be contacted for further research within this project?

- Yes
- No

Q8. Please leave your email address below:

Appendix B

Code

B.1 Data Structure Hexagonal Grid

```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [102.0, 0.6]
      },
      "properties": {
        "prop0": "value0"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "LineString",
        "coordinates": [
          [102.0, 0.0], [103.0, 1.0], [104.0, 0.0], [105.0, 1.0]
        ]
      },
      "properties": {
        "prop1": 0.0,
        "prop0": "value0"
      }
    },
```

Listing B.1: Standard geoJSON feature collection format (Butler et al., 2016)

```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates":
        [
            [
                [ 5.430763172023569, 51.474578 ],
                [ 5.43206221012924б, 51.476828 ],
                [ 5.434660286340599, 51.476828 ],
                [ 5.435959324446276, 51.474578 ],
                [ 5.434660286340599, 51.472328 ],
                [ 5.432062210129246, 51.472328 ],
```

```
                [ 5.430763172023569, 51.474578 ]
            ]
        ]
      },
      "properties": {
        "population": 3545,
        "green": 312739,
        "numberOfTrafficAccidents": 4,
        "buildingHousesArea": 171344,
        "buildingHousesPC": 12.58,
        "intersections": 344,
        "retailLanduseArea": null,
        "retailBuildingArea": null,
        "commercialArea": 229,
        "commercialPC": 0.02,
        "industrialArea": 6365,
        "industrialPC": 0.47,
      }
    }, ...
```

Listing B.2: geoJSON Format for Hexagonal grid

B.2 Data points Data Structure

```
dataPoint = {
    'geometry':{
        'type': 'Point',
        'coordinates':coor,
    },
    'properties':{
        'indexVar':{
            'airQuality':{
                'PM25': pmTwo,
                'PM10': pmTen,
                'NO2': noTwo,
                'CO': co
            },
            'heat':{
                'temperature': temp,
                'humidity': hum
            },
            'sound': sound
        },
        'time': current_time,
        'date': current_date
    }
}
```

Listing B.3: geoJSON Format data points

B.3 Query Method

```
const query = Datapoint.find({
    'properties.date.0': year,
    'properties.date.1': month,
    'properties.date.2': day,
  });
  const datapoints = query.exec();
```

Listing B.4: example of MongoDB query using Mongoose

B.4 Functions

```
function loadData(
  greenFilter,
  trafficFilter,
  walkFilter,
  heatFilter,
  aqFilter,
  soundFilter
) {
  //Load the Hexagonal Grid from local directory
  d3.json('../data/hexagonalGrid.geojson', function (err, data) {
    //Throw error if error occurs
    if (err) throw err;
```

Listing B.5: Loading data into JavaScript

```
//Initialize variables for identification and selection of best scoring hexagon
    let num = 0;
    window.best = 0;

    //For each hexagon in grid, calculate the corresponding UHI values
    data.features.forEach((f) => {
      num += 1;
      const id = num;

      //Step 1: Calculate the Traffic Safety score
      const trafScore = trafficScore(
        f.properties.numberOfTrafficAccidents,
        f.properties.population
      );

      //Step 2: Calculate the Green Spaces score
      const greenScore = greenSpaceScore(
        f.properties.green,
        f.properties.population
      );

      //Step 3a: Calculate the Normalize Dwelling Density
      const normDwellingDensity = ndd(f.properties.building_houses_pc);

      //Step 3b: Calculate the Normalized Connectivity
      const normConnect = nc(
        f.properties.NUMPOINTS,
        f.properties.shape_area
      );
      //Step 3c: calculate the relative land use percentages
      const p = [
        f.properties.building_houses_pc / 100,
        f.properties.Commercial_pc / 100,
        f.properties.Industrial_pc / 100,
      ];
      //Step 3c: calculate the Land Use Mix
      const landUseMix = lum(p);

      //Step 3d: calculate the Net Retail Area
      const netRetailArea = nra(
        f.properties.retail_building_area,
        f.properties.retail_landuse_area
      );
      //Step 3: Calculate the walkability
      const walkability =
        (normDwellingDensity +
          normConnect +
          landUseMix +
          netRetailArea) /
        4;
```

Listing B.6: Calculating sub-indices

B.4.1 Static Variable Functions

```
function trafficScore(trafficAccidents, population) {
  if (population === 0) {
    return 0;
  } else {
    safety = 1 - trafficAccidents / population;
    if (safety <= 0) {
      return 0;
    } else {
      return safety;
    }
  }
}
```

Listing B.7: Calculation of the Traffic Safety sub-index

```
function greenSpaceScore(gsArea, population) {
  const gsMin = 9;
  const gsMax = 50;
  gs = gsArea / population;
  if (population === null || population === 0) {
    return 0;
  } else {
    if (gs < gsMin) {
      return 0;
    } else if (gs > gsMax) {
      return 1;
    } else {
      return (gs - gsMin) / (gsMax - gsMin);
    }
  }
}
```

Listing B.8: Calculation of the Green sub-index

```
function ndd(dwellingDensity) {
  return dwellingDensity / 21.81976;
}
```

Listing B.9: Normalized Dwelling Density

```
function nc(inter, totalArea) {
  const maxCon = 1407.231314;
  const conNorm = inter / maxCon;
  const con = conNorm / (totalArea / 1000000);
  return con;
}
```

Listing B.10: Normalized Connectivity

```
function lum(p) {
  let numerator = 0;
  const N = p.length;
  for (let i = 0; i < N; i++) {
    if (p[i] === 0) {
      numerator += 0;
    } else {
      numerator += p[i] * Math.log(p[i]);
    }
```

```
  }
  shanon = -(numerator / N);
  return shanon;
}
```

Listing B.11: Land Use Mix

```
function nra(gra, total) {
  if (total === 0) {
    return 0;
  } else if (gra === null || total === null) {
    return 0;
  } else {
    return gra / total;
  }
}
```

Listing B.12: Net Retail Area

B.4.2 Dynamic Variable Functions

```
//Step 1: Set an empty dictionary to save the values of the datapoints in this
    hexagon
const containedPoints = {
  sound: [],
  temperature: [],
  humidity: [],
  CO: [],
  PM10: [],
  PM25: [],
  NO2: [],
};
```

Listing B.13: Dictionary for storing relevant datapoint values

```
//Step 2: For each datapoint, check if it is in this hexagon
for (let datapoint of datapoints) {
  point = turf.point(datapoint.geometry.coordinates);
  poly = turf.polygon(f.geometry.coordinates);
  isContained = turf.booleanPointInPolygon(point, poly);
  //Step 3: If the datapoint is in this hexagon, save the corresponding values
      to the previously created empty dictionary
  if (isContained) {
    containedPoints['sound'].push(
      datapoint.properties.indexVar.sound
    );
    containedPoints['temperature'].push(
      datapoint.properties.indexVar.heat.temperature
    );
    containedPoints['humidity'].push(
      datapoint.properties.indexVar.heat.humidity
    );
    containedPoints['PM10'].push(
      datapoint.properties.indexVar.airQuality.PM10
    );
    containedPoints['PM25'].push(
      datapoint.properties.indexVar.airQuality.PM25
    );
    containedPoints['NO2'].push(
      datapoint.properties.indexVar.airQuality.NO2
    );
    containedPoints['CO'].push(
      datapoint.properties.indexVar.airQuality.CO
    );
  }
```

```
}
```

Listing B.14: Check which data points are within this hexagon and add those values to the dictionary

```
//If this hexagons has recorded datapoints, calculate the UHI using those
    datapoints
if (containedPoints['temperature'].length !== 0) {
  //Step 4: Calculate the Heat Index
  const heatScore = heatIndex(
    average(containedPoints['temperature']),
    average(containedPoints['humidity'])
  );
  //Step 5: Calculate the Air Quality Index
  const aqScore = airQualityIndex(
    average(containedPoints['NO2']),
    average(containedPoints['PM10']),
    average(containedPoints['PM25']),
    average(containedPoints['CO'])
  );
  //Step 6: Calculate the Sound Index
  const soundScore = soundIndex(
    average(containedPoints['sound'])
  );
```

Listing B.15: Calculate UHI using sub-indices and sensor values

```
function heatIndex(T, R) {
  cOne = -8.78469475556;
  cTwo = 1.61139411;
  cThree = 2.33854883889;
  cFour = -0.14611605;
  cFive = -0.012308094;
  cSix = -0.0164248277778;
  cSeven = 0.002211732;
  cEight = 0.00072546;
  cNine = -0.000003582;
  hi =
    cOne +
    cTwo * T +
    cThree * R +
    cFour * T * R +
    cFive * T * T +
    cSix * R * R +
    cSeven * T * T * R +
    cEight * T * R * R +
    cNine * T * T * R * R;
  if (hi < 27) {
    hi = 27;
  } else if (hi > 58) {
    hi = 58;
  }
  return 1 - (hi - 27) / (58 - 27);
}
```

