GENERATIVE DESIGN FOR WALKABLE CITIES: A CASE STUDY OF SOFIA

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ABSTRACT:

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. 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, an 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, develop a workflow to integrate walkability and parametric modelling based on comfort dimensions to create walkability-optimal-urban-plans.

1. INTRODUCTION

Pedestrian-friendly environments are essential in creating healthy and productive communities. This could be accomplished by improving walkability within the urban context by more consistent and strategic placement of amenities and improved transport options (Zhang and Mu, 2019). 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. The walkable city concept aligns with Sofia's Green City Action Plan initiatives.

Urban planning is a fundamental discipline that enables walkability improvement through sustainable urban development planning. While walkability has the potential to be a significant criterion influencing urban design, it is currently only utilised for design assessment rather than as a design goal (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 for urban planning. 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, optimisation methods are integrated with relevant parametric models to semi-automatically generate near-optimum designs 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 (Zhang and Liu, 2019). A generative design approach can also be implemented for walkability-optimal design. However, in the current state-of-art, the generative design approach for walkability only considers one leading indicator: the distance to amenities. In this case, amenities meant the place of where people can conduct their errands, namely, school, office, parks, grocery shops, retail, etc.

Studies in recent years have proven that the walkable city concept is not only about "distances" but should also consider comfort as one of its dimensions (Koo et al., 2022). Providing a sense of comfort to people may influence overall perceptions of walkability and potentially contribute to their walking behaviour. One of the mainstream indicators of comfort is urban greeneries. Urban greeneries play a significant part in walkable environments since they generate shade and greenery, increasing people's willingness to walk by providing visual aesthetics and a sense of comfort (Ulmer et al., 2016). At the same time, 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).

Aside from being shaped and analysed by its built environment, walkability is also highly personal. Daily activities and cultural backgrounds could also shape an individual's perceived walkability and reflect on their action. Moreover, when trying to evaluate walkability in terms of comfort, the combination of different indicators is usually done. But it is nearly impossible to generalise which indicator is more important to people. Since we cannot overlook the fact that walkability is highly personal, people with different backgrounds may have different perspectives on factors that influence walkability. Therefore, planning a walkable city should not only be based on quantitative analysis but also incorporate a human perspective. Building up on that, this research aims to develop a workflow for strategic

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placement of amenities and urban greeneries with the incorporation of a human perspective to create walkability-optimal-urban-plans.

The remaining of the paper is structured as follows: Section 2 describes the area of study, Section 3 outlines the research methodology, Section 4 describes the proposed workflow, Section 5 presents the proposed workflow implementation, Section 6 presents the obtained results and Section 7 discusses the results, and Section 8 outlines the conclusion of the research.

2. STUDY AREA

2.1 Study area and data description

As a typical highly urbanised capital city with predominantly used car transport the city of Sofia has been selected for the current research. The focus is on one of the newest neighbourhoods called Krastova Vada. The data for the research has been provided by Sofiaplan, which is a municipal enterprise responsible for the spatial and strategic planning of Sofia 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 paper.

Data Input	Format	Source
Buildings vector	.shp	SofiaPlan
Amenities vector	.shp	SofiaPlan
Street network vector	.shp	SofiaPlan
Orthophoto (30 cm) based on digital aerial data acquisition	.tif	GIS-Sofia

Table 1. Data description

Krastova Vada quarter 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 quarter to Vitosha quarter, 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 the Green City Action Plan (Municipality of Sofia et. al., 2020).

3. METHODOLOGY

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.

4. PROPOSED WORKFLOW

This section describes the proposed workflow for strategic placement of amenities and urban greeneries with the human perspective that has been developed following the methodology. Figure 2 outlines the main parts 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.

