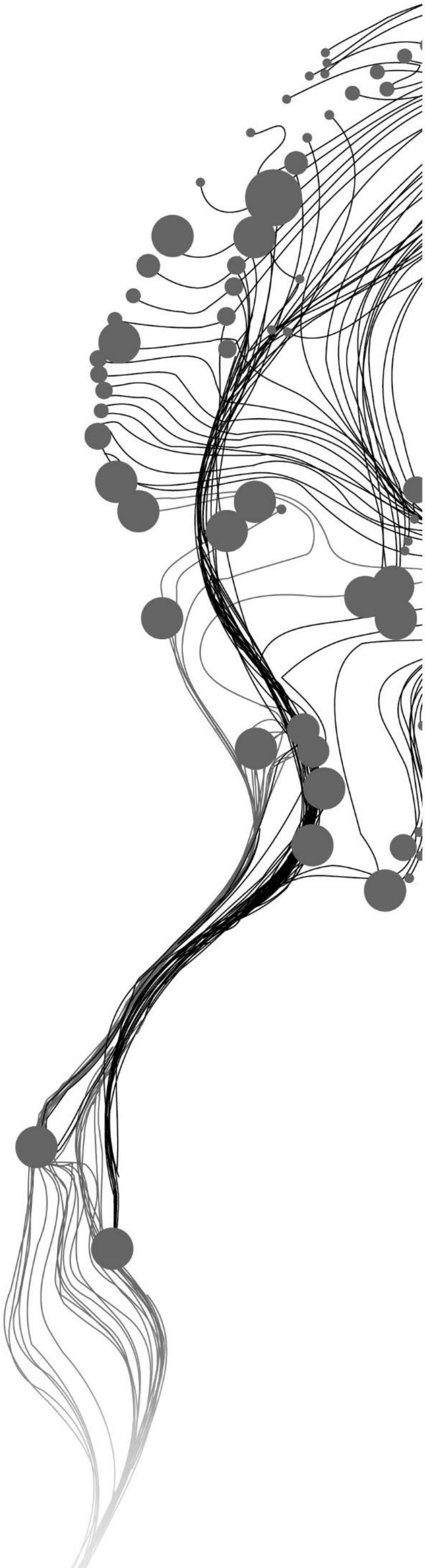
# GENERATIVE DESIGN FOR WALKABLE CITIES: A CASE STUDY OF SOFIA

DEWI KUMALASARI
[July 2022]

SUPERVISORS:
Dr. M.N Koeva
Dr.ir. F. Vahdatikhaki

EXTERNAL SUPERVISORS:
Prof. Desislava Petrova-Antonova

ADVISOR:
Dr. M. Kuffer



# GENERATIVE DESIGN FOR WALKABLE CITIES: A CASE STUDY OF SOFIA

DEWI KUMALASARI
Enschede, The Netherlands, July 2022

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialization: Urban Planning and Management

SUPERVISORS:
Dr. M.N Koeva
Dr.ir. F. Vahdatikhaki

EXTERNAL SUPERVISOR:
Prof. Desislava Petrova-Antonova

ADVISOR:
Dr. M. Kuffer

THESIS ASSESSMENT BOARD:
Prof.dr. R. V. Richard Sliuzas John (Chair)
Kaloyan Karamitov (External Examiner, Sofia University)

# ABSTRACT

Pedestrian-friendly environments are essential in creating healthy and productive communities. People in many large cities worldwide, including the city of Sofia (Bulgaria), are more likely to use private vehicles, resulting in high particulate matter concentrations. Therefore, Sofia municipality intends to tackle the air pollution issue by working towards improved walkability. Urban planning is a fundamental discipline that enables walkability improvement through sustainable urban development planning. Currently, the implementation of walkability is limited to something "nice to know about" rather than a "must-have" criterion for sustainable planning. To address this issue, integration between walkability and mainstream design approach, such as generative design, can be a solution. In addition, walkability in the generative design domain only considers one primary indicator: "distance to amenities". While in fact, other dimensions could represent walkability, namely the comfort dimension. In this study, we tried to combine distance to amenities and urban greeneries to represent the comfort dimension. Since walkability is highly personal, we also incorporated the human perspective.

Furthermore, we aim to develop a workflow to integrate walkability and parametric modelling based on comfort dimensions to create walkability-optimal-urban-plans. To reach the aim of this research, an initial review and problem analysis of the walkability assessment method in the previous research has been done. Through this stage, the research gap and method have been identified. The Walkscore method has been selected to be developed in this research due to its familiarity and multi-dimensionality. Building upon the research gap and identified method, a workflow is developed based on integrating the distance to amenities and urban greeneries with the human perspective input on the generative design domain. After that, the proposed workflow needs to be implemented in the study area (Krastova Vada) to generate walkability-optimal-urban-plans. Since the human perspective is considered, a walking preference survey with the citizen of Sofia has been organized. To validate the proposed workflow, it is also implemented in another location, "Lozenets", to compare its baseline walkability score with the people's walking experience. Implementing the proposed workflow has resulted in three different amenities and urban greeneries placement scenarios. The walkability score has increased from 56.93 to 82.43 in scenario 1, 74.40 in scenario 2, and 73.12 in scenario 3.

In conclusion, this study has shown that walkability can be useful for a "must-have" design criterion rather than just a "nice to know about" assessment tool. The implementation of the proposed workflow has shown that the chosen location of amenities and urban greeneries have helped increase the walkscore, thus can be interpreted as increasing the neighbourhood's walkability. In addition, incorporating human perspective and urban greeneries have also successfully given a new variety of walkability assessments in the generative design domain. The different scenarios developed also show the capability of the proposed workflow as the main objective of this study, as well as the incorporation of generative design into the urban planning process to be a discussion tool for the policymakers, stakeholders, and other parties involved. However, further discussion with stakeholders is needed to determine constraints to produce more reliable scenarios that better represent the actual condition. Selecting constraints is essential in determining what scenarios to make and fit the stakeholders' preferences, which could also align with Sofia's building code regulation. It is also essential to notice that strategic planning of a location for different categories of amenities and locations for urban greeneries installation is needed to increase the walkability of a neighbourhood.

**Keywords**: Walkability, Parametric Modelling, Urban Planning, Generative Design, Comfort Dimension

# ACKNOWLEDGEMENTS

I would like to acknowledge and give my best gratitude to my supervisor, dr. M.N. Koeva (Mila), dr.ir. F. Vahdatikhaki (Farid), and Prof. D. Petrova-Antonova (Desi), who helped me from the beginning and made this work possible. Your guidance, advance, and feedback have carried me through all the stages of composing my thesis, and I can finally present you this. I would also like to thank dr. M. Kuffer (Monika) and Prof.dr. R.V. Sliuzas (Richard) for your suggestions and comments during the process.

I would like to give special thanks to my parents, Djoni Ismanto and Erry Makonda, for your continuous support and understanding through all my life stages. Without you, I will not be able to achieve any of this. I will always try to make you proud. I would also like to mention Chibi, my cat. Thanks for being the cutest cat ever and accompanying me since my bachelor years!

I would also like to give my warmest thanks to my friends, Wiyanda, Maul, Elpha, Nivi, Lynette, Diana, Mahnoor, Sahara, Tsaqif, and Bryan. Thank you for making me feel like Enschede is my "home-away-from-home". During the covid times, I would feel super lonely, depressed, and sad if I did not spend most of my time with you guys. I guess Enschede is an exceptional place for us.

Finally, I would like to thank Allah for letting me through all the difficulties. I may not be the most religious person, but I will keep trusting You for my future. Thank you for all your blessings.

Lastly, I would like to thank myself for not giving up when times are tough. Keep reminding me of the meaning of enough and let go.

*-After the rain, instead of sadness, a happy end-*

Enschede,

2022

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF APPENDICES

# 1. INTRODUCTION

## 1.1. Background and justification

Pedestrian-friendly environments are essential in creating healthy and productive communities (Battista & Manaugh, 2019). The walkable city concept is an extent to which the built environment motivates people to walk by providing comforting pedestrian ways, linking people to various amenities in a fair amount of time and effort (Southworth, 2005). Research by (Turoń et al., 2017) stated that one of the options for implementing sustainable mobility is the notion of a walkable city. The higher walkability between neighbourhoods and their amenities may reduce the need to use private transportation, producing lower carbon emissions, and reducing people's health risks caused by lack of activities (Erickson and Jennings, 2017; Landrigan, 2017).

People in many large cities worldwide, including Sofia, are more likely to use private vehicles, resulting in high particulate matter concentrations. The municipality of Sofia intends to tackle the air pollution issue by working towards improved walkability. Thus, the municipality of Sofia, the European Bank for Reconstruction and Development (EBRD) and ARUP have created an initiative called Green City Action Plan. This initiative aims to create sustainable transportation in Sofia by promoting walking and improving pedestrian infrastructures (Municipality of Sofia et al., 2020). Therefore, by working on this goal, Sofia Municipality has the opportunity to improve its walkability, thus reducing air pollution.


Figure 1. Illustration of pedestrian in Sofia (source: google street view)

Improving walkability can be accomplished by (1) more consistent and strategic placement of amenities (e.g., shopping centres, restaurants, schools, etc.), (2) improved transport options, and (3) improving the urban design along the street (e.g., urban greeneries) (Zhang and Mu, 2019). Assigning a strategic location for amenities may improve walkability since the people may efficiently access a variety of essential amenities around them (Baobeid et al., 2021). Thus, it lowers their need for cars, enhances liveability, and suggests lower BMI by reducing people's dependency on automobiles (Baobeid et al., 2021).

According to the study by (Habibian and Hosseinzadeh, 2018), the first attempt to quantify walkability was developed by Frank et al., in 2005. The walkability index by Frank et al. (2005) is a score-based measure that considers design, diversity, and density. It was done by giving values accordingly to design, diversity, and density, based on their conditions (e.g., higher values for good design and lower values for a bad design). These values are standardized and combined to find the average to reflect the state of walkability (Frank et al., 2010).

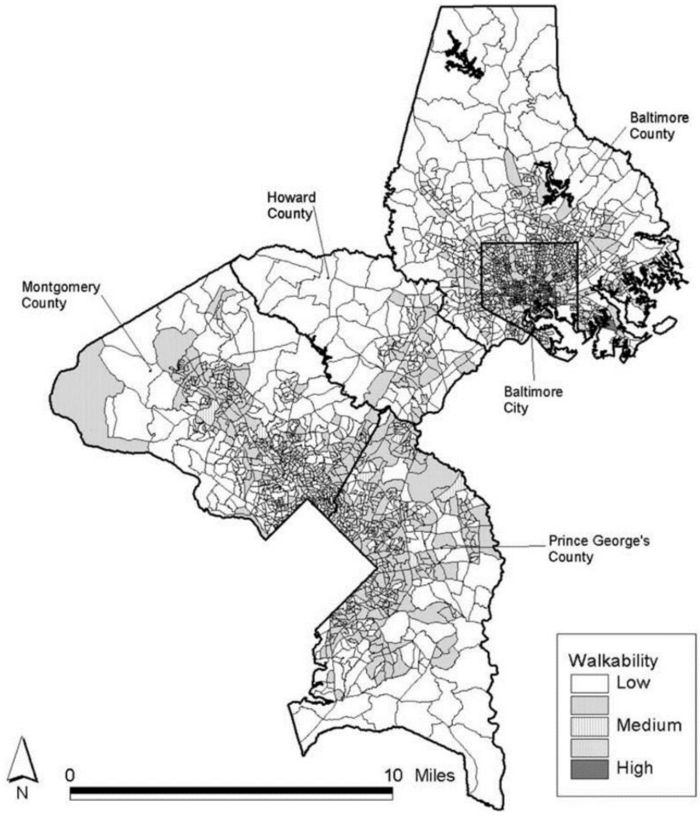



Figure 2. Distribution of Baltimore-Washington walkability measures by Frank et. al (2010)

## 1.2. Research problem

Urban planning is a fundamental discipline that enables walkability improvement through careful and sustainable urban development planning. It generally manages and controls cities' physical development and growth process (Fainstein, 2005; Islam, 2011). Therefore, walkability planning is essential because it can influence how people move and predict how they will move in the future (Masoumzadeh & Pendar, 2019). Researchers have concluded that walkability is a valid assessment indicator that positively impacts urban design (Abastante et al., 2020; Gilderbloom et al., 2015; Habibian and Hosseinzadeh, 2018). Although various studies have demonstrated that walkability can be utilized as one of the criteria to develop a master plan, its actual implementation is still limited to being an assessment indicator (Masoumzadeh and Pendar, 2019). This limited implementation leaves us with an issue of walkability as something "nice to know about" rather than a "must-have" criterion. Meanwhile, walkability is also considered one of the driving factors for future sustainable urban planning (Erickson & Jennings, 2017; Rees, 2003). In order to address this issue, walkability should be integrated into the mainstream urban design process.

In recent years, the generative design approach has gained popularity in the urban design community. In generative design, optimization methods are integrated with relevant parametric models to semiautomatically generate near-optimum solutions that meet a set of pre-defined criteria. Generative design can operate as a platform for dialogues between stakeholders to make better decisions by generating multiple near-optimal alternatives (GATE and Sofia University, 2019; Zhang and Liu, 2019). A generative design approach can also be implemented for a walkability-optimal master plan. In the generative design domain, to our knowledge, limited research has been done to assess walkability (Indraprastha & Pranata Putra, 2019; Leong Yee, 2019; Rakha & Reinhart, 2012). The integration between walkability and parametric modelling for generative design was done directly in a parametric modelling environment (e.g., Grasshopper, UMI) and based on the Walkscore method. The measurement of walkability was done by defining residential buildings as the starting nodes, amenities as ending nodes, and street networks as the path. However, to the best of our knowledge, in the current state-of-art, the generative design approach for walkability only considers the distance from residential buildings to amenities indicator.

Studies in recent years have proven that the comfort dimension in the walkable city concept is essential. Providing a sense of comfort to people may influence overall perceptions of walkability and potentially contribute to their walking behaviour (Koo et al., 2022). Comfort is provided by the urban design characteristics such as urban greeneries as one of the street's "internal" elements. Urban greeneries play a significant part in walkable environments since they generate shade and greenery, which may increase people's willingness to walk by providing a sense of comfort (Ulmer et al., 2016). In addition, the distance to amenities could also be seen as one of the highly associated indicators for comfort dimensions in terms of walkability. A closer distance to amenities could make the users more comfortable since they could carry their errands with a fair amount of time or less effort (al Shammas and Escobar, 2019; Irafany et al., 2020). Thus, distance to amenities could be integrated with urban greeneries to represent the comfort dimension in a generative design approach for walkability.

Other than that, we cannot overlook the fact that walkability is highly personal. Daily activities, urban settings, and cultural backgrounds are things that shape each individual's perceived walkability. Moreover, when evaluating walkability, integration between different indicators is usually done. Nevertheless, it is nearly impossible to generalise which indicator is more important to people. Arvidsson et al. (2012) also discovered that people with different backgrounds have different perspectives on walkability. Therefore, planning a walkable city should not only be based on quantitative analysis but is also essential to incorporate the human perspective.

In summary, the integration between walkability and generative design has the ability to address the limited implementation of walkability in urban planning. However, this approach is mainly defined through the distance to amenities. This simplified definition of walkability ignored other aspects to define walkability: (1) "comfort" that influences people's willingness to walk, (2) subjective aspect to represent an individual's perceived walkability. Therefore, a more comprehensive approach is needed to capture those aspects of walkability. Furthermore, this study will propose a workflow for strategically placing amenities and urban greeneries with a human perspective to create walkability-optimal-urban plans. In the future, the proposed workflow could also be helpful for urban planners, urban designers, and architects to develop a more complicated parametric model and eventually contribute to the decision-making process.

## 1.3. Research objectives

### 1.3.1. Main objective

The main objective of this thesis is to develop a workflow of walkability-optimal-urban-plans considering comfort dimensions through strategic placement of amenities and urban greeneries.

#### 1.3.2. Sub objectives

1. To review how walkability assessment has been done
2. To develop a workflow based on the integration of comfort dimension indicators
3. To implement the proposed workflow as a case study

#### 1.3.3. Research questions

Sub-objective 1 (SO1):

1. What kind of method and input data is needed to quantify walkability?
2. How to integrate walkability with parametric modelling for generative design?

Sub-objective 2 (SO2):

1. What method is used to quantify distance to amenities?
2. What method is used to quantify urban greeneries indicators?
3. What method is used to integrate chosen indicators with a human perspective?

Sub-objective 3 (SO3):

1. How do people perceive the study's chosen indicators?
2. How much does the implementation of the proposed workflow improve the walkability?
3. How does implementing the proposed workflow in different locations correspond with people's walking experience?

### 1.4. Anticipated results

Table 1 represents the anticipated results based on the study objectives. It will be elaborated further in the overall approach section.

Table 1. Anticipated Results

| Sub-Objective | | Anticipated Results |
|---|---|---|
| 1 | To review how walkability assessment has been done | - Lists of input data<br>- Methods to quantify walkability<br>- Method to integrate walkability with parametric modelling |
| 2 | To develop a workflow based on the integration of comfort dimension indicators | - Method to quantify distance to amenities<br>- Method to quantify urban greeneries<br>- Method to integrate both indicators for walkability based on human perspective<br>- Proposed workflow |
| 3 | To implement the proposed workflow as a case study | - Human perspective of walkability in the chosen study area<br>- Walkability-optimal-urban-plans |

| | | |
|---|---|---|
| | | - Comparison between the proposed workflow's baseline walkscore and people's walking experience |

### 1.5. Conceptual framework

Figure 3 represents the central concept that is being used for the study. Distance to amenities and urban greeneries are the chosen indicators to represent comfort in terms of walkability. These indicators would then be incorporated into a parametric modelling approach for optimization. Ultimately, walkability-optimal urban plans will be generated based on comfort dimensions.

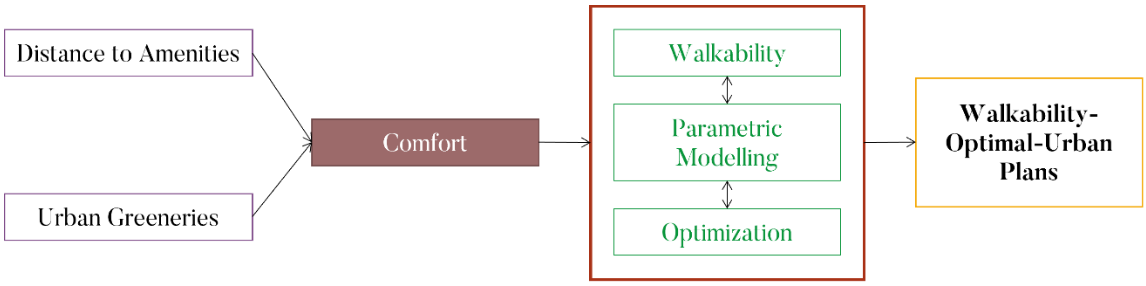



Figure 3. Conceptual Framework

### 1.6. Study area and available data-set

The chosen study area of this research is within the city of Sofia, precisely one of the neighbourhoods called Krastova Vada, as shown in Figure 4, due to data availability. Most of the available data sets were provided by Sofiaplan, which is a municipal enterprise responsible for the spatial and strategic planning of Sofia


Figure 4. Aerial image of Krastova Vada (source: iSofMap)

Municipality and GIS-Sofia. The data is confidential and used by the GATE Institute of Sofia University only for research purposes such as those of this thesis.

Table 2 shows the overview of the available data set. The complete data sets of the Krastova Vada will be available in Appendix 1.

Table 2. Overview of Available Dataset

| Data Input | Format | Source | Details |
|---|---|---|---|
| Buildings Vector File (commercial, education, healthcare, residential, industrial, etc.) | .shp | Sofiaplan | Vector of buildings in Krastova Vada (incl. footprint, height, number of floors, and some specifications) |
| Street Network Vector File (main road, pedestrian, bus lines) | .shp | Sofiaplan | Polyline of street network with some specification |
| Amenities Vector File (green spaces, public transport stops) | .shp | Sofiaplan | Vector of amenities located in Krastova Vada |
| Terrain and Waterbodies Vector File | .shp | Sofiaplan | Polyline of terrain elevation and water bodies in Krastova Vada |
| Orthophoto (30 cm) based on digital aerial data acquisition | .tif | GIS-Sofia | Raster image of Krastova Vada with 30 cm accuracy |

Krastova Vada neighbourhood is increasingly establishing itself as a desirable location for constructing single-family homes, gated communities, and, to a lesser extent, industrial and commercial facilities. The development of main roads, namely Todor Kableshkov Blvd. from Gotse Delchev to Vitosha, will significantly improve the transportation infrastructure in the following years. Therefore, with this quarter's vast development, careful planning is needed to align the built environment with Sofia Green Plan Initiatives.

### 1.7. Thesis structure

This thesis consists of five parts:

Chapter 1, introduction, explains the backgrounds and justifications, research problem, research gap, objectives and research questions, anticipated results, conceptual framework, and study area of this thesis.

Chapter 2, literature review, related to walkability assessment, including methods, input data, and indicators needed for parametric modelling environment. Moreover, the relationship between walkability and distance between amenities to the residential building are described.

Chapter 3, methodology, explains the appropriate method used in this study to achieve objectives.

Chapter 4, proposed workflow, explains the proposed workflow in general due to following the methodology.

Chapter 5, implementation of the workflow, presents the implementation of the proposed workflow in the study area to test the functionality.

Chapter 6, results, presents the result of workflow implementation in from of walkability-optimal-urban-plans.

Chapter 7, discussion, discusses and elaborates on the results in line with the study's objective and limitations.

Chapter 8, conclusion and recommendation, is related to the summary of the whole study process and how this study has addressed the objective. This chapter will also recommend for future studies.

Chapter 9, ethical consideration, outlines the ethical consideration which confirms the data confidentiality and informed consent from the survey.

### 1.8. Summary

The background of the study, research problem, and gap, are explained in this chapter. Based on that, the research objectives are defined with anticipated results, conceptual framework, and the study area. The structure of this thesis is outlined in this chapter.

# 2. LITERATURE REVIEW

## 2.1. Walkability Assessment

Walkability assessment that has been done up until now has shown the utilization of index. In the process of quantifying walkability, different components (design, diversity, density) have been combined to determine a neighbourhood's "walkability level". These components have different measurement units, making the index method preferable. For instance, the walkability assessment by Frank et al. (2010) was done by creating a walkability index that consists of four components: residential density, retail floor area ratio, intersection density, and land-use mix. These components are given a normalized Z value and combined to get the walkability level. The research concluded that the walkability index is suitable for looking into the relationship between urban form and various outcomes, identifying priority locations for transportation improvements and redevelopment, and tracking changes in urban form through time.

The walkability index was also developed using other criteria and combinations. Glazier et al. (2014) measured walkability in Toronto, Canada, using population density, housing density, roadway connectivity, and retail locations and services within a 10-minute walk of census tract centroids (Glazier et al., 2014). Aside from that, Walkscore (available at www.walkscore.com) is another extensively used index for walkability assessment (Habibian and Hosseinzadeh, 2018). Walkscore is a North American way to quantify walkability that implements Dijkstra's algorithm. It is a metric that recognizes and rewards initiatives at the building and street level by finding the shortest path to get to amenities from the residential and the availability of the street network (Jakubiec et al., 2013).

Most of the walkability assessments mentioned above are done in the GIS domain. Despite that, some researchers also try incorporating walkability assessments into the mainstream design process called generative design (see 2.3). Integrating walkability with the generative design should be an advantage. Since they can provide different scenarios based on evaluating near-optimum solutions, thus act as a discussion tool for the stakeholders in the decision-making process. However, the main limitation of walkability in the generative design domain is the limited utilization of indicators to represent walkability. To the best of our knowledge, it is only based on one indicator: distance to amenities.

Research by Koo et al. (2022) has tried to assess walkability based on the comfort in the GIS domain. The research aimed to find the relationship between walkability through "Walkscore" data and comfort indicators, such as urban greeneries, the presence of street furniture, and noise. The research has resulted that "comfort" can influence people's overall perceptions of walkability, thus potentially contributing to their walking behaviour. There are several indicators known to represent the comfort dimension. Since we are aiming to develop walkability-optimal-urban plans based on generative design, the optimum value of chosen indicator should be available. As shown in Table 3, only two indicators with their optimal value were identified regarding walkability: urban greeneries and distance to amenities.