Listing B.16: Calculate Heat Index

```
function airQualityIndex(nitrogen, pmTen, pmTwo, carbonMonoxide) {
  if (pmTen == null) {
    pmTen = 0;
  }
  //calculate nitrogen index (nIndex)
  if (nitrogen >= 0 && nitrogen < 100) {
    nIndex = nitrogen / 2;
  } else if (nitrogen >= 100 && nitrogen < 200) {
    nIndex = 0.25 * nitrogen + 25;
```

```
  } else if (nitrogen >= 200 && nitrogen < 400) {
    nIndex = 0.125 * nitrogen + 50;
  } else {
    nIndex = 100;
  }
  //calculate pm10 index (tenIndex)
  if (pmTen >= 0 && pmTen < 50) {
    tenIndex = pmTen;
  } else if (pmTen >= 50 && pmTen < 90) {
    tenIndex = 0.625 * pmTen + 18.75;
  } else if (pmTen >= 90 && pmTen < 180) {
    tenIndex = (10 / 36) * pmTen + 50;
  } else {
    tenIndex = 100;
  }
  //calculate PM2.5 index (twoIndex)
  if (pmTwo >= 0 && pmTwo < 30) {
    twoIndex = (5 / 3) * pmTwo;
  } else if (pmTwo >= 30 && pmTwo < 50) {
    twoIndex = 1.25 * pmTwo + 12.5;
  } else if (pmTwo >= 50 && pmTwo < 100) {
    twoIndex = 0.5 * pmTwo + 50;
  } else {
    twoIndex = 100;
  }
  //calculate CO index (cIndex)
  if (carbonMonoxide >= 0 && carbonMonoxide < 5000) {
    cIndex = 0.005 * carbonMonoxide;
  } else if (carbonMonoxide >= 5000 && carbonMonoxide < 10000) {
    cIndex = 0.01 * carbonMonoxide - 25;
  } else if (carbonMonoxide >= 10000 && carbonMonoxide < 20000) {
    cIndex = 0.0025 * carbonMonoxide + 50;
  } else {
    cIndex = 100;
  }
  //Check which index is the highest
  indices = [nIndex, tenIndex, twoIndex, cIndex];

  high = 0;
  for (let i = 0; i < indices.length; i++) {
    if (indices[i] > high) {
      high = indices[i];
    }
  }
  aqIndex = high / 100;
  return [nIndex, tenIndex, twoIndex, cIndex, aqIndex];
}
```

Listing B.17: Calculate Air Quality Index

```
function soundIndex(soundLevel) {
  if (soundLevel > 53) {
    return 0;
  } else {
    return 1;
  }
}
```

Listing B.18: Calculate Sound Index

B.4.3 Urban Health Index Calculation

```
//Check which filters are 'on'
  const totalVar =
    greenFilter +
```

```
    trafficFilter +
    walkFilter +
    heatFilter +
    aqFilter +
    soundFilter;

  //Step 7: calculate UHI using selected filters
  window.urbanHealthIndex =
    (greenScore * greenFilter +
      trafScore * trafficFilter +
      walkability * walkFilter +
      heatScore * heatFilter +
      aqScore[4] * aqFilter +
      soundScore * soundFilter) /
    totalVar;

  //Step 8: Set index scores as properties to each hexagon
  f.properties = {
    id: id,
    greenscore: greenScore,
    trafficScore: trafScore,
    walkability: walkability,
    heatscore: heatScore,
    airquality: aqScore,
    soundscore: soundScore,
    uhi: window.urbanHealthIndex,
  };
```

Listing B.19: Set attributes of hexagon to calulated values

B.5 Map Visualization

```
//Initialize Mapbox map
const map = new mapboxgl.Map({
  container: 'map',
  style: 'mapbox://styles/mapbox/light-v10',
  center: [5.449679, 51.449897],
  zoom: 12,
});

//Access the Mapbox API client
const mapboxClient = mapboxSdk({ accessToken: mapboxgl.accessToken });

//Initialize a geocoder
const geocoder = new MapboxGeocoder({
  accessToken: mapboxgl.accessToken,
  mapboxgl: mapboxgl,
  placeholder: 'UHI at your Location',
  zoom: 13,
});
//Add map controls
map.addControl(geocoder);

//Show geocoder results
geocoder.on('result', function (e) {});

//Add geocoder
map.addControl(new mapboxgl.NavigationControl());
```

Listing B.20: Initialize Mapbox

```
map.on('load', function () {
  //Add the hexagonal grid to the Mapbox map
  loadData(
```

```
    window.greenFilter,
    window.trafficFilter,
    window.walkFilter,
    window.heatFilter,
    window.aqFilter,
    window.soundFilter
  );

  //Create legend for map
  for (let i = 0; i < valuesArray.length; i++) {
    const range = 10 * valuesArray[i];
    const color = colorArray[i];
    const item = document.createElement('div');
    const key = document.createElement('span');
    key.className = 'legend-key';
    key.style.backgroundColor = color;
    if (i === 0) {
      key.style.opacity = 0.4;
    } else {
      key.style.opacity = 0.4;
    }

    const value = document.createElement('span');
    value.innerHTML = range;
    item.appendChild(key);
    item.appendChild(value);
    legend.appendChild(item);
  }
});
```

Listing B.21: Create map visualization when map is loaded

```
const filterGreen = document.querySelector('input[id=filterGreen]');
filterGreen.addEventListener('change', function () {
  map.removeLayer('outline');
  map.removeLayer('uhi');
  map.removeSource('hexgrid');
  if (this.checked) {
    window.greenFilter = 1;
  } else {
    window.greenFilter = 0;
  }
  dataFiltered = loadData(
    window.greenFilter,
    window.trafficFilter,
    window.walkFilter,
    window.heatFilter,
    window.aqFilter,
    window.soundFilter
  );
});
```

Listing B.22: Filter for the UHI map

```
map.addSource('hexgrid', {
      type: 'geojson',
      data: data,
      generateId: true,
    });
```

Listing B.23: Addition of map source

```
map.addLayer({
  id: 'uhi',
  type: 'fill',
  source: 'hexgrid',
```

```
  layout: {},
  paint: {
    'fill-color': [
      'case',
      ['boolean', ['feature-state', 'hover'], false],
      '#ff4929',
      colors,
    ],
    'fill-opacity': [
      'case',
      ['boolean', ['feature-state', 'hover'], false],
      0.8,
      0.4,
    ],
  },
});
map.addLayer({
  id: 'outline',
  type: 'line',
  source: 'hexgrid',
  layout: {
    'line-join': 'round',
    'line-cap': 'round',
  },
  paint: {
    'line-color': '#74C69D',
    'line-width': 0.5,
    'line-opacity': 1,
  },
});

let lastFeature;
let hexID = null;
map.on('mousemove', 'uhi', function (e) {
  const f = map.queryRenderedFeatures(e.point)[0];
  if (f.properties.id !== lastFeature) {
    lastFeature = f.properties.id;
    if (hexID || lastFeature === 1) {
      map.removeFeatureState({
        source: 'hexgrid',
        id: hexID,
      });
    }
    hexID = e.features[0].id;

    map.setFeatureState(
      {
        source: 'hexgrid',
        id: hexID,
      },
      {
        hover: true,
      }
    );
  }
});
```

Listing B.24: Addition of map layers

```
//Add popup to hexagons, when clicked UHI is display + link to show page
map.on('click', 'uhi', function (e) {
  coord = e.lngLat;
  score = roundFloat(10 * e.features[0].properties.uhi);
  id = e.features[0].properties.id;
  mapboxClient.geocoding
    .reverseGeocode({
      query: [coord.lng, coord.lat],
```

```
    })
    .send()
    .then((response) => {
      const match = response.body.features[1].place_name;
      const neighborhood = match.split(',');
      const htmlText =
        '<div class="alert alert-primary mb-0" role="alert">' +
        `<h4 class="alert-heading">${neighborhood[0]}</h4>` +
        `<p>Urban Health Index of <b>${score}</b> out of 10.</p>` +
        '<hr>' +
        `<a href="/${id}/${history}" class="alert-link mb-0">More information</
            a>` +
        '</div>';

      window.popup = new mapboxgl.Popup()
        .setLngLat(coord)
        .setHTML(htmlText)
        .addTo(map);
    });
});
```