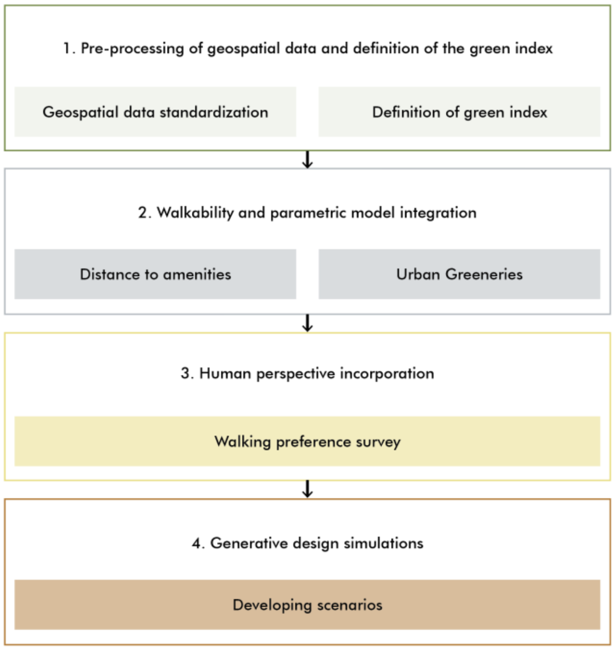

Figure 1. Overview of the proposed workflow

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 geospatial data by generalizing the shapefiles UTM into WGS84, filtering data, and vector correction, to make it fit for use. The output of this standardisation is used to generate the primary data input for walkability. Three parameters are identified to quantify walkability based on comfort: street network, residential buildings, amenities vectors, 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.

The green index is based on the calculated NDVI. The NDVI raster is produced through processing the orthophoto file to NDVI format and generating the NDVI raster based on the formula below.

$$NDVI = (IR - R)/(IR + R) \tag{1}$$

where IR = the spectrum in the near-infrared section
R = the spectrum in the red section

The generated NDVI raster needs to be combined with a 4 m buffer of street segments from the pedestrian network shapefiles through spatial join to produce the street with an NDVI score. The 4 m buffer of the pedestrian network is chosen since we aim to evaluate the urban greeneries along the street only, and 4 m is the length of approximate tree coverage along the pedestrian (Teshnehdel et al., 2020). This buffer also includes the general extent of a pedestrian.

4.2 Walkability and parametric model integration

The data input from the previous part should be utilised to create the parametric model by importing the relevant shapefiles to the parametric modelling software and transforming the data based on the needs (e.g., polylines to brep). The generated parametric model is utilised for both indicator measurements. The distance to amenities-based measurement is generating a walkability score from 0 to 100 (a higher score means higher walkability). The walkability score based on the distance to amenities needs to be incorporated with evaluation point A. Evaluation point A is the midpoint of the available land dedicated to future urban planning. This evaluation point A is utilised as the land that is evaluated and chosen as the location of strategic placement of amenities for the generative design simulations.

In addition, the distance to amenities is done individually based on each category of amenities to avoid fallacy. For instance, if all amenities are considered 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. Ultimately, we still need to combine these amenities to generate the average walkability score as a baseline. Each amenity should be weighted based on its importance. Since the perceived importance of amenities may differ between locations, a human perspective is also incorporated in this part (see 5.1.3).

The urban greeneries-based measurement needs to produce a walkability score from 0 to 100 (same as the distance to amenities), which is based on the NDVI values from the aggregated street segment with the NDVI. The walkability score based on urban greeneries should then be 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 incorporation

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 leads to this formula:

$$WI = (WF1\ x\ NF1) + (WF2\ x\ NF2) \tag{2}$$

where
WI = integrated walkability score
WF1 = distance to amenities values
WF2 = urban greeneries values
NF1 = weighted value for distance to amenities
NF2 = weighted value for urban greeneries

There are some limitations to this method. (1) it is almost impossible to determine whether one indicator is more important than the other is the same in different contextual locations, and (2) walkability is highly based on the individual's preference and cultural behaviour. To our knowledge, there are no other methods to combine different walkability indicators based on comfort that could address these limitations. To address these limitations, this study developed a walking preference survey which aims to get the people's preferences to determine the weightage value for each indicator on the formula. This needs to be done since the human perspective is considered highly important in walkability, minding the integration method's limitations. There are four primary points which are the essential information from the survey that should be implemented in the workflow, (1) the people's profile (residential location), (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 the base "walkability level" in their neighbourhood qualitatively, which is why a crosstabulation between Walking Experience and residential location is done. So that, we could have the information of each residential location's current walkability based on the local people's perspective. This information could be useful 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.

