Bjørnar Longva

Digital Twin for Walkability Assessment in City Planning

Master's thesis in Simulation and Visualization
Supervisor: Ricardo Da Silva Torres
Co-supervisor: Dina Margrethe Aspen

July 2021

Master's thesis

NTNU
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Preface

This master thesis is written as a part of the Master of Science degree at the Simulation and Visualization program at the Norwegian University of Science and Technology (NTNU). The project is done in a collaboration between NTNU and the Ålesund Municipality in the context of the Smart Plan project, and was carried out during the spring of 2021. This project explores how to design, implement, and validate a digital twin to support the assessment of walkability indicators in cities.

Acknowledgment

First of all, I would like to thank my main supervisor, Ricardo da Silva Torres for supporting me all the way. You have given me motivation to continue when times were hard, and have been available at all times, guiding me in the right direction throughout the completion of this master thesis.

I would also like to thank Dina Margrethe Aspen for proposing and giving me the opportunity to work on this topic. It has been both very exciting and educational.

The case study of this master thesis would never have been accomplished without the support of Andreas Amundsen from the Ålesund Municipality. I am thankful for his assistance, for providing me with relevant information, and for supporting me with the arrangements related to the conducted evaluation.

At last, I would like to thank all the participants that took part in the evaluation of my case study. You gave me great feedback to improve the framework and application developed in this study.

This project has been developed in the context of the NFR Smart Plan project.

Summary

A walkable city is something that is important for the future wealth, health, and sustainability. A lot of research in the area has been done and several cities have been developing initiatives towards becoming more walkable. This thesis introduces the development of a generic framework for walkability assessment to support the planning process in cities. The framework encompasses an interface layer that supports the specification of parameters and visualization of results; modules dedicated to the computation of walkability indicators and their aggregation; and components in charge of data acquisition and curation. The framework was used to develop an application to perform the assessment of walkability in the Ålesund region. A user study was conducted with target users involved with planning processes in the Ålesund Municipality. Obtained results demonstrate that the developed application is promising for supporting walkability analysis, which takes into account different criteria encoded as indicators.

Abbreviations

AoI Area of Interest.

API Application Programming Interface.

AR Augmented Reality.

CRS Coordinate Reference System.

EPSG European Petroleum Survey Group.

ETRS89 European Terrestrial Reference System 1989.

GIS Geographic Information System.

JSON JavaScript Object Notation.

PAZ Pedestrian Analysis Zones.

PIE Pedestrian Index of the Environment.

SDK Software Development Kit.

UTM Universal Transverse Mercator.

VR Virtual Reality.

WGS84 World Geodetic System.

WI Walkability Index.

WLC Weighted Linear Combination.

WS Walkability Score.

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Chapter 1

Introduction

This first chapter presents context of the developed work, as well outlines the objective and the research questions addressed.

1.1 Background

A walkable city is something that is important for the future wealth, health, and sustainability [1]. A lot of research in the area has been done and several cities have been developing initiatives towards becoming more walkable.

Walkability refers to how friendly a given region is to walking activities. In general, the analysis of walkability depends of the employed criteria, often encoded as indicators, and the objectives of the study. For example, while some city planners may be interested in analyzing walkability aspects from security or safety perspectives, others may be interested in giving more importance to the presence of amenities and attractions in a given location. To cope with such diverse analysis scenarios, the creation frameworks and digital twin applications that support the walkability assessment according to different perspectives is of paramount importance. Such digital twins should not only support the selection of walkability indicators that make sense for the target study, but also give the opportunity to users to indicate the importance of indicators (e.g., definition of different weights).

This is particularly true in the context of ongoing initiatives in the Ålesund region. Ålesund is a city that is focusing on smart innovation and digital technology and has been part of United Nations Smart Cities program. They have their own organisation, United Future Lab Norway,[1] that works with the challenges of becoming a smarter and more sustainable society. In connection with this initiative, Ålesund has established a plan to provide better conditions for both

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[1]https://www.unitedfuturelab.no/prosjekt/smart-plan---planlegging-gjennom-visualisering-og-simulering/ (As of June 2021).

cycling and walking.[2]

1.2 Objectives

The main objective of this Master's project is to design, implement, and validate a digital twin to support the assessment of walkability indicators in cities. The design, development, and validation has been performed with the goal of addressing the following research questions:

- **RQ1:** How to construct a generic framework for walkability assessment to support the planning process?

- **RQ2:** Would this framework lead to effective assessment of walkability for the Ålesund region?

1.3 Approach

A generic framework was constructed for walkability assessment to support planning processes. The architecture is based on a client server architecture with four layers. Each layer in the server is responsible for separate tasks, working independent of each other. The communication and transferring of data between the server and client is done using a web API. This makes it possible to visualize walkability results and to interact with the server using different types of devices. The framework is configurable in such a way that it could be applied for any city. The generic framework was used when developing a digital twin application for walkability assessment for the Ålesund region. The application was evaluated by participants from Ålesund Municipality and United Future Lab Norway, involved in smart city planning processes.

1.4 Contributions

A generic framework for walkability assessment to support the planning process has been introduced. The generic framework was verified and proven to be successful when developing the application for walkability assessment for the Ålesund region. Based on the results of the evaluation and personal communications, the framework could, with further development, potentially lead to an effective walkability assessment for the Ålesund region.

1.5 Outline

This document is organzied as follows:

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[2]https://www.vegvesen.no/vegprosjekter/prosjekt/bypakkealesund/ (As of June 2021).

- **Chapter 2 - Background and Related Work:** This chapter overviews relevant background concepts related to the conducted research and describes related work concerning studies involving walkability.

- **Chapter 3 - Generic Framework for Walkability Computation:** This chapter introduces and describes the proposed generic framework for the construction of tools that support the analysis of walkability.

- **Chapter 4 - Case Study: Walkability in the Ålesund Municipality:** This chapter describes study concerning the instatiation of the proposed framework by means of a construction of a digital twin application that supports walkability analysis in the Ålesund region.

- **Chapter 5 - Evaluation and Discussion:** This chapter is dedicated to the description of activities related to the evaluation of the developed application in the context of the assessment of the walkability in the Ålesund region.

- **Chapter 6 - Conclusions:** This chapter summarizes the main contributions of the conducted study and discusses potential future work.

Chapter 2

Background and Related Work

This chapter provides an overview of relevant background concepts related to the conducted research, as well as describes related work concerning studies involving walkability.

2.1 Walkability

This section defines the walkability concept and presents and discusses related work associated with this topic.

2.1.1 What is walkability?

When reading through the literature, several different definitions of the term walkability is used. In short, we could say that "Walkability is a measure of how friendly an area is to walking."[1]

Forsyth [2] reviewed different definitions proposed in research literature, common practices, and popular discussions and divided those studies into three clusters with a total of nine themes of definitions . The first cluster focuses on the *means or conditions* and defines a walkable area as being:

- Traversable: it refers to the basic physical condition to allow people to easily get from one place to another.

- Compactness: it refers to the existence of a short distance to destinations.

- Safety: this is concerned with crime and traffic safety.

- Physically enticing: this has to do with the possibility of the environment include full pedestrian facilities, such as sidewalks and pedestrian crossings. It may also include interesting architecture or other pleasant views.

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[1]https://en.wikipedia.org/wiki/Walkability (As of June 2021).

The second set of definitions relates to the *outcomes or performance* of such walkable environments:

- Lively and sociable: this concerns with if the environment is pleasant, clean, and full of interesting people.

- Sustainable transportation options: this refers to the existence of suitable transportation alternatives, i.e., if it is possible to save time and energy when walking longer distances as well as give opportunities for disabled people.

- Exercise-inducing: the environment has features that lead people to exercise.

The last one uses the term as a *proxy for better urban places*:

- Walkability is multidimensional in terms of means and these dimensions are measureable.

- Enhancing walkability provides a holistic solution to a variety of urban problems.

Table 2.1 contains different definitions consolidated in the work of Hall and Ram [3]. This paper presents and discuss the Walk Score®,[2] service used in the analysis of walkability in other studies to compute a Walkability Score (WS).

2.1.2 Benefits

The concept of walkability supports urban planning processing through considering important quantitative and qualitative aspects of walking in cities [10]. Pedestrian planning is essential for economic development, public health, and well-being, and environmental sustainability [11]. According to the American city planner, Jeff Speck [1], the three issues – wealth, health, and sustainability – are the three principal arguments for making our cities more walkable. He is a writer and lecturer who has co-authored or authored several books about urban sprawl and walkability [1, 12, 13]. He has also attended several TED Talks to lecture about the topic[3] and how to improve the walkability experience in cities.[4]

2.1.3 Measuring walkability

One of the common challenges in measuring a walkability index is the complexity of the connection between the subjective indices resulting from public opinion and objective measures of geographic data [14]. These are measures based on Geographic Information Systems (GIS) data.

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[2]https://www.walkscore.com/methodology.shtml (As of June 2021).
[3]https://www.ted.com/talks/jeff_speck_the_walkable_city (As of June 2021).
[4]https://www.ted.com/talks/jeff_speck_4_ways_to_make_a_city_more_walkable (As of June 2021).

Table 2.1: Table of walkability definitions [3].