Listing B.25: Popup for hexagon

B.6 Historical Data Visualization

```
//Add popup to hexagons, when clicked UHI is display + link to show page
//Check which months and days are included in the recorded datapoints
for (let dp of historyDatapoints) {
  if (!months.includes(dp.properties.date[1])) {
    months.push(dp.properties.date[1]);
  }
}
for (let dp of historyDatapoints) {
  if (!days.includes(dp.properties.date[2])) {
    days.push(dp.properties.date[2]);
  }
}

//Sort the months and days
months.sort(function (a, b) {
  return a - b;
});
days.sort(function (a, b) {
  return a - b;
});

//Create a labels array + an empty values array for later use in the History
    Graph based on selected historic period (month or year)
if (historyPeriod === 'month') {
  for (let month of months) {
    if (month in [1, 2, 5, 6, 8, 10, 12]) {
      for (i = 1; i <= 31; i++) {
        if (month != parseInt(currentMonth)) {
          //BEGIN
          if (i < 10 && i > parseInt(currentDay)) {
            labels.push(`0${i}/${month}/2021`);
            values.push({
              month: month,
              day: parseInt(`0${i}`),
              heat: [],
              aq: [],
              sound: [],
              uhi: [],
            });
          } else if (i > parseInt(currentDay)) {
```

```
              labels.push(`${i}/${month}/2021`);
              values.push({
                month: month,
                day: i,
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            }
            //END
          } else if (
            month === parseInt(currentMonth) &&
            i <= parseInt(currentDay)
          ) {
            //BEGIN
            if (i < 10 && i <= parseInt(currentDay)) {
              labels.push(`0${i}/${month}/2021`);
              values.push({
                month: month,
                day: parseInt(`0${i}`),
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            } else if (i <= parseInt(currentDay)) {
              labels.push(`${i}/${month}/2021`);
              values.push({
                month: month,
                day: i,
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            }
            //END
          }
        }
      } else if (month in [4, 7, 9, 11]) {
        for (i = 1; i <= 30; i++) {
          if (month != parseInt(currentMonth)) {
            //BEGIN
            if (i < 10 && i > parseInt(currentDay)) {
              labels.push(`0${i}/${month}/2021`);
              values.push({
                month: month,
                day: parseInt(`0${i}`),
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            } else if (i > parseInt(currentDay)) {
              labels.push(`${i}/${month}/2021`);
              values.push({
                month: month,
                day: i,
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            }
            //END
          } else if (
```

```
            month === parseInt(currentMonth) &&
            i <= parseInt(currentDay)
          ) {
            //BEGIN
            if (i < 10 && i <= parseInt(currentDay)) {
              labels.push(`0${i}/${month}/2021`);
              values.push({
                month: month,
                day: parseInt(`0${i}`),
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            } else if (i <= parseInt(currentDay)) {
              labels.push(`${i}/${month}/2021`);
              values.push({
                month: month,
                day: i,
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            }
            //END
          }
        }
      } else {
        for (i = 1; i <= 28; i++) {
          if (month != parseInt(currentMonth)) {
            //BEGIN
            if (i < 10 && i > parseInt(currentDay)) {
              labels.push(`0${i}/${month}/2021`);
              values.push({
                month: month,
                day: parseInt(`0${i}`),
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            } else if (i > parseInt(currentDay)) {
              labels.push(`${i}/${month}/2021`);
              values.push({
                month: month,
                day: i,
                heat: [],
                aq: [],
                sound: [],
                uhi: [],
              });
            }
            //END
          } else if (
            month === parseInt(currentMonth) &&
            i <= parseInt(currentDay)
          ) {
            //BEGIN
            if (i < 10 && i <= parseInt(currentDay)) {
              labels.push(`0${i}/${month}/2021`);
              values.push({
                month: month,
                day: parseInt(`0${i}`),
                heat: [],
                aq: [],
                sound: [],
```

```
              uhi: [],
            });
          } else if (i <= parseInt(currentDay)) {
            labels.push(`${i}/${month}/2021`);
            values.push({
              month: month,
              day: i,
              heat: [],
              aq: [],
              sound: [],
              uhi: [],
            });
          }
          //END
        }
      }
    }
  }
  }
```

Listing B.26: Generate the labels for the historical data graph

```
function createHistoryGraph(labels, heat, aq, sound, uhi) {
  const historyGraph = document
    .getElementById('historyGraph')
    .getContext('2d');
  const dataHistory = {
    labels: labels,
    datasets: [
      {
        label: 'Heat Index',
        backgroundColor: 'transparent',
        borderColor: chartColors[0],
        borderWidth: indexThick,
        pointBackgroundColor: chartColors[0],
        pointBorderColor: '#FFF',
        pointBorderWidth: 2,
        data: heat,
      },
      {
        label: 'Air Quality',
        backgroundColor: 'transparent',
        borderColor: chartColors[1],
        borderWidth: indexThick,
        pointBackgroundColor: chartColors[1],
        pointBorderColor: '#FFF',
        pointBorderWidth: 2,
        data: aq,
      },
      {
        label: 'Sound Index',
        backgroundColor: 'transparent',
        borderColor: chartColors[2],
        borderWidth: indexThick,
        pointBackgroundColor: chartColors[2],
        pointBorderColor: '#FFF',
        pointBorderWidth: 2,
        data: sound,
      },
      {
        label: 'UHI',
        backgroundColor: 'transparent',
        borderColor: chartColors[3],
        borderWidth: uhiThick,
        pointBackgroundColor: chartColors[3],
        pointBorderColor: '#FFF',
        pointBorderWidth: 2,
```

```
        data: uhi,
      },
    ],
  };

  new Chart(historyGraph, {
    type: 'line',
    data: dataHistory,
    options: {
      tooltips: {
        mode: 'point',
        intersect: false,
      },
      hover: {
        mode: 'point',
        intersect: false,
      },
      onClick: function onClick(evt, activeElements) {
        console.log(activeElements);
        if (!activeElements || !activeElements.length) {
          for (let i = 0; i <= 3; i++) {
            let activeDataset = this.data.datasets[i];
            if (i < 3) {
              activeDataset.borderWidth = indexThick;
            } else {
              activeDataset.borderWidth = uhiThick;
            }
            activeDataset.borderColor = chartColors[i];
            activeDataset.pointBackgroundColor = chartColors[i];
            this.update();
          }
          lastHovered = null;
        } else {
          let datasetIndex = activeElements[0].datasetIndex;
          if (!lastHovered && lastHovered !== 0) {
            let activeDataset = this.data.datasets[datasetIndex];
            activeDataset.borderWidth += 5;
            activeDataset.borderColor = '#127FAF';
            activeDataset.pointBackgroundColor = '#127FAF';
            lastHovered = datasetIndex;
            this.update();
          } else if (datasetIndex !== lastHovered) {
            activeDataset = this.data.datasets[lastHovered];
            activeDataset.borderWidth -= 5;
            activeDataset.borderColor = chartColors[lastHovered];
            activeDataset.pointBackgroundColor =
              chartColors[lastHovered];

            activeDataset = this.data.datasets[datasetIndex];
            activeDataset.borderWidth += 5;
            activeDataset.borderColor = '#127FAF';
            activeDataset.pointBackgroundColor = '#127FAF';
            lastHovered = datasetIndex;
            this.update();
          }
        }
      },
      elements: {
        line: {
          tension: 0.4,
        },
        point: {
          radius: 3,
        },
      },
      scales: {
        y: {
```

```
          max: 10,
          beginAtZero: true,
          title: {
            display: true,
            text: 'Index Score',
          },
        },
      },
    },
  });
}
```

Listing B.27: Generate the historical data graph

```
if (hexId === f.properties.id) {
        window.uhi = roundFloat(urbanHealthIndex * 10);
        dataElements.push(
          roundFloat(greenScore * 10),
          roundFloat(trafScore * 10),
          roundFloat(walkability * 10),
          roundFloat(averageHeatScore * 10),
          roundFloat(averageAqScore[4] * 10),
          roundFloat(averageSoundScore * 10)
        );
      }
```

Listing B.28: Generate data for score graph

```
function createScoreGraph(colors, data, uhi) {
  const scoreGraph = document.getElementById('scoreGraph').getContext('2d');

  const scoreData = {
    labels: [
      'Green',
      'Traffic Safety',
      'Walkability',
      'Heat Index',
      'Air Quality',
      'Sound Index',
    ],
    datasets: [
      {
        data: data,
        label: 'Index Scores',
        backgroundColor: 'rgba(216, 243, 220, 0.5)',
        borderColor: colors[5],
      },
    ],
  };

  new Chart(scoreGraph, {
    type: 'radar',
    data: scoreData,
    options: {
      responsive: true,
      plugins: {
        title: {
          display: true,
          text: `Today's Urban Healht Index scores ${uhi}`,
        },
      },
    },
  });
}
```

Listing B.29: Generate score graph

Appendix C

Validation Test

C.1 Context

You are looking for the healthiest location in the city and want to do some exploring. Imagine you are interested in both short-term, and, long-term information.

This test will ask you to complete several small tasks. Each task will be posed to you and all necessary tools for completing the task are available in the application. When you feel you have completed the task, you are asked to give two scores based on how easy it was to complete the task and how useful the found information is.