4.4 Generative design simulations

The generative design consisted of two main components, the parametric model and optimisation. The generative design simulations are based on integrating both indicators (distance to amenities and urban greeneries) to generate near-optimum solutions for the strategic placement of amenities and urban greeneries. The objective function should be the walkability score. These indicators should already be in the form of a parametric model component (see 5.2.1). The simulations should be able to provide 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 optimisation component.

In the generative design domain, the near-optimum solutions are generated through an optimisation component which consists of a series of "the fittest selection" (see Figure 3). The optimisation starts with generating populations of solutions. In our case, the population of solutions means that the available selections and

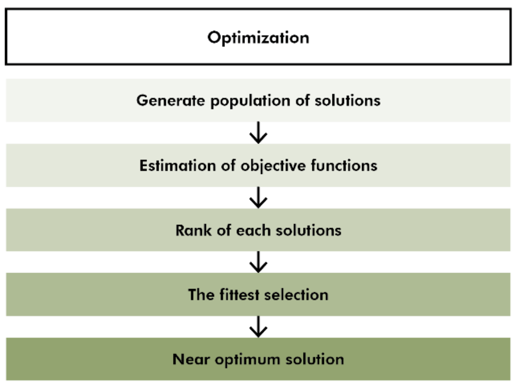

Figure 2. Optimization approach

combinations of Evaluation point A and Evaluation point B as the decision variables are calculated and generate a series of solutions. The next part is estimating objective functions, where the population of solutions from the previous part is estimated to meet certain objective functions. After that, these solutions are ranked from the best to the worst. Thus, the fittest solutions should be selected depending on our objective functions and become the "near-optimum solution". The lists of near-optimum solutions act as the options to be discussed and developed as the implemented walkability optimal urban plans by the stakeholders.

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 Section 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 was done in 4 weeks and gained 55 respondents. The survey is divided into four primary points, which are mentioned in section 4.3. The full version of the walking preference survey can be seen on the following link https://forms.gle/qCSsgvbHiTyvnXik9.

5.1.1 Walking experience and residential location

Presented in Table *2*, 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. While 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 nicer pedestrian infrastructure with enough greenery compared to other districts.

Residential District	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**

Table 2. People's walking experience average each residential quarter

5.1.2 Walking preference

Based on the survey result in Table *3*, 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). Hence, in the general condition, 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.

Distance to Amenities	Urban Greeneries
8 (Median)	8 (Median)
7.95 (Mean)	7.6 (Mean)
0.55 (Weighted Value)	**0.45 (Weighted Value)**

Table 3. The importance of each indicator from people's perceptive

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 a higher distance to amenities means urban greeneries are more important. In contrast, fewer urban greeneries mean shorter distances are more important. 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).

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

As mentioned in 4.2, the proposed workflow for determining distance to amenities is done individually. Ultimately, each amenity is weighted based on its importance to generate the base walkability score. The perceived importance of amenities is different for every location, and a human perspective is incorporated in this part. This section is an additional part which contains the people's preferences regarding several categories of amenities.

As shown in Table *4*, considering the average and median perceived importance by survey respondents, 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.

Category of Amenities	Perceived Importance		Weighted Value
	Average	Median	
Grocery store, 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
Health Care Category	5.33	5	0.05
Shopping Center (Commercial Category)	5.47	6	0.10
Public Transport	7.42	8	0.20

Table 4. Category of amenities perceived importance

5.2 Workflow implementation

5.2.1 The generation of a parametric model

All the essential geospatial input data for walkability were imported using a ShrimpGIS plug-in to the relevant parametric modelling software (Grasshopper). Importing the geospatial data with the **.shp* format resulted in several geometries in Grasshopper; for instance, residential buildings, amenities, and potential property were represented as polygons, which were then converted to a *.brep (boundary representation) format. The pedestrian network was represented as lines which were then converted to polylines. The imported data converted geometries were then transformed into several geometries: for buildings, incorporating Z-unit (height) is essential to make generated 3D buildings to enhance the visualisation.