Paper	Definition of walkability
Carr et al. [4]	Walkability is the neighborhood's capacity to support lifestyle physical activity.
Duncan et al. [5]	Collectively, features that promote various forms of physical activity (such as walking) can be referred to as 'neighborhood walkability'. This concept often includes access to walking destinations, such as retail stores and parks, and community design features, such as street connectivity and sidewalk access.
Hajna et al. [6]	The variables that best capture design, diversity and density are street connectivity, land use mix and residential density (collectively referred to as neighborhood walkability).
Pivo and Fisher [7]	Walkability is the degree to which an area within walking distance of a property encourages walking trips from the property to other destinations. It interacts with the property users' walking preferences and capabilities to produce the timing, quantity and distance of walking trips that occur. Several different physical and social attributes of the area around a property can affect walkability. As such, it is a multidimensional construct composed of different factors that together comprise a single theoretical concept. Contributing attributes include urban density, land use mixing, street connectivity (i.e., the directness of links and the density of connections), traffic volume, distance to destinations, sidewalk width and continuity, city block size, topographic slope, perceived safety and aesthetics.
Reyer et al. [8]	Walkability is "the extent to which the built environment is walking-friendly" [9].

The objective measures result in different indicators that could be used to automatically compute a Walkability Index (WI). Different ways of weighting schemes are then used to aggregate and to compute a WS

In [15], the walkability was analysed for a single street divided into five segments of equal length. Their method is described in four steps:

- Selecting built environment indicators that affect walking activities,

- Quantifying selected indicators,

- Weighting the indicators, and

- Indicator aggregation and index composition.

The indicators selected was quantitative variables that were closely related to the definition of walkability. They were divided into the three categories, namely: safety, quality, and attractiveness (Table 2.2). The authors visited the streets to count or measure the selected indicators. As the selected indicators were measured in different units, they could not be aggregated. A way to solve this was to convert the indicators to dimensionless numbers, by means of the so-called normalization. A weight was then assigned to each of the indicators, showing the relative importance and influence that each considered indicator has on walkability. The indicators were aggregated using the Weighted Linear Combination (WLC) as shown in Equation 2.1.

$$WI = \sum W_{ij} X_{ij} \tag{2.1}$$

where WI is a walkability index, W_i is the weight of indicator i in category j, and X_i is the normalised value of indicator i in category j.

A similar approach was adopted by Lefebvre-Ropars et al. [16] in the assessment of a composite walkability index: Pedestrian Index of the Environment (PIE). In their work, the analysis did not focus on a single street, but considered a larger area of a city. The main difference is that this is a grid-based measure, computed on a grid of 80m by 80m cells called Pedestrian Analysis Zones (PAZ). Each calculation includes a kernel density algorithm that takes into account a decreasing value as the distance increases from the measurement point. The decay function used is a quartic function, as shown in Figure 2.1, with the centroid of the PAZ used as the measurement point. The normalization is not done before aggregating the indicators as shown in Equation 2.2.
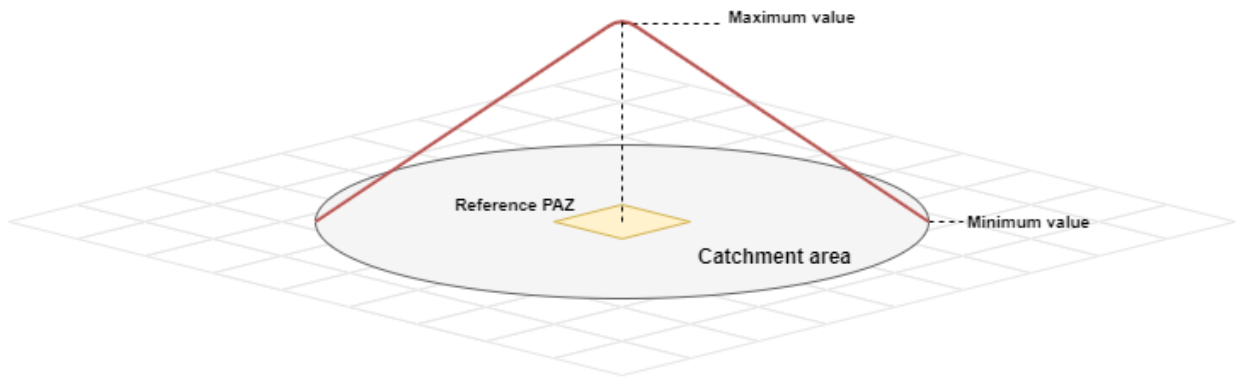

Figure 2.1: Illustration of the kernel density calculation for a PAZ.

$$PIE = \sum k \times \beta_i \times S_i \tag{2.2}$$

where PIE refers to the Pedestrian Index of the Environment, k is a Normalization Coefficient,

β_i is a weight coefficient, and S_i is an indicator score.

2.1.4 Walkability indicators

The objective methods typically use indicators, such as population density, dwelling density, land use mix, access to stores and urban services, connectivity, intersection density and network density [17, 18, 19, 20]. Some also add the retail floor area ratio [20]. These indicators are briefly described in the following:

- Population and residential dwelling density: Number of people living in specific areas [17, 18, 19, 20].

- Street connectivity and intersections: Feasibility of walking from one point to another [17, 18, 19, 20].

- Land use mix: Restaurants and workplaces co-located in a neighborhood [17, 18, 19, 20].

- Retail floor area ratio: The amount of retail floor area in relation to the total amount of land area that serves retail use [20].

In his work, Lo [21] presents a number of commonalities in the criteria employed in the walkability assessment of different cities [21], such as:

- Presence and continuity of sidewalks and pedestrian routes.

- Accessibility of facilities to people with different abilities.

- Directness of pedestrian paths and connectivity of the street network.

- Connections to frequent transit services.

- Ease and safety of crossings.

- Visual interest.

- Perceived or actual security.

Several studies have categorized walkability indicators [15, 22]. For example, the work of Reisi et al. [15] divides walkability indicators into three categories: safety, quality, and amenities and attractions. Table 2.2 presents the indicators considered in each category.

Lee & Talen [22], in turn, proposed a categorization composed of four classes: land uses, walking path and sidewalks, vehicle-pedestrian interactions, and safety and appeal. Their categorization takes into account the combination of GIS data and information from Google Street View from an in-person observation. Table 2.3 lists their set of indicators and the categories to which those indicators belong.

Table 2.2: Categorization of walkability indicators according to Reisi et al. [15].

Category	Indicators
Safety	Lighting
	Crossing availability
	Potential for vehicle conflicts
Quality	Sidewalk width
	Obstructions
	Support facilities
	Facilities for disabled people
Amenities and Attractions	Natural features (trees) or parks
	Cinemas, cultural centres (historical places, architecture)
	Retail trade/ gastronomy / services
	Fixed furniture: presence of benches and other places to rest
	Public toilets
	Public transportation

Table 2.3: Categorization of walkability indicators according to Lee & Talen [22].

Category	Indicators
Land uses	Land uses (types, intensities, destinations)
Walking path/sidewalks	Sidewalk presence
	Sidewalk qualities (materials, obstructions, uniformity)
	Slope
	Natural barriers (ditch, creek)
Vehicle-pedestrian interactions	Street supports for walking (crosswalks, traffic lights)
	Traffic volume
	Parking (on and off-street)
	Speed limits
	Segment/road connectivity
	Road conditions (materials, uniformity)
	Traffic calming (chokers, chicanes)
Safety and appeal	Lighting
	View/surveillance
	Aesthetics (incivilities, gardening, appeal)
	Unique markers/memorability
	Architectural variety
	Enclosure
	Tree presence

2.2   GIS and associated technologies

Spatial data, also known as geospatial data, is a term used to describe any data related to or containing information about a specific location on the Earth's surface.[5] A common way to process, analyze, and visualize spatial data relies on the use of a Geographic Information System (GIS). According to Esri,[6] a GIS is a framework for gathering, managing, and analyzing data. Rooted in the science of geography, GIS integrates many types of data. It analyzes spatial location and organizes layers of information into visualizations using maps and 3D scenes.

2.2.1   Vector and raster data

Spatial referenced data could be classified into two different types: vector and raster.

Vector data

There are three main types of vector data: points, lines, and polygons as shown in Figure 2.2. A sequence of points joined together forms a line, and connecting lines that create an enclosed area forms a polygon. A point represent a single point in space and it is either two-dimensional (x, y) or three dimensional (x, y, z). Example of points would be the location of schools, stores, or other points of interests. Examples of lines would be a road centerline, rivers or pipelines. Examples of polygons would be a building footprint or a park area. The most common vector file type used in GIS is the Shapefile (.shp).

Figure 2.2: Examples of vector data.

Raster data

Raster data is made up of cells or pixels composed of rows and columns. Each cell contains a value representing a feature for a geographical region. The size of the region is also know as the spatial resolution of the raster image. Figure 2.3 provides an example of a raster image where each pixel represents an area of 1 square meter. An example of a raster image would be a landuse raster containing discrete categorical data. Another example is an elevation or

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[5]https://www.safe.com/what-is/spatial-data/ (As of June 2021).
[6]https://www.esri.com/en-us/what-is-gis/overview (As of June 2021).

temperature raster image containing continuous values. Raster data is also good for images that depict the real world surface (e.g. satellite images) as shown in Figure 2.6. The most widely supported raster data format used in GIS is the GeoTIFF. GeoTIFF is a bitmap image that allows georeferencing information to be embedded within the metadata in a TIFF file.
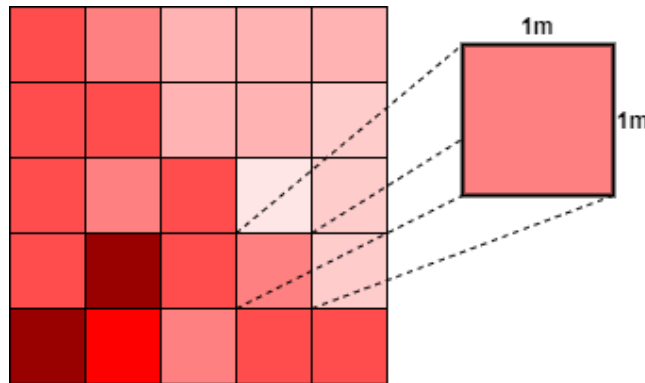

Figure 2.3: Examples of raster data.