C.2 Assessement Form

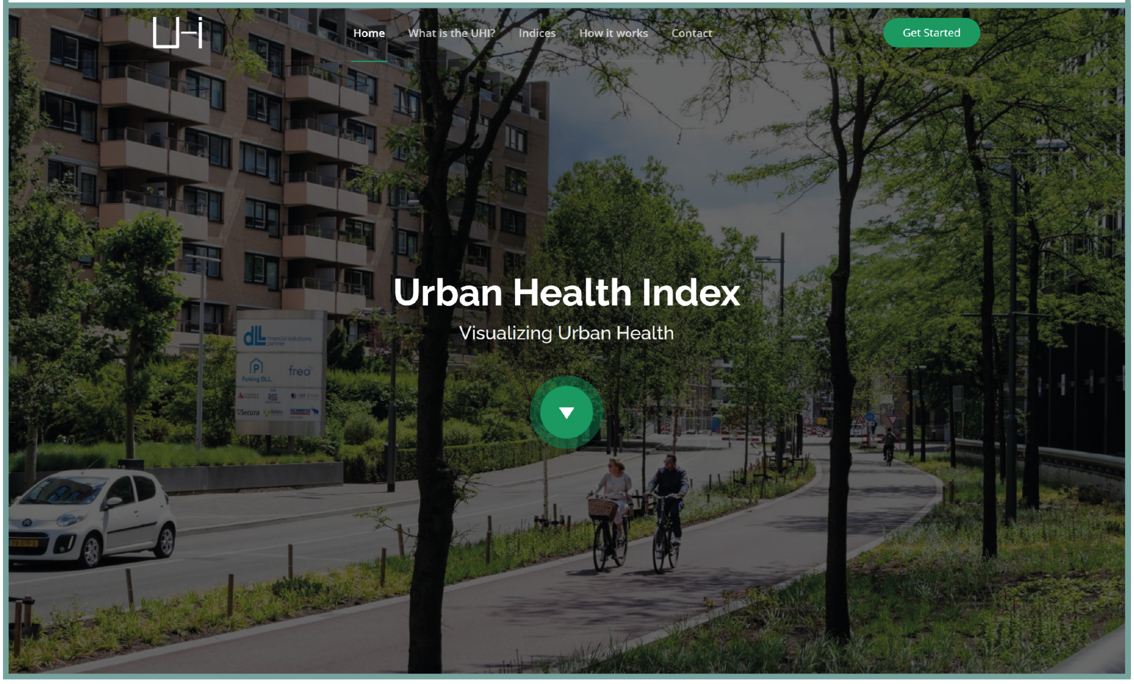
Home Page (Educate)	
1	Can you explain what the UHI is?
	Ease / 10 Validity / 10
2	Which six indices are used for the calculation of the UHI
	Ease / 10 Validity / 10
Map (Explore)	
3	Can you look up the best scoring location?
	Ease / 10 Validity / 10
4	What is the UHI score of that location?
	Ease / 10 Validity / 10
History (Investigate)	
5	What are the sub-index scores for that location?
	Ease / 10 Validity / 10
6	What was the UHI score on 23 May?
	Ease / 10 Validity / 10
7	Can you make a comparison of ONLY the UHI and Heat Index?
	Ease / 10 Validity / 10
Home Page (Educate)	
8	How is the Heat Index calculated?
	Ease / 10 Validity / 10
Map (Explore)	
9	Can you look up the best scoring location again, but without the Heat Index?
	Ease / 10 Validity / 10

Appendix D

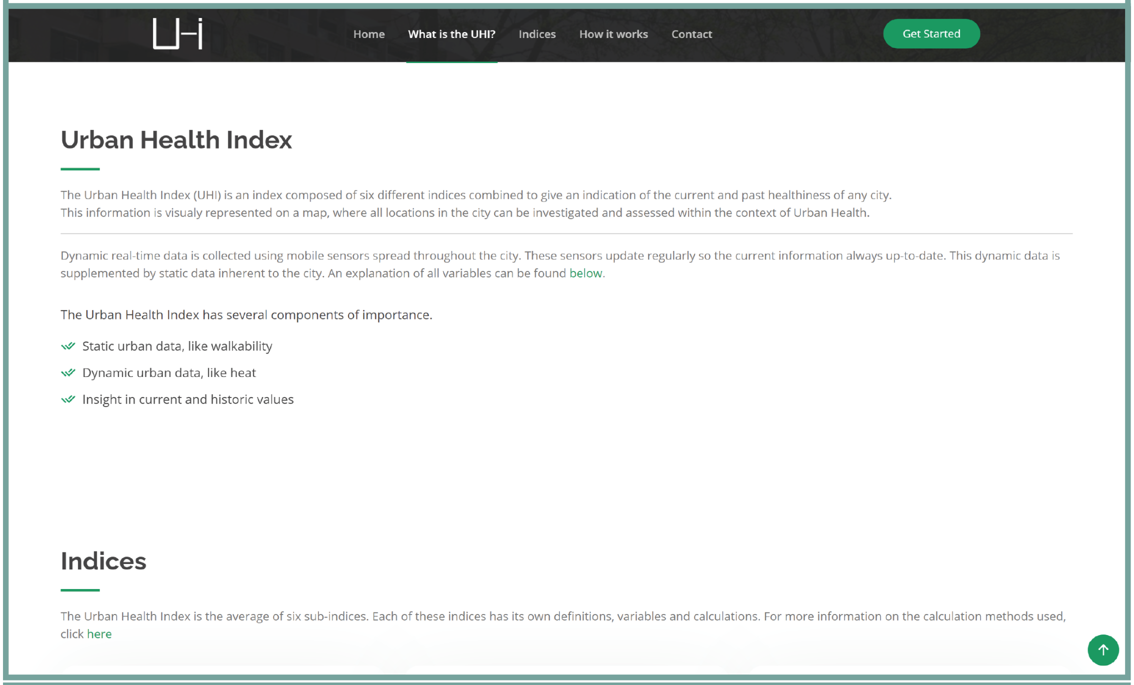
Application Results

Educate

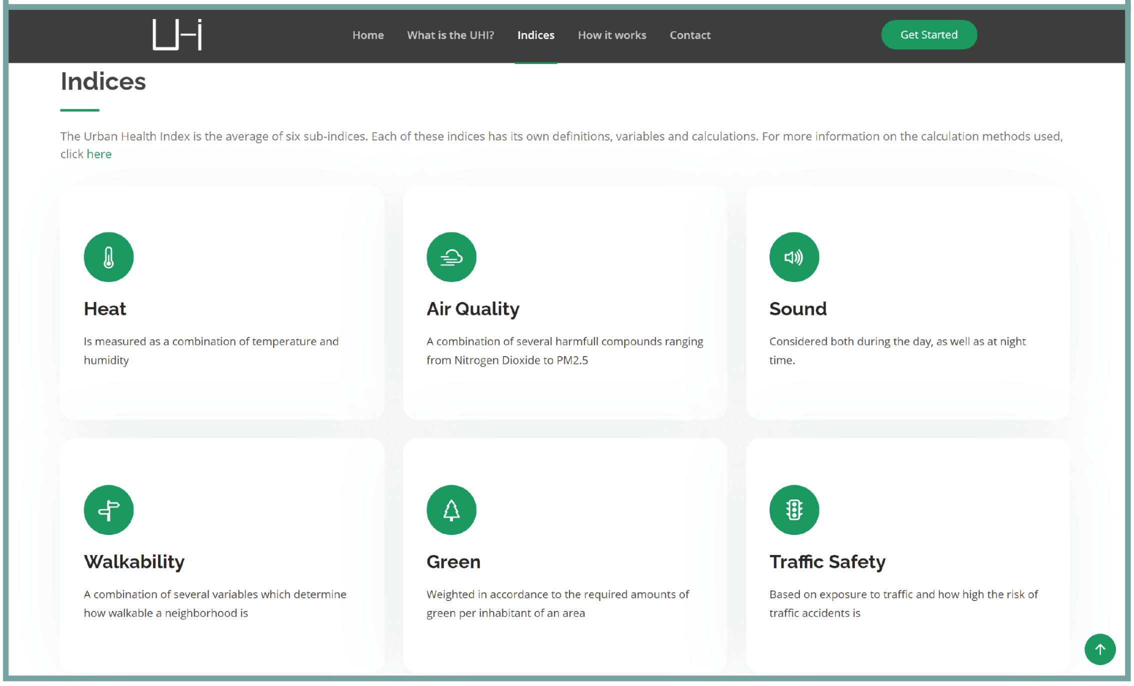
1. Home



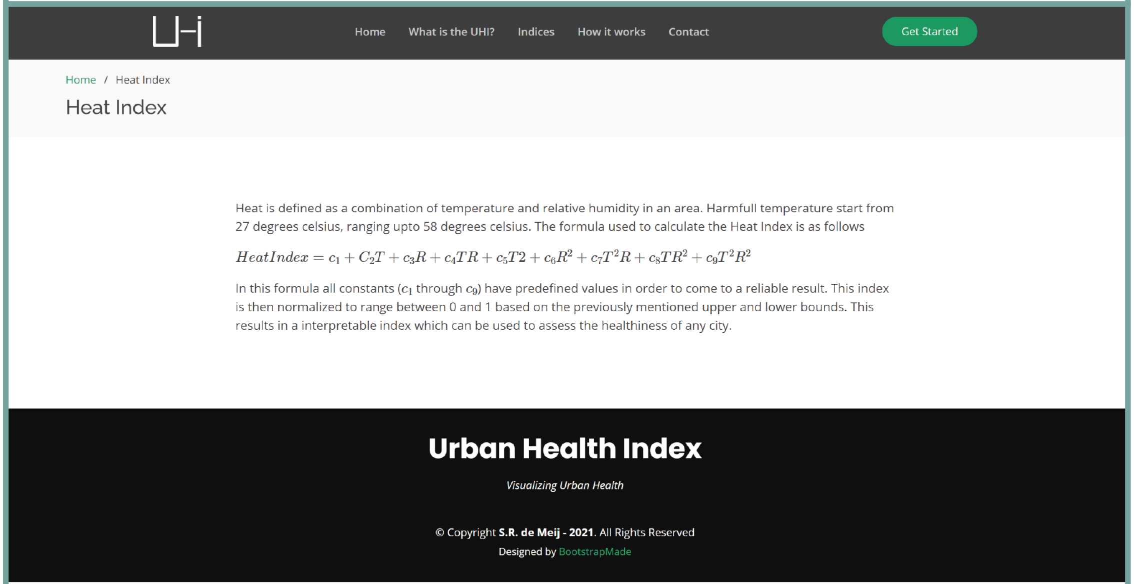
2. What is the UHI?