5.2.2 The distance to the amenities-based measurement

The shortest distance was generated based on incorporating lengths between nodes from the starting points to the main objective. In this study, the starting point is the closest point on the street to residential buildings, and the main objective is the closest point on the street to amenities. Thus, it was needed to have three main data inputs: the residential midpoints, pedestrian network, and amenity midpoints. After determining the starting point and the main objective with an available network, the data were incorporated into the ShortestWalk plug-ins to run the A* algorithm and find the shortest distances between each residential building 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.

After getting the shortest distances, the standardisation should be done to get a range from 0 to 100 values with the introduction of 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. As mentioned in 4.2, the amenities were calculated individually based on their category since each category of amenities has a different weight in the people's perspective. Hence, the walking preference survey from Table *4* is implemented. The table shows that each amenity category has different importance according to people.

5.2.3 The urban greeneries-based measurement

The urban greeneries-based measurement workflow started with the normalisation of NDVI on the produced Streets with the NDVI score data. It is found that the relationship between the presence of greeneries and walkability is not linear. The positive relationship between greeneries and walkability is highest at 0.4 NDVI and starts declining afterwards until 0.6 NDVI. In the NDVI normalisation phase, this study has divided the NDVI into four classes.

The first class is NDVI score within -1 to 0.1, where an immediate 0 score was given to this class. The score was given as the -1 to 0 NDVI indicates water, roads, building surfaces, and rocks, which means there are no urban greeneries. The second class is NDVI scores from 0.1 to 0.4, which were normalised to 0 to 100 as the optimum value of greeneries for walkability is on the 0.4 NDVI. The third class is NDVI score from 0.4 to 0.6, which was normalised to 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 negative association of walkability with denser urban greeneries (>0.6) are often associated with suburban areas, which often have low walkability, and higher crime rates are also recorded in areas with denser urban greeneries (around 0.8 NDVI) (Shuvo et al., 2021).

5.2.4 Integration of distance to amenities and urban greeneries with the human perspective

As mentioned in section 5.1.2, 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. The integration between indicators is based on formula (2) in section 4.3.

The integration between distance to amenities and urban greeneries and human perspective has resulted in a Comfort-based Walkability Score of 56.93, composed of distance to amenities and urban greeneries score. This walkability score belongs to the "Somewhat Walkable" category according to the Walkscore.com classification, which means that some errands can be accomplished on foot.

5.2.5 Generative design simulations

The generative design simulation workflow utilises the input of Evaluation Point A, Evaluation Point B, and integration of walkability score based on the previous step (4.3.4) to find a near-optimum location for the placement of amenities and urban greeneries. When implemented specifically in Grasshopper, the input for generative design simulation is Fitness and Genome. Fitness is acting as the primary objective function, which we aim to get in the form of a value that needs to be optimised. At the same time, Genome is acting as the decision variable in the form of parameters that can influence Fitness. In this study, Evaluation Point A & B acted as the Genome since they are the midpoints of available land that could be utilised as the location for amenities or urban greeneries. Different locations' placement for amenities or urban greeneries should be able to influence the walkability score by generating different scores per location. At the same time, the integrated walkability score acted as the Fitness since the aim of the research is to have the highest walkability score, which indicates an improvement in walkability to generate walkability-optimal urban plans.

In the neighbourhood of Krastova Vada, Vitosha, the available land that could be utilised as the location for amenities, which act as the Evaluation Point A, are 200 locations. The available street segments for placement of urban greeneries, which act as Evaluation Point B, are 66 streets. The optimisation process in the generative design simulations is divided into three different scenarios: (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 more favourable to the stakeholders. (3) to find four different locations for amenities, followed by seven street segments for urban greeneries, in the case of the implementation of urban greeneries is more favourable by the stakeholders.