Table 3. Comfort dimension indicators

| **Indicators** | **Identified Optimal Value** | **Source** |
|---|---|---|
| Urban Greeneries | Yes | (Lai et al., 2022) |
| Distance to Amenities | Yes | (Irafany et al., 2020; Rakha and Reinhart, 2012) |

| | | |
|---|---|---|
| Noise | No | (Franěk et al., 2018) |
| Street Furniture | No | (Galal Ahmed and Alipour, 2021) |
| Shading | No | (al Shammas and Escobar, 2019; Galal et al., 2020) |
| Visual enclosure | No | (Zhu et al., 2019) |

As seen on Table 3, the distance to amenities indicator could also represent the comfort factor. A study by Irafany et al. (2020) tried to measure the comfort level of the pedestrian street through a pedestrian comfort index. The study's pedestrian comfort index has resulted in the notable importance of "distance to amenities" as one of the comfort factors of walkability since it represents street connectivity. This result also aligns with al Shammas & Escobar (2019) study, which concludes that a closer distance to amenities makes the pedestrians feel more comfortable since they can follow their desired activities in a fair amount of time and effort. (Urban greeneries will be elaborated on 2.4)

Walkability assessments are also made within the qualitative domain. Researchers are motivated to assess walkability based on the human perspective. Other than the built environment, people's daily activities, cultural background, and even their neighbour's behaviour could shape people's perceived walkability (Battista and Manaugh, 2019). Research by Zhang and Mu (2019) proposed a walkability assessment based on people's perceived importance of walkability. The research was done by spreading a questionnaire to get people's perceived importance of different walkability factors. This research managed to capture subjective and objective characteristics of the pedestrian street condition. Another research by Arvidsson et al. (2012) discovered that people with different cultural backgrounds and urban settings have a different perception of walkability, thus supporting the need for human perspective incorporation on walkability assessment.

In summary, through this literature review on walkability assessment, it has been concluded that (1) walkability assessment utilizes the index method, (2) walkability assessment based on generative design is limited to distance to amenities, (3) walkability assessment can also be done based on "comfort" dimension, and (4) human perspective is essential to include in walkability assessment.

## 2.2. Walkscore

Walkscore is a North American way to quantify walkability that implements Dijkstra's algorithm. It is a freely accessible website initially created for real estate applications and is used to estimate the number of local walking destinations or facilities (see Figure 5). Walkscore was created to efficiently identify nearby amenities and calculate neighbourhood walkability scores (Walk Score®, 2022).

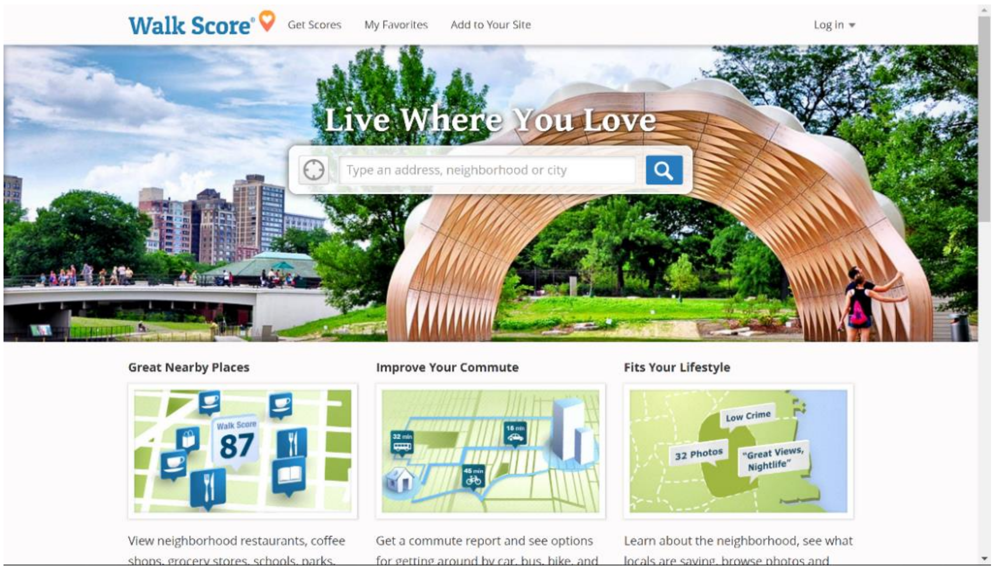



Figure 5. Walkscore interface (www.walkscore.com)

Walkscore is a metric that recognizes and rewards initiatives at the building and street level by finding the shortest path to get to amenities from the residential building and the availability of the street network (Jakubiec et al., 2013). Hence, the data input for the Walkscore method could be determined as such; street network, residential buildings, and lists of amenities. The score is earned depending on the street length (distance) from residential to amenities that are normalized from 0 to 100. The developer's algorithm divided the scores into five classes, as in Table 4.

Table 4. Walkscore Category (source: www.walkscore.com)

| Score | Category |
|---|---|
| 90 – 100 | **Walkers' Paradise**<br>(Daily activities do not require the use of a car) |
| 70 – 90 | **Very Walkable**<br>(The majority of activities may be completed on foot) |
| 50 – 70 | **Somewhat Walkable**<br>(Some activities are possible to complete on foot) |
| 25 – 50 | **Not Walkable**<br>(Most activities demand the use of a car) |
| 0 – 25 | **Car-dependent**<br>(Almost all activities demand the use of a car) |

The Walkscore developers did not specifically define the category of amenities that applies to the Walkscore calculation itself. However, based on previous research (Carr et al., 2011; Koo et al., 2022; Koohsari et al., 2021; Rakha and Reinhart, 2012) and by Walkscore itself (Walk Score®, 2022), the category of amenities that are commonly used for Walkscore calculation has been retrieved. The commonly used category of amenities are as follows; Grocery Shop, Food Vendors (Restaurant, Café, Bars), School (Education), Office, Parks, Health Facility, Retails (Clothing, Hardware, Music, Book), Entertainment (Sports Club, Cinema, Libraries), and Public Transport Hub.

The Walkscore method has also been validated in previous research. One of the research projects aims to compare Walkscore to scientifically measured (GIS) walkable amenities in the state of Rhode Island to see how reliable and valid it is as a proxy for gauging access to local neighbourhood amenities. The study of Carr et al. (2011) backed Walkscore as a legitimate and trustworthy measure for determining locations with a high density of walkable facilities. Thus, the Walkscore can be implemented in future environmental studies related to the physical activity of urban planning. Apart from that, Walkscore might be used as an intervention tool to educate participants about their existing access to surrounding recreational facilities such as parks and fitness centres. Because of its ability to visually depict surrounding walkable amenities (Carr et al., 2011).

Another research by Koohsari et al. (2021) investigates the links between Walkscore and perceived walkable environmental qualities in Japan's ultra-high-density places. The 4-point Likert scale (strongly agree, slightly agree, somewhat disagree, and strongly disagree) was utilized to investigate the perceived walkability. It is based on the cross-sectional data gathered to see any social or urban design links between passive behaviour and physical activity among middle-aged Japanese. Meanwhile, the investigated walkability indicators are population density, shops access, public transport, sidewalks, bike lanes, access to recreational facilities, aesthetics, traffic safety, and safety from crime. The study concluded that population density, access to shops and recreational facilities, public transport, and the availability of sidewalks and bike lanes are strongly connected with Walkscore (Koohsari et al., 2021).

In summary, the Walkscore method is one of the walkability indexes that can be utilized for walkability assessment. The flexibility of the Walkscore method can also be an advantage when developing a walkability assessment in a different domain, namely generative design, as the primary data input is multi-dimensional and consists of three components: (1) street network, (2) residential buildings, and (3) lists of amenities. Moreover, the Walkscore method is also not limited to these components, meaning that we could still determine what types of amenities we want to include and have the freedom to add different components when assessing walkability.

## 2.3. Parametric modelling

In order to implement the generative design approach for walkability, building a parametric model is necessary. The research focused on building a parametric model at a neighbourhood level up to now shows the usage of visual programming tools, namely Grasshopper (Canadinc et al., 2020; Mousiadis and Mengana, 2016; Rakha and Reinhart, 2012; Wang et al., 2020). Grasshopper is an open-license plug-in available within Rhinoceros (see Figure 6). Generative design in Grasshopper can optimize the design through changing features or parameters related to and defining constraints. Walkability assessment based on the Walkscore

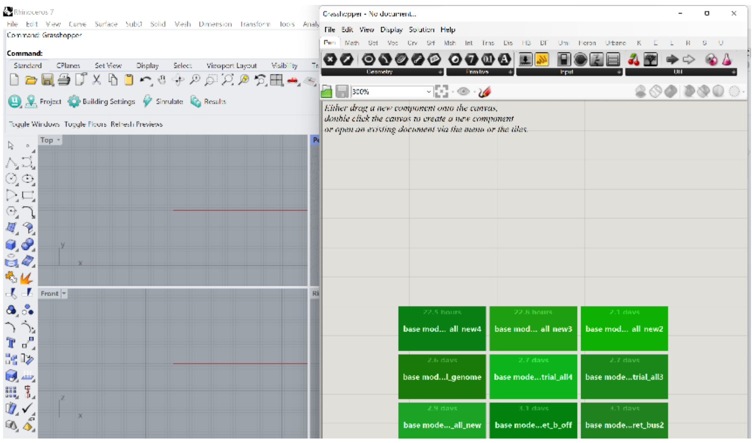


Figure 6. Rhinoceros and Grasshopper Interface

method and generative design can be conducted directly at Grasshopper itself using the extension of shortestWalk and Galapagos add-ons (available freely at https://www.food4rhino.com/).

ShortestWalk plug-in is a tool that calculates the shortest distance from start point to endpoints in a network (Piacentino, 2011). It is based on the A* search algorithm and a topology calculator. A* is an informed search algorithm-an extension of Dijkstra's Algorithm, which means it starts from a particular starting node in a graph and seeks to discover the shortest path to the provided objective node (Russel and Norvig, 2020).

$$f(n) = g(n) + h(n)$$

A* specifically selects the minimum path $f(n)$. As seen in the formula above, where $(n)$ is the next node on the path, $g(n)$ is the distance from a node to node, and $h(n)$ is a heuristic function that calculates the shortest path from starting node to the objective (Russel and Norvig, 2020).

So far, studies in the generative design domain for walkability have shown promising results by increasing walkability. However, aside from only based on the distance to amenities, they did not define what type of amenities they placed. Research by Rakha and Reinhart (2012) developed a workflow for urban analysis using Rhinoceros and Grasshopper using the Walkscore method. The study estimates the walkability of three urban form options and applies evolutionary algorithms to optimize walkability through land-use allocation. The evaluation was conducted by creating street grids from available data and linking them to a Grasshopper Walkscore definition, assuming each block comprises amenities and residential units. The shortest walking distance to amenities is used to determine the score. The study's land-use allocation was done using the Genetic Algorithm (GA). A GA begins with randomly selected sites for amenities (genes), with parent zoning solutions (chromosomes) generated from a restricted search space to establish an initial population. The positioning of genes inside each chromosome generates a Walkscore. The method will result in other generations being tested and reselected, and the chromosomes within the final populations will be near-optimal after many generations. Their study concluded that the workflow promotes the production of sustainable urban form, which makes it significant. The workflow also complements current urban modelling improvements as it can examine urban metrics using placeholders (Rakha and Reinhart, 2012).

Another research by Indraprastha & Pranata Putra (2019) proposes a parametric and data-informed strategy using the walkscore method, based on the walkability concept to improve urban analysis and decision-making. They stated that their approach might be utilized to assess many scenarios based on data-set combinations and rules via parametric and iterative solution development. Their study aims to find the most significant accessibility of each amenity by walking at 5 km/s and calculating the maximum distance between them compared to the distance to amenities based on the shortest walking time (in minutes). Within the implementation of the optimization approach, the simulation shows that when new amenities are located in the study area, their walkability score improved significantly from 57.9 to 92.3. The key conclusion of this study is that the methodology has the potential to be implemented as part of the tools used by policymakers and local governments to analyze and prepare for urban regeneration initiatives (Indraprastha and Pranata Putra, 2019).

In summary, the integration between walkability and parametric modelling can be done in visual programming tool. Building a parametric model from geospatial data is essential since generative design simulation can be done based on a parametric model. It is also essential to notice that the walkability assessment in the generative design domain is based on the development of the Walkscore method. The Walkscore method's utilisation in this domain is due to its flexibility and universal knowledge of this method since the GIS domain has extensively used it.

## 2.4. Comfort dimension and urban greeneries

The comfort dimension is one of the general dimensions in the walkability concept. The comfort dimension can be defined as the "street-level" elements that provide physical ease to pedestrian users through urban characteristics (e.g., trees, visual enclosure, street elements). Therefore, it has the ability to increase people's willingness to walk (Teshnehdel et al., 2020). A study by al Shammas & Escobar (2019) has developed a walkability index (WI) based on the comfort dimension in the GIS domain, which was represented by noise pollution, sunshade and other dimensions, namely, the proximity of destinations and street connectivity (accessibility). Their research claimed to have more dynamic WI since it could be computed at various times of the day and on various days of the year. The study factors were represented as shapefile format polygons with normalized values. Using the equation below, the WI of each component was computed.

$$WI = (WF1 \times NF1) + (WF2 \times NF2) + (WF3 \times NF3) + (WF4 \times NF4)$$

Where: *WI* is the walkability index, *WF* is the walkability factor normalized value, and *NF* is the weightage value of a particular factor. The study concluded that they had created a complex *WI* that was thematically rich and factored in dynamic comfort aspects (al Shammas and Escobar, 2019).

Urban greeneries have been identified as one of the indicators to represent the comfort dimension (Koo et al., 2022; Lai et al., 2022; Ulmer et al., 2016). People's appreciation of urban greenery has been found to be strongly correlated with its presence. From an aesthetic and comfort standpoint, pedestrian users prefer to walk on the streets with greenery than those without (Klemm et al., 2015). Research by Lai et al. (2022) measured the relationship between urban greeneries, walkability, and arterial stiffness. They applied the Normalized Difference Vegetation Index (NDVI), an objective index of relative overall greenness associated with vegetation cover from remotely sensed data. The NDVI measures the distinct spectral fingerprints of chlorophyll in healthy plants and indicates green quality and intensity. In the research, residential walkability and greenness are inversely related to arterial stiffness, with greenness's positive benefits (approximately 0.4 NDVI) being significant in the highest walkability quartile. In addition, the greenness' positive benefits have declined after 0.4 NDVI up until 0.6 NDVI. Above 0.6 NDVI, the greenness had shown that they started to have a negative impact when associated with walkability. The research also concluded that the findings are beneficial to urban planners and designers who are working on creating healthy neighbourhoods with appropriate green space and a design that supports threshold levels of accessibility to essential services and attractions to encourage walking and physical exercise (Lai et al., 2022).

In summary, walkability assessment in the generative design domain needs other variety besides "distance to amenities", and the comfort dimension seems a good alternative. The assessment based on the comfort dimension can be represented by urban greeneries and distance to amenities to fill the current research gap. Thus, due to the flexibility of the Walkscore method, integrating these indicators for walkability assessment should be possible. The primary input data would consist of (1) street network, (2) residential buildings, (3) amenities, and (4) urban greeneries.

## 2.5. Summary

This chapter contains the relevant literature study. A literature review is done to gain more profound knowledge about walkability assessments, analyse the current research gap, and determine the relevant indicators, methods and data input.

# 3. METHODOLOGY

## 3.1. Overall approach

To meet the objectives of this research, an overview of the research methodology has been developed, presented inFigure 7.

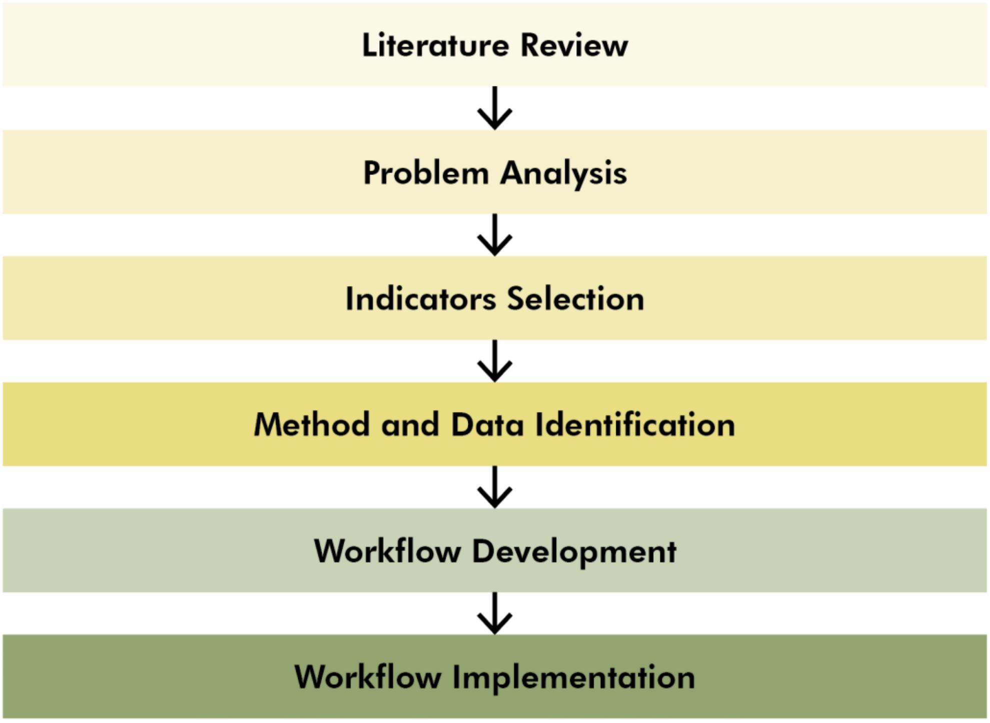



Figure 7. Overview of research methodology

The literature review was done mainly to compose a background knowledge about how walkability assessment has been done in previous research, including what type of methods are used, the integration between walkability and generative design, what type of indicator is used, as well as what another research has been done in the generative design domain. Then, after having a profound knowledge regarding walkability assessment, including the limitation in the current state-of-art, this part resulted in identifying a relevant research gap in the domain.

Following the research gap identification, relevant indicators, methods, and data input were identified. This was the starting point of developing the workflow. Indicators, methods, and data input were also identified by determining the requirements for integrating walkability with generative design and what may be incorporated as an additional component when developing the workflow. The chosen indicators' optimum value regarding walkability must be identified because the generative design aims to find near-optimal solutions. In addition, the indicators selected were affecting the type of data used as an input and must be able to be integrated with the chosen walkability assessment method. The walkability assessment method chosen is a quantitative analysis. However, the available method identified for integrating different indicators needs to incorporate a human perspective. It was also identified that the human perspective is found to be essential in the problem analysis phase. This qualitative aspect must be considered to comply with the "personal" aspect of walkability. Thus, the proposed workflow should combine both quantitative and qualitative analysis.

After the proposed workflow was developed, it was implemented in an appropriate environment (e.g., Grasshopper). In order to test the functionality of the proposed workflow, a case study was conducted in the study area of Krastova Vada, Sofia. Aside from that, implementing the proposed workflow acts as a validation tool since it presents how the workflow is executed. The walking preference survey was conducted in Bulgarian using Google Form. The survey was done to get the information input on how people perceived walkability in Sofia to be integrated later. At the same time, the relevant geospatial data representing the walkability component of each indicator were imported into a visual programming tool to generate a parametric model. Then, the walkability assessment method of each indicator was implemented. These indicators were then integrated along with qualitative data (human perspective) from the survey to generate the base walkability score. The generative design simulation was done to find the near-optimum solutions with a walkability score as the objective function. Whilst the decision variable would correspond with the chosen indicator (e.g., placement of amenities and urban greeneries). The result of the implementation should be walkability-optimal urban plans for Krastova Vada, Sofia.

Another validation of the proposed workflow is also done. The proposed workflow is also implemented-in another location in Sofia. Then, the base walkability score from the main study area and the second neighbourhood was compared with its people's walking experience. The comparison was made to check whether the proposed workflow corresponds with the people's perceived walkability within the study area.

### 3.2. Summary

This chapter contains the appropriate method that will be used and developed to achieve this study's main objective and sub-objective. The overall approach summarises the method used in this research which was developed to achieve all objectives in this study.

# 4. PROPOSED WORKFLOW

This chapter describes the proposed workflow for strategic placement of amenities and urban greeneries with the human perspective that has been developed following the methodology. Figure 8 outlines the overview of the proposed workflow: (1) Pre-processing of geospatial data and definition of the green index, (2) Walkability and parametric model integration, (3) Human perspective incorporation, and (4) Generative design simulations.

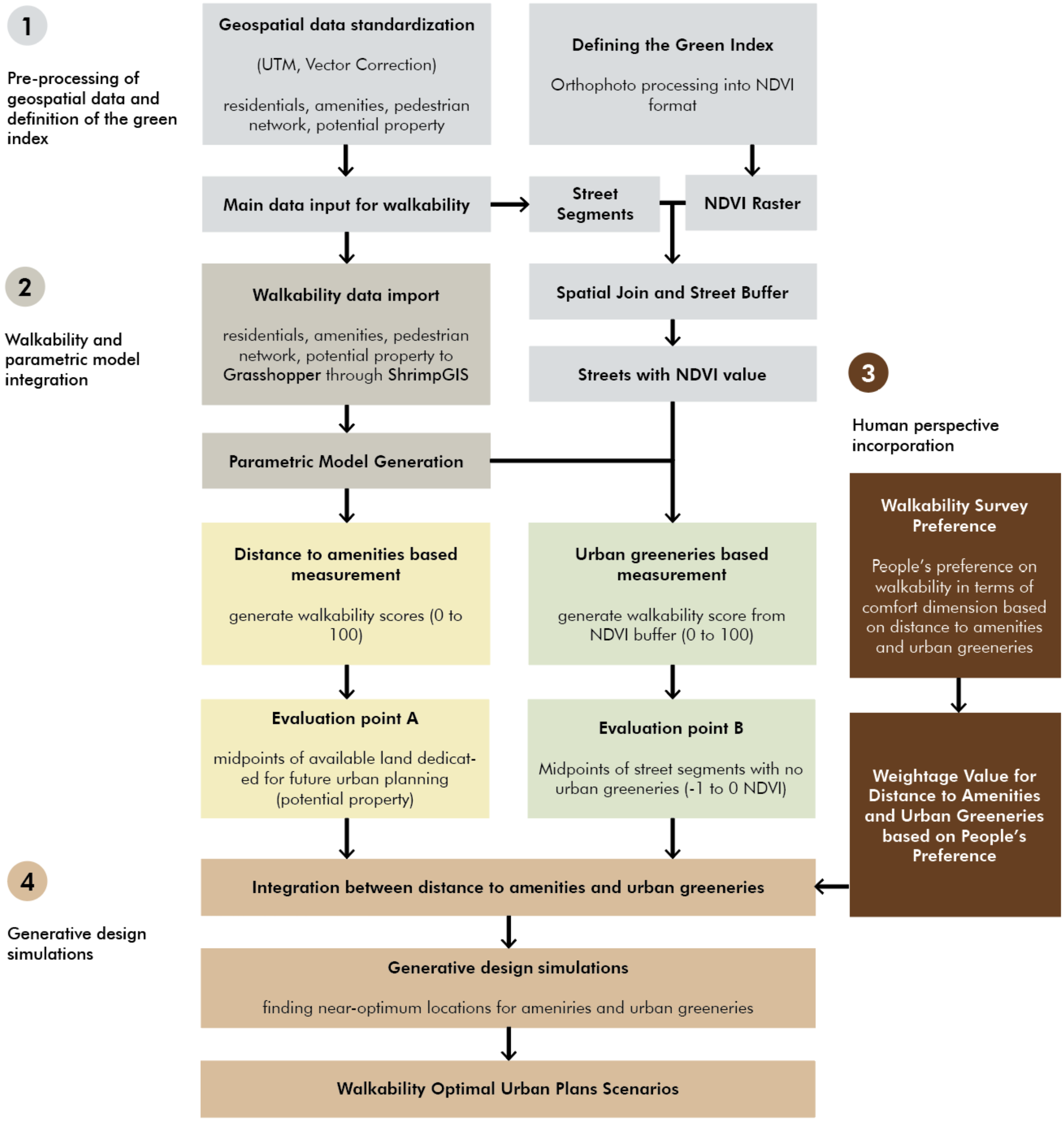



Figure 8. Overview of proposed workflow

## 4.1. Pre-processing of geospatial data and definition of the green index

The pre-processing of the geospatial data is done through the preparation of data by generalizing the shapefiles UTM into the same format (e.g., WGS84), filtering data, and vector correction to make it fit for use. The output of this preparation is used to generate the primary data input for walkability. Based on the literature review section, four parameters are needed for walkability assessment based on comfort: street network, residential buildings, amenities, and NDVI along the street. (1) Grocery shops, Food Vendors (Restaurant, Café, Bars), (2) School (Education), (3) Office, (4) Parks, (5) Health Facility, (6) Retails (Clothing, Hardware, Music, Book) and Entertainment (Sports Club, Cinema, Libraries), and (7) Public Transport Hub, has been defined as the category of amenities. However, the additional input parameter will be needed to run the generative design simulation to find a strategic placement for amenities and urban greeneries (see 4.2, Evaluation point A & B).