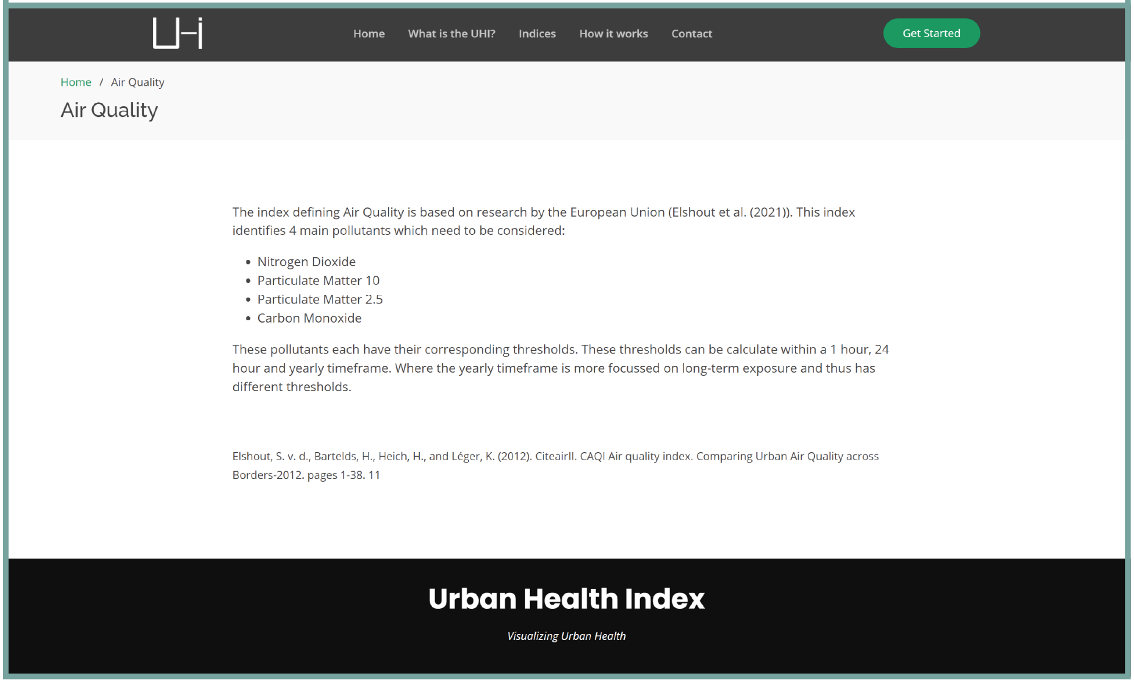
3. Indices

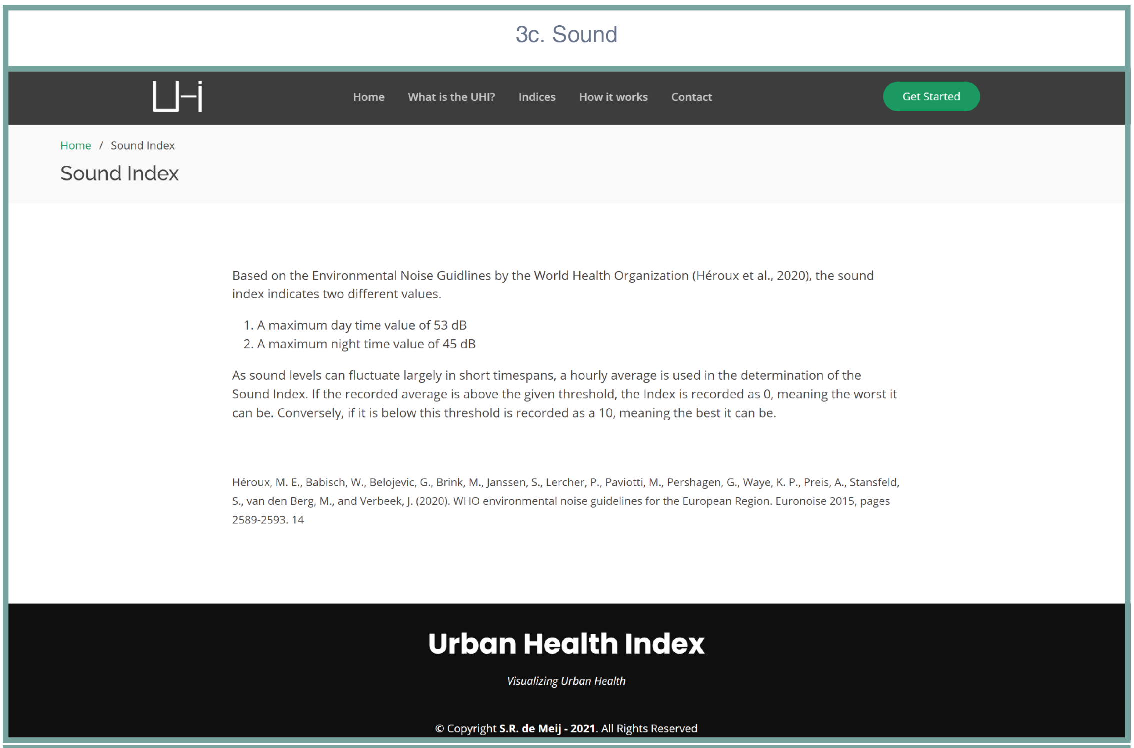


3a. Heat



3b. Air Quality





3c. Sound

Home What is the UHI? Indices How it works Contact Get Started

Home / Sound Index

Sound Index

Based on the Environmental Noise Guidlines by the World Health Organization (Héroux et al., 2020), the sound index indicates two different values.

1. A maximum day time value of 53 dB
2. A maximum night time value of 45 dB

As sound levels can fluctuate largely in short timespans, a hourly average is used in the determination of the Sound Index. If the recorded average is above the given threshold, the Index is recorded as 0, meaning the worst it can be. Conversely, if it is below this threshold is recorded as a 10, meaning the best it can be.

Héroux, M. E., Babisch, W., Belojevic, G., Brink, M., Janssen, S., Lercher, P., Paviotti, M., Pershagen, G., Waye, K. P., Preis, A., Stansfeld, S., van den Berg, M., and Verbeek, J. (2020). WHO environmental noise guidelines for the European Region. Euronoise 2015, pages 2589-2593. 14

Urban Health Index

Visualizing Urban Health

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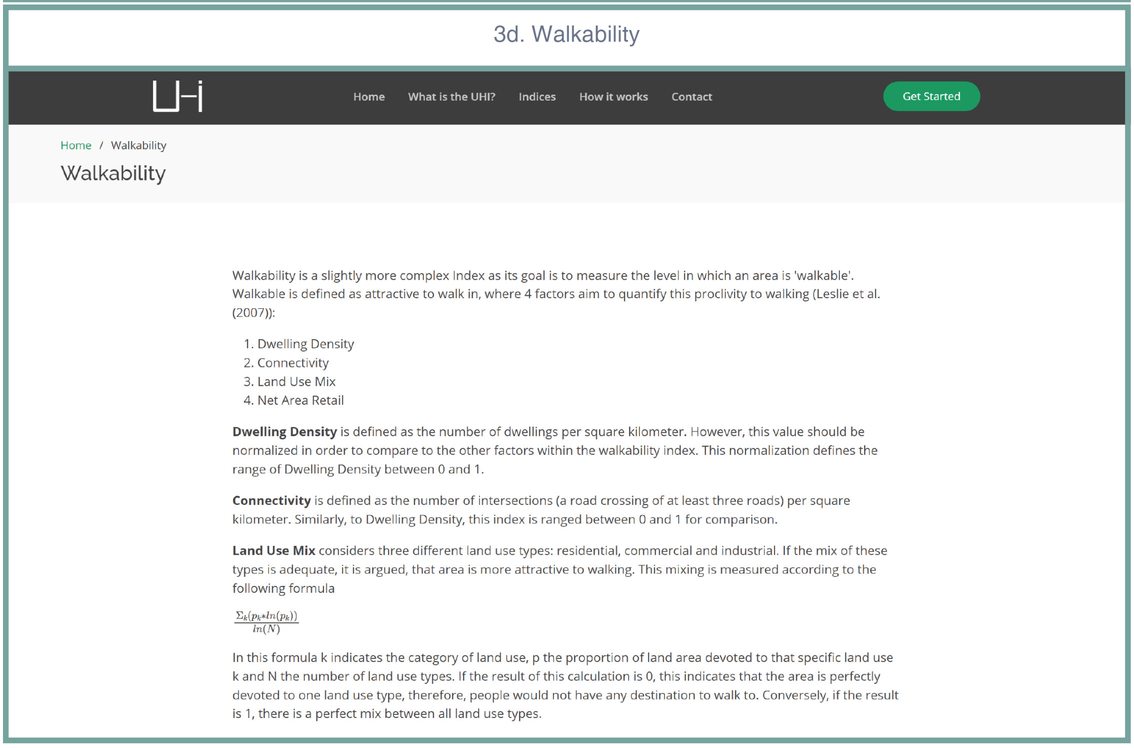