Based on a factorial formula (3) to calculate the number of possible solutions, if seven locations for amenities placement alone are implemented, there could be approximately 2.2839E+12 possible solutions. While where seven street segments for urban greeneries placement alone are implemented, there could be approximately 778,789,440 possible solutions. Within this scope of possible solutions, a generative design will surely be an advantage in creating walkability-optimal-urban-plans.

$$nCr = \frac{n!}{r! \times (n-r)!} \tag{3}$$

where nCr = number of possible combinations
$n!$ = total number of items
$r!$ = number of items being chosen

6. RESULTS

This section presents the obtained results which show the different scenarios generated from the implementation of workflow. 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 proposed workflow. As discussed in 4.4, the generative design algorithm had the ability to generate multiple solutions for placing amenities and urban greeneries, increasing the neighbourhood walkability score when implemented. In addition, implementing different scenarios in the generative design simulations should generate different options in case one indicator is more favourable than the other. The stakeholders can discuss these options or even compromise if their main scenario possesses characteristics that the stakeholders are not willing to compromise (e.g., having to cut off trees or planting a new one).

Table 5 shows different near-optimum solutions generated through the defined scenarios in the generative design simulation process. The stakeholders can start a discussion based on these available scenarios to determine which one is fit to be implemented according to their vision and best interest to improve the neighbourhood's walkability.

Scenarios	Walkability Score
Base Scenario	56.93
Scenario 1	82.43
Scenario 2	74.40
Scenario 3	73.12

Table 5. Different scenarios based on generative design simulations

Figure 4-7 presents the walkability score 3D map of the baseline, scenario 1, scenario 2, and scenario 3, respectively. As shown in Figure 4, 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 5-7) which corresponds to their walkability score (see Table 5).

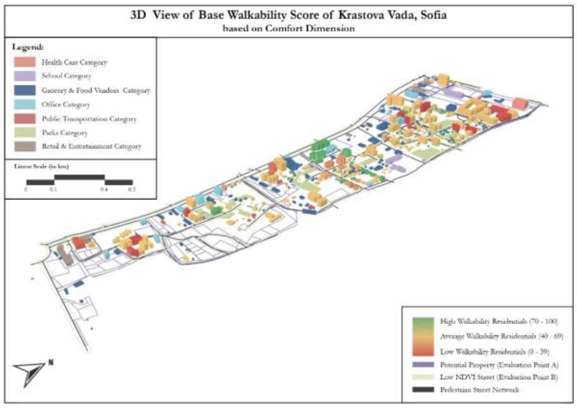

Figure 3. Base walkability score 3D map

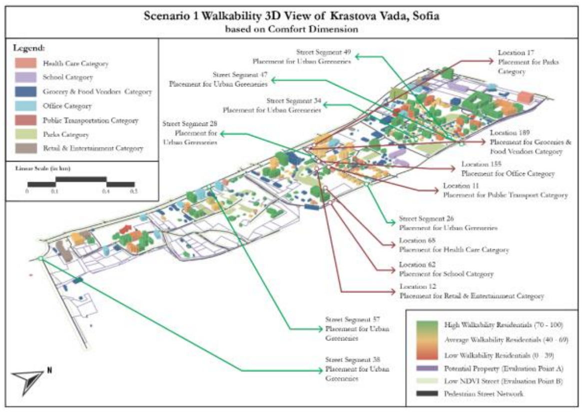

Figure 4. Scenario 1 walkability score 3D map

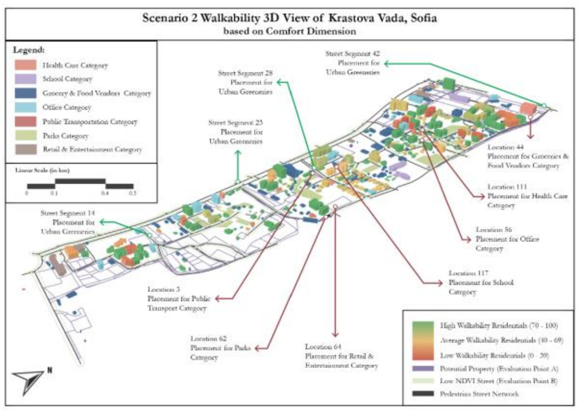

Figure 5. Scenario 2 walkability score 3D map

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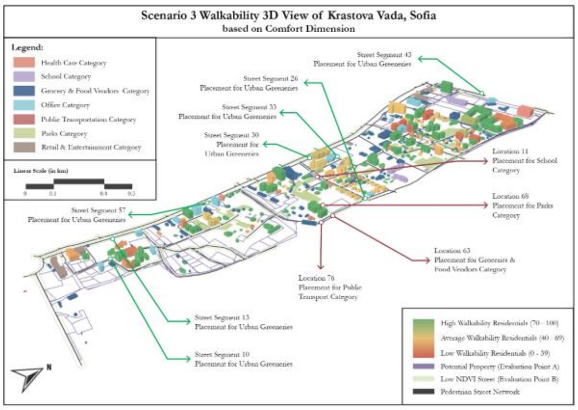