Meanwhile, the definition of the green index is based on the processing of the orthophoto file to an NDVI format, which is done based on the following equation:

$$NDVI = (IR - R)/(IR + R)$$

Where, *IR (Infrared Band)* is the electromagnetic spectrum in the near-infrared section and *R (Visible Band)* is the electromagnetic spectrum in the red section.

The NDVI raster was based on transforming a *.tif format (orthophoto) into a single-band data set that primarily represents vegetation density and vigour. According to ESRI (2021), the spectral reflectivity of solar radiation allows for monitoring of density and relative vigour of vegetation development utilizing differential reflection in the red (R) and infrared (IR) bands. The equation will result in a value range of -1 to 1. Low NDVI values (0.1 and lower) correspond to a barren rock, sand, or snow environments. Shrub and grassland have moderate values (0.2 to 0.3), while moderate and tropical rainforests have high values (0.6 to 0.8) (ESRI, 2021).

The generated NDVI raster should be combined with a 4 m buffer of street segments from the pedestrian network shapefiles. The combination should be conducted through spatial join to produce the street with an NDVI value. The 4 m buffer of the pedestrian network is chosen since we aim to only evaluate the urban greeneries along the street, and 4 m is the length of approximate tree coverings along the pedestrian (Teshnehdel et al., 2020). This buffer also includes the general extent of a pedestrian. The street with NDVI value will be utilized for the urban greeneries-based measurement.

## 4.2. Walkability and parametric model integration

The transformed primary data input from the previous part creates the parametric model by importing the relevant shapefiles to the parametric modelling software and transforming the data into a 3D model (e.g., polylines to brep). As frequently addressed in the scientific community, 3D modelling allows for an additional perspective that is not visible in a 2D model. Hence, the 3D model allows for a better interpretation of an idea by instantly enhancing viewers' perception of what they see. The 3D model in this study can assist the stakeholders in decision-making by providing a clear visualization of when a change occurred in the area of interest (Zhu et al., 2019).

Figure 9 presents the detailed proposed workflow for the parametric model creation. All the identified data from the previous part needs to be imported as a walkability data input. After that, these data inputs' base geometries can be modified as a 3D parametric model for visualization. Evaluation point A is used for the future placement of amenities, while the street with Evaluation point B is used for the placement of urban greeneries (see 4.3). In addition, sometimes, when imported to the appropriate visual programming environment (depending on the importing plug-ins), the data input should automatically be transformed into a parametric model component (e.g., street network from .shp to curves). The generated parametric model is used for both indicator measurements.

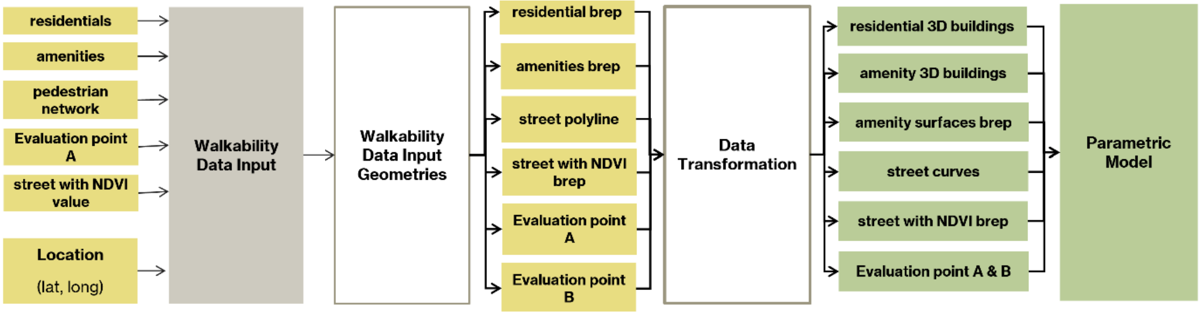



Figure 9. Proposed workflow for parametric model creation

#### 4.2.1. Distance to amenities

The distance to amenities indicator is based on the A* algorithm following the Walkscore method. As mentioned in 2.2, the A* algorithm aims to find the shortest distance from the starting node to the main objective with a heuristic function. The shortest distance was generated based on calculating the path lengths between nodes from the starting points to the main objective. In our case, we need to have three main data inputs: the residential midpoints (as a starting point), pedestrian network (as a path), and amenity midpoints (as the primary objective), as shown in Figure 10. After the A* algorithm is implemented, the list of distances from residential buildings to amenities is generated. The normalization should be done to get a range from 0 to 100 (a higher score means higher walkability) to match with the Walkscore method category, along with introducing reward and penalty. An immediate 100 score was given if the distance was shorter than 400 m, meaning that people could walk to the destination for less than 5 minutes. While an immediate 0 score was given if the distance was longer than 2400 m, meaning that people should walk to the destination for more than 30 minutes. The walkability score based on the distance to amenities indicator is the final result of this phase. The generated walkability score should then be incorporated into evaluation point A. This evaluation point A is the midpoint of available lands being evaluated and chosen as a new strategic placement of amenities in the generative design simulations.

The distance to amenities measurement was calculated individually based on each category of amenities, e.g., (walkability score for School, walkability score for Office) to avoid fallacy. For instance, if we consider all amenities as one, there is a possibility that a particular residential building would get a high walkability score even though it is only close to parks but far away from others like groceries or school. Before integrating both indicators, the walkability score from distance to amenities needs to be combined. It is also acknowledged that each amenities category has different importance from people's perspectives. Hence, the walkability score from each amenity needs to be weighted according to people's perspectives before being integrated.

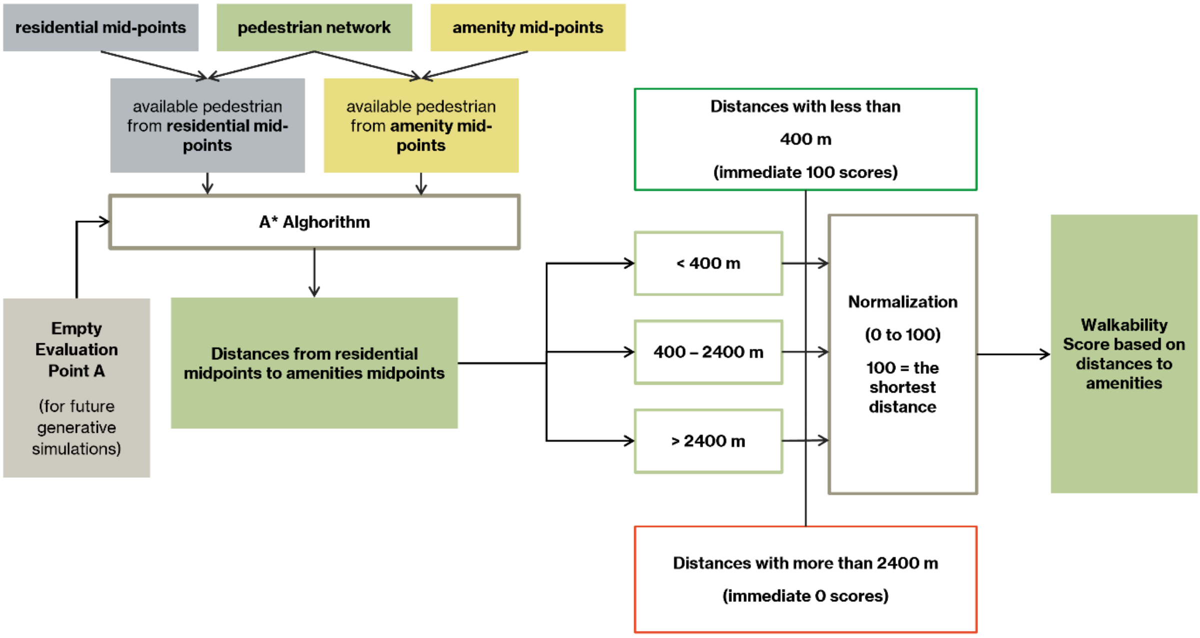



Figure 10. Proposed workflow for distance to amenities indicator

### 4.2.2. Urban greeneries

The urban greeneries-based measurement also produced a walkability score from 0 to 100, based on the street with the NDVI value file in the previous part. As shown in Figure 11, the NDVI needs to be normalized. In the normalization phase, the NDVI was divided into four different classes. The first class is

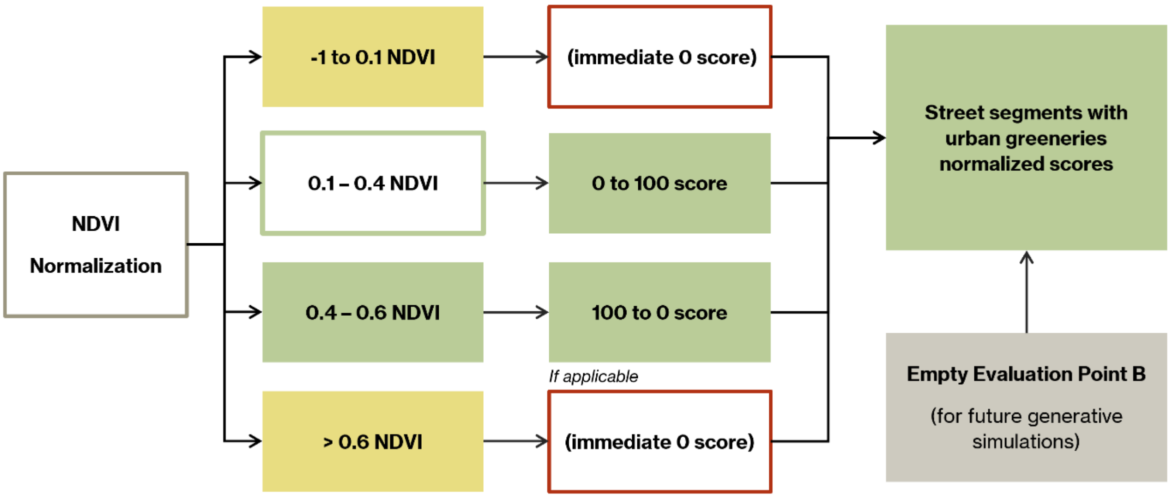



Figure 11. Proposed workflow for urban greeneries indicator

NDVI score within -1 to 0.1, where an immediate 0 score was given to this class. The 0 scores were given as the -1 to 0 NDVI indicates water, roads, building surfaces, and rocks, which means there are no urban greeneries. In the second class, the NDVI scores within 0.1 to 0.4 was normalized from 0 to 100 as the optimum value of greeneries for walkability is on the 0.4 NDVI. The third class is NDVI score within 0.4 to 0.6, which was normalized from 100 to 0 as the positive influence of NDVI on walkability starts declining at 0.4 NDVI. The fourth class is the NDVI score of more than 0.6, where an immediate 0 score penalty was given. The penalty was introduced within the fourth class as an NDVI score of more than 0.6 is negatively associated with walkability. The second and third class was normalized based on the following formula:

The formula for 0.1 – 0.4 NDVI Normalization:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

The formula for 0.4 – 0.6 NDVI Normalization:

$$X_{norm} = \frac{X - X_{max}}{X_{max} - X_{min}}$$

Where $X_{norm}$ is the normalized NDVI value, $X$ is the NDVI original value, $X_{min}$ is the minimum NDVI value, and $X_{max}$ is the maximum NDVI value.

The walkability score based on urban greeneries was then incorporated with evaluation point B. Evaluation point B is the midpoints of the street segments with low to no greeneries (-1 to 0.1 NDVI). The evaluation point B is needed as the evaluated street segments for strategic placement of urban greenery for generative design simulations.

### 4.3. Integration between indicators and human perspective

The integration between distance to amenities and urban greeneries-based measurement is essential as they both are indicators which represent comfort for walkability in this study. Currently, the available integration method in the field to represent comfort is based on the combination of each indicator's multiplication with their weightage value, which brings us to this formula:

$$WI = (WF1\ x\ NF1) + (WF2\ x\ NF2)$$

Where, *WI* is the integrated walkability score, *WF1* is the distance to amenities standardized score, *NF1* is the weight value of distance to amenities, *WF2* is the urban greeneries standardized score, and *NF2* is the weight value of urban greeneries.

There are some limitations to this method. (1) we do not know for sure whether the importance of one indicator over the other is the same in different contextual locations, (2) walkability is highly based on the individual's preference and cultural behaviour, (3) the loss of actual measurement units cannot be avoided and there is also a chance of overestimating or underestimating the walkability of the particular indicator. However, there are no other methods to combine different walkability indicators based on comfort that could address these limitations.

In order to address some of the limitations of the integration method, the proposed workflow included a walking preference survey which aims to get the people's preferences to determine the weightage value for each indicator on the formula. The walking preference survey consisted of four primary points which captured essential information input: (1) the people's profile (location, age group, transportation mode), (2) the people's walking experience, (3) the people's perceived importance between distance to amenities and urban greeneries, (4) the people's perceived importance between different amenities.

People's perceived walking experience is essential since it reflects the condition of their neighbourhood's "walkability level" qualitatively. This is why a crosstabulation between the Walking Experience and residential location should be composed. So that we could have the information on each residential location's current walkability based on the local people's perspective. This information was needed as a validation tool for the proposed workflow to see how much it corresponds with the actual condition. In addition, a walkable neighbourhood should promote people's willingness to walk by providing a walking infrastructure that gives them a good walking experience. Figure 12 illustrates the incorporation of the human perspective in the proposed workflow of the integration part.

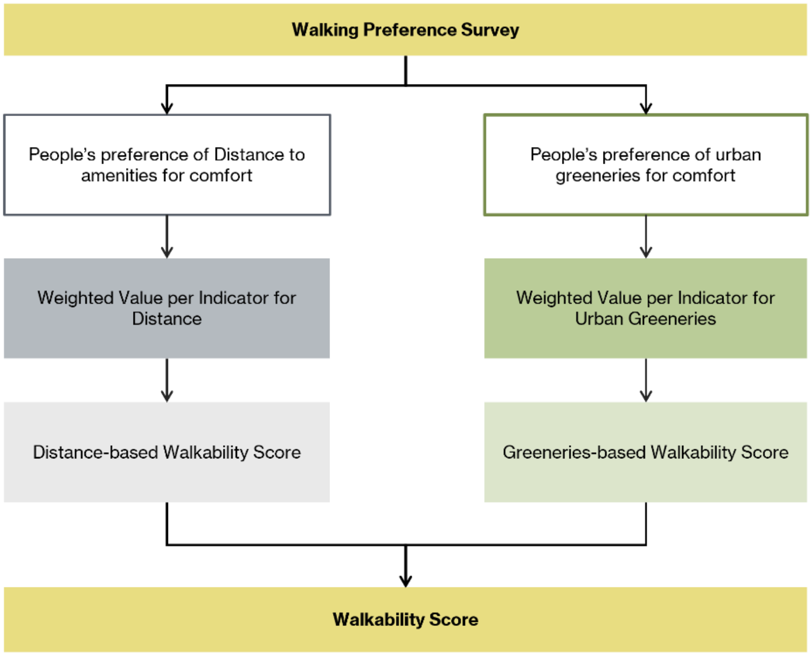



Figure 12. Proposed workflow for the integration between indicators and human perspective

### 4.4. Generative design simulations

The generative design consisted of two main components, the parametric model and optimization. The generative design simulation is based on integrating both indicators to generate near-optimum solutions for the strategic placement of amenities and urban greeneries. The objective function is the walkability score. These indicators should already be in the form of a parametric model component. The simulations should explore different solutions, e.g., locations for amenities and urban greeneries placement, when a generative design approach is applied to produce walkability-optimal urban plans to represent the optimization component.

In the generative design domain, the near-optimum solutions are generated through an optimization component which consists of a series of "the fittest selection". Presented in Figure 13, the optimization started with generating populations. Populations, in this case, are the solutions which the algorithm has evaluated before moving on to the following optimized result. The next part estimated objective functions, where the generated solutions in the previous part are estimated to meet certain objective functions. After that, these solutions should be ranked from the best to the worst. Thus, the fittest solutions then are selected depending on our objective functions and become "near-optimum solutions". The lists of near-optimum solutions will act as options to be discussed and developed as the implemented walkability optimal urban plans by the stakeholders.

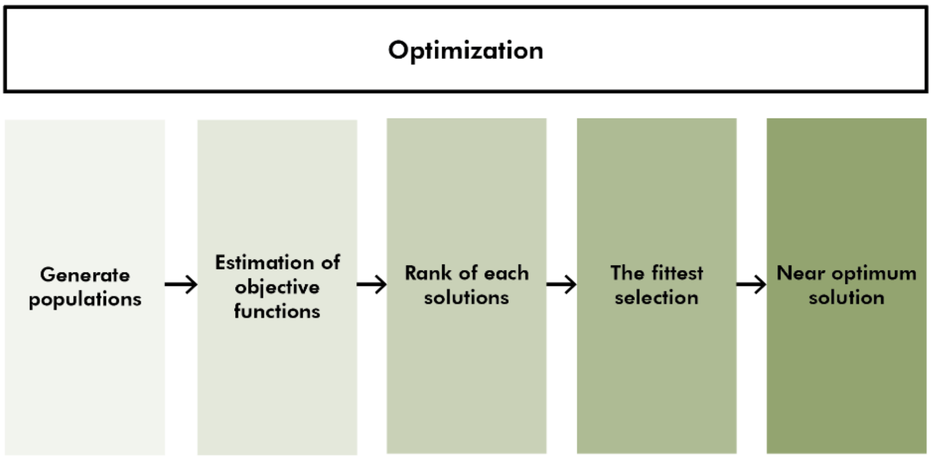


Figure 13. Optimization approach

### 4.5. Summary

This chapter discusses how the proposed workflow is working in general. The overall workflow has also been defined into four parts consisting of (1) Pre-processing of geospatial data and definition of the green index, (2) Walkability and parametric model integration, (3) Integration between indicators and human perspective, and (4) Generative design simulations.

# 5. IMPLEMENTATION OF THE WORKFLOW

This section presents the implementation of the workflow in the study area following the steps of the previous section (see Chapter 4), which started with the walking preference survey that served as the input information for the human perspective aspect, followed by the generation of the parametric model, along with indicators and human perspective integration for generative design simulation using the data and information input.

## 5.1. Walking preference survey

The walking preference survey was done within four weeks and gained 55 respondents. It was constructed following the four primary points mentioned in section 4.3. The walking preference survey was also translated into Bulgarian, as shown in Figure 14 since the target respondents are people of Sofia. The survey was created on the Google Form platform due to its familiarity with the people. The full version of the walking preference survey can be seen on the following link [https://forms.gle/qCSsgvbHiTyvnXik9](https://forms.gle/qCSsgvbHiTyvnXik9).

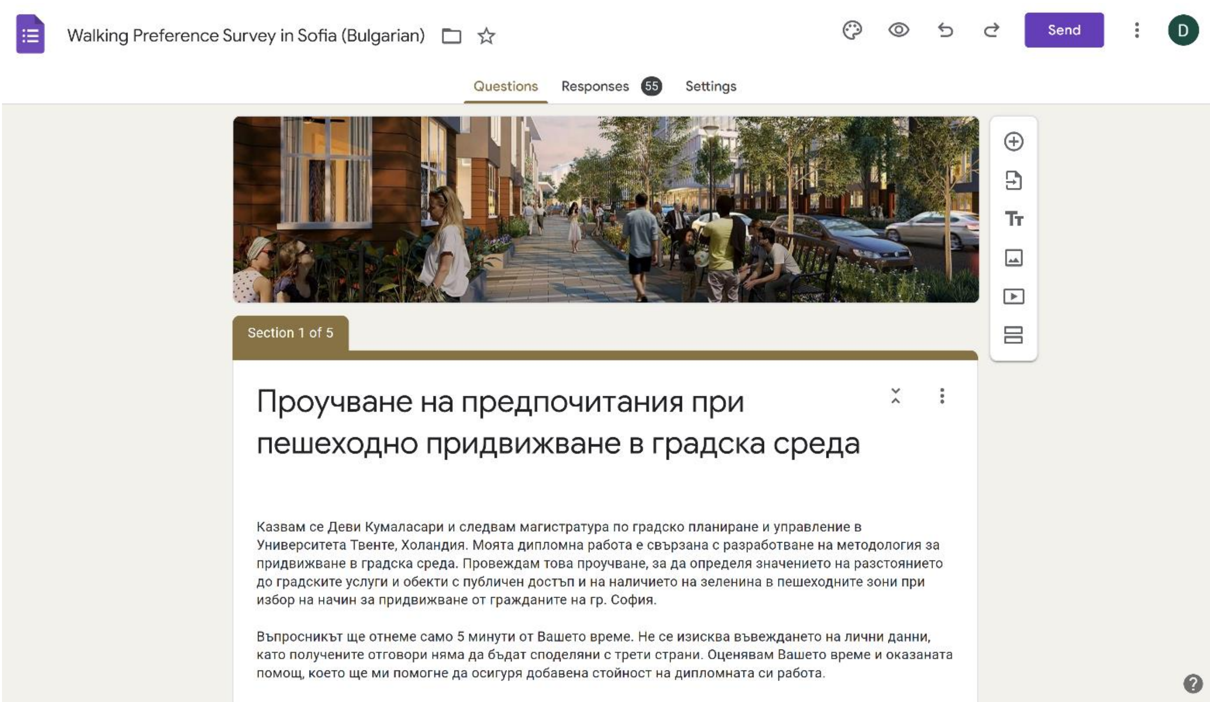



Figure 14. Screenshot of Walking preference survey in Sofia

### 5.1.1. Walking experience and residential location

This section mainly discussed the relationship between the people's walking experience and their residential location since the information input is essential for workflow validation. Detailed information regarding their preferred transportation mode and age group will be available in Annex 2. In the survey, people are asked to give their personal walking experience a score (0 being the worst and 10 being the best experience). On average, their personal walking experience is 5.39, which means it is not really bad but not really good (neutral experience). Presented in Table 5, the lowest walking experience is in the Ovcha Kupel (1.80% respondents), with a 0 score (worst experience). Apparently, the residential location in Ovcha Kupel is known to be far from the city centre and amenities.

In comparison, the highest walking experience (6.6) is in the Studentski district with 9.10% of respondents since the district is full of students without a private vehicle. Furthermore, respondents from the top 2 districts, Vitosha (21.80%) and Izgrev (12.70%) stated their walking experiences were 5.42 (neutral-to-good) and 6.57 (good). These two districts are known to be closer to the city centre with amenities around them and better pedestrian infrastructure with enough greenery compared to other districts.