3d. Walkability

Home What is the UHI? Indices How it works Contact Get Started

Home / Walkability

Walkability

Walkability is a slightly more complex Index as its goal is to measure the level in which an area is 'walkable'. Walkable is defined as attractive to walk in, where 4 factors aim to quantify this proclivity to walking (Leslie et al. (2007)):

1. Dwelling Density
2. Connectivity
3. Land Use Mix
4. Net Area Retail

Dwelling Density is defined as the number of dwellings per square kilometer. However, this value should be normalized in order to compare to the other factors within the walkability index. This normalization defines the range of Dwelling Density between 0 and 1.

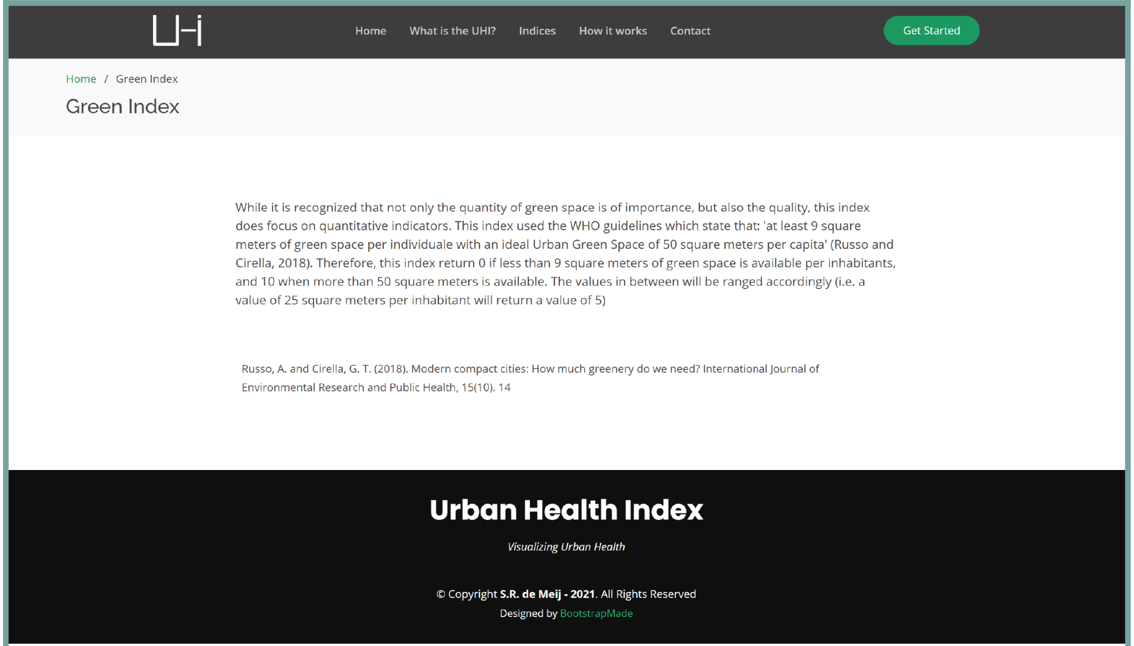
Connectivity is defined as the number of intersections (a road crossing of at least three roads) per square kilometer. Similarly, to Dwelling Density, this index is ranged between 0 and 1 for comparison.

Land Use Mix considers three different land use types: residential, commercial and industrial. If the mix of these types is adequate, it is argued, that area is more attractive to walking. This mixing is measured according to the following formula

$$\frac{\Sigma_k(p_k * ln(p_k))}{ln(N)}$$

In this formula k indicates the category of land use, p the proportion of land area devoted to that specific land use k and N the number of land use types. If the result of this calculation is 0, this indicates that the area is perfectly devoted to one land use type, therefore, people would not have any destination to walk to. Conversely, if the result is 1, there is a perfect mix between all land use types.

3e. Green



UHI Home What is the UHI? Indices How it works Contact Get Started

Home / Green Index

Green Index

While it is recognized that not only the quantity of green space is of importance, but also the quality, this index does focus on quantitative indicators. This index used the WHO guidelines which state that: 'at least 9 square meters of green space per individuale with an ideal Urban Green Space of 50 square meters per capita' (Russo and Cirella, 2018). Therefore, this index return 0 if less than 9 square meters of green space is available per inhabitants, and 10 when more than 50 square meters is available. The values in between will be ranged accordingly (i.e. a value of 25 square meters per inhabitant will return a value of 5)

Russo, A. and Cirella, G. T. (2018). Modern compact cities: How much greenery do we need? International Journal of Environmental Research and Public Health, 15(10). 14

Urban Health Index

Visualizing Urban Health

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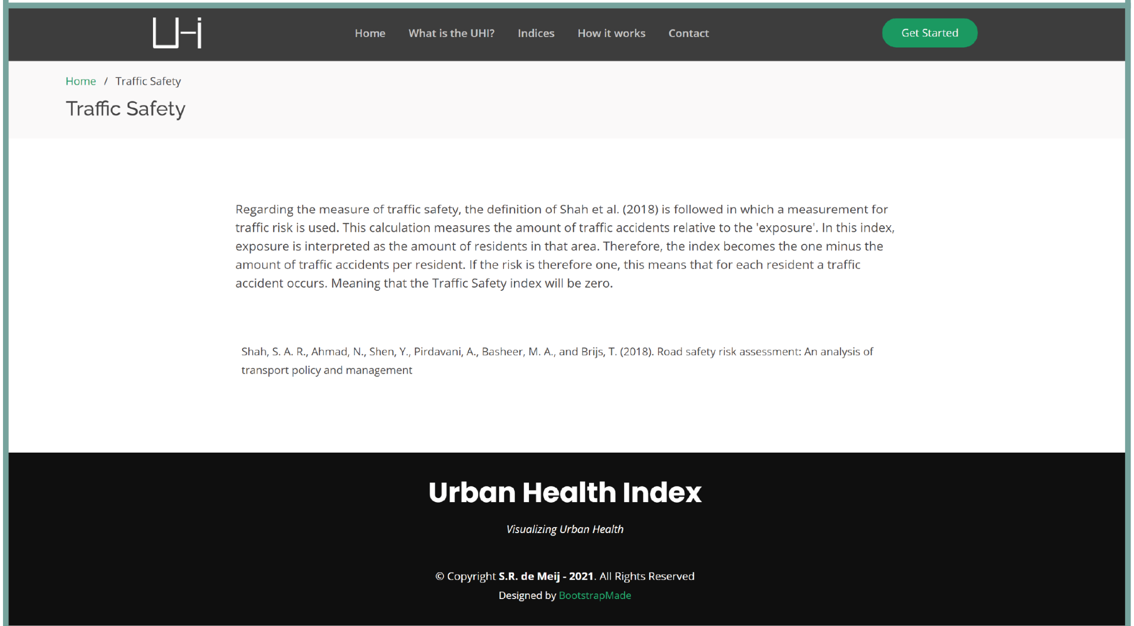
3f. Traffic Safety



UHI Home What is the UHI? Indices How it works Contact Get Started

Home / Traffic Safety

Traffic Safety

Regarding the measure of traffic safety, the definition of Shah et al. (2018) is followed in which a measurement for traffic risk is used. This calculation measures the amount of traffic accidents relative to the 'exposure'. In this index, exposure is interpreted as the amount of residents in that area. Therefore, the index becomes the one minus the amount of traffic accidents per resident. If the risk is therefore one, this means that for each resident a traffic accident occurs. Meaning that the Traffic Safety index will be zero.