While vector data gives a high geographic accuracy, raster data are associated with a certain spatial resolution that could lead to a pixelated look and feel, as illustrated in Figure 2.4.

Figure 2.4: Examples of vector (left) and raster (right) data.

A raster image could contain several layers with different features representing the same spatial area. This is called a multi-band image. One of the advantages of a multi-band raster is that it makes it easy to perform map algebra between the layers, as illustrated in Figure 2.5.

2.2.2 Projections

Map projections are used to flatten the earths spherical shape into a two-dimensional plane. The location on earth could be given by the Earth latitude and longitude coordinates. A Coordinate Reference System (CRS) defines how those coordinates should be located on the plane. A transformation will always lead to some distortion. The amount of distortion is depending on which CRS used. A specific CRS could be referred to using a EPSG code. Universal Transverse Mercator (UTM) is a set of map projections divided into zones that covers most of the world. The CRS information is embedded in vector shape- and GeoTIFF raster files. A common process in GIS is to reproject data from different layers into a common CRS. This is to be able to analyze the spatial relationship between them and to perform mathematical operations.
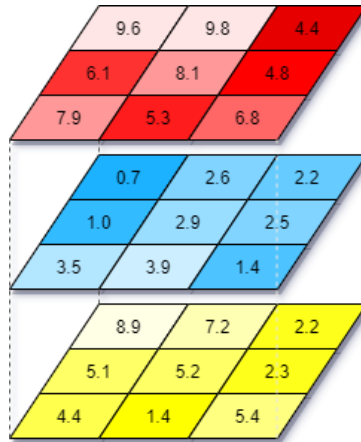
Figure 2.5: Illustration of raster algebra computation.

Below, we list some of CRS we had deal with in the context of this project:

- WGS84 (EPSG:4326) used in GPS;

- Spheric/Web Mercator (EPSG:3857) used in Google Maps and OpenStreetMap;

- EUREF89 (ETRS89) UTM Zone 33N (EPSG: 3045) used in Norway;

- EUREF89 (ETRS89) UTM Zone 32N (EPSG: 25832) used in Norway.

2.3 Unity

Unity is a cross-platform game engine developed by Unity Technologies[7], which is primarily used to develop video games and simulations for computers, consoles and mobile devices. It also supports WebGL build options to run Unity content in a web browser.

Unity Map SDKs

A Unity Software Development Kit (SDK) enables Unity applications to interact with a web service to download raster images of the landscape using an Application Programming Interface (API). Most of the SDKs have a free-to-use licence as long as the developed application is non-profit and with a limited number of users or downloads. Table 2.4 presents a list of Unity map SDK providers and their lowest cost pricing.

Map raster images are typically downloaded as several tiles that combined into a larger map, as shown in Figure 2.6.

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[7]https://unity.com/ (As of June 2021).

Table 2.4: Unity Map SDK providers.

Unity SDKs provider	Pricing (non-profit)
ArcGIS - Maps SDK for Unity	Free up to 2.000.000 map tiles per month
WRLD - Unity SDK	16 USD per month, unlimited monthly active users
Bing - Maps SDK for Unity	Free up to 125.000 billable transactions each year
Google - Maps SDK for Unity	Free up to 30.000 daily users each month
Mapbox - Maps SDK for Unity	Free up to 25.000 monthly active users
Geopipe - Unity SDK	Free trial. 100 USD per month
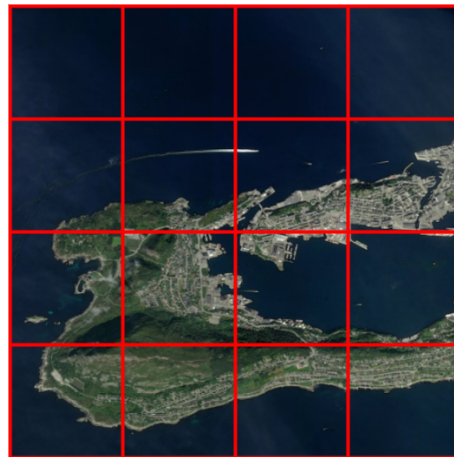
Figure 2.6: Raster image of the Ålesund area.

2.4 Evaluation Framework

The DECIDE framework [23] presents a structure for planning evaluation studies. The framework provides a high-level organizational guidance for evaluation of interaction designs and consist of six steps:

1. **D**etermine the overall goals that the evaluation addresses.
   This component is concerned with the identification of the high-level goals that should guide the evaluation. For example, why is the evaluation performed? Who wants it? What is expected?

2. **E**xplore the specific questions to be answered.
   This component refers to the identification of the key questions behind the study. The answers should be able to satisfy the overall goals. A goal question could be divided into several sub-questions.

3. **C**hoose the evaluation paradigm and techniques to answer the questions.
   This component refers to the set of method will be used in the evaluation process.

4. **I**dentify the practical issues that must be addressed, such as selecting participants.
   This component is related to definition of the participants who will be involved with the evaluation process. Key issues refer to the identification of background or skills required and equipment that will be used to collect their answers. Other relevant questions include: What kind of material is needed? How much time is needed and when will is be performed? Are there any budget involved?

5. **D**ecide how to deal with the ethical issues
   This refers to the communication with participants about the goal of the study. Key questions refer to anonymity and confidentiality aspects will be addressed during and after the evaluation session.

6. **E**valuate, interpret, and present the data.
   This component is concerned with the definition of the the type of data that will be collected and how they will be analyzed. Also, the definition on how the findings will be presented is addressed in this component.

Chapter 3

Generic Framework for Walkability Computation

This chapter describes the proposed generic framework for the construction of digital twin tools that support the analysis of walkability.

This section is organized as follows: Section 3.1 presents the architectural view of the framework; Section 3.2, in turn, addresses implementation aspects.

3.1   Architectural View

The framework is based on a server client solution as shown in Figure 3.1. The server is in charge of the processing of the walkability calculations, while clients are responsible for the visualization and interactions with users. The clients communicates with the server using an Application Programming Interface (API). This allows the application to have several client users at the same time.
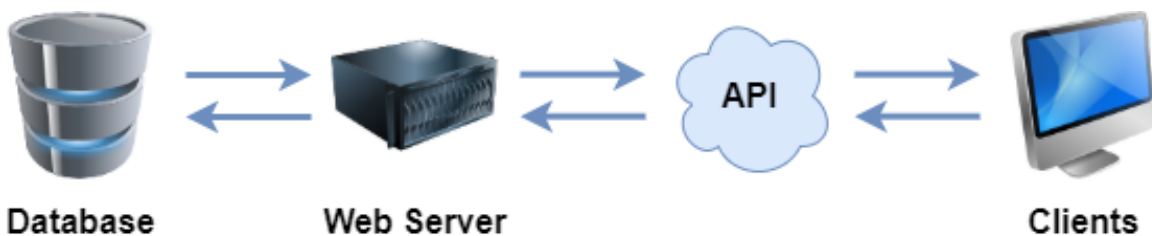

Figure 3.1: Client-server model employed in the development of the framework.

The system architecture is divided into four layers: The visualization and interaction layer, the decision support layer, the sustainability impact assessment layer and the data repository layer. These four layers are shown in Figure 3.2 and they are described in the next sections.
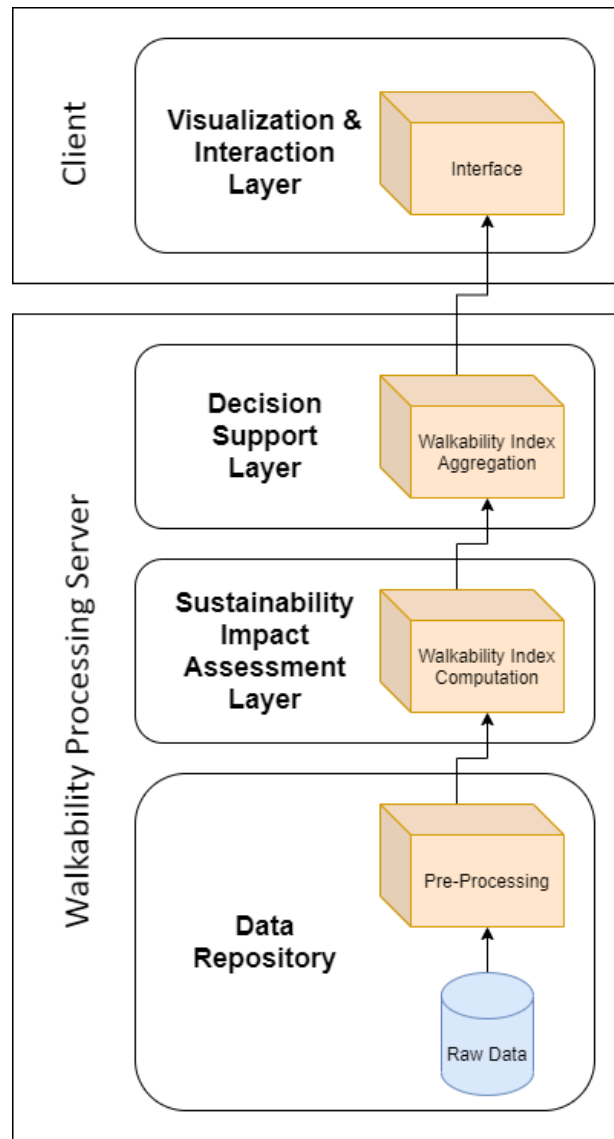
Figure 3.2: Framework architecture.