Table 5. Crosstabulation between walking experience and residential location

| Residential Location | Walking Experience |
|---|---|
| Bankya | 5 |
| Izgrev | 6.57 |
| Krasna Polyana | 6.5 |
| Krasno Selo | 4.75 |
| Lozenets | 6 |
| Lyulin | 3 |
| Mladost | 5 |
| Oborishte | 6 |
| Ovcha Kupel | 0 |
| Pancharevo | 6 |
| Poduyane | 4.5 |
| Slatina | 3.5 |
| Studentski | 6.6 |
| Triaditsa | 5 |
| Vazrazhdane | 5 |
| Vitosha | 5.42 |
| **Average Score** | **5.39** |

#### 5.1.2. Walking preference

This section contains the people's walking preferences regarding distance to amenities and urban greeneries. The people were asked to score both indicators based on their importance (0 being not important and 10 being highly important). As shown in Table 6 below, people perceived distance to amenities as slightly higher (7.94) than urban greeneries (7.6) in terms of comfort. Hence, in the general condition, distance to amenities is perceived as a more critical indicator compared to urban greeneries for the comfort dimension. A similar result was also gained in the study of al Shammas & Escobar (2019), where they also sent out a questionnaire to walkability experts to weigh different walkability factors. The study resulted in a 7.94 mean of importance for accessibility and a 6.80 mean of importance for shading factor (greeneries) (al Shammas and Escobar, 2019). Furthermore, the weightage of distance to amenities should be slightly higher than the indicator of urban greeneries. Furthermore, a weightage value of 0.55 was given to the distance to amenities and a weightage value of 0.45 to the urban greeneries to address the people's preference for this aspect.

Table 6. Importance of distance to amenities and urban greeneries indicator

| Distance to Amenities | Urban Greeneries |
|---|---|
| 8 (Median) | 8 (Median) |
| 7.95 (Mean) | 7.6 (Mean) |

| 0.55 (Weighted value) | 0.45 (Weighted Value) |
|---|---|

However, when more specific questions were asked (e.g., how many minutes are you willing to walk within dense urban greeneries?), it was discovered that longer distance to amenities increases the importance of urban greeneries. At the same time, fewer urban greeneries increase the importance of distance to amenities. In the presence of medium urban greeneries, people are willing to walk for 11 to 30 minutes (880m to 2400m). While, in the presence of fewer greeneries, people are only willing to walk for a maximum of 20 minutes (1600m), and in the presence of denser urban greeneries, their willingness to walk starts from more than 30 minutes (>2400m) (see Figure 15). This allows for a non-linear weightage integration between distance to amenities and urban greeneries.

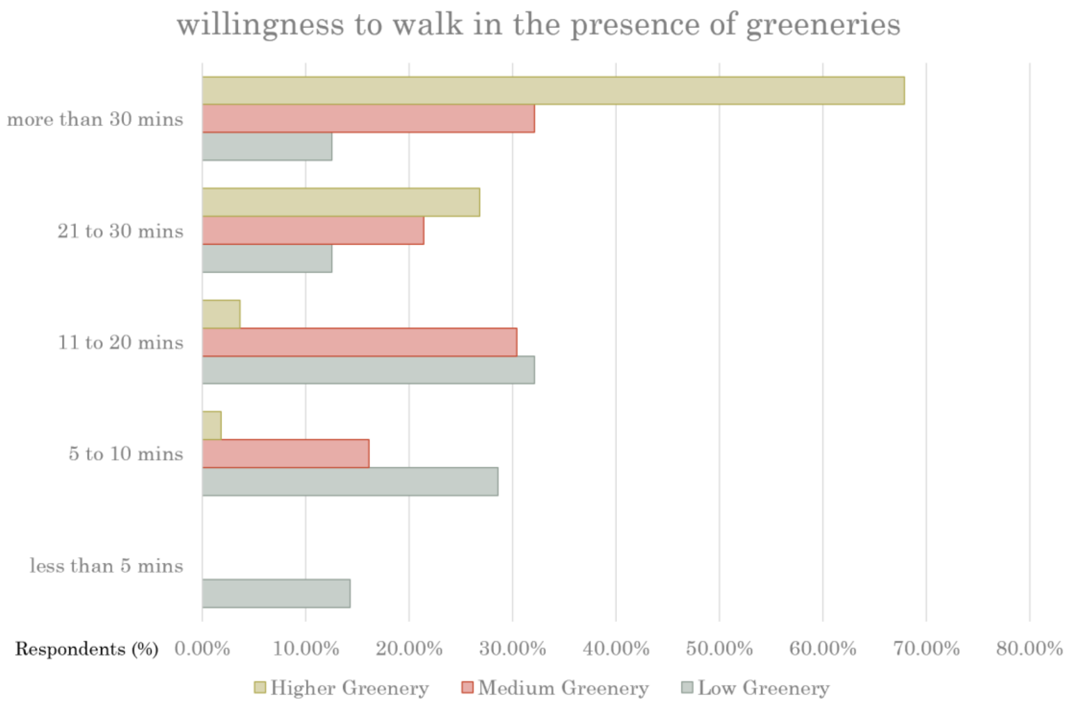



Figure 15. People's willingness to walk in the presence of greeneries

Although some of the people's willingness to walk overlap, it is still essential to notice that people are more willing to walk for longer minutes when denser urban greeneries are present. This could be an input for the government, stakeholders, and Sofia Green City Action Plan board that to build a walkable environment, urban greeneries are one of the essential factors to increase the willingness of people to walk. Pun-Cheng & So (2019) also found that greeneries are essential comfort-related factors perceived by pedestrians. Hence, the study suggested that increasing greeneries in the pedestrian network is necessary to be considered by the policymakers.

#### 5.1.3. Amenities preference

This section contains the people's amenities preference, an essential information input for distance to amenities indicator. As mentioned in 4.2.1, the perceived importance of amenities may differ for every location, which is why the survey captures this point. The people were presented with seven categories of amenities defined in this study and asked to give them an importance score, respectively.

As presented in Table 7, considering survey respondents' average and median perceived importance, a weighted value was assigned to each amenities category. The medical centre received the lowest importance with an average of 5.33 and a median of 5 compared to other categories, so it has the lowest weighted value. Public transport (AVG: 7.42, MED: 8) and the park (AVG: 7.62, MED: 8) received the highest importance compared to the other category, which has the highest weighted value. While for the Industrial category, School, and Office, received the same perceived importance according to their median and thin difference in their average, thus the same weighted value.

Table 7. Category of amenities perceived importance

| Category of Amenities | Perceived Importance | | Weighted Value |
|---|---|---|---|
| | Average | Median | |
| Grocery store, food supplier, restaurants (Industrial Category) | 6.82 | 7 | 0.15 |
| School | 6.64 | 7 | 0.15 |
| Office | 6.64 | 7 | 0.15 |
| Park | 7.62 | 8 | 0.20 |
| Medical Center (Health Care Category) | 5.33 | 5 | 0.05 |
| Shopping Center (Commercial Category) | 5.47 | 6 | 0.10 |
| Public Transport | 7.42 | 8 | 0.20 |

When linked to the age group, most of the age group (under 18 years old, 18 to 24 years old, 25 to 31 years old, 32 to 38 years old, 46 to 52 years old, and 53 to 59 years old) perceived the medical centre as being the least essential amenity. In comparison, only people over 60 perceived the medical centre as the most important amenity. This could be because the people within the active age group do not have any medical issues that require them to go to health care often, while the people over 60 years old may have some medical issues that require them to go to the medical centre often (Hargreaves et al., 2012). While Public Transport is perceived as one of the most crucial categories of amenities by most age groups since 31.41% of them claim to have public transport/metro as their preferred transportation mode, making a public transport hub an essential amenity for them.

## 5.2. Workflow implementation model

After gaining the essential information input from the walking preference survey, the workflow should be constructed by generating the parametric model from the defined input data. In the end, the implementation of the workflow should be able to result in walkability-optimal-urban plans.

### 5.2.1. Pre-processing of geospatial data and definition of the green index

Following section 4.1, the identified input data needs to be pre-processed. The input data for each parameter were obtained through the available data set provided by Sofiaplan, presented in Table 8. All input data were prepared by generalizing the UTM zone into WGS84, filtering the attribute, rechecking the geometries, and removing the null values in the ArcGIS Pro environment.

Table 8. Input data for the workflow implementation

| Parameters | Data Input | Format | Source | Details |
|---|---|---|---|---|
| Street Network | Pedestrian Street | .shp | Sofiaplan | Polyline of the current pedestrian street in Krastova Vada |
| Residential Buildings | Buildings_residential | .shp | Sofiaplan | Vector of the current residential buildings in Krastova Vada (229 buildings) |
| Amenities | Buildings_industrial | .shp | Sofiaplan | Vector of the grocery shop, food vendors, and entertainment category in Krastova Vada |
| | Buildings_education | .shp | Sofiaplan | Vector of the school category in Krastova Vada |
| | Buildings_office | .shp | Sofiaplan | Vector of the office category in Krastova Vada |
| | Green_areas_public | .shp | Sofiaplan | Vector of the parks category in Krastova Vada |
| | Buildings_healthcare | .shp | Sofiaplan | Vector of health facility category in Krastova Vada |
| | Buildings_retails | .shp | Sofiaplan | Vector of retail category in Krastova Vada |
| | Public_transport_stops | .shp | Sofiaplan | Vector of the public transport hub category in Krastova Vada |
| Amenities Placement | Potential_properties | .shp | Sofiaplan | Vector of the available land for new amenities placement |
| Urban Greeneries | Orthophoto | .tiff | GATE | Raster of Krastova Vada neighbourhood |
| Urban Greeneries Placement | Street with low to none NDVI score | .shp | Own processing | Vector of the spatial join between NDVI and street segments with low to no NDVI score |

As for the green index, the processing of the orthophoto file to NDVI format is done in the ArcGIS Pro environment, where the processing the based on the NDVI formula in section 4.1. Following the essential steps on section 4.1, resulted in (1) NDVI raster of Krastova Vada as shown in Figure 16, and (2) street with NDVI value as shown in Figure 17.

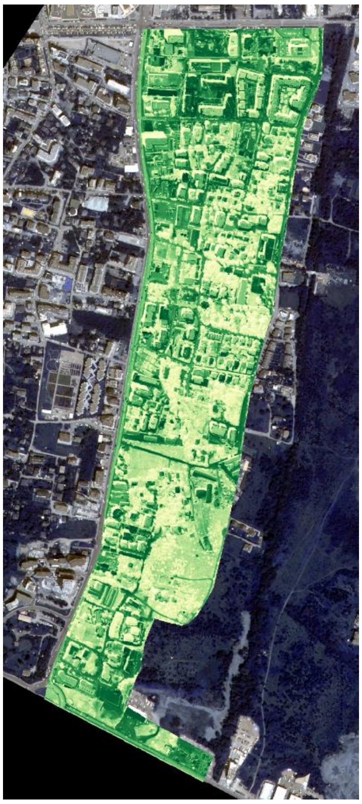


Figure 16. NDVI raster

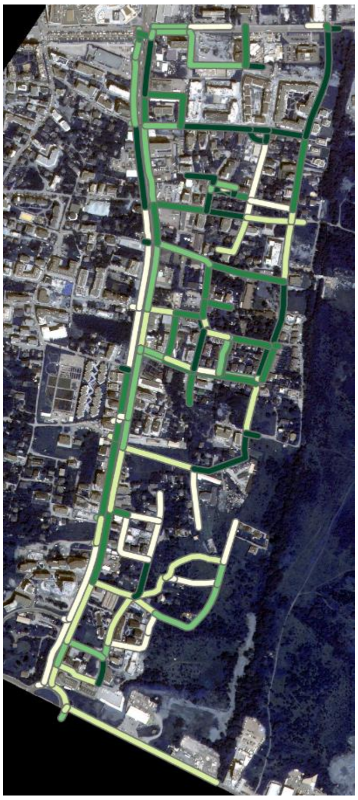


Figure 17. Street with NDVI value

#### 5.2.2. Parametric model generation

All the essential geospatial input data for walkability, such as residential buildings, amenities, pedestrian networks, and potential property, prepared in section 4.1 were imported using a ShrimpGIS plug-in to the relevant parametric modelling software (Grasshopper). The latitude and longitude of Krastova Vada are also added to ensure that the imported file's geo-location is correct. Importing the geospatial data with the *.shp* format resulted in several geometries in Grasshopper; for instance, residential buildings, amenities, and potential property were converted to a brep (boundary representation) format. The pedestrian network was represented as lines and then converted to a curve format. Especially for buildings, the imported data should be transformed to construct a 3D model using their height as a Z-unit component (see Figure 18).

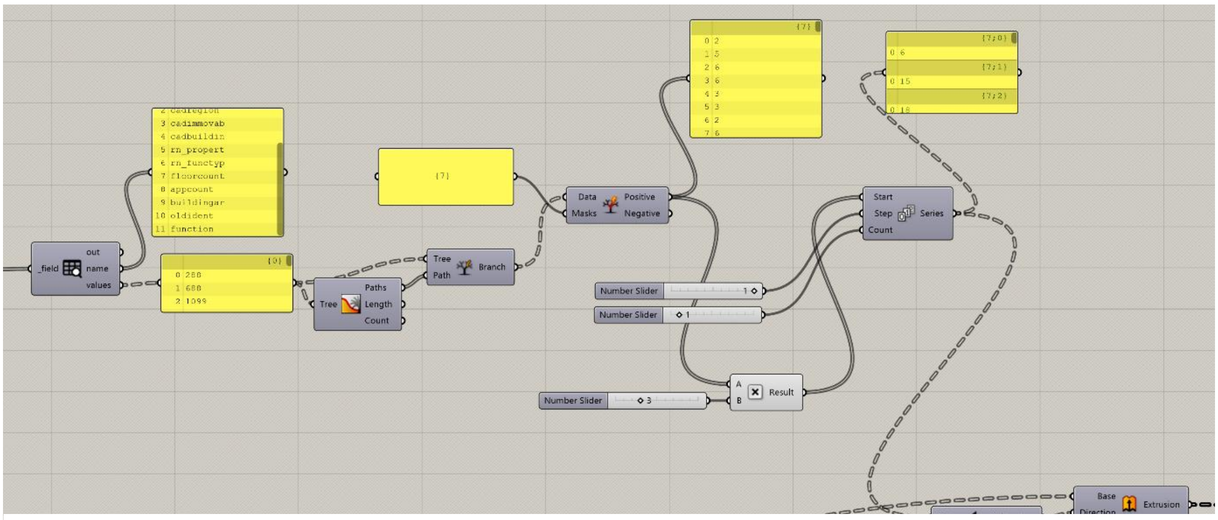
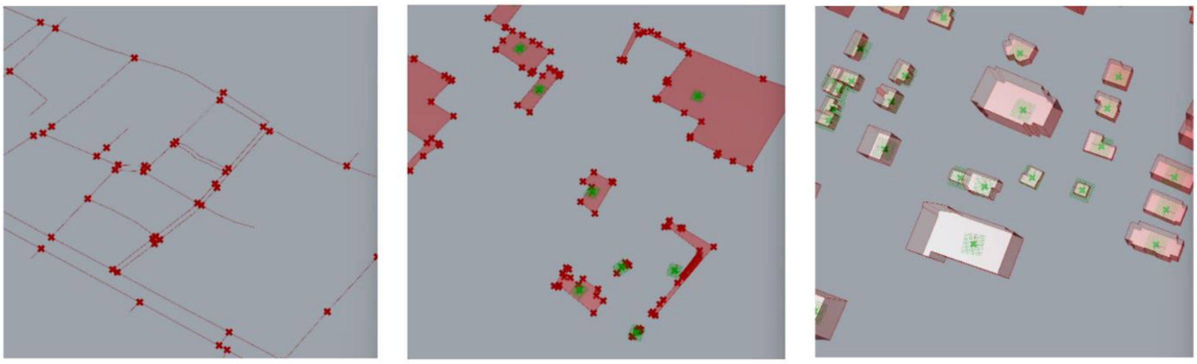



Figure 18. Part of 3D model generation workflow in Grasshopper

### 5.2.3. Distance to amenities

After the generation of the parametric model, the measurement of the distance to amenities indicator should be performed. Following the explanation on 4.2.1, the available network (nodes in pedestrian), the main objective (amenities midpoints), and the starting point (residential midpoints), from the parametric model were incorporated into the ShortestWalk plug-ins to run the A* algorithm (see Figure 19(a-c)). ShortestWalk plug-in was generating the shortest distances between residentials and amenities. An empty evaluation point A (midpoints of available lands for future urban planning) is also incorporated into the ShortestWalk to be used for generative design simulation.



(a) (b) (c)

Figure 19(a) curve parameter points, (b) amenities midpoints, (c) residential midpoints

After the list of distances has been generated, it needs to be normalized. The workflow for this phase should be done seven times according to the number of amenities categories identified. Furthermore, when each walkability score per category has been generated, the weightage from walking preference survey (see Table 7) should be incorporated to produce the combined walkability score based on the distance to amenities indicator for integration. The workflow implementation in this part has resulted in a 54.45 walkability score. This score of 54.45 belongs to the "Somewhat Walkable" in the Walkscore category, which means that some activities can be completed on foot (see Table 4).

### 5.2.4. Urban greeneries

Based on the street with the NDVI value file that has been imported, a list of NDVI values per street is gained. Following the workflow procedure in 4.2.2, the NDVI has been divided into four classes, even though the highest NDVI found in the case study was only 0.4. This was done to show that the workflow can still be implemented in different situations. Implementing workflow has resulted in a 59.96 walkability score based on urban greeneries. The score of 59.96 belongs to the "Somewhat Walkable" in the Walkscore category (see Table 4). Figure 20 presented the interface of urban greeneries indicator in Grasshopper.

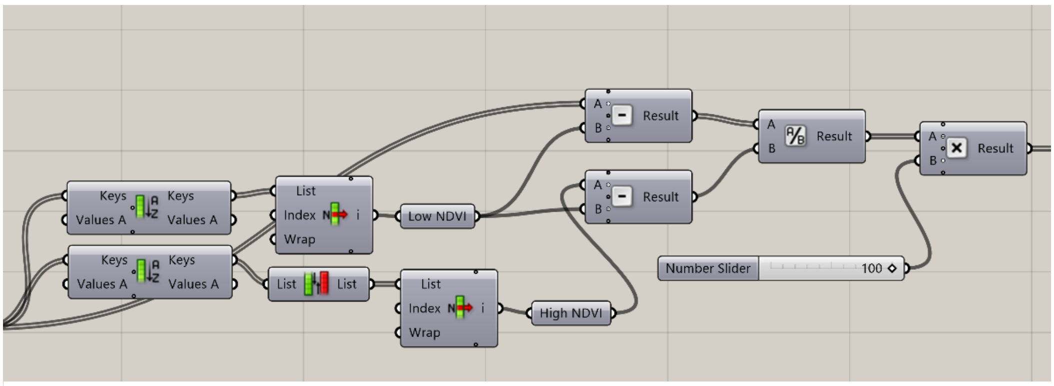



Figure 20. urban greeneries measurement in Grasshopper

#### 5.2.5. Integration between indicators and human perspective

Based on the walking preference survey, the walking preference of people resulted in two different ways of indicators and human perspective integration, namely: (1) linear weightage and (2) non-linear weightage.

##### 5.2.5.1. Linear weightage

Based on the walking preference survey result (see Table 6), a weightage value of 0.55 was given to the distance to amenities and a weightage value of 0.45 to the urban greeneries to address the people's preference between the comfort dimension's indicators. Following the proposed workflow, these results were implemented in the integration formula on 4.3. The integration between indicators and human perspective based on linear weightage has resulted in a Walkability Score of 56.93 and belongs to the "Somewhat Walkable" category (see Table 4).

##### 5.2.5.2. Non-linear weightage

Non-linear weightage is another takeaway from the walking preference survey result. Figure 15 shows a more specific relationship between distance to amenities and urban greeneries, where the increase of urban greeneries makes the distance to amenities less important. This finding makes each indicator can be classified and weighted, as presented in Table 9. (The detailed version is on Annex: 5)

Table 9. Non-linear weightage of indicators

| **Classes** | **< 400m** | **400 - 1600m** | **1600 - 2400m** | SUM |
|---|---|---|---|---|
| **0.3 - 0.4 NDVI** | 0.201 | 0.131 | 0.071 | 0.403 |
| **0.2 - 0.3 NDVI** | 0.181 | 0.111 | 0.041 | 0.333 |
| **0.1 - 0.2 NDVI** | 0.151 | 0.091 | 0.022 | 0.264 |
| SUM | 0.533 | 0.333 | 0.134 | **1** |

In this non-linear weightage integration, the distance to amenities will be classified into three groups since the willingness to walk ranges from 400m to more than 2400m. As for the urban greeneries, it is also decided to keep the range from 0.1 to 0.4 NDVI. This was because an NDVI less than 0.1 do not contribute to walkability and the highest NDVI in the study area is 0.4. In addition, the illustration of higher greenery in the survey referred to the range of 0.3 to 0.4 NDVI.

To proceed with the non-linear weightage, a slight modification from the previous distance to amenities and urban greeneries workflow. For instance, the "linear weightage" was implemented after the walkability score had been generated, while the "non-linear weightage" was implemented in the classification. The classification was also modified by incorporating the classification from Table 9 (See Figure 21).

The non-linear weightage has resulted in the base walkability score of 68.94 scores. This score belongs to the "Very Walkable" category (see Table 4), which is one category higher compared to the linear weightage. The result is probably because the shortest distance (<400m) category and higher urban greenery (0.3 – 0.4 NDVI) are weighted twice as much compared to the one without. This base walkability score of 68.94 does not reflect Sofia's current walkability condition. According to research and the personal opinion of people living in Sofia, walking is not the best experience (will be elaborated on 7.3). This is why it has decided to proceed with the generative design simulation with linear weightage integration.

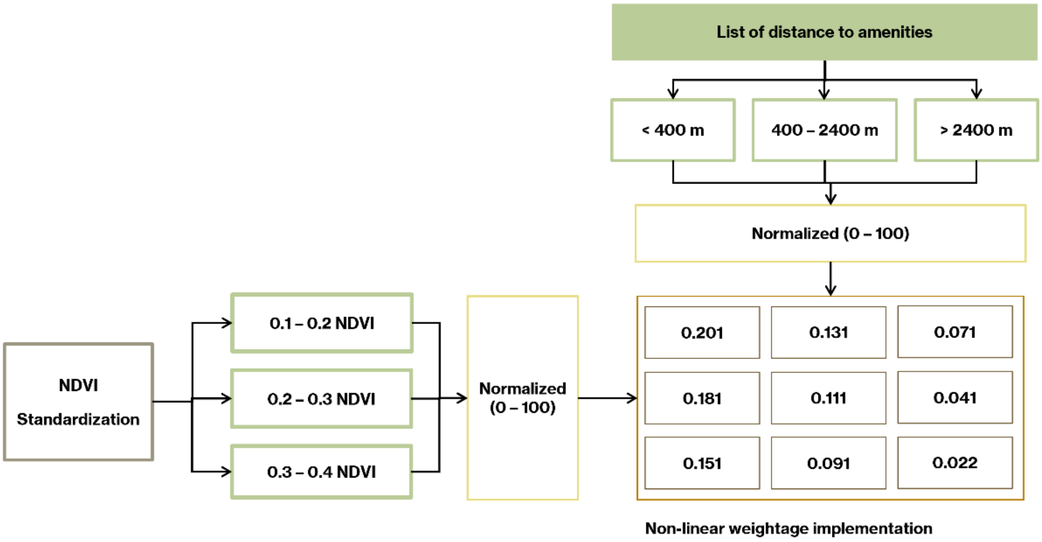



Figure 21. Adjusted classification workflow for non-linear integration

### 5.2.6. Generative design simulations

The generative design simulation workflow used the previous input of Evaluation Point A, Evaluation Point B, and the integrated walkability score to find a near-optimum solution for the placement of amenities and urban greeneries (see Figure 22). When implemented in Grasshopper, the input for generative design simulation is Fitness and Genome. Fitness acted as the primary objective function, which we aim to get in the form of a value that needs to be optimized. At the same time, Genome acted as the decision variable in the form of parameters that can influence Fitness.