Shah, S. A. R., Ahmad, N., Shen, Y., Pirdavani, A., Basheer, M. A., and Brijs, T. (2018). Road safety risk assessment: An analysis of transport policy and management

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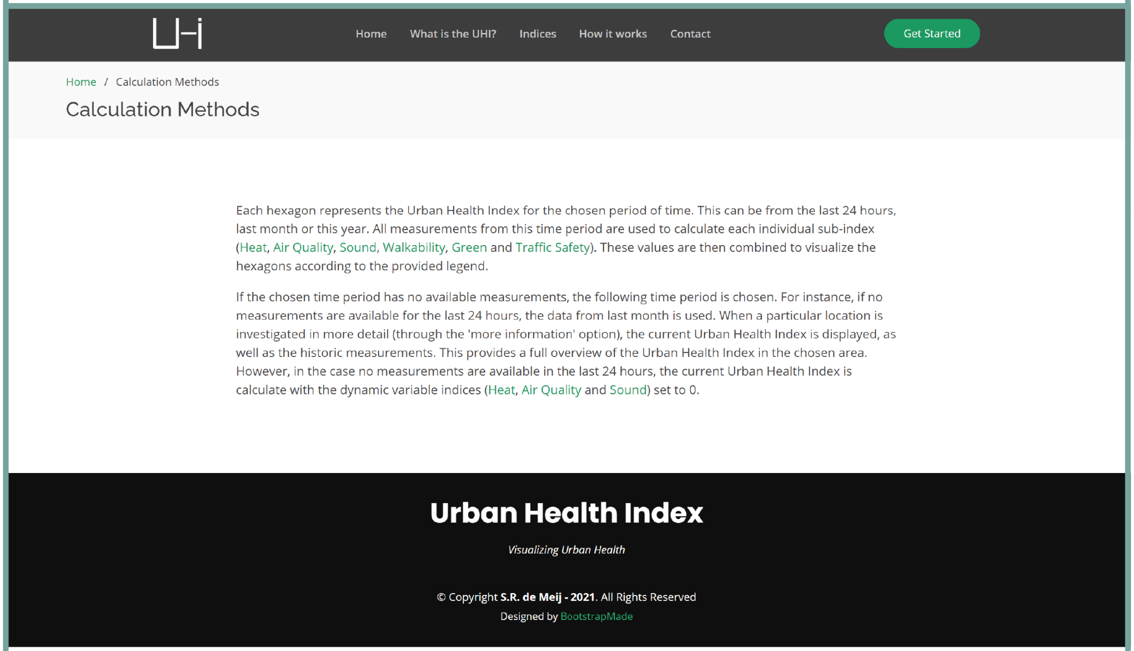
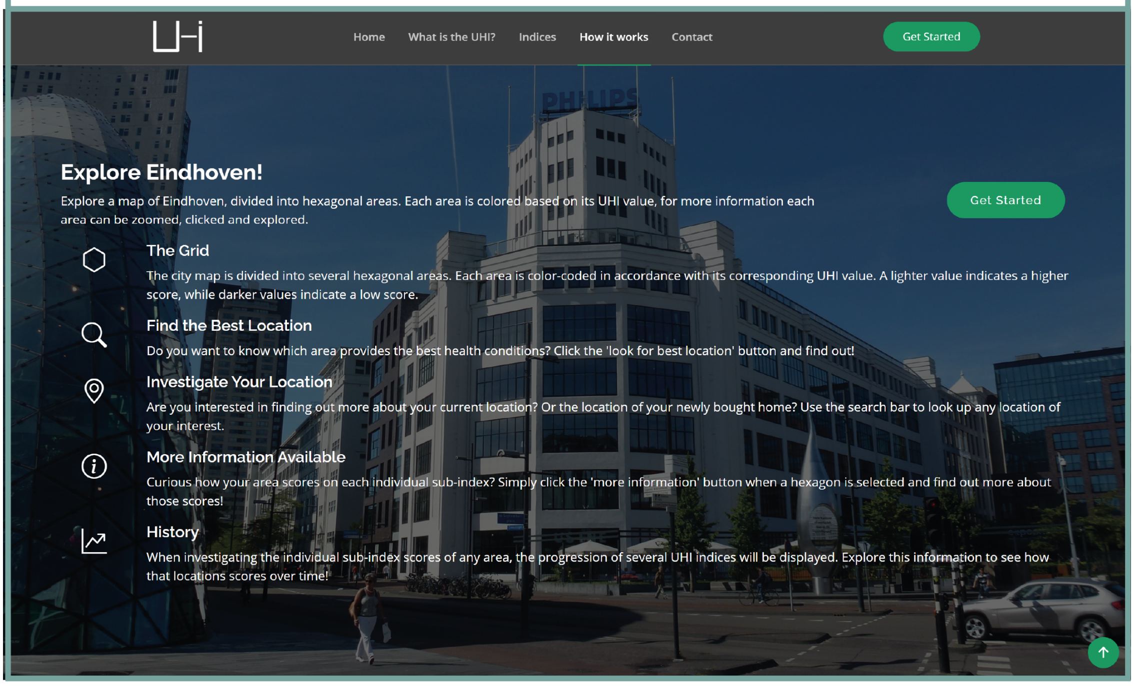
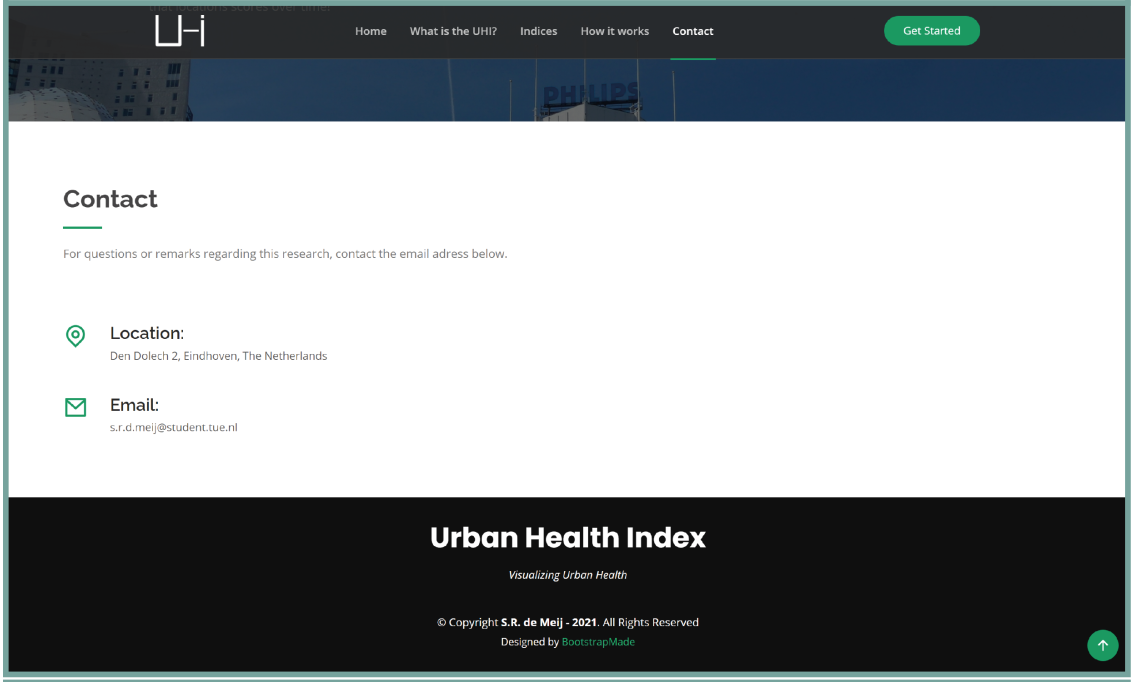
3g. Caclulation Method