3.1.1 Visualization & Interaction Layer

The visualization & interaction layer mainly consists of a user interface for configuration settings and interaction controls implemented on top of two raster images. The two raster images are a map layer overlaid by a grid layer, whose the goal is to support the visualization of walkability computation results, as shown in Figure 3.3.

Figure 3.4 shows the visualization layer and its components. The map layer is downloaded from the map API (region labeled with 1) as a raster image (label 2) and used as the first layer in the visualization (label 9). The parameters (label 3) containing information about aggregating functions, categories, indicators, selections, and weights are then loaded from the walkability processing server. The parameters are then used to instantiate the user interface (label 4) for
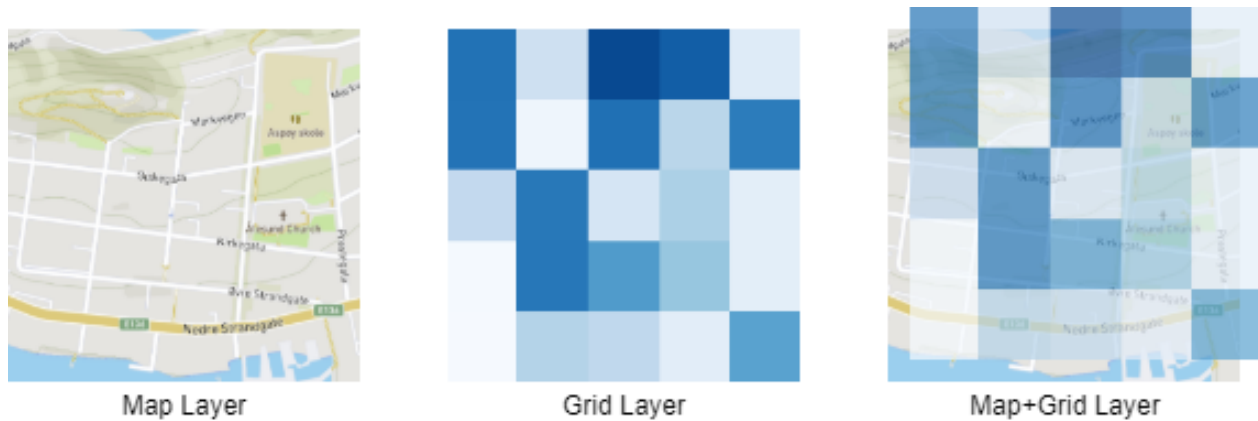
Figure 3.3: Examples of different visualization layers.

walkability calculation. A weighted function can then be used to aggregate the indicators either individually or by categories. A user can select which indicator/category to use as well as set the weight which is expected to encode its importance/relevance for the walkability computation. A user interaction (label 5) will update the parameters and send them back to the server. The decision support layer will then compute the walkability score (label 6) and generate the grid raster image (label 7) and send it to the client. The grid layer (label 8) is updated and used as the second layer in the visualization (label 9).

Figure 3.4: The visualization layer and its components.

3.1.2 Decision Support Layer

The decision support layer is responsible for aggregating the walkability index based on the user interactions.

Figure 3.4 shows the decision support layer and its components. First, it receives a multi-band raster image (region labe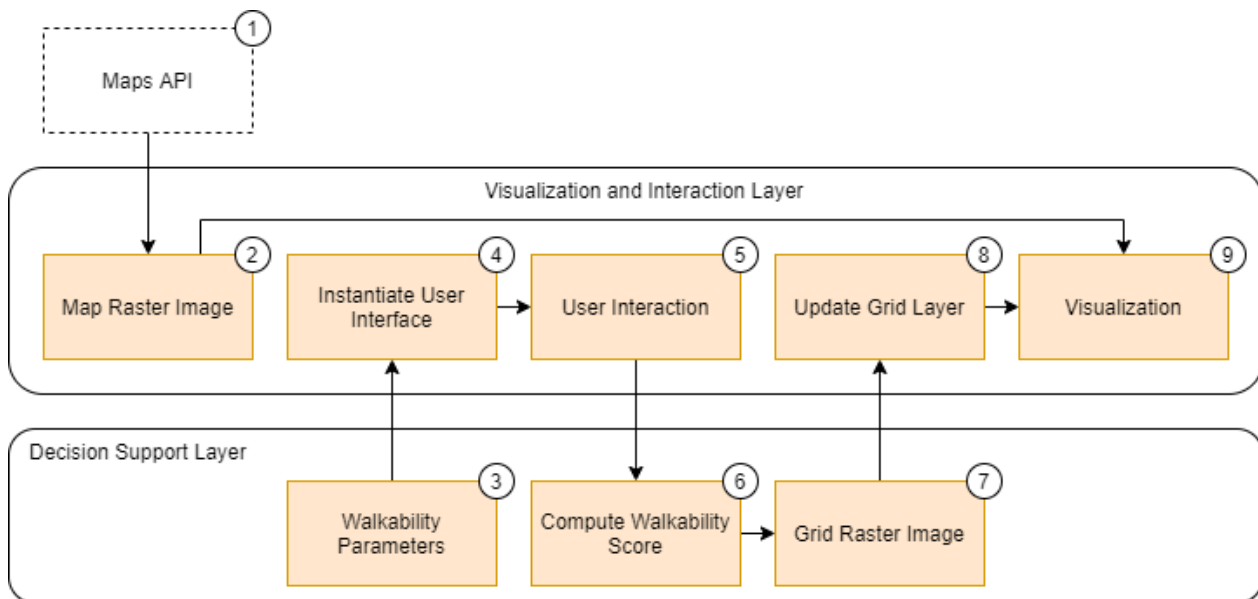led with 1) from the sustainability impact assessment layer containing all the individual computed walkability indices for the different indicators. Based on the selected aggregation function, indicators, and assigned weights (label 2), it will compute a single band raster image (label 3). Next, this layer will scale and normalize each pixel value between 0 and 255 (8bit) using min/max scaling (label 4). Then, it will generate a four-band raster image, a rgba color image (label 5), in which pixel colors are defined using a color map (label 6). Finally, the four-band raster image (label 7) is transferred to the visualization and interaction layer, in which it is used to present (label 8) the walkability results.
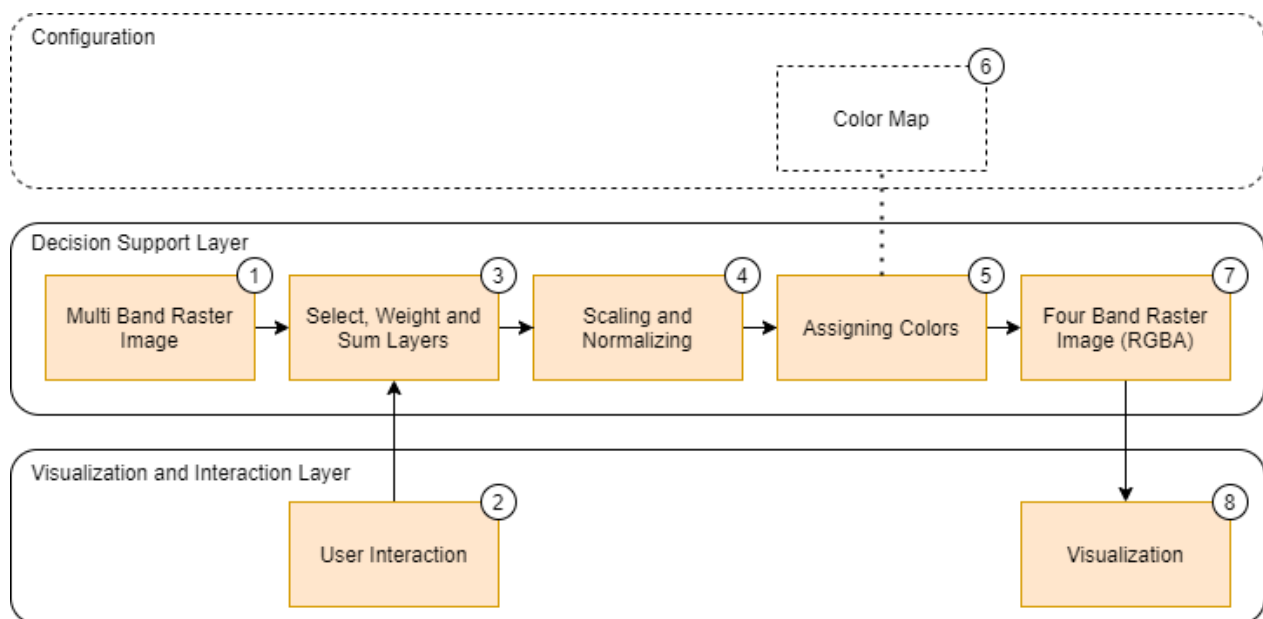
Figure 3.5: The decision support layer and its components.

3.1.3 Sustainability Impact Assessment Layer

The sustainability impact assessment layer is responsible for computing the walkability index for each indicator. The input indicator data could either be in a vector or raster data format. The output is a multi-band raster image containing all the walkability indices.