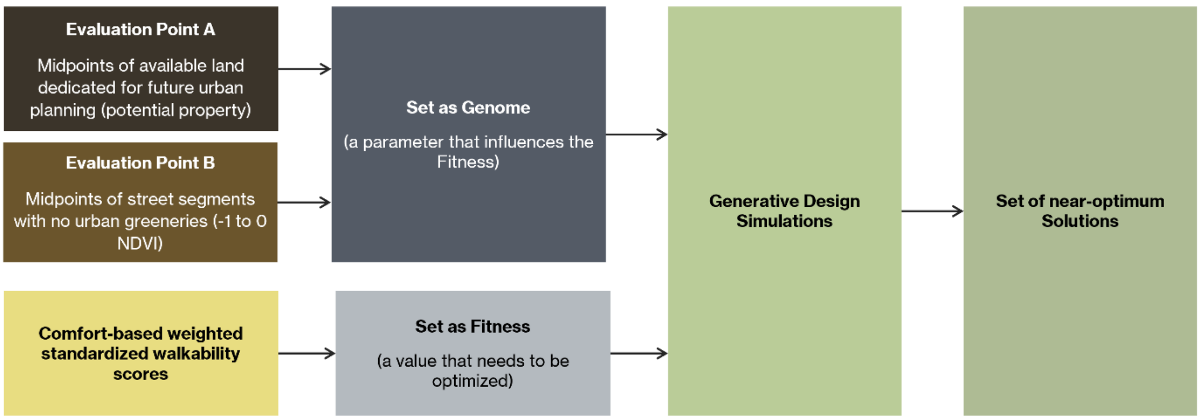



Figure 22. Implementation of generative design simulations workflow

In this implementation, Evaluation Point A & B will act as the Genome since they are the midpoints of available land that could be utilized as the location for amenities or urban greeneries. Different locations' placement for amenities or urban greeneries should be able to influence the integrated walkability score since scores are different locations. At the same time, the integrated walkability score acted as the Fitness since we aim to have the highest walkability score, which indicates an improvement of walkability to generate walkability-optimal urban plans. In the neighbourhood of Krastova Vada, Vitosha, the available land for future amenities placement (Evaluation Point A) are 200 locations. The available street segments for placement of urban greeneries (Evaluation Point B) are 66 street segments. In the generative design simulation, a combinations formula based on factorial can be used to mathematically calculate the number of possible combinations.

$$nCr = \frac{n!}{r! \times (n-r)!}$$

Where *nCr* is the number of possible combinations, *n!* is the total number of items, and *r!* is the number of items being chosen.

Based on the formula above, if seven additional locations for amenities placement are planned, there could be approximately 2.2839E+12 possible combinations (minding the available 200 locations). Aside from that, if seven additional street segments for urban greeneries placement are planned, there could be approximately 778,789,440 possible combinations (minding the available 66 street segments). Moreover, if both seven additional locations for amenities and urban greeneries are implemented, there should be many more combinations. Minding the number of possible combinations, implementing generative design simulation should be an advantage.

The optimization process in the generative design simulations is divided into three different scenarios (see Figure 23): (1) to find seven different locations for amenities representing the seven types of amenity category, followed by seven different street segments for urban greeneries to comply with the chosen amenities. (2) to find seven different locations for amenities, followed by four different street segments for urban greeneries, in the case of implementing amenities, is preferred to the stakeholders. (3) to find four different locations for amenities, followed by seven street segments for urban greeneries, in the case of implementing urban greeneries, is preferred by the stakeholders.

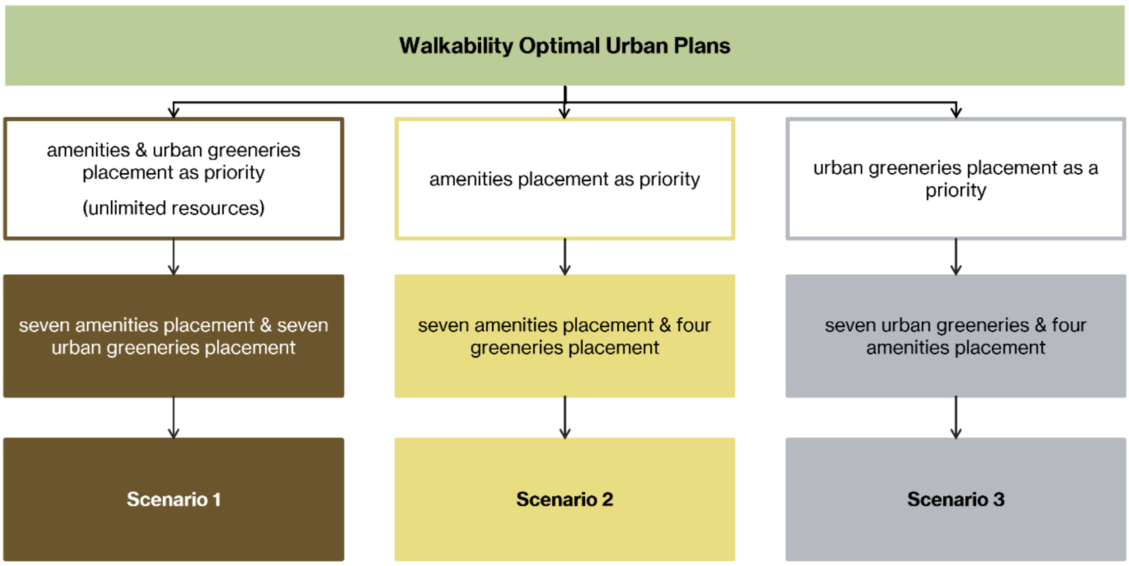



Figure 23. Different scenarios for walkability optimal urban plans

Aside from the limited number of chosen locations and street segments, no constraint was introduced for the scenarios. Although other constraints could be introduced, such as budget, time, FAR, or regulation-related-constraint, a further discussion with stakeholders is needed to determine the constraint. However, due to the limited time, the discussion with stakeholders is not done in this study. Discussion with stakeholders to determine constraints is essential in generating more realistic scenarios in the study area.

Despite that, the scenarios in this study are meant to be a proof of concept that the proposed workflow has the ability to generate different scenarios to help the decision-making process.

The interface of generative design simulations in Grasshopper+Galapagos is presented in Figure 24. The orange graph shows how many iterations had been done. The orange graph indicates the average of how high or low the score of each combination each iteration produces. In comparison, the graph in the middle-bottom is a multidimensional-point-graph. It represents the total "Genome" calculated in a vertical line. Each "Genome" is then represented by a polyline that connects these vertical lines at the same percentage of their slider value-individually. While the values with green colour on the bottom right corner rank the solutions as results of the process, starting from a lower value solution at the bottom until the highest one they have so far.

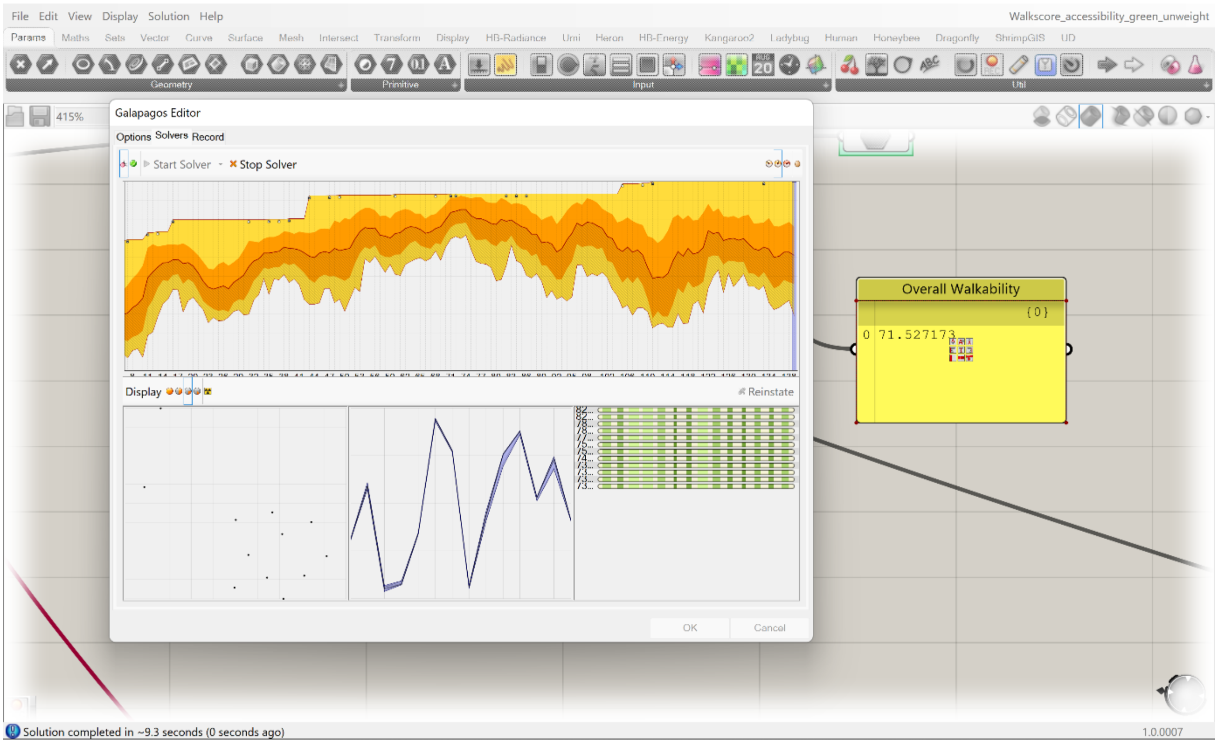



Figure 24. Generative design interface

In addition, Galapagos is an iterative search engine for generative design simulation that continuously looks for a combination of "Genomes" that provide better "Fitness". In this implementation, the Galapagos algorithm repeatedly runs for up to 381 steps using 50 populations by default. After the Galapagos algorithm evaluates the near-optimum combination of "Genome", the process will automatically stop, which in this case study takes approximately 30 hours.

## 5.3. Summary

This chapter discusses how the proposed workflow has been implemented. The workflow was implemented in Grasshopper as one of the visual programming environments. The input data were imported from **.shp* format to a parametric model. This chapter ends with the creation of three different scenarios for generative design simulations to produce walkability-optimal-urban-plans.

# 6. RESULTS

This chapter presents the results that show the different scenarios generated from the workflow implementation. Validation through the workflow implementation in another location of "Lozenets" is also presented in this section.

## 6.1. Walkability-optimal-urban-plans

### 6.1.1. Generated Scenarios

The walkability optimal urban plans are the result of the workflow implementation. As discussed in 4.4, the generative design algorithm had the ability to generate multiple solutions for placing amenities and urban greeneries. Producing different scenarios is essential in case one indicator is preferable to the others. The stakeholders can start a discussion based on available options to determine which one is fit to be implemented according to their vision of improving the neighbourhood's walkability. Table 10 shows different scenarios generated in the generative design simulation process.

Table 10. Different scenarios based on generative design simulations

| Scenarios | Walkability Score |
|---|---|
| Baseline Scenario | 56.93 |
| Scenario 1 | 82.431 |
| Scenario 2 | 74.392 |
| Scenario 3 | 73.120 |

Figure 25 - 28 presents the walkability score 3D map of baseline, scenario 1, scenario 2, and scenario 3, respectively. At the same time, the 2D map will be available in Annex 3. As shown in Figure 25, the residential buildings are mostly coloured within the average walkability score, which corresponds to its walkability score (56.93 out of 100). After the strategic placement of amenities and urban greeneries, the residential buildings changed into the range of high walkability scores (Figure 25 - 28), corresponding to their walkability score (see Table 10).

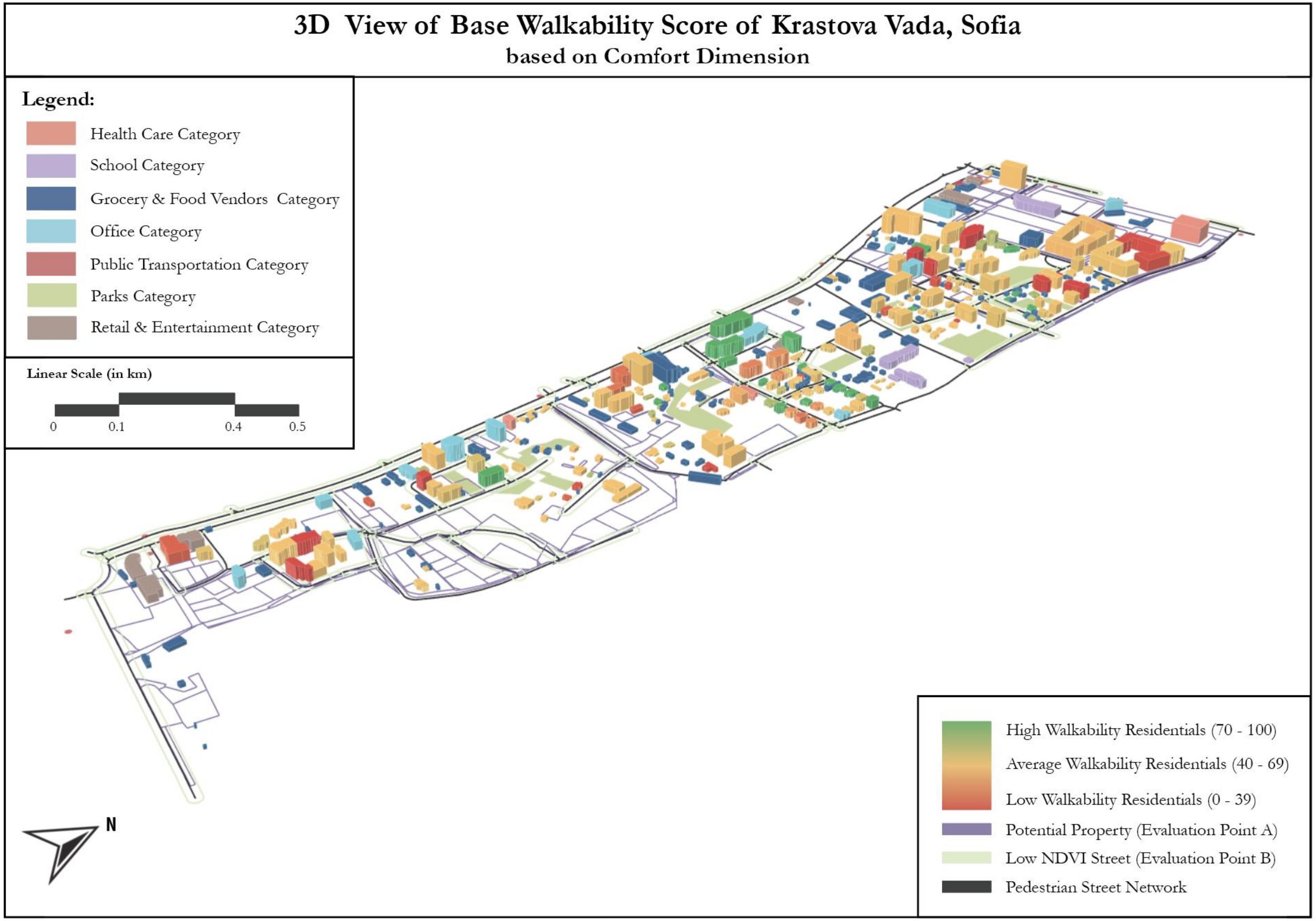



Figure 25. 3D map of base walkability score in Krastova Vada

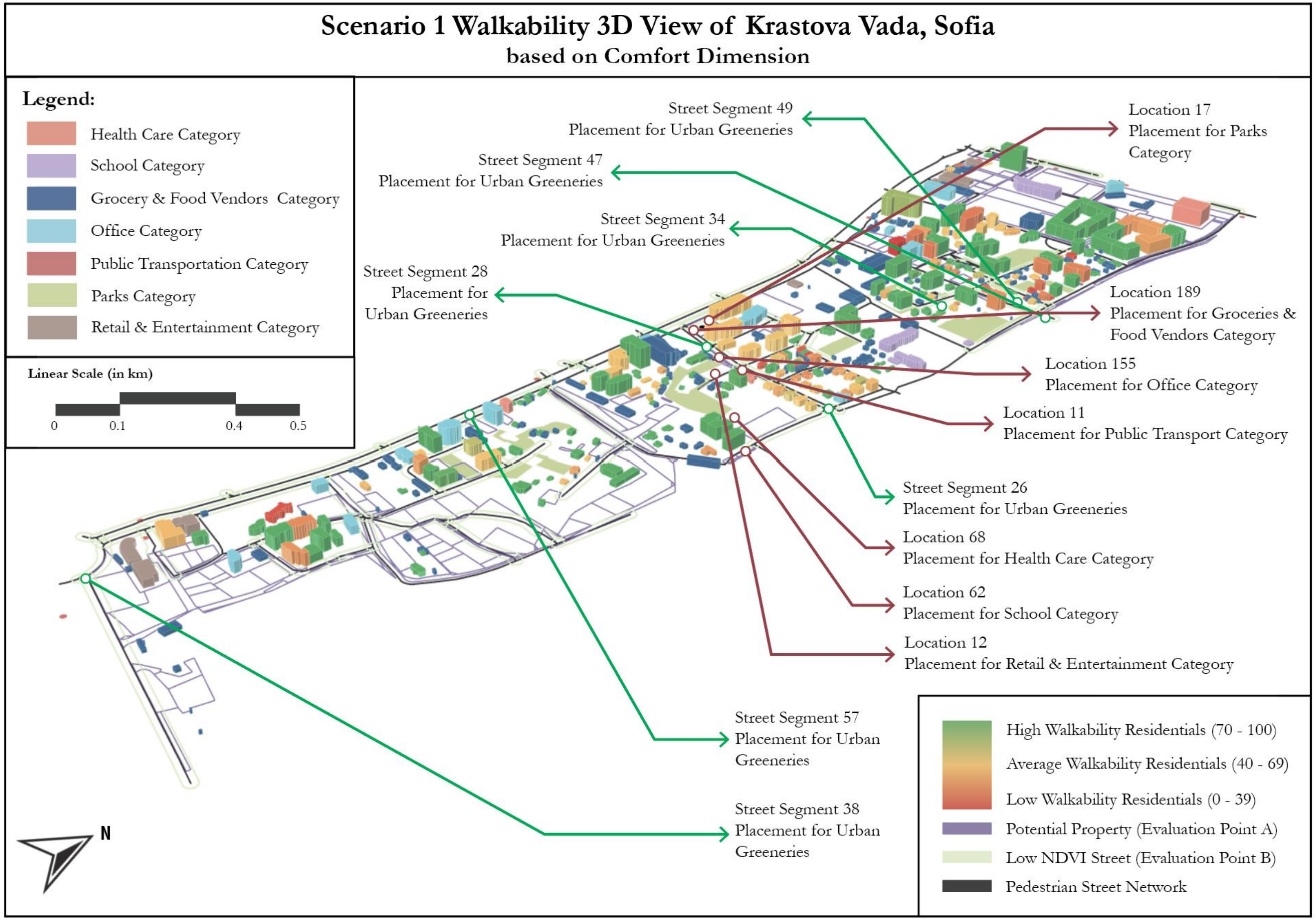



Figure 26. 3D walkability map of scenario 1 in Krastova Vada

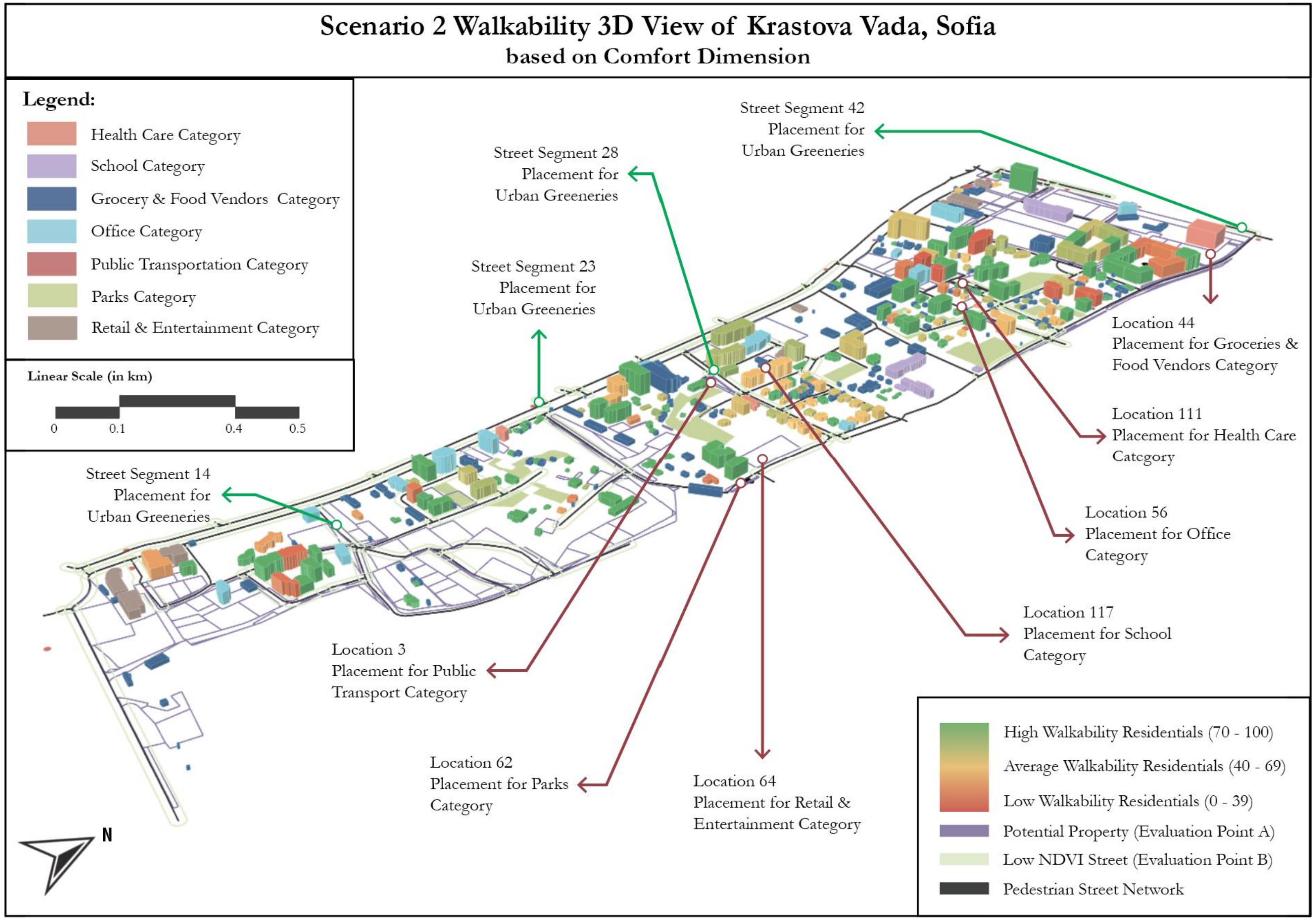



Figure 27. 3D walkability map of scenario 2 in Krastova Vada

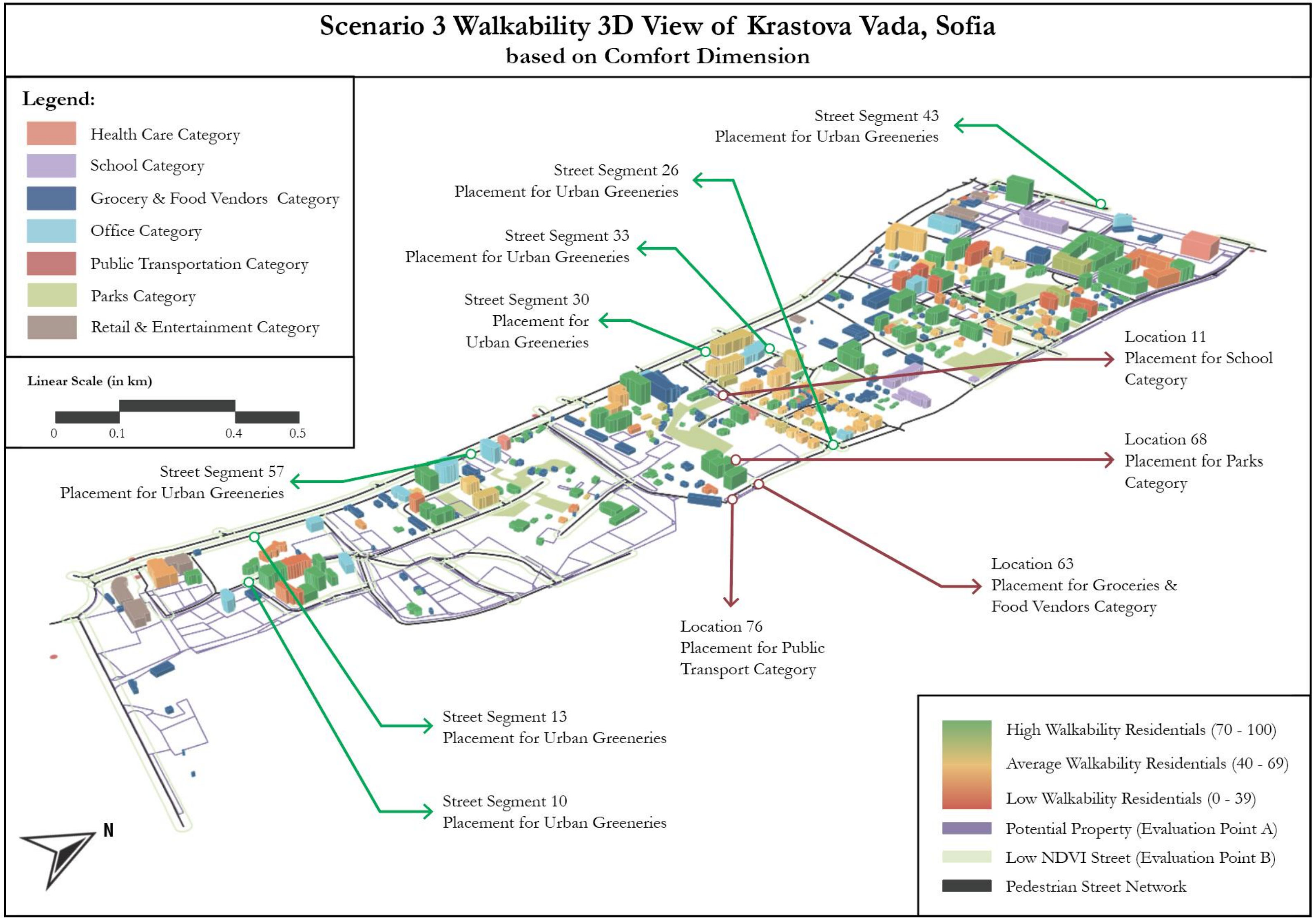



Figure 28. 3D walkability map of scenario 3 in Krastova Vada

#### 6.1.2. Comparison between scenarios

After generating all scenarios with their walkability score, each scenario's chosen location for amenities and urban greeneries are compared based on a google street view image. The comparison is presented in Table 11.