4. How it works

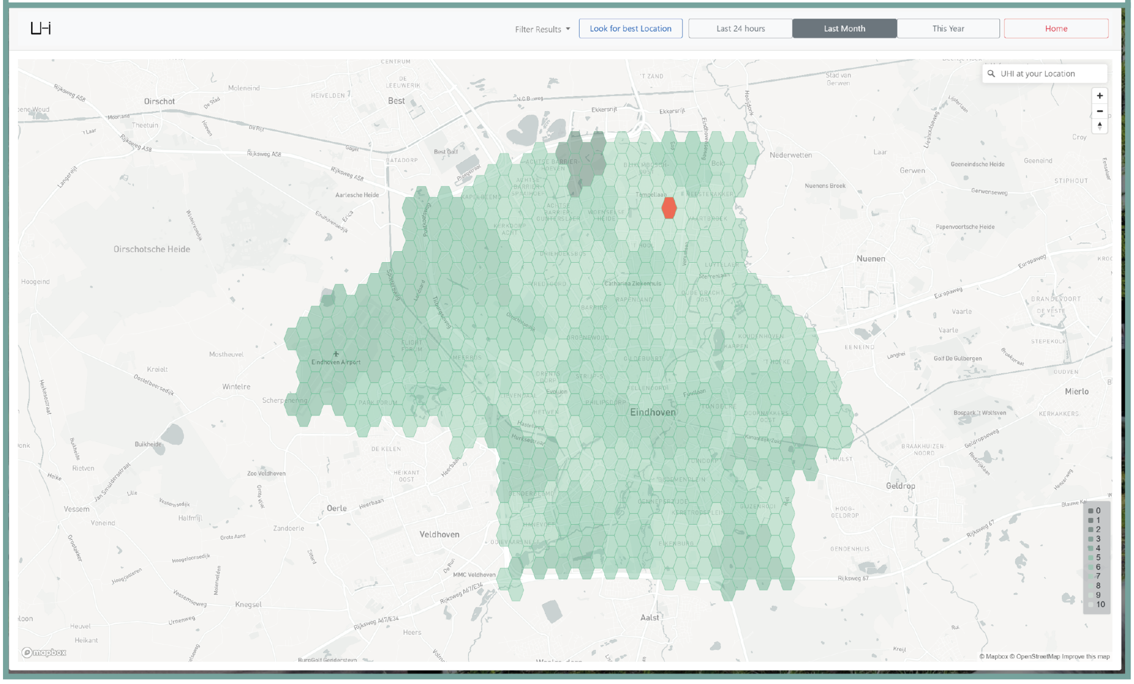


5. Contact

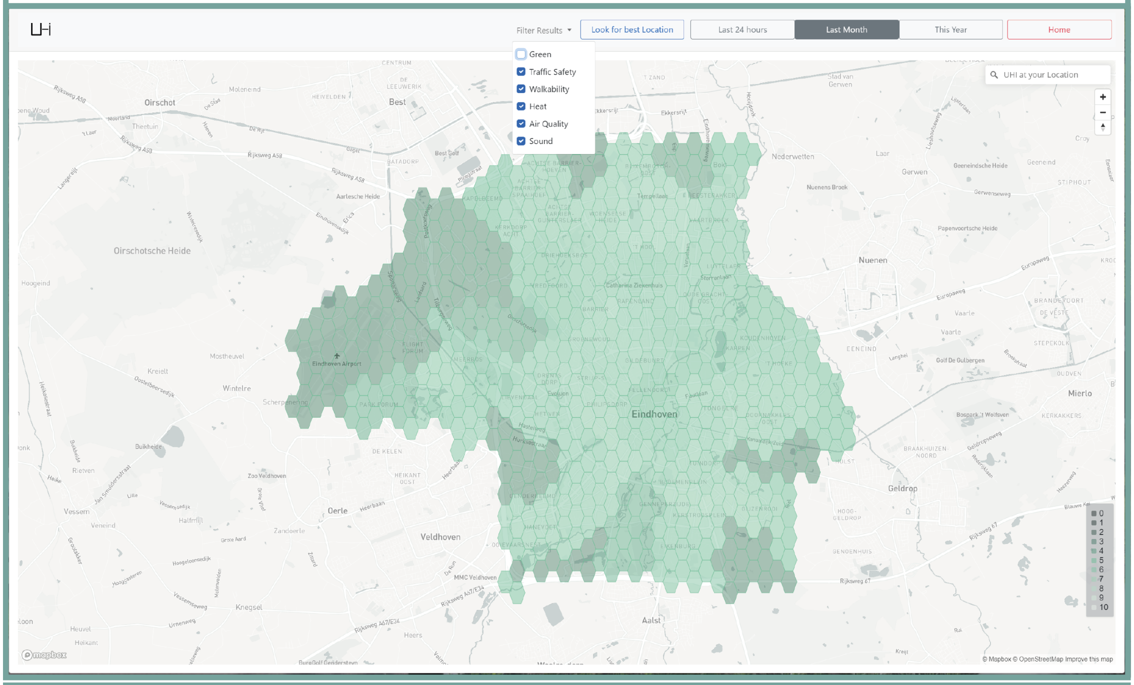


Explore

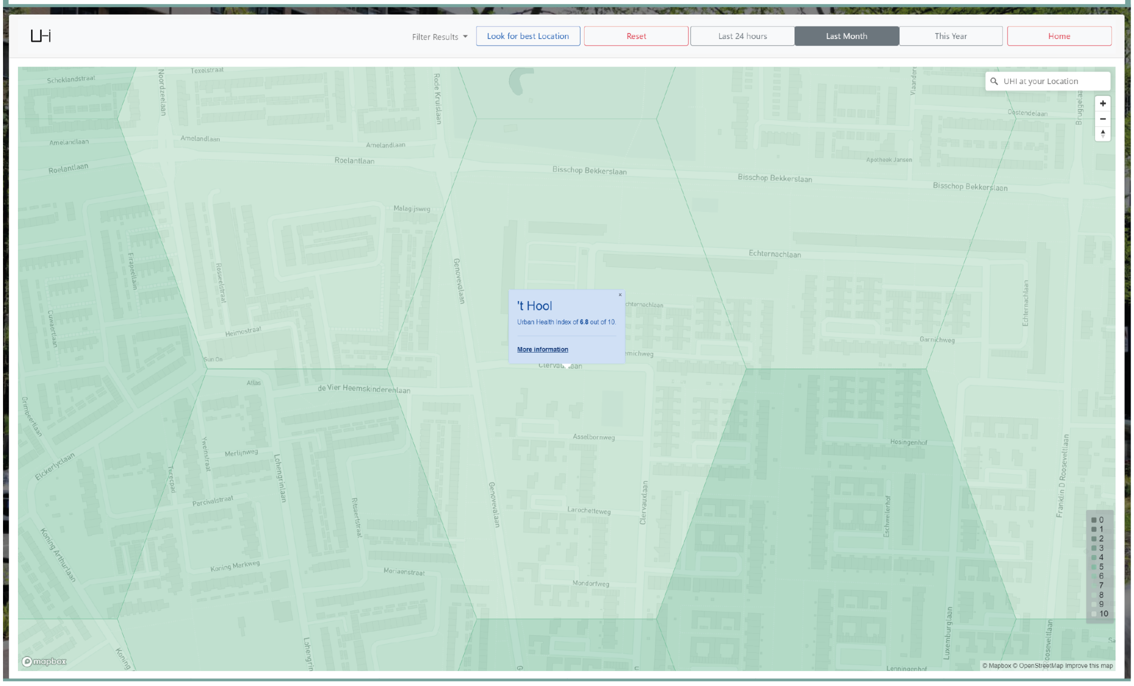
6. Map



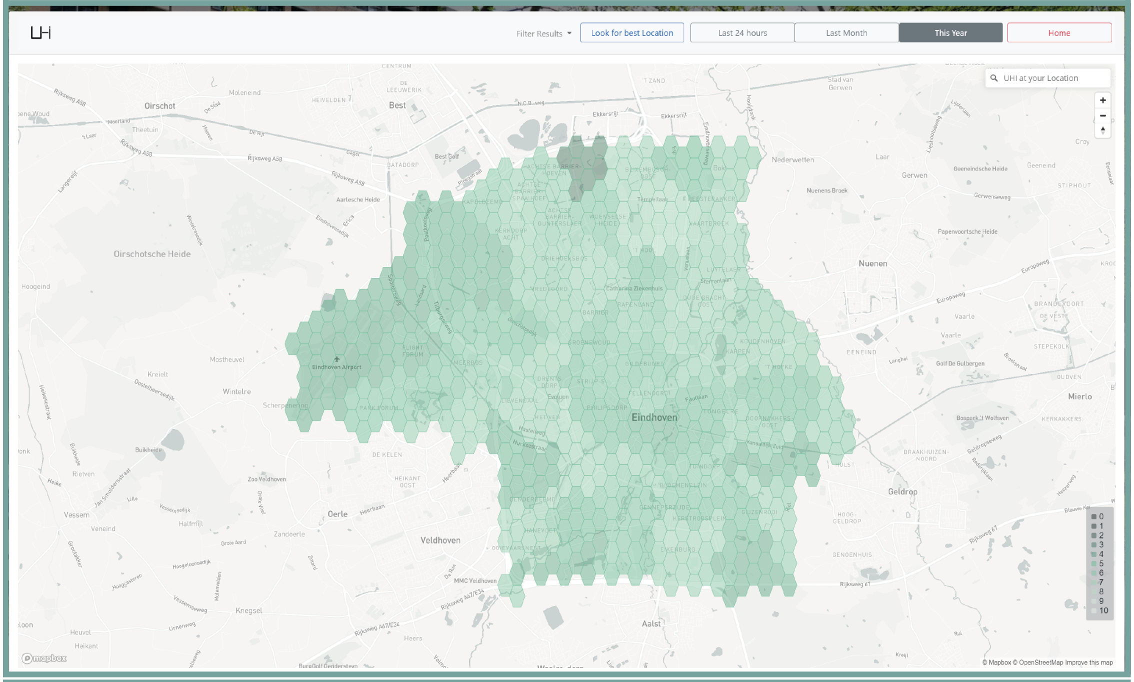
7. Filter Results



8. Look for best Location



9. Select Time Frame



Investigate

10. Historic Data