Figure 3.6 shows the sustainability impact assessment layer and its components. First, the pre-processed indicator data (region labeled with 1) and the grid shape (label 2) are read from the data repository layer. In case of vector data, the walkability index is computed (label 3)

using the indicator data (label 1), the grid shape (label 2), and a configured radius of walking distance (label 4). The computation is done for each grid cell and it differs for each indicator. It could for instance use techniques as counting data values inside the grid cell or measuring lengths between the center of the cell to the data points if it is within a defined walking distance. Examples of methods are described in Chapter 4 in which the generic framework is used in a case study. Each pixel value is then scaled and normalized between 0 and 255 (8bit) using min/max scaling (label 5). The next step is then to rasterize (label 6), i.e., to convert vector shapes into a single band raster image. This is done by using the so-called painters algorithm, which encodes the pixels covered by the polygon shapes into a raster image. The raster image is set to cover all the vector grid cells with a configured pixel resolution. The image is encoded in the GeoTIFF format as a single band raster image (label 8).

The process is similar for indicators pre-processed as raster data (label 9). The only difference is that the data used in the walkability index computation is already calculated and it is only needed to crop it out (label 10) using the grid shape (label 2). Also, resampling (label 11) needs to be done to match the pixel resolution used in the other images.

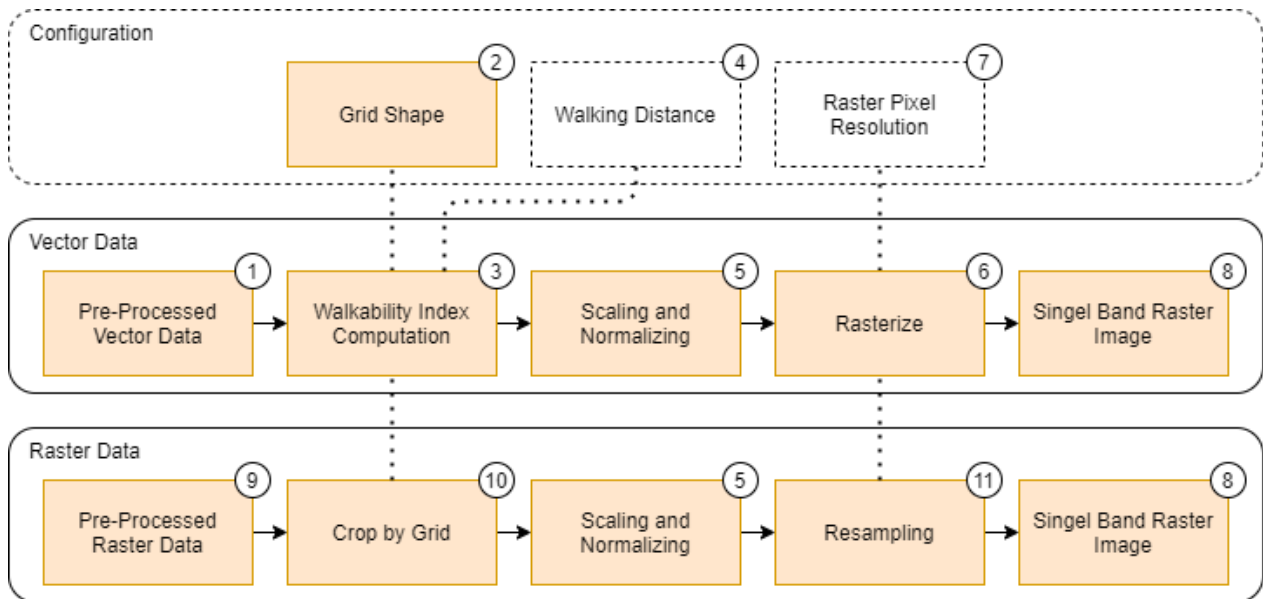Figure 3.6: The sustainability impact assessment layer and its components.

After all the individual single band raster images are computed, they are stored in a multi-band image as illustrated in Figure 3.7.

3.1.4 Data Repository Layer

The data repository layer is responsible for retrieving, storing, and pre-processing the data for each indicator. The input indicator data could either be in a vector or raster data format.
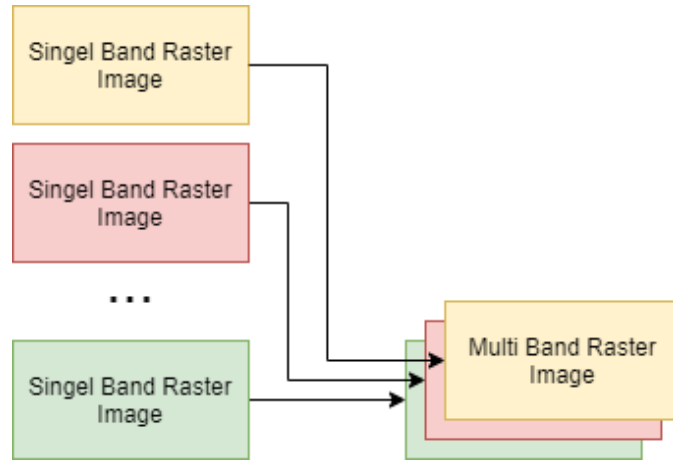
Figure 3.7: Illustration of the computation of a multi-band image in the Sustainability Impact Assessment Layer.

Figure 3.8 shows the data repository layer and its components. First, the raw data has to be downloaded from a data provider and stored in the data reporistory either as vector data (region labeled with 1) or as raster raster data (label 2). Next, these data have to be reprojected (label 3) into the same CRS using the EPSG defined in the configuration (label 4). After the data are reprojected, cropping is performed (label 5) according to the Area of Interest defined in configuration (label 6). Since the vector data could include several attributes for each shape, only the attributes needed for the walkability computation are selected (label 7). The pre-processed data is then stored in the data repository as either vector data (label 8) or as raster data (label 9).

Figure 3.8: The data repository layer and its components.

3.2 Implementation Aspects

This section covers the main technologies employed in the implementation of the framework.

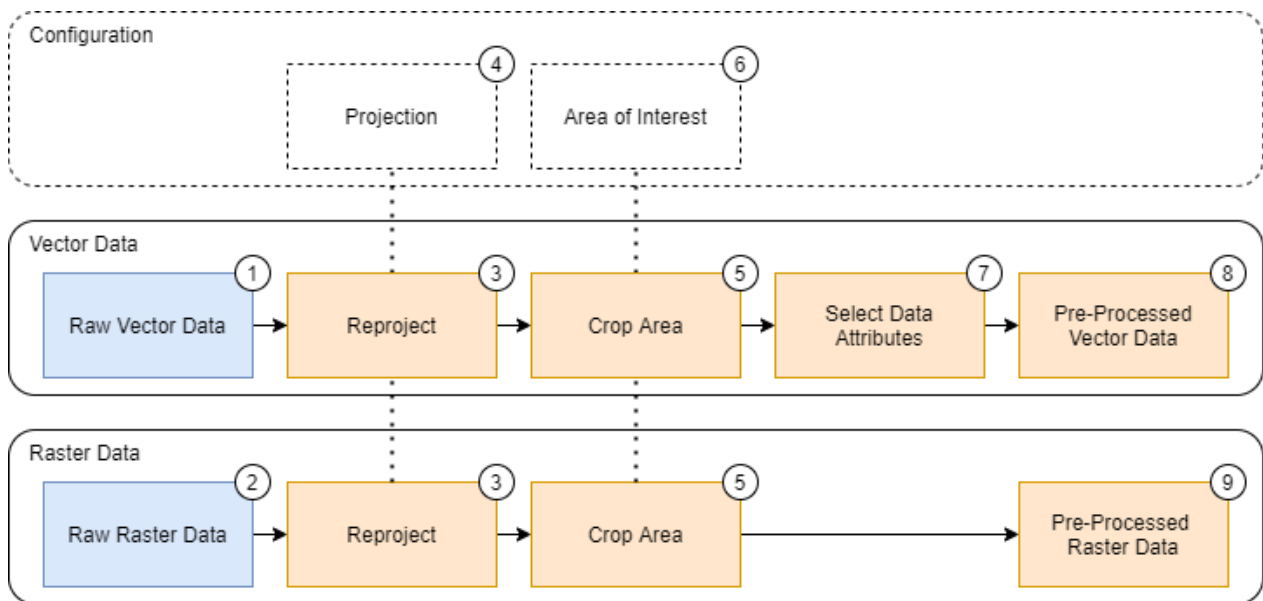The server application is developed using the Python programming language while the client has been developed in Unity[1] and C#.

3.2.1 Communication

Clients communicate with the server using an Application Programming Interface (API). This allows the application to have several client users at the same time. Raster images are transferred either in the GeoTIFF or the PNG format while settings and the configurations are transferred using the JavaScript Object Notation (JSON) data format.

The specific file structure is shown in Figure 3.9. The JSON object contains a list of *indicators*, *categories*, and *aggregator* objects. The aggregator object contains an id, name, description, and a selected key. The categories object contains an id, name, description, an enabled key, and a weight key. The indicator object contains an id, category id, name, description, an enabled key, and a weight key. The category id in the indicator object is related to the id in categories.
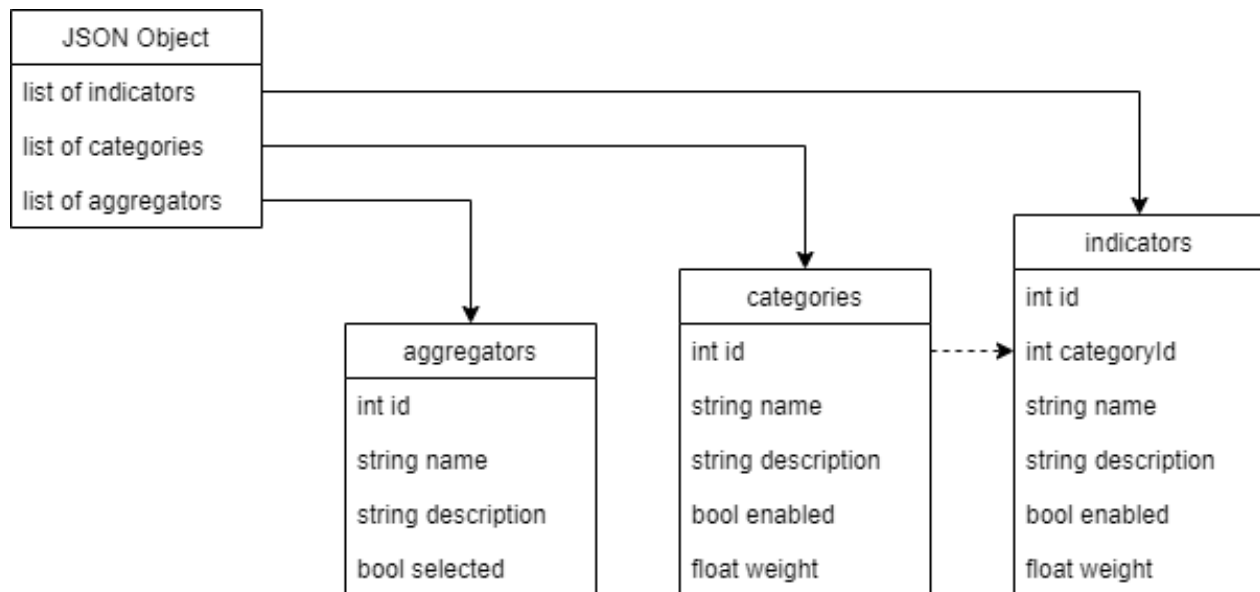

Figure 3.9: Walkability parameters encoded as JSON data.

3.2.2 Implementation in Unity

Figure 3.10 shows the main components of the implementation in Unity. In the center, we have the three C# script components and, on the right, we have the visual objects, named game ob-

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[1] https://unity.com/ (As of June 2021).

jects in Unity.

In this project, Mapbox has been chosen as the map provider for the Unity application. The map layer (region labeled with 6) is downloaded from the Mapbox API (label 1) as a raster image using the Mapbox SDK (label 4). The API Client script (label 3) handles the communication between the walkability processing server (label 2) and the walkability handler script (label 5). The walkability handler script instantiates the user interface (label 8) for walkability calculations based on the parameters received from the walkability processing server. The parameters are updated based on user interactions and sent back as a request to compute the walkability calculation. The grid layer (label 7) is updated with the responded raster image from server.
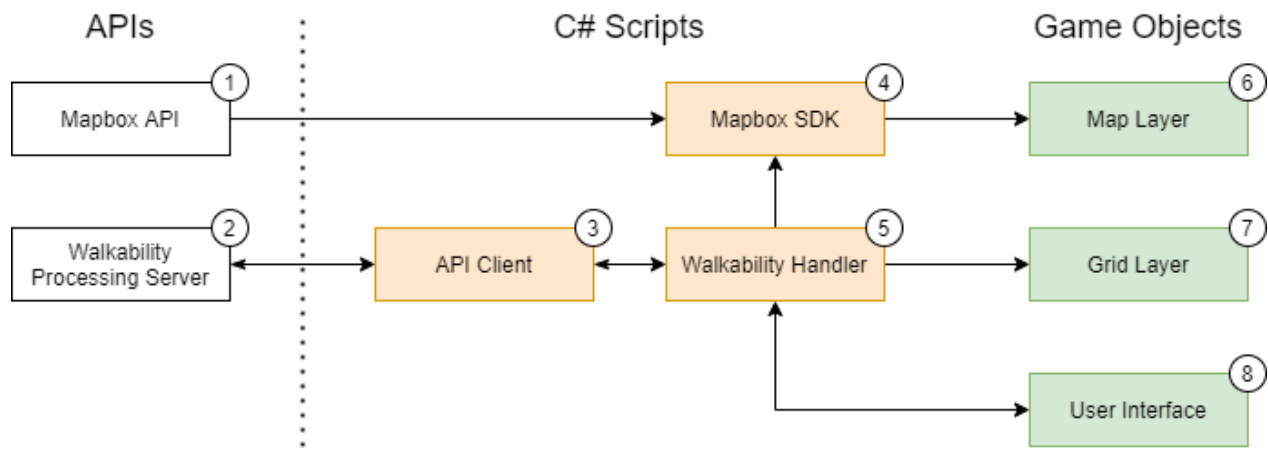
Figure 3.10: Main components of the implementation in Unity.

3.2.3 Implementation in Python

Table 3.1 presents the Python packages used in the web server. The Flask package, with its included dependencies, is hosting the web server application. It handles the requests of the walkability parameters, as well as the image file transfer. The JSON package is used to convert the walkability parameters between JSON and Python dictionaries. The Flask-CORS extension was used to enable and allow clients downloading the computed walkability raster image.

3.2.4 GIS using Python

There are several packages available for the Python programming language to perform GIS processing operations. Table 3.2 presents the main packages used in each layer. Table 3.3 presents the main packages used in this framework with a short description and how they are used.

Table 3.1: Table of Python packages used in web server.

Name	Short Description	Usage
JSON	A built in Python package, which can be used to work with JSON data.	Convert python dictionaries from the database into the JSON format.
Flask	Flask is a micro web framework	Running a web server and handling Get and Post requests of the walkability parameters as well as image file transfer.
Flask-CORS	A Flask extension for handling Cross Origin Resource Sharing (CORS), making cross-origin AJAX possible.	Enable file access and transfers between client and server

Table 3.2: Table of Python packages used in different layers.

Layer	Process	Packages Used
Data Repository Layer	Read Raw Data	Fiona, Geopandas, Rasterio, OSMnx
	Reproject	Pyproj, Geopandas, Rasterio
	Crop Area	Shapely, Geopandas, Rasterio
	Select Data Attributes	Pandas, Geopandas
	Save Pre-Processed Data	Fiona, Geopandas, Rasterio
Sustainability Impact Assessment Layer	Read Pre-Processed Data	Fiona, Geopandas, Rasterio
	Walkability Index Computation	Numpy, Pandas, Shapely, Geopandas, Rasterio
	Scaling and Normalizing	Numpy, Pandas, Geopandas
	Rasterize/Resample	Rasterio
	Save Singel Band Raster Image	Rasterio
	Merge Multi Band Raster Image	Rasterio
Decision Support Layer	Read Multi Band Raster Image	Rasterio
	Select, Weight and Sum Layers	Numpy
	Scaling and Normalizing	Numpy
	Assigning Colors	Matplotlib, PIL
	Store Raster Image (RGBA)	Rasterio

Table 3.3: Table of Python GIS packages.

Name	Short Description	Usage
Numpy	Numpy is a fundamental package for science computing and working with arrays.	Create arrays and perform mathematical operations.
Pandas	Pandas is a package frequently used in data manipulation and analysis.	Sort, filter, concatenate, and group data.
Shapely	Shapely is a package for doing various geometric operations.	Compute intersections, calculate centroids and buffer radius and measure distance between points, lines, and polygons.
Fiona	Fiona is a package for reading and writing geographic vector data files.	Read and write vector shape files.
Pyproj	Pyproj is a python interface to PROJ: A generic coordinate transformation software that transforms geospatial coordinates from one coordinate reference system (CRS) to another.	Reproject vector and raster data between different coordinate reference systems.
Geopandas	Geopandas combines the capabilities of the data analysis library pandas with other packages like shapely, fiona and pyproj for managing spatial data.	Perform operations of pandas, shapely, fiona, and pyproj.
Rasterio	Rasterio is a python interface to GDAL: A module for raster processing supporting all the most common file formats	Open/save single/multi-band raster, merge raster images, transform and reproject, mask (crop) based on vector shapes and rasterize vector data to raster data.
OSMnx	OSMnx is a package for downloading geospatial data from OpenStreetMap and model, project, visualize, and analyze real-world street networks and any other geospatial geometries.	Download data from OpenStreetMap including roads, intersections.
Matplotlib	Matplotlib is the most common plotting library used to visualize data in Python	Visualize data during pre-processing. Create color maps used when assigning colors to raster images.
Contextily	Contextily is a package to add background maps to matplotlib.	Add background maps when analysing GIS data.
PIL	Python Imaging Library is a package with image processing capabilities	Create an image from a numpy array, colored by matplotlib used as a color bar in the visualization.

Chapter 4

Case Study: Walkability in the Ålesund Municipality

This chapter describes the case study concerning the instantiation of the framework described in previous chapter towards the creation of a digital twin application of Ålesund. The main goal is to support walkability analysis in the Ålesund region.

This chapter is organized as follows: Section 4.1 presents information about providers from which data about Ålesund were collected; the implemented indicators are described in Section 4.2; finally, details regarding the implementation of the user interface are provided in Section 4.3.

4.1 Data Providers

Table 4.1 presents the data providers used in this case study.

Table 4.1: Table of data providers

Data Provider	Description
GeoNorge[1]	Geonorge is the national website for map data and other location information in Norway. Here, users of map data can search for and access what is available from such information.
OpenStreetMap[2]	Open Street Map is a free, editable map of the whole world that is being built by volunteers.
Nasjonal Vegdatabank (NVDB)[3]	The National Road Data Bank is a database with information on state, municipal, private, county and forest roads.

4.2 Indicators

Table 4.2 presents the indicators used in this case study. They encompass indicators belonging to the categories amenities and attractions; walking path and sidewalks; and safety. The table also indicates the file types associated with the data used for computing indicators, as well as the data provider.

Table 4.2: Indicators considered in the case study.

Category	Indicator	File Type	Data Provider
Amenities and attractions	Population Density	SOSI	GeoNorge
	Park Areas	XML	OpenStreetMap
Walking path/sidewalks	Street Connectivity	XML	OpenStreetMap
	Slope/Elevation	GeoTIFF	GeoNorge
Safety	Speed Limits	XML	OpenStreetMap
	Pedestrian Crossings	SOSI	Nasjonal Vegdatabank

4.2.1 Configuration

Some configuration parameters are common when processing the walkability calculations. The settings used is listed as follows:

- Area of Interest: It was set to the Ålesund city region and was used when collecting indicator data.

- Projection: All data is set to be projected into the Web Mercator (EPSG: 3857) CRS.

- Shape of grid: This was computed based on the grid extracted from the population density indicator.

- Walking distance radius: This was set to 800 meters, the farthest radial distance based on a ten minutes walk.[4]

- Raster image resolution: The resolution was set to 2048 × 2048 pixels. This configuration was used when rasterizing and resampling. It was observed that it was a good enough resolution in practical terms. Another positive aspect refers to the fact it is associated with files with small size.

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[1] https://www.geonorge.no/ (As of June 2021).
[2] https://www.openstreetmap.org/ (As of June 2021).
[3] https://dataut.vegvesen.no/dataset/nasjonal-vegdatabank (As of June 2021).
[4] https://www.dcla.net/blog/walkability-standards (As of June 2021).

- Color Map: It was set to red (0), yellow (50), and green (100) gradient. This color map was used when assigning colors to the raster image of the aggregated walkability index.

4.2.2 Area of Interest

The Area of Interest (AoI) is defined as a rectangle in the Web Mercator (EPSG: 3857) CRS and it is used in the data repository layer to crop and select from raw data. The rectangle coordinates are defined by the points 675,000 E / 8,966,000 N and 701,000 E / 8,975,000 N. In the WGS84 (EPSG: 4326), this corresponds to latitude from 62.4473° to 62.4847° and longitude from 6.0636° to 6.2972°. Figure 4.1 shows the area that stretches from west to east including the regions/-places: Hessa, Aspøya, Nørvøya, Gåseid, and Hatlane.
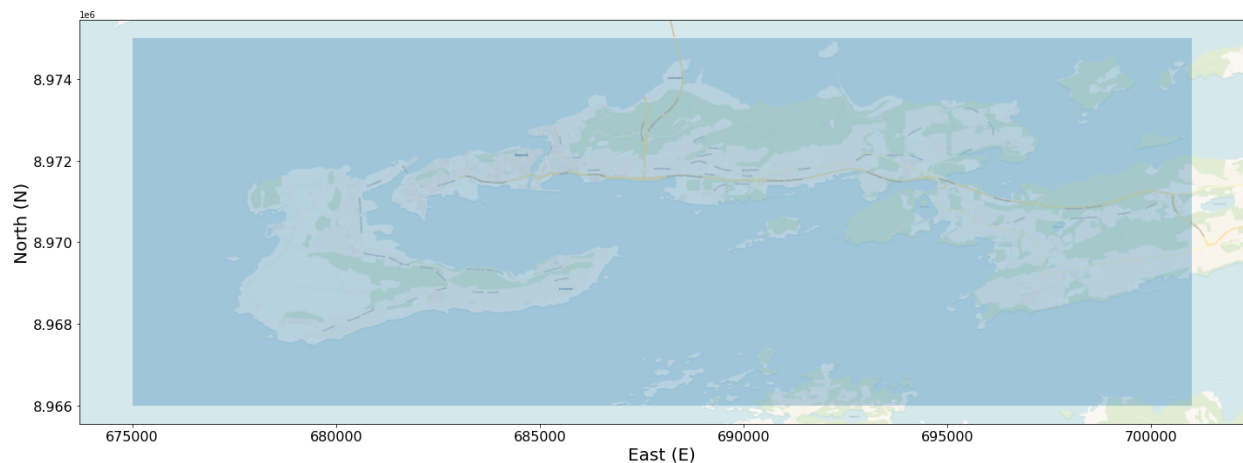

Figure 4.1: Area of interest considered in the case study.

4.2.3 Population Density Indicator & Grid

The population density dataset of the Ålesund municipality was downloaded from GeoNorge[5] as a grid of squares (250m × 250m). The dataset has the EUREF89 (ETRS89) UTM Zone 32N (EPSG: 25832) projection and it is stored in a SOSI file format. It is converted to the Shape file format using the online tool "SOSI to Shape" converter.[6] The raw data is first reprojected into the Web Mercator (EPSG: 3857) projection. The AoI is then used to crop out the shapes within the rectangle. Figure 4.2a shows the original dataset and Figure 4.2b shows the AoI (red) on top of the reprojected data (blue).

Figure 4.3 shows a number of 189 grid squares extracted from the population density dataset. These grid shapes are used when computing the walkability index for all the indicators. The

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[5] https://www.geonorge.no/ (As of June 2021).
[6] https://geodata.no/geodataprodukter/sosi-shape (As of June 2021).

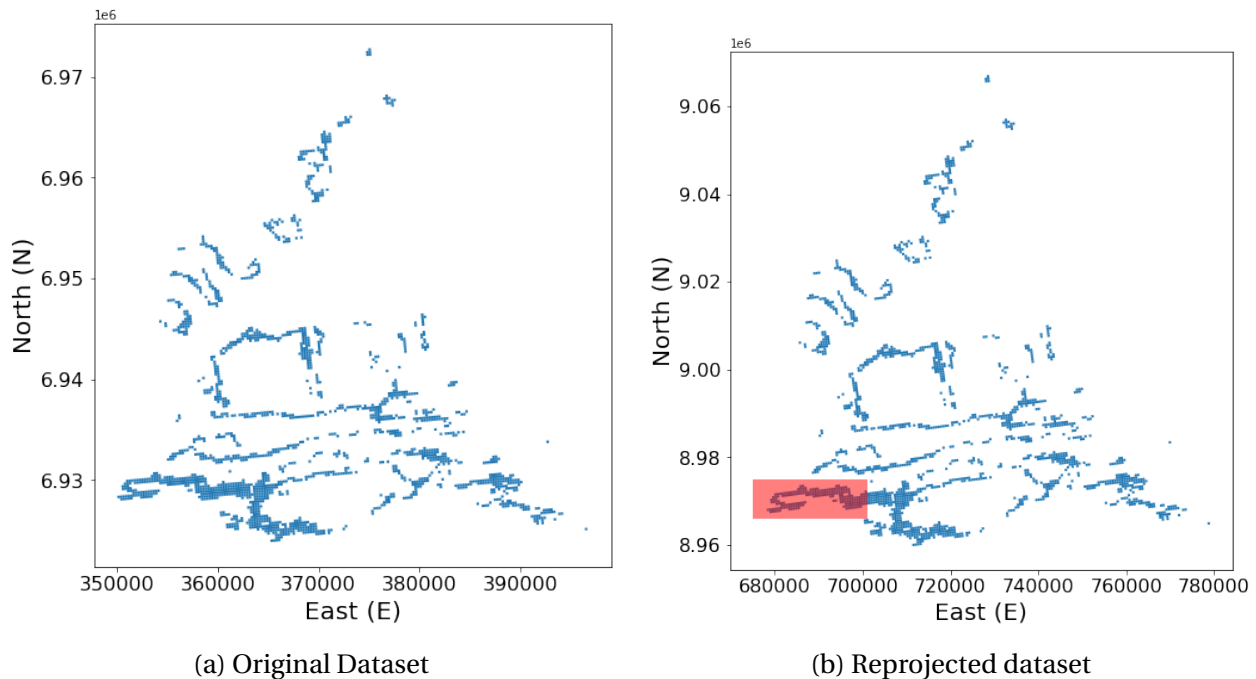(a) Original Dataset

(b) Reprojected dataset

Figure 4.2: Visualization of the population density dataset before (a) and after (b) reprojection.
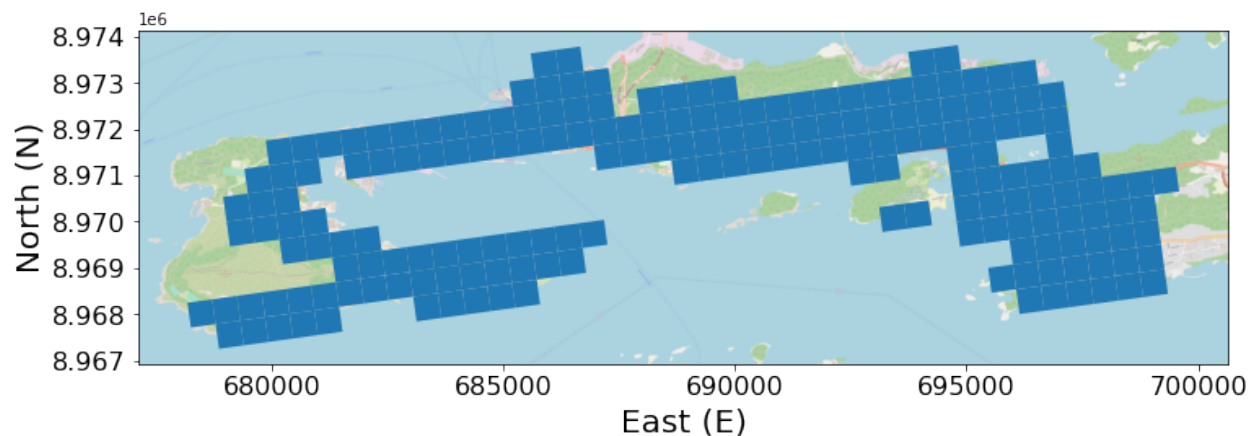

Figure 4.3: Grid related to the population density. It was used for walkability computation and visualization.

population density dataset contains the number of residents in each grid cell. Figure 4.4 shows the population density after normalizing and scaling the values between 0 and 100.

4.2.4 Park Areas Indicator

The dataset related to park areas was downloaded from OpenStreetMap using the OSMNX Python Package. This package provides an API that can be used to call functions to receive tagged geometries and data by specifying the tags and a bounding box. The tag is defined by the key

Figure 4.4: Visualization of the computed walkability indicator related to population density.
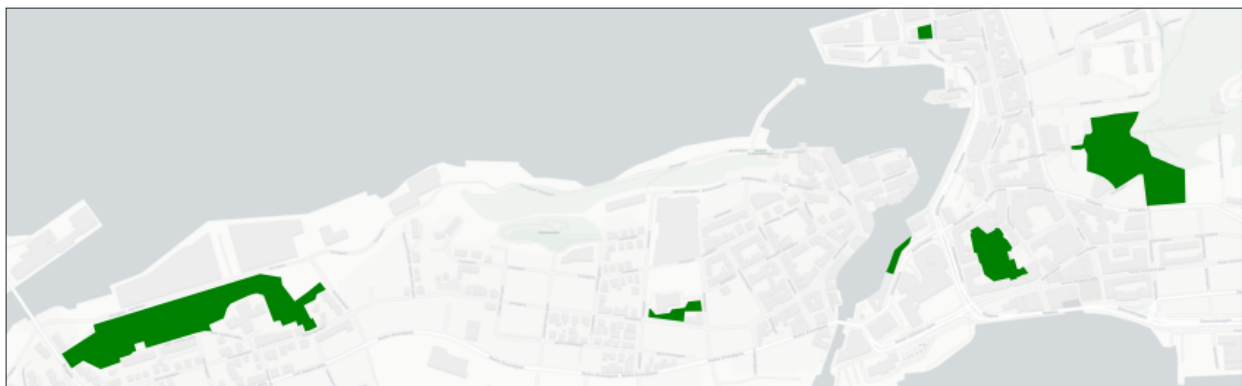

Figure 4.5: Park areas in Ålesund from Open Street Map.

'leisur' and value 'park' and the bounding box is defined in terms of the AoI in the WGS84 (EPSG: 4326) format. Figure 4.5 shows the park areas in the AoI after projecting it into the Web Mercator (EPSG: 3857) projection.

The grid extracted from the population density dataset is used when calculating the walkability index for all indicators. Figure 4.6 shows the park areas with the overlaying grid cells.

To compute the walkability index for the park areas indicator, a circle with a radius of walking distance is added from the center of each grid cell as shown in Figure 4.7. A spatial join is then performed to obtain a reference to each park that intersects within the walking distance of each grid cell as show in Listing 4.1. A walkability index score is calculated by measuring the distance to the closest park as shown in Listing 4.2. It will give a score of zero if there is no park within the walking distance and full score if the distance is zero.

Figure 4.8 shows the distance to parks after normalizing and scaling the values between 0 and 100.

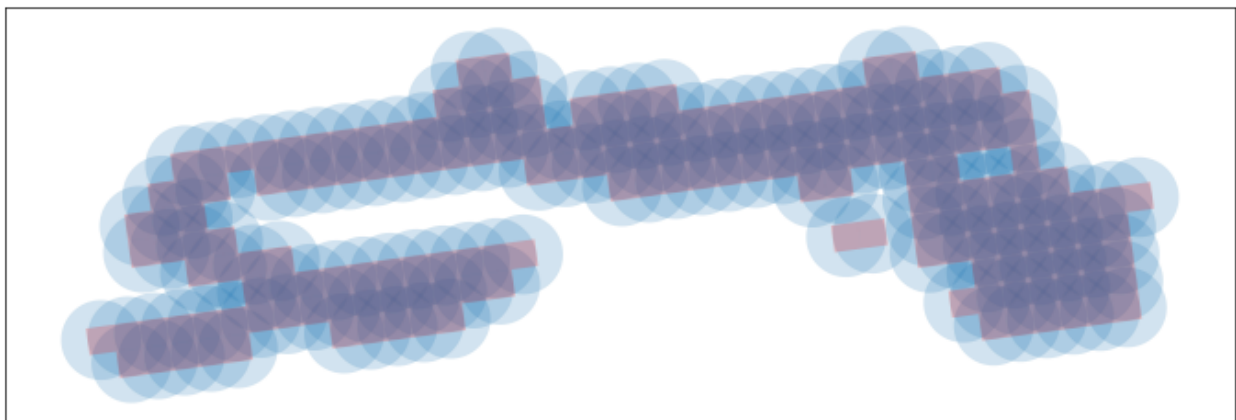Figure 4.6: Park Areas in Ålesund with the overlaying grid.

Figure 4.7: Grid radius associated with the computation of the indicator related to park areas.
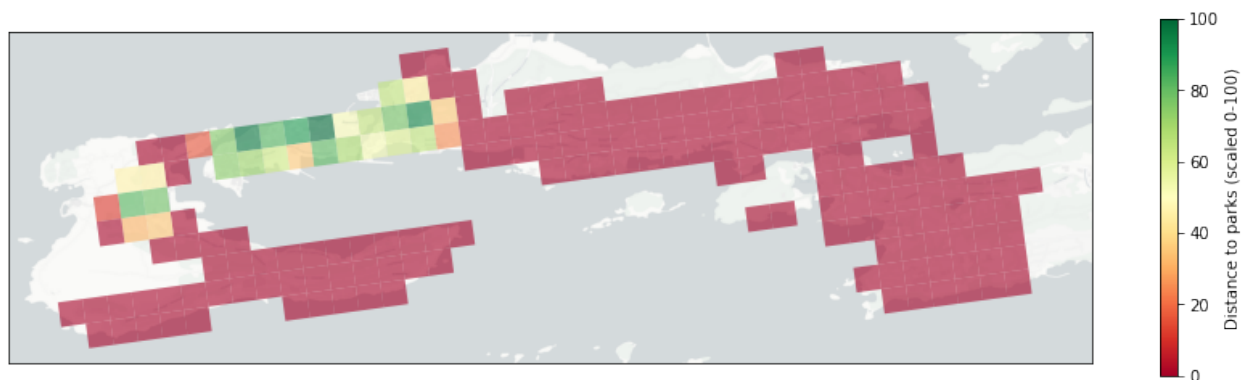

Figure 4.8: Computed walkability indicator for park areas.

4.2.5 Street Connectivity Indicator

The street network dataset is downloaded from OpenStreetMap using the OSMNX Python Package. This package provides an API with functions to support the acquisition of streets (edges)

Listing 4.1: Spatial join computation.

```
for gridCell in grid:
    gridCell.parks = []
    for park in parks:
        if(intersect(gridCell,park)):
            gridCell.parks.append(park)
```

Listing 4.2: Shortest distance computation.

```
for gridCell in grid:
    gridCell.score = 0
    for park in gridCell.parks:
        newScore = radius – distance(gridCell.centroid,park)
        If newScore > gridCell.score:
            gridCell.score = newScore
```

and intersections (nodes), according to a pre-defined bounding box. Information associated with streets includes the geometry shapes with their coordinates and speed limit attribute used to compute the walkability index for speed limits. The edges include the geometry shapes and coordinates with a speed limit attribute used to compute the walkability index for the speed limits. For nodes, there is information regarding the intersection points and coordinates with a number of intersecting streets, attribute used to compute the walkability index for street connectivity. Figure 4.9 shows the streets and intersections in the AoI after projecting it into the Web Mercator (EPSG: 3857) projection.
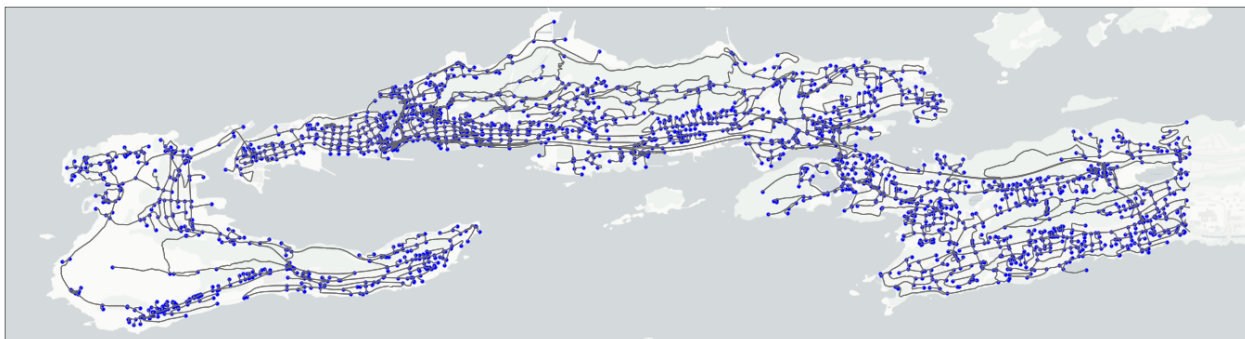

Figure 4.9: Streets and intersections in Ålesund obtained from Open Street Map.

To compute the walkability index for the indicator related to street intersections, a circle with a radius of walking distance is added from the center of each grid cell as shown in Figure 4.10. A walkability index score is calculated by counting the number of street intersections within a walking distance as shown in Listing 4.3. Figure 4.11 shows the number of street intersections