Table 11. Physical comparison between scenarios

| | **Scenario 1** | **Scenario 2** | **Scenario 3** |
|---|---|---|---|
| **School** | An empty lot which surrounded by residential buildings and a grocery shop. The pedestrian street needs much improvement. | An empty lot which surrounded by residential buildings. | Located in front of a mid-rise apartment building and utilized as an urban garden. The pedestrian street is well-built. |
| **1st Urban Greeneries** | Located next to a highway with no urban greeneries. | Located next to the main road. It is a pedestrian street with built pathway. | Located near an industrial building and residentials. There is a presence of grass and no pathway. Currently utilized as a parking spot. |
| **Public Transport** | Located in front of a mid-rise apartment building and utilized as an urban garden. The pedestrian is well-built. | An empty lot with medium greenery (grass and several trees) and urrounded by residential buildings. | An empty lot and utilized as a parking lo. Located near an industrial building and residentials. |
| **2nd Urban Greeneries** | Located next to empty lands leading to residentials with no pathway on the pedestrian street. | Located next to the main road and the pedestrian is well-built (visible pathway). | Located next to the main road and the pedestrian is well-built (visible pathway). |
| **Parks** | An empty lot and located next to a mid-rise apartment building. | An empty lot and surrounded by residential buildings and a grocery shop. The pedestrian street needs much improvement. | An empty lot and surrounded by residential buildings and a grocery shop. The pedestrian street needs much improvement. |
| **3rd Urban Greeneries** | Located near construction with less urban greenery (dry area). | Located next to the main road. There is a pathway on the street. | Located next to the main road. There is a pathway on the street. |
| **Health Care Facility** | An empty lot that surrounded by residential buildings and a grocery shop. The pedestrian street needs much improvement. | An empty lot with little greenery (dry grass) and located near a school and surrounded by residentials | - |

| | | | |
|---|---|---|---|
| **4th Urban Greeneries** | Located next to the main road with less urban greenery (dry grass). | Located next to empty lands leading to residentials with no pathway on the pedestrian street. | Located next to empty lands leading to residentials with no pathway on the pedestrian street. |
| **Grocery Shops & Food Vendors** | An empty lot that located next to a mid-rise apartment building. | An empty lot with dense greeneries (grass and trees) with no pathway in the pedestrian. | An empty lot that located next to an industrial building and residentials with no pathway in the pedestrian. |
| **5th Urban Greeneries** | Located in the residential area with no presence of greenery. | - | Located in the residential area with no presence of greenery. |
| **Office** | Located next to a park and residentials with a presence of dense greenery. | An empty lot which located next to the residential area. | - |
| **6th Urban Greeneries** | Located near construction with less urban greenery (dry area). | - | Located next to the main road with well-built pedestrian (visible pathway). |
| **Retail & Entertainment** | Located in front of the mid-rise apartment building and utilized as an urban garden with well-built pedestrian street. | An empty lot which located next to an industrial building and residentials. There is no pathway in the pedestrian | - |
| **7th Urban Greeneries** | Located next to empty lands leading to residentials. No pathway on the pedestrian street. | - | Located next to the main road with well-built pedestrian (visible pathway) |
| **Walkability Score** | 82.431 | 74.392 | 73.120 |

Based on Table 11 above, the highest walkability score is by Scenario 1. This is likely due to the placement of seven amenities and seven urban greeneries in this scenario, which means more locations and street segments are implemented compared to other scenarios. The second highest walkability score is gained in Scenario 2, slightly different from the lowest walkability score in Scenario 3. The higher score of Scenario 2 could happen due to the higher weightage of amenities compared to the weightage of urban greeneries. Because Scenario 2 has more amenities than Scenario 3 (7 to 4), Scenario 3 has more urban greeneries than Scenario 2 (7 to 4).

Besides, every chosen location or street segment has characteristics that could be discussed in the decision-making process. The stakeholders might discuss trading off the walkability score with specific location/street characteristics that align more with their vision and regulations. For example, a chosen location for Office in Scenario 1 (Location 155) is an empty lot with dense greenery. While the chosen location for Office in Scenario 2 (Location 56) is an empty lot without greenery (dry area). Thus, if the stakeholders want to keep the carbon storage within that greenery, they must trade the walkability score with carbon storage and proceed with Scenario 2, which has a less walkability score.

### 6.2. Proposed workflow validation

People's walking experience score reflects the current walkability level in their neighbourhood. Thus, the walking experience data could be helpful as a validation tool. The validation is essential to ensure the proposed workflow is aligned with people's perceived walkability. Due to data availability, another neighbourhood in the Lozenets district has been chosen as the second neighbourhood for validation. The proposed workflow has been implemented in the second neighbourhood and resulted in a 61.79 base walkability score, which belongs to the "Somewhat Walkable" category. Table 12 compares the walking experience and the proposed workflow's base walkability score.

Table 12. Comparison between walking experience and proposed workflow's base walkability score

| Neighbourhood | Walking Experience | Walking Experience Source | Proposed Workflow's Walkability Score |
|---|---|---|---|
| Main study area | 60 | Lozenets district walking experience | 56.93 |
| Second neighbourhood | 60 | Lozenets district walking experience | 61.79 |

Figure 29 shows the base walkability score 3D map of second neighbourhood in Lozenets. Most of the residential buildings on this figure are within the average walkability score range, even though it is evident that some of the residential buildings are within the high walkability score range. This visualization corresponds with the Lozenets base walkability score (61.79 out of 100).

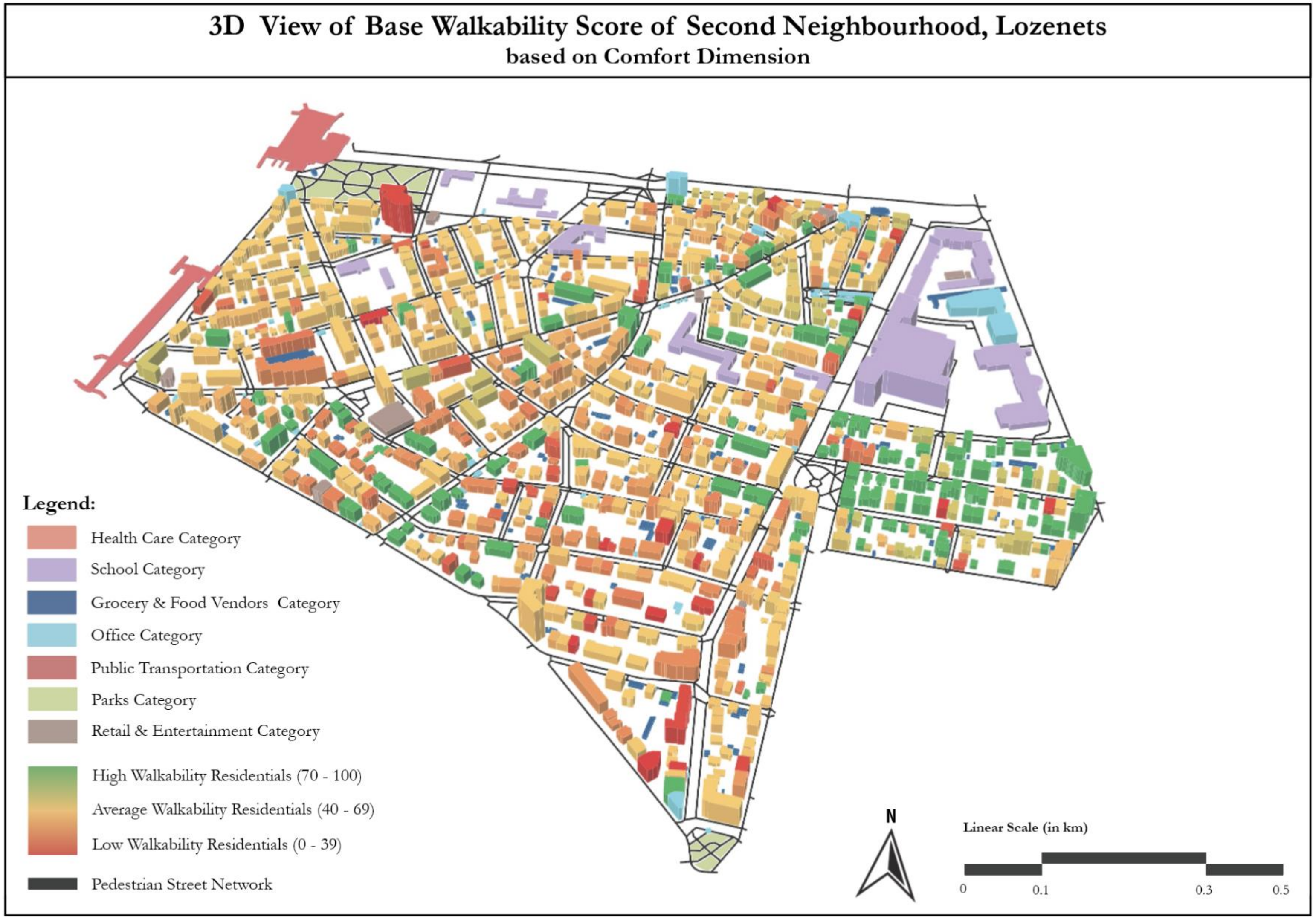



Figure 29. 3D map of base walkability score in the second neighbourhood of Lozenets

### 6.3. Summary

This chapter contains the generated results from the implementation of workflow. There is an evident change in 3D map when the amenities and urban greeneries has been placed in Scenario 1, 2, 3. Other than that, the comparison between walking experience and proposed workflow's base walkability score have shown an accordance.

# 7. DISCUSSION

This chapter contains discussions and limitations regarding the objectives of this study, including the proposed workflow, implementation of the workflow, and retrieving results of this study.

## 7.1. Walkability assessment

A literature review was done to compose a background knowledge on how walkability assessment has been done. This includes the methodology, input data needed, and indicators in the generative design domain. The index method is essential since different components are needed to determine walkability. The "index method" is not perfect because we lost specific values representing each component in the process. However, the flexibility, familiarity, and ease of interpretation still make the index relevant to be implemented. The Walkscore method is also part of the index which has been chosen for this study. Its multi-dimensionality (street and building elements) and universality should open a way for better interpretation regarding walkability by the stakeholders. Consequently, practical decisions are made.

Walkability assessment in the generative design domain is found only based on the distance to amenities. This study has proven that incorporating new indicators is possible in the domain. The urban greenery and human perspective were integrated to create walkability-optimal-urban-plans in the comfort dimension. Nevertheless, we have to make sure that we acknowledge the optimum value of the indicator, which is one of the main reasons for including distance to amenities and urban greeneries. In reality, other indicators that represent the comfort dimension have been used outside the generative design domain: noise, shading, street furniture, and building ratio (al Shammas and Escobar, 2019; Galal et al., 2020). Currently, there are no studies that have determined the optimum value of these indicators. Adding urban greeneries in the generative design domain of walkability gives a variety of how walkability can be assessed in this domain. The urban greeneries can also be implemented in other applications that measure walkability based on distance, such as a walking navigation application. The current walking navigation application only shows the user information based on distance and time. If other factors like the presence of greeneries are included in the algorithm, it may help provide people on choosing the path they are most comfortable walking with.

## 7.2. Proposed workflow

The proposed workflow was constructed based on two indicators representing comfort; (1) distance to amenities and (2) urban greeneries. The distance to amenities indicator was conceptualized based on the A* algorithm, following the Walkscore method. The available lengths from certain residential buildings to different amenities categories have been obtained and normalized. Since the calculation was done individually per category, it gave us the advantage of weighing each amenity differently. It was acknowledged that different amenities have different importance in people's perceptive, which is why the amenities preference point for the walking preference survey is conceptualized. This method should be able to avoid a fallacy in the process. There should be no residential building that would get a high walkability score even though it is only close to parks but far away from others like groceries or school. In the placement of amenities phase, this method allows us to define what amenities category will be placed to increase the walkability.

The urban greeneries were represented by NDVI. NDVI is a well-known index representing the density of "healthy" vegetation in remote sensing. Other than NDVI, another vegetation index to measure walkability is called the green view index. The green view index is retrieved by calculating the percentage of green in a street view image. Although the green view index could capture the greenness along the street more accurately, this method would take so much time. The optimal value of urban greeneries, which regards walkability, is measured in NDVI (0.4 NDVI, see 2.4). This is why the NDVI approach is preferable in the workflow. The integration of urban greeneries into the Walkscore method is also done. Aside from the normalization to the 0 – 100 score range, the integration is also done within the street elements. The street element is essential as one of the data inputs for the Walkscore method. This is why the spatial join is performed between the NDVI and the 4m street buffer to incorporate the urban greeneries in the parametric model environment.

Incorporating the human perspective is also one of the highlights of this proposed workflow, as walking behaviour is based on an individual's cultural background, contextual location, and preference. The walking preference survey has helped us determine what people prefer between a shorter distance or higher greeneries' density for their walking comfort in general. Other studies have also proven that incorporating a qualitative walkability assessment could have a more significant impact than those without. The human perspective is also helpful in reflecting on and understanding the current walkability state (Battista and Manaugh, 2019; Raswol, 2020). However, the weightage value would still need to be adjusted when this workflow is implemented in another location to match the people's behaviour. The walking preference survey should still need to be done.

There are many differences in individuals' wishes regarding walkability that we cannot set aside. For instance, people who want to go on a diet would prefer longer distances and people who want to use their time efficiently would prefer shorter distances, making it almost impossible to occupy what everyone wants. This walkability aspect is complicated, and researchers are still trying to find the best solution. Although it would not make everyone happy, it should not stop us from planning a walkable city either, as it has many benefits in terms of sustainability and health. What we can do is, when designing or planning for a walkable city, it is essential to have a concept of what type of walkable city we aim to create and try to occupy what the individuals want based on that concept.

## 7.3. Workflow implementation

After the workflow had been developed, it was implemented in a study area of Krastova Vada, Sofia, to test the functionality and validate it. The walking experience, people's preference, and amenities information has been retrieved through a walking preference survey as information input. As presented in 5.2.5.2, an attempt has been made to integrate the distance to amenities indicator and urban greeneries indicator in a non-linear weightage. However, the base walkscore of this integration has shown to be higher than the actual condition. According to research and the opinion of people who live in Sofia, walking is not an enjoyable experience, and the walking infrastructure is not the best. For instance, the Sofia Integrated Urban Transport Project, which has been developing since 2011, focuses solely on motorized vehicles and public transportation and prioritizes motorized mobility above non-motorized mobility (Dimitrova, 2010). Prioritizing private automobile transportation in urban planning implies prioritizing car-oriented infrastructure in the future. This regulation reduces investments in pedestrian, bicycle, and public transportation infrastructure. As a result, persons driving their automobiles have a relatively quick and (illusory) pleasurable experience, whereas pedestrians, cyclists, and public transportation users have an unpleasant and inconvenient experience.

Several studies have been done on the overestimation and underestimation of walking time compared to the actual objective (McCormack et al., 2007; Pun-Cheng and So, 2019). These studies have found that objective and perceived walking times did not comply very well. People who do not choose to walk as their preferred transportation mode tend to overestimate their capability of walking (e.g., in reality, they could only walk for 15 mins but admitted to would have walked for 30 mins). In this study, only 29.03% of the respondents prefer to walk, while 70.97% choose another transportation mode as their preferred mode. This overestimation could have been the reason why there is a discrepancy between the weighted walkability score and the actual infrastructure condition. However, it is still important to note that people are willing to walk if the government has given a proper pedestrian infrastructure.

The implementation of workflow also managed to generate a 3D model. It is essential to notice that the 3D model produced in each scenario shows a better visualization than those in 2D (see Figure 30). The 3D view of each scenario, including the base walkability, has shown us the apparent change in residential buildings when the placement of amenities and urban greeneries are implemented, making it evident that the implementation of the proposed workflow, in this case, helped in increasing the walkability. Although, implementing a 3D model could be more than just a visualization tool. The study by (Zhu, 2019) attempted to utilize the 3D to measure the walkability on a "street-design-level" by (1) measuring the proportion of the sky, (2) measuring the proportion of street wall, and (3) calculating the index of closure. This research demonstrates how using the Urban Design Tool in 3D models may be beneficial for evaluating street walkability at the urban scale. It enables computer algorithms to examine and rate a significant number of neighbourhoods. Besides that, 3D should also be helpful in the case of measuring the Z-unit-related indicator for walkability. For instance, shading is one of the elements that provide comfort. With 3D, measuring and simulating the shade coverage of each building in a neighbourhood to quantify walkability is possible.

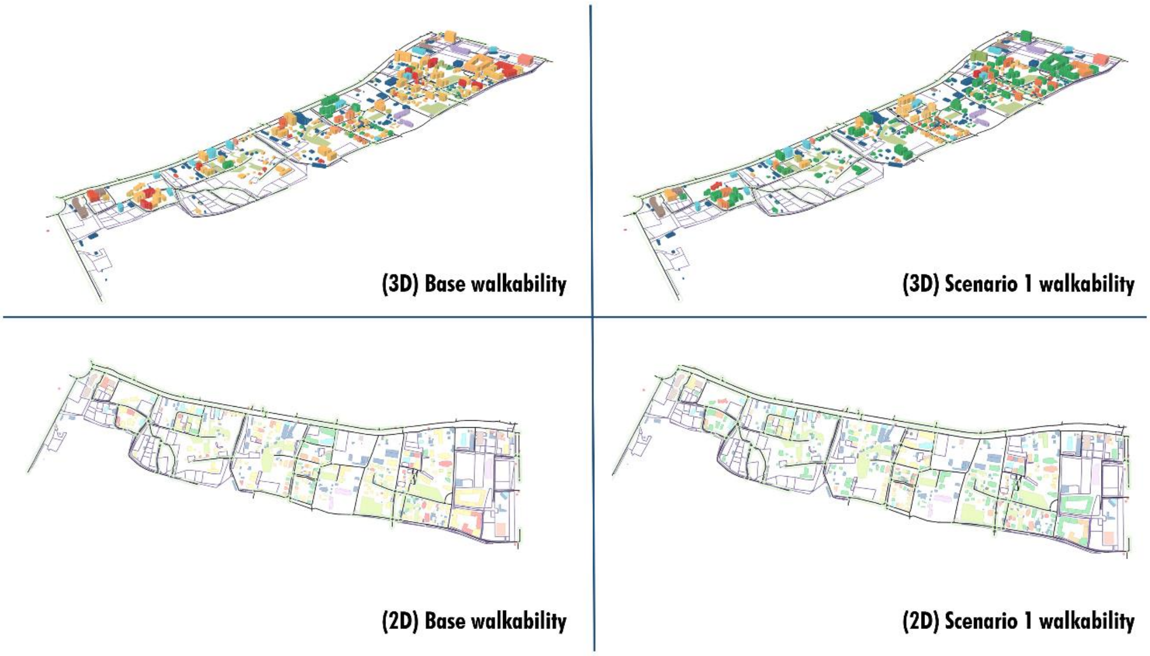



Figure 30. Comparison between 2D and 3D

The implementation of the proposed workflow also shows us that the chosen location of amenities and urban greeneries have helped increase the walkscore, thus interpreting the neighbourhood's walkability. The different scenarios developed also show the capability of the proposed workflow as the main objective of this study, as well as the incorporation of generative design into the urban planning process to be a discussion tool for the policymakers, stakeholders, and other parties involved. However, further discussion with stakeholders is needed to determine constraints to produce more reliable scenarios that better represent the actual condition. It is also essential to notice that strategic planning of a location for different categories of amenities and locations for urban greeneries installation is needed to increase the walkability of a neighbourhood. The solutions are produced through generative design simulations.

In addition, as shown in Table 12, the workflow's base walkability score and walking experience are compared. Differences between these walkability scores could be due to people's slight overestimation or underestimation of their neighbourhood's current walkability level (Main study area: 56.93 & Second neighbourhood: 61.79, compared to 60 of Lozenet's walking experience). Even though there are these slight differences, all walkability scores still belong to the same category of "Somewhat Walkable". In conclusion, based on the proposed workflow's implementation in the second neighbourhood, the proposed workflow appears to be aligned with the people's walking experience.

### 7.4. Limitations

Some limitations have been identified during the study's process. As mentioned in section 4.3, this study is trying to combine two indicators with different units, making the utilization of the index highly important. An index is a method that is highly popular, multidimensional, as well as easy to understand by the general public. However, implementing the index could also lead to the loss of actual measurement units that cannot be avoided. Hence, this study produced walkability optimal urban design with a standardized score unit instead of being specific to what distance or how much density of greenery it represents. The second limitation is that even though it has been concluded that the proposed workflow could also work multi-dimensionally, the urban greenery indicator in this study only applies during the daytime and spring-summer season. This season limitation is due to the NDVI extracted from the orthophoto during summer and the need for urban greeneries as natural shading may differ each season. The third limitation is the walking preference survey. The survey has a limited period of only four weeks, which may reduce the number of respondents we got. Other than that, the age group spread is unequal as most respondents are from 39 to 52 years old. In addition, to avoid any overestimation of willingness to walk, a survey needs to be done in a different form instead of only based on a google form. The fifth limitation is that the proposed workflow does not include additional constraints such as time, budget or even regulatory aspects, e.g., floor area ratio (FAR). Selecting constraints is essential in determining what scenarios to make and fit the stakeholders' preferences, which could also align with Sofia's building code regulation.

# 8. CONCLUSION AND RECOMMENDATION

The research questions are addressed in this chapter, as well as suggestions for further research.

## 8.1. Conclusions

This research aimed to develop a workflow of walkability-optimal urban plans considering comfort dimensions through strategic placement of amenities and urban greeneries. A neighbourhood in Sofia, Bulgaria's Vitosha quarter's Krastova Vada area, was chosen as the case study for implementing the proposed workflow. In order to reach the objective, several research questions were addressed:

6.1.1 To review how walkability assessment has been done

1. What kind of method and input data is needed to quantify walkability?

Based on the literature review 2.1, the quantification of walkability has been done with the walkability index method, developed by Frank et al. (2010). Furthermore, the walkability index has been developed using other criteria and combinations, such as (1) by Glazier et al. (2014), which measured walkability based on population density, housing density, roadway connectivity, and retail locations and services within 10-minute of walking, (2) Walkscore (www.walkscore.com), which recognizes and rewards initiatives at the building and street-level by finding the shortest path to get to amenities.

Based on the literature review section 2.1, three main parameters are needed to quantify walkability based on comfort: street network, residential buildings, amenities, and NDVI along the street. Grocery shops, Food Vendors (Restaurant, Café, Bars), School (Education), Office, Parks, Health Facility, Retails (Clothing, Hardware, Music, Book) and Entertainment (Sports Club, Cinema, Libraries), and Public Transport Hub, has been defined as the category of amenities. Table 3 shows the specified input data to quantify walkability in this study. Two indicators have been determined to represent the comfort dimension: (1) distance to amenities and (2) urban greeneries.

3. How to integrate walkability with parametric modelling for generative design?

Based on the literature review section 2.3, the integration between walkability with parametric modelling can be done through visual programming software. The initial geospatial data should be imported through a plug-in in the chosen visual programming software, and the parametric model can be developed. The integration is essential since we must create a parametric model based on walkability input data to run the generative design.

6.1.2 To develop a workflow based on the integration of comfort dimension indicators

1. What method is used to quantify distance to amenities?

Through the literature review, A* algorithm (see 2.3) has been identified and implemented to quantify distance to amenities indicator for walkability assessment in the generative design domain.

2. What method is used to quantify urban greeneries?

Through the literature review, NDVI (see 2.4) has been identified and implemented to quantify urban greeneries indicators for walkability assessment in the generative design domain.

3. What method is used to integrate the distance to amenities and urban greeneries indicators?

Based on the literature review and elaborated in the proposed workflow (4.3), it has been defined that the currently available method used to integrate two different indicators with different units is also based on an index. However, it is also has been identified that there are limitations to this method. For instance, walkability is based on personal experience and cultural background. Thus, the integration method will also incorporate the personal opinion of people who live in the study area and is based on a walking preference survey.

6.1.2 To implement the proposed workflow in a case study

1. How do people perceive the study's chosen indicator?

Initially, determining which indicators are more important than the others to represent the comfort dimension based on the literature review has not given an appropriate value for the weightage. As it has been partly answered in the previous research question, incorporating a human perspective is essential since walkability is based on personal experience and an individual's cultural background. In order to get the human perspective, a walking preference survey has been conducted. In addition, it is also decided to determine the weight between the indicators based on the survey.

The walking preference survey contains the people of Sofia's personal experience in walking and their preference when they have to state each indicator's importance. Since the results show that distance to amenities received more importance than the urban greeneries, the weight value of distance to amenities is higher in the integration process, as shown in 5.1.2.

2. How much does the implementation of the proposed workflow improves the walkability?

As shown in section 6.1.1, the initial value for standardized walkability score is 56.93, which belongs to the "Somewhat Walkable" category. The near-optimum solutions have been generated after implementing generative design simulations with three different scenarios. Table 10 shows the three scenarios that show an increase from the initial score and upgraded the base walkability into the "Very Walkable" category. Hence, it is concluded that the strategic placement of amenities and urban greeneries implementation can improve the overall standardized walkability score.

3. How does implementing the proposed workflow in different locations correspond with the people's walking experience?

Presented in 6.2, the comparison between people's walking experience and the proposed workflow's base walkscore has been made. The comparison has resulted in the proposed workflow aligning with the people's walking experience.

## 8.2. Recommendations for further studies

This study focuses on developing a workflow for walkability assessment and planning based on the comfort dimension. It also has been mentioned that there are limitations of this study. However, these limitations can always be addressed and improved in future studies.

First, since the proposed workflow is multidimensional but is only based on a specific season (summer) and does not include a time of day, it is recommended to have an additional dimension of different seasons or times of the day. Adding seasons or time of day is essential to portray a more realistic situation to create walkability-optimal-urban plans.

Second, as there is a probability of an overestimation of willingness to walk in the walking preference survey, we recommend that the walking preference survey could be done based on technology like AR or VR. This type of technology can lead to more accurate results of perceived walking time and objective, as it is based on an individual's virtual experience to determine their actual walking time in such an environment, rather than just estimating it.

Third, if a survey is needed to determine the importance of indicators, we recommended that a more extended period for the survey is needed. More respondents could represent better the actual condition of people's walking preference. In addition, an equal spread of respondents' backgrounds could give an advantage in interpreting the walking preference of the survey.

Fourth, the utilization of 3D could be done in the future to measure the Z-unit-related indicator for walkability. As discussed in discussion 6.2, measuring and simulating shade coverage of buildings to quantify walkability is possible, which we believe would be an added value for 3D-based simulation.

At last, more constraints should be introduced to make the walkability-optimal urban plan more realistic. In determining the type of constraint that can be introduced, we recommend having a further discussion with stakeholders. Choosing a relevant constraint should lead to a generation of more accurate and realistic scenarios to be implemented in the neighbourhood.

# 9. ETHICAL CONSIDERATION

All of the information that Sofiaplan gave was confidential and was solely used for research purposes. The respondents' agreement was requested before, and the survey was conducted anonymously. The data collected was only used solely for this study.

# LIST OF REFERENCES


Abastante, F., Lami, I.M., Riccia, L. la, Gaballo, M., 2020. Supporting resilient urban planning through walkability assessment. Sustainability (Switzerland) 12. https://doi.org/10.3390/SU12198131

al Shammas, T., Escobar, F., 2019. Comfort and Time-Based Walkability Index Design: A GIS-Based Proposal. International Journal of Environmental Research and Public Health 16. https://doi.org/10.3390/IJERPH16162850

Arvidsson, D., Kawakami, N., Ohlsson, H., Sundquist, K., 2012. Physical activity and concordance between objective and perceived walkability. Medicine and Science in Sports and Exercise 44, 280–287. https://doi.org/10.1249/MSS.0B013E31822A9289

Baobeid, A., Koç, M., Al-Ghamdi, S.G., 2021. Walkability and Its Relationships With Health, Sustainability, and Livability: Elements of Physical Environment and Evaluation Frameworks. Frontiers in Built Environment 7. https://doi.org/10.3389/FBUIL.2021.721218

Battista, G.A., Manaugh, K., 2019. Generating walkability from pedestrians' perspectives using a qualitative GIS method. Travel Behaviour and Society 17, 1–7. https://doi.org/10.1016/J.TBS.2019.05.009

Canadinc, S.T., Wang, B., Pi, Y., Yan, W., 2020. Multi-User and Web-based Parametric Modeling with Multiple Visual Programming Tools. Werner, L and Koering, D (eds.), Anthropologic: Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference - Volume 1, TU Berlin, Berlin, Germany, 16-18 September 2020, pp. 19-28.

Carr, L.J., Dunsiger, S.I., Marcus, B.H., 2011. Validation of Walk Score for estimating access to walkable amenities. British Journal of Sports Medicine 45, 1144–1148. https://doi.org/10.1136/BJSM.2009.069609

Dimitrova, E., 2010. The present day of Sofia: vulnerability and vitality of public urban space, in: Scientific Conference on Cultural Historic Heritage of Sofia: Problems and Perspectives. Sofia Museum of History, Sofia, pp. 234–238.

Erickson, L.E., Jennings, M., 2017. Energy, Transportation, Air Quality, Climate Change, Health Nexus: Sustainable Energy is Good for Our Health. AIMS Public Health 4, 47. https://doi.org/10.3934/PUBLICHEALTH.2017.1.47

ESRI, 2021. ArcGIS Pro.

Fainstein, S.S., 2005. Fainstein Planning Theory and the City Planning Theory and the City. Journal of Planning Education and Research 25, 121–130. https://doi.org/10.1177/0739456X05279275

Franěk, M., Režný, L., Šefara, D., Cabal, J., 2018. Effect of Traffic Noise and Relaxations Sounds on Pedestrian Walking Speed. International Journal of Environmental Research and Public Health 2018, Vol. 15, Page 752 15, 752. https://doi.org/10.3390/IJERPH15040752

Frank, L.D., Sallis, J.F., Saelens, B.E., Leary, L., Cain, L., Conway, T.L., Hess, P.M., 2010. The development of a walkability index: application to the Neighborhood Quality of Life Study. British Journal of Sports Medicine 44, 924–933. https://doi.org/10.1136/BJSM.2009.058701

Frank, L.D., Schmid, T.L., Sallis, J.F., Chapman, J., Saelens, B.E., 2005. Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ. American Journal of Preventive Medicine 28, 117–125. https://doi.org/10.1016/J.AMEPRE.2004.11.001

Galal Ahmed, K., Alipour, S.M.H., 2021. More dense but less walkable: the impact of macroscale walkability indicators on recent designs of emirati neighborhoods. City, Territory and Architecture 8, 1–26. https://doi.org/10.1186/S40410-021-00140-3/TABLES/7

Galal, O.M., Sailor, D.J., Mahmoud, H., 2020. The impact of urban form on outdoor thermal comfort in hot arid environments during daylight hours, case study: New Aswan. Building and Environment 184, 107222. https://doi.org/10.1016/J.BUILDENV.2020.107222

GATE, Sofia University, 2019. GATE Project [WWW Document]. GATE Project at a glance. URL https://www.gate-coe.eu/about.html (accessed 6.19.21).

Gilderbloom, J.I., Riggs, W.W., Meares, W.L., 2015. Does walkability matter? An examination of walkability's impact on housing values, foreclosures and crime. Cities 42, 13–24. https://doi.org/10.1016/J.CITIES.2014.08.001

Glazier, R.H., Creatore, M.I., Weyman, J.T., Fazli, G., Matheson, F.I., Kaufman-Shriqui, V., 2014. Correction: Density, Destinations or Both? A Comparison of Measures of Walkability in Relation to Transportation Behaviors, Obesity and Diabetes in Toronto, Canada. PLOS ONE 9, e91485. https://doi.org/10.1371/JOURNAL.PONE.0091485

Habibian, M., Hosseinzadeh, A., 2018. Walkability index across trip purposes. Sustainable Cities and Society 42, 216–225. https://doi.org/10.1016/J.SCS.2018.07.005

Hargreaves, D.S., Sizmur, S., Viner, R.M., 2012. Do Young and Older Adults Have Different Health Care Priorities? Evidence From a National Survey of English Inpatients. Journal of Adolescent Health 51, 528–532. https://doi.org/10.1016/J.JADOHEALTH.2012.05.016

Indraprastha, A., Pranata Putra, B.D., 2019. Informed walkable city model. Intelligent and Informed - Proceedings of the 24th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2019 2, 161–170.

Irafany, S.A., Wunas, S., Trisutomo, S., Akil, A., Arifin, M., Rasyid, A.R., 2020. Walkability index based on pedestrian needs in the Losari beach area of Makassar city. Indian Journal of Forensic Medicine and Toxicology 14, 7936–7947. https://doi.org/10.37506/IJFMT.V14I4.12899

Islam, S., 2011. Traditional urban planning approaches and sustainable city. Open House International 36, 15–23. https://doi.org/10.1108/OHI-02-2011-B0003

Jakubiec, J.A., Reinhart, C.F., Dogan, T., Rakha, T., Sang, A., 2013. UMI - An urban simulation environment for building energy use, daylighting and walkability, in: Proceedings of Building Simulation. Chambery, pp. 476–483.

Klemm, W., Heusinkveld, B.G., Lenzholzer, S., van Hove, B., 2015. Street greenery and its physical and psychological impact on thermal comfort. Landscape and Urban Planning 138, 87–98. https://doi.org/10.1016/J.LANDURBPLAN.2015.02.009

Koo, B.W., Guhathakurta, S., Botchwey, N., 2022. How are Neighborhood and Street-Level Walkability Factors Associated with Walking Behaviors? A Big Data Approach Using Street View Images. Environment and Behavior 54, 211–241. https://doi.org/10.1177/00139165211014609

Koohsari, M.J., McCormack, G.R., Shibata, A., Ishii, K., Yasunaga, A., Nakaya, T., Oka, K., 2021. The relationship between walk score® and perceived walkability in ultrahigh density areas. Preventive Medicine Reports 23. https://doi.org/10.1016/J.PMEDR.2021.101393

Lai, K.Y., Kumari, S., Gallacher, J., Webster, C., Sarkar, C., 2022. Associations of residential walkability and greenness with arterial stiffness in the UK Biobank. Environment International 158, 106960. https://doi.org/10.1016/J.ENVINT.2021.106960

Landrigan, P.J., 2017. Air pollution and health. The Lancet Public Health 2, 4–5. https://doi.org/10.1016/S2468-2667(16)30023-8

Leong Yee, W., 2019. Application of parametric components in architectural planning. IOP Conference Series: Materials Science and Engineering 636. https://doi.org/10.1088/1757-899X/636/1/012003

Masoumzadeh, S., Pendar, H., 2019. Walking as a medium of comprehending contextual assets of historical urban fabrics. Urban Research & Practice 14, 50–72. https://doi.org/10.1080/17535069.2019.1652931

McCormack, G.R., Cerin, E., Leslie, E., du Toit, L., Owen, N., 2007. Objective Versus Perceived Walking Distances to Destinations: Correspondence and Predictive Validity. Environment and Behaviour 40, 401–425. https://doi.org/10.1177/0013916507300560

Mousiadis, T., Mengana, S., 2016. Parametric BIM: Energy Performance Analysis Using Dynamo for Revit. Stockholm.

Municipality of Sofia, ARUP, European Bank for Reconstruction and Development, 2020. Green City Action Plan. Sofia.

Piacentino, G., 2011. ShortestWalk.

Pun-Cheng, L.S.C., So, C.W.Y., 2019. A comparative analysis of perceived and actual walking behaviour in varying land use and time. Journal of Location Based Services 13, 53–72. https://doi.org/10.1080/17489725.2018.1563308

Rakha, T., Reinhart, C., 2012. Generative Urban Modelling: A design workflow for walkability-optimized-cities. SimBuild 255–262.

Raswol, L.M., 2020. Qualitative Assessment for Walkability: Duhok University Campus as a Case Study. IOP Conference Series: Materials Science and Engineering 978. https://doi.org/10.1088/1757-899X/978/1/012001

Rees, W., 2003. Ecological Footprints and Urban Transportation, in: Tolley, R. (Ed.), Sustainable Transport. Woodhead Publishing Limited, pp. 3–19.

Russel, S., Norvig, P., 2020. Artificial Intelligence: A Modern Approach, 4th ed. Pearson, Boston.

Southworth, M., 2005. Designing the Walkable City. Journal of Urban Planning and Development 131, 246–257. https://doi.org/10.1061/(ASCE)0733-9488(2005)131:4(246)

Teshnehdel, S., Akbari, H., di Giuseppe, E., Brown, R.D., 2020. Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran. Building and Environment 178, 106899. https://doi.org/10.1016/J.BUILDENV.2020.106899

Turoń, K., Czech, P., Juzek, M., 2017. The concept of a walkable city as an alternative form of urban mobility. Transport: Politechnika Śląska 95, 223–230. https://doi.org/10.20858/SJSUTST.2017.95.20

Ulmer, J.M., Wolf, K.L., Backman, D.R., Tretheway, R.L., Blain, C.J., O'Neil-Dunne, J.P., Frank, L.D., 2016. Multiple health benefits of urban tree canopy: The mounting evidence for a green prescription. Health & Place 42, 54–62. https://doi.org/10.1016/J.HEALTHPLACE.2016.08.011

Walk Score®, 2022. Walk Score [WWW Document]. URL https://www.walkscore.com/ (accessed 1.31.22).

Wang, L., Chen, K.W., Janssen, P., Ji, G., 2020. Enabling Optimisation-based Exploration for Building Massing Design: A Coding-free Evolutionary Building Massing Design Toolkit in Rhino-Grasshopper, in: Holzer, D., Nakapan, W., Globa, A., Koh, I. (Eds.), Anthropocene, Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference - Volume 1. Chulalongkorn University, Bangkok, pp. 255–264.

Zhang, X., Mu, L., 2019. The perceived importance and objective measurement of walkability in the built environment rating: Environment and Planning B: Urban Analytics and City Science 47, 1655–1671. https://doi.org/10.1177/2399808319832305

Zhang, Y., Liu, C., 2019. Parametric modeling for form-based planning in dense urban environments. Sustainability (Switzerland) 11, 1–14. https://doi.org/10.3390/su11205678

Zhu, W., Hua, Y., Dogan, T., 2019. Evaluating Street Quality for Walkability from 3D Models. IOP Conference Series: Earth and Environmental Science 294, 012025. https://doi.org/10.1088/1755-1315/294/1/012025

# APPENDIX

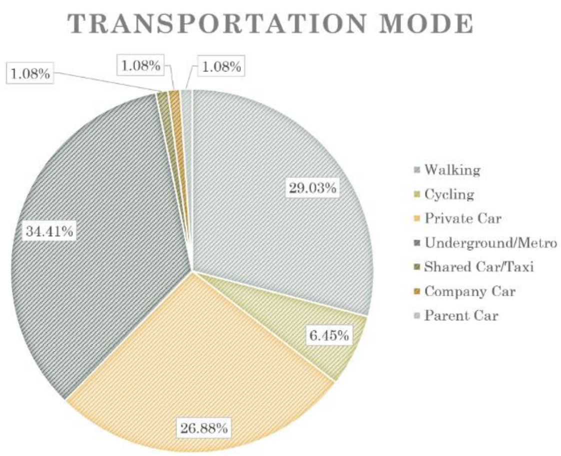
**Annex 1: Available dataset**

Appendix 1. Complete set of available data

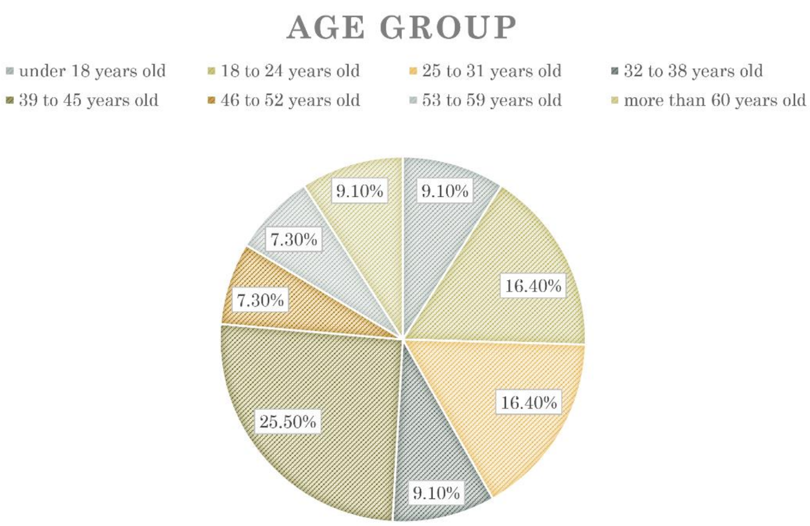
| Data Input | Format | Source | Details |
|---|---|---|---|
| BGR_Sofia.156140_IWEC | .epw | EnergyPlus | Sofia weather file 2020 |
| Buildings_commercial | .shp | SofiaPlan | Vector of buildings in Krastova Vada (including building footprint, height, number of floors, and some specifications) |
| Buildings_education | | | |
| Buildings_healthcare | | | |
| Buildings_hotels | | | |
| Buildings_industrial | | | |
| Buildings_office | | | |
| Buildings_residential | | | |
| Buildings_technical_facility | | | |
| Bus_lines | .shp | SofiaPlan | Polyline of bus network with some specification |
| City_unit | .shp | SofiaPlan | Vector file of city unit |
| Existing_pedestrian_network | .shp | SofiaPlan | Polyline of pedestrian network with some specification |
| Existing_street_network | .shp | SofiaPlan | Polyline of street network with some specifications (e.g., travel speed, vehicles) |
| Green_areas_private_urban_forest | .shp | SofiaPlan | Vector file of urban forest as private green area |
| Green_areas_public_urban_forest | .shp | SofiaPlan | Vector file of urban forest as public green area |
| Green_private_areas | .shp | SofiaPlan | Vector file of private green areas |
| Neighbouring_city_units | .shp | SofiaPlan | Administrative vector file of neighbouring city units |
| Noise_levels | .shp | SofiaPlan | Polyline of noise levels |
| Points_of_interest | .shp | SofiaPlan | Point vector of area with interest in development |
| Population_age_structure | .shp | SofiaPlan | The number of population with age structure in vector file |
| Potential_merge_properties | .shp | SofiaPlan | Vector file of areas with potential merging development |
| Potential_single_properties | .shp | SofiaPlan | Vector file of areas with a single potential development |
| Property_boundaries_cadastre | .shp | SofiaPlan | Administrative vector file of property boundaries |
| Public_transport_stops | .shp | SofiaPlan | Point vector file of public transport stops |
| Sewerage_pipe_network | .shp | SofiaPlan | Polyline of sewerage pipe network |

| | | | |
|---|---|---|---|
| Subway_station | .shp | SofiaPlan | Point vector of the location of the subway station |
| Subway_station_entrance | .shp | SofiaPlan | Point vector of the subway entrance location |
| Terrain_elevation | .shp | SofiaPlan | Polyline of terrain elevation |
| Water_bodies | .shp | SofiaPlan | Polyline of waterbodies network |
| Waterbodies_buffer50m | .shp | SofiaPlan | Buffered line of waterbodies network |
| Water_supply_pipe_network | .shp | SofiaPlan | Polyline of water supply pipe network |
| Sofia_20cm_8bands | .tif | GATE Project | Raster file of Sofia with eight bands |

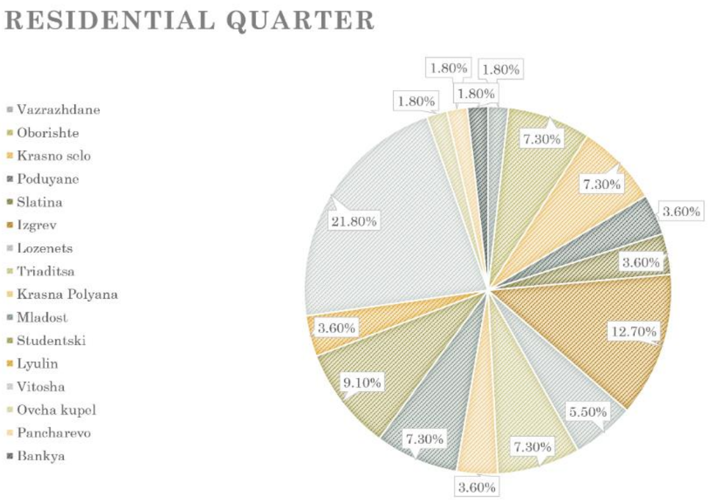
**Annex 2: Walking preference survey result**




Appendix 2. Preferred transportation mode of respondents




Appendix 3. Age group of respondents




Appendix 4. Residential location of respondents

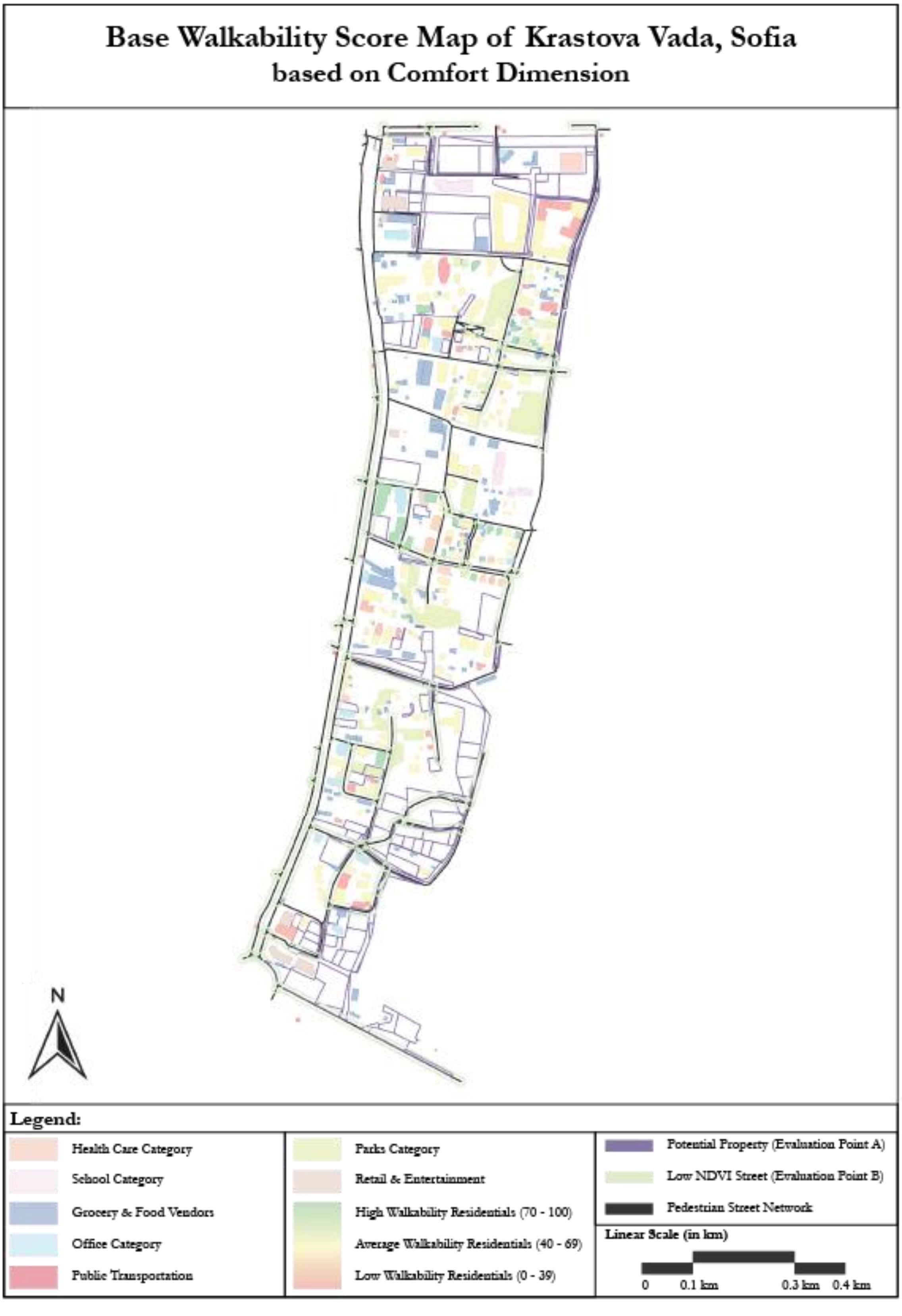
Appendix 5. Crosstabulation of preferred transportation and walking experience

| Transportation Mode | Walking Experience |
|---|---|
| Company car | 7 |
| Personal car | 5.3 |
| Public transport / Metro | 5.5 |
| Walking | 5.6 |
| Cycling | 4 |
| Parent Car | 5 |
| **Average Score** | **5.39** |

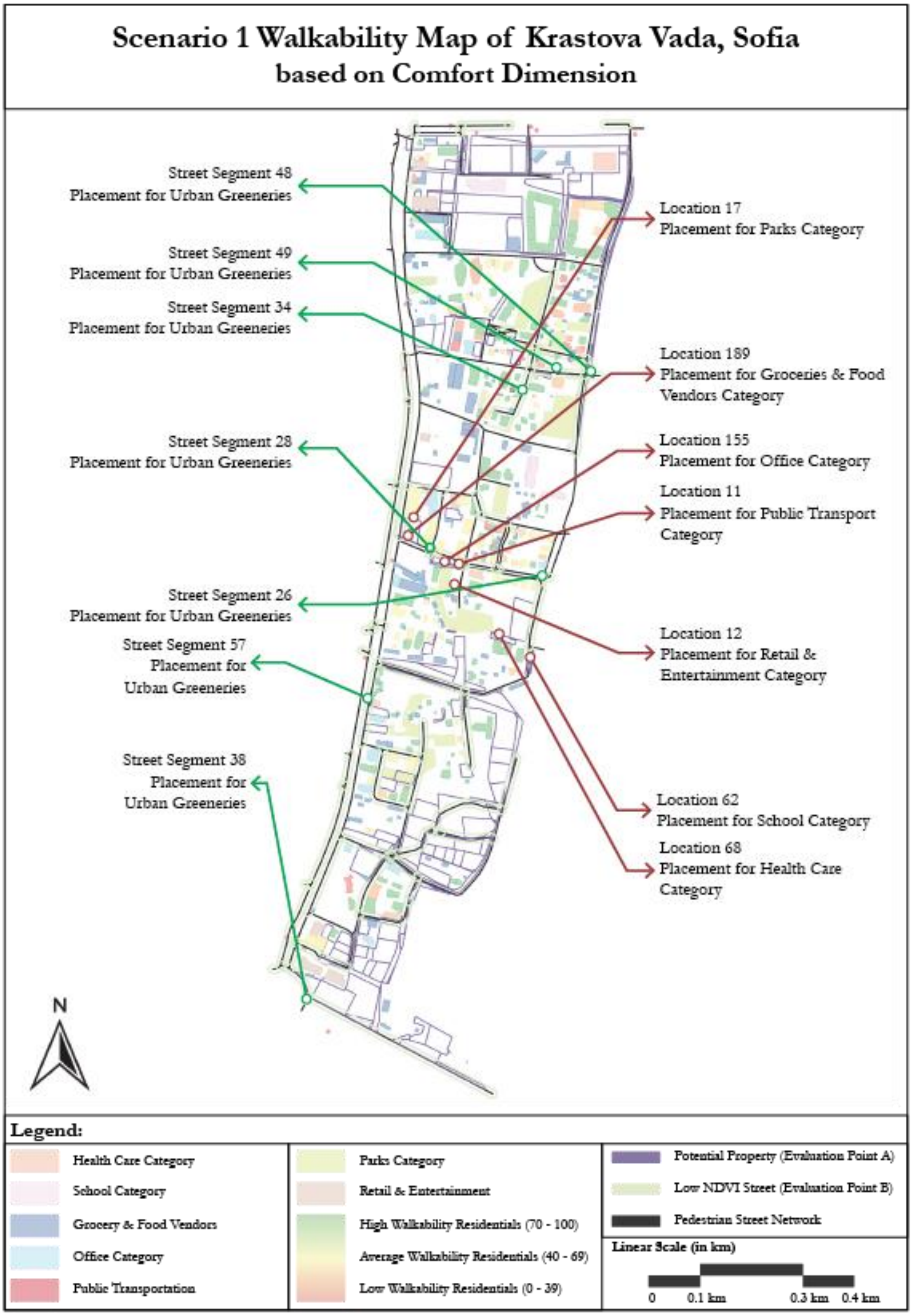
Appendix 6. Crosstabulation of age group and walking experience

| Age Group | Walking Experience |
|---|---|
| 18 to 24 years | 6.56 |
| 25 to 31 years | 5.22 |
| 32 to 38 years | 5.25 |
| 39 to 45 years | 4.71 |
| 46 to 52 years | 6.5 |
| 53 to 59 years | 7 |
| over 60 years | 5 |
| under 18 years | 3.8 |
| **Average Score** | **5.39** |

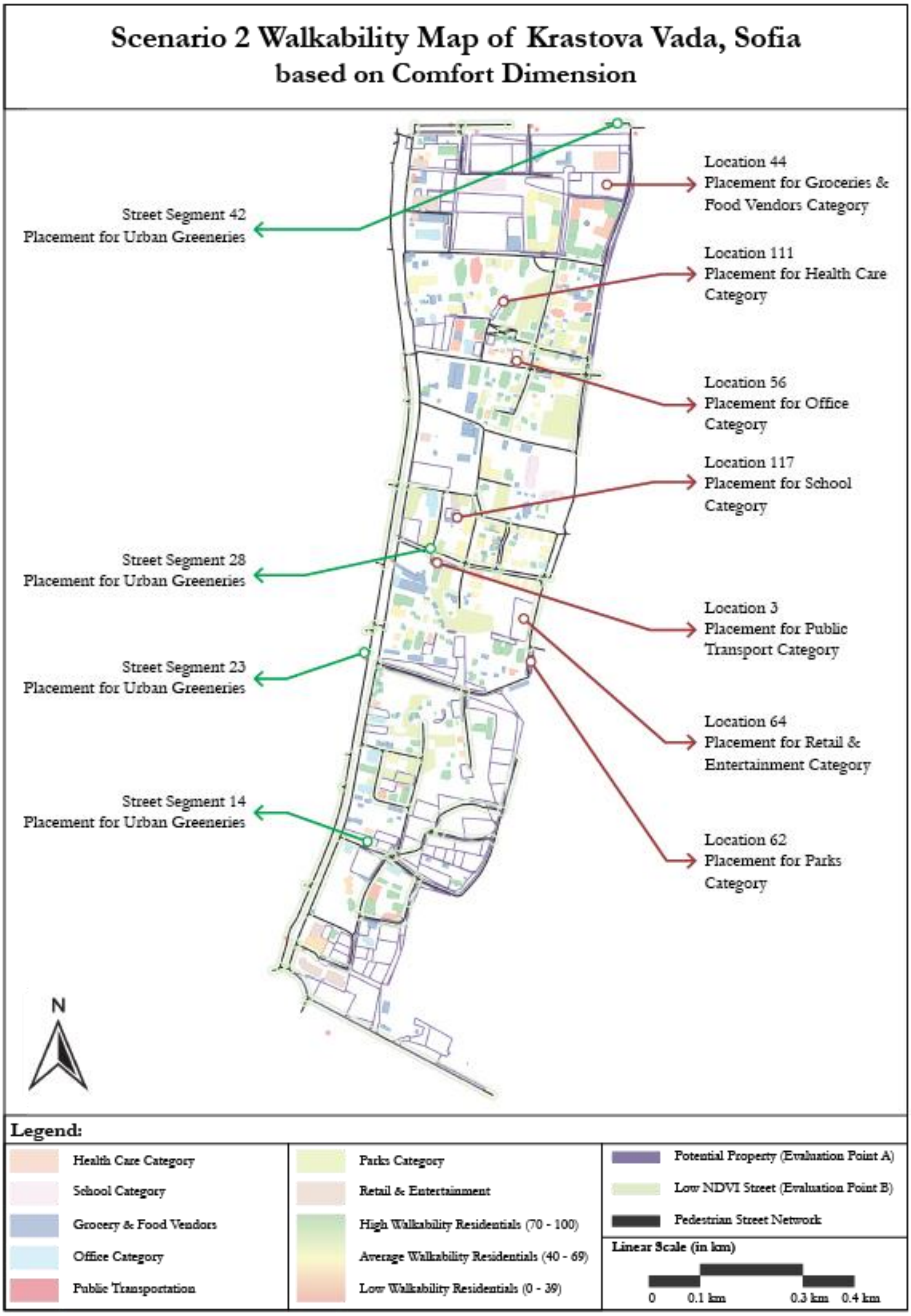
**Annex 3: Walkability Maps**



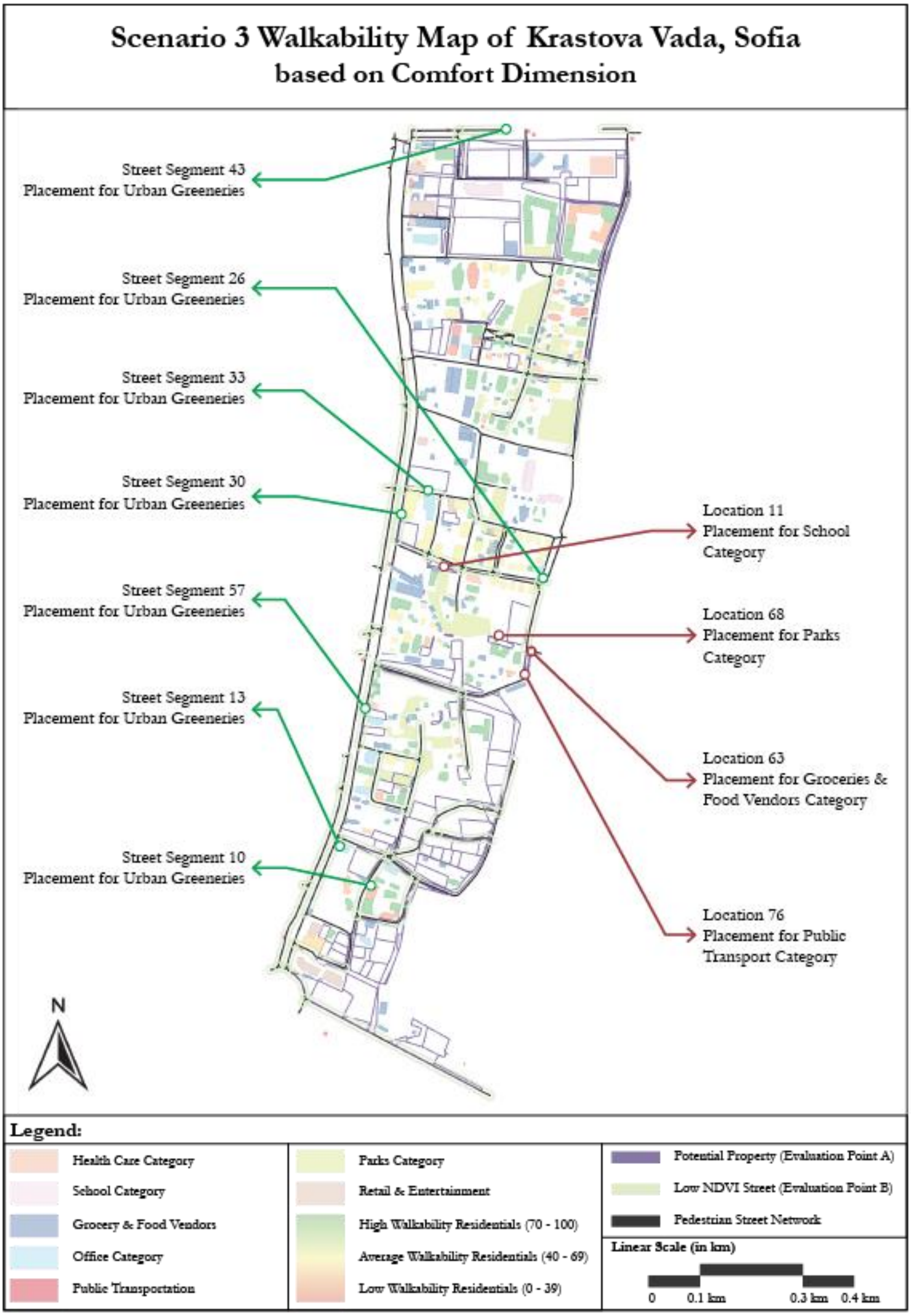

Appendix 7. Base walkability score map of Krastova Vada




Appendix 8. Scenario 1 walkability map of Krastova Vada

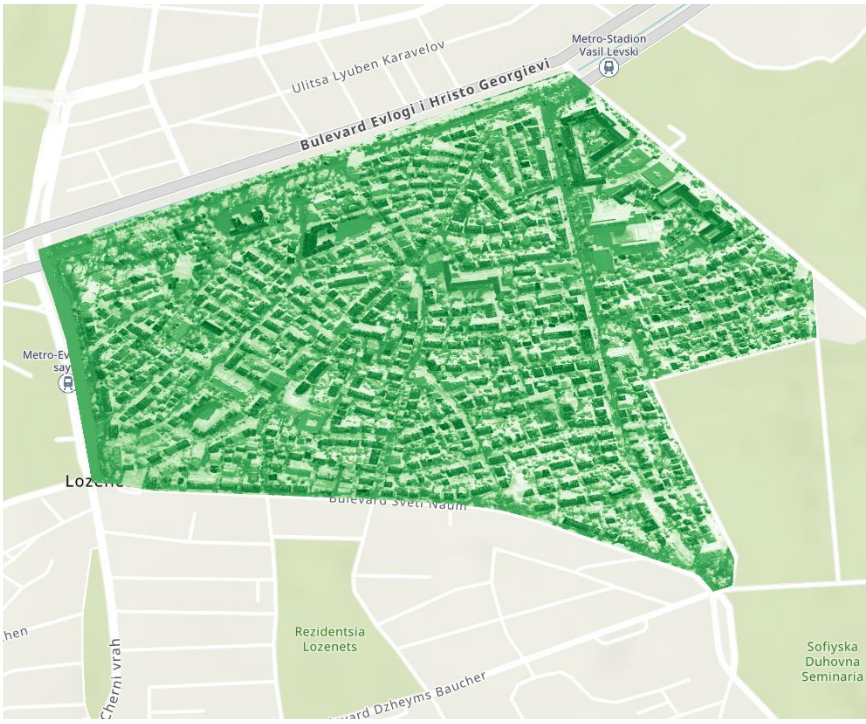



Appendix 9. Scenario 2 walkability map of Krastova Vada

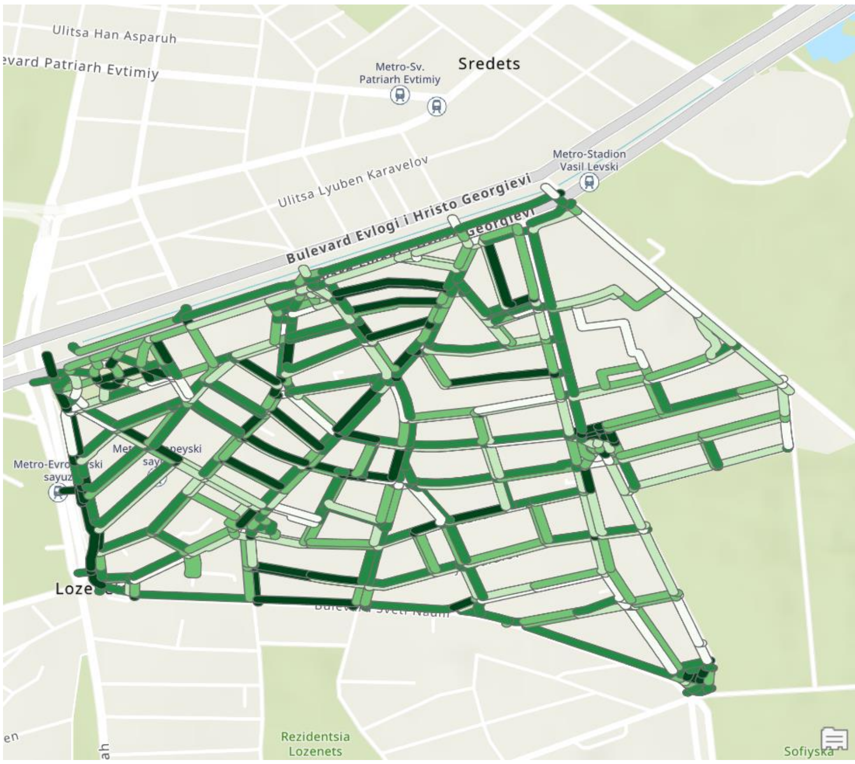



Appendix 10. Scenario 3 walkability map of Krastova Vada

**Annex 4: Lozenets**

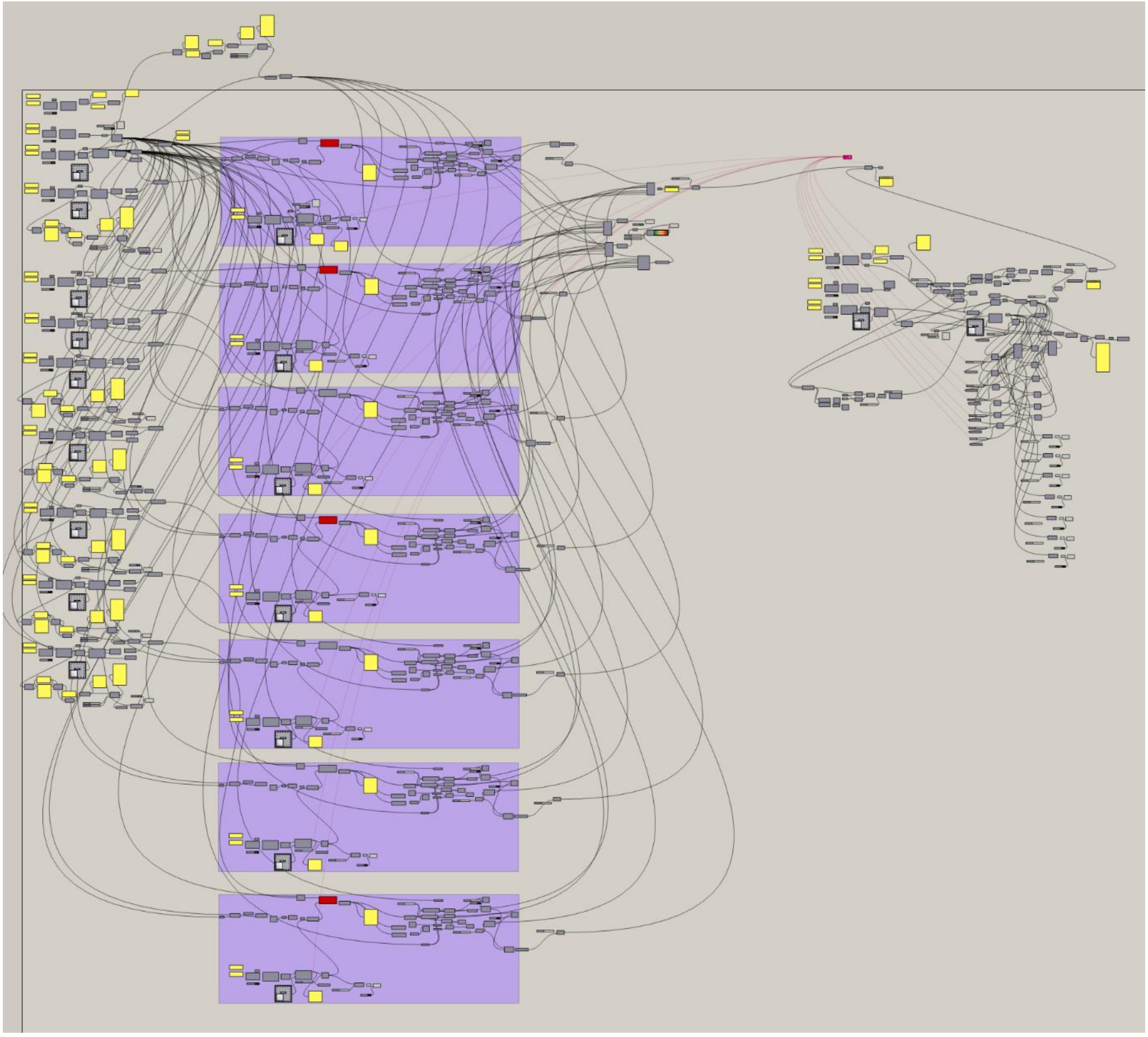



Appendix 11. Lozenets NDVI




Appendix 12. Lozenets' street with NDVI

**Annex 5: Grasshopper workflow**



Appendix 13. Overview of workflow implementation in Grasshopper

**Annex 6: Non-linear weightage**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | <400m | | | | | | | | | |
| | | 0.111 | <400m | | | | | | | | |
| High green | 0.09 | 0.201 | 0.101 | <400m | | | | | | | |
| | Mid green | 0.08 | 0.181 | 0.081 | 400-1600m | | | | | | |
| | | Low green | 0.07 | 0.151 | 0.071 | 400-1600m | | | | | |
| | | | High green | 0.06 | 0.131 | 0.061 | 400-1600m | | | | |
| | | | | Mid green | 0.05 | 0.111 | 0.051 | 1600-2400m | | | |
| | | | | | Low green | 0.04 | 0.091 | 0.041 | 1600-2400m | | |
| | | | | | | High green | 0.03 | 0.071 | 0.021 | 1600-2400m | |
| | | | | | | | Mid green | 0.02 | 0.041 | 0.012 | |
| | | | | | | | | Low green | 0.01 | 0.022 | SUM |
| | | | | | | | | | | SUM | 1 |

Appendix 14. Detailed non-linear weightage