Figure 6. Scenario 3 walkability score 3D map

6.1.2 Comparison between scenarios

As shown in Table 5, the highest walkability score is by Scenario 1. This is likely to occur 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 that, 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 reliable. Due to data availability, a 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 6 presents the proposed workflow's base walkability score of two neighbourhoods, and the walkability score from people's walking experience is in accordance. However, the differences between these walkability scores could be due to people's slight overestimation or underestimation of their neighbourhood's current walkability level. Moreover, an uneven age group distribution in the survey might also be another reason for these differences. 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.

Neighbourhood Location	Walking Experience	Walking Experience Normalized	Proposed Workflow Walkability Score
First neighbourhood (primary)	6	60	56.93
Second neigbourhood	6	60	61.79

Table 6. Comparison between people's walking experience and proposed workflow walkability score

Figure 8 shows the base walkability score 3D map of Lozenets district. 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 seems to correspond with the Lozenets base walkability score (61.79 out of 100).

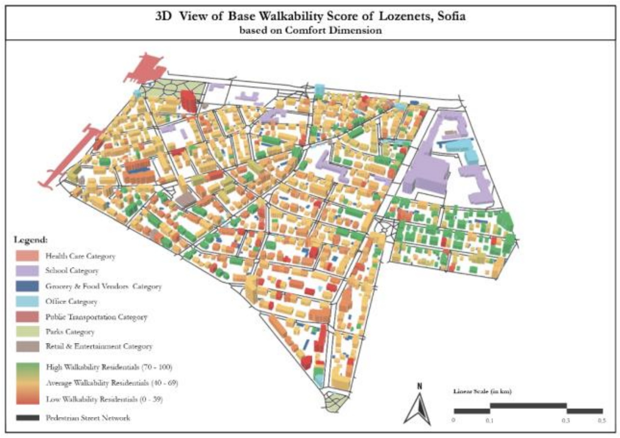

Figure 7. Second neighbourhood base walkability score 3D map

7. DISCUSSION

The proposed workflow presented in this study has been shown to work multi-dimensionally. If another indicator for the comfort dimension is interesting enough to be integrated in the future, it could be easily integrated within the workflow. For instance, the initial indicator for walkability based on the generative design is only based on the distance to amenities. However, this study has proven that incorporating urban greenery and human perspective is possible to create a walkability optimal urban plan based on the comfort dimension. Although, it is needed to ensure that the optimum value of the incorporated indicator is known, which is one of the main reasons for including distance to amenities and urban greeneries for the comfort dimension. Other indicators that represent the comfort dimension have been used in other studies aside from the generative design approach, namely, noise, shading, street furniture, and building ratio (al Shammas and Escobar, 2019; Galal et al., 2020). However, there are no studies that have determined the optimum value of these indicators.

Comparing the 2D and 3D outputs, the 3D model outperforms in terms of clarity. The 3D view of each scenario, including the base walkability, shows the change in residential buildings when the placement of amenities and urban greeneries are implemented. Thus, making it evident that the implementation of the proposed workflow, in this case, helped in increasing the walkability.

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 shows 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 performed each time.

8. CONCLUSIONS

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.

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REFERENCES

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.

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.

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.

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.

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.

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

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.

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.

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.

Shuvo, F.K., Mazumdar, S., Labib, S.M., 2021. Walkability and greenness do not walk together: Investigating associations between greenness and walkability in a large metropolitan city context. *International Journal of Environmental Research and Public Health* 18. https://doi.org/10.3390/IJERPH18094429.

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.

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.

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 modelling for form-based planning in dense urban environments. Sustainability (Switzerland) 11, 1–14. https://doi.org/10.3390/su11205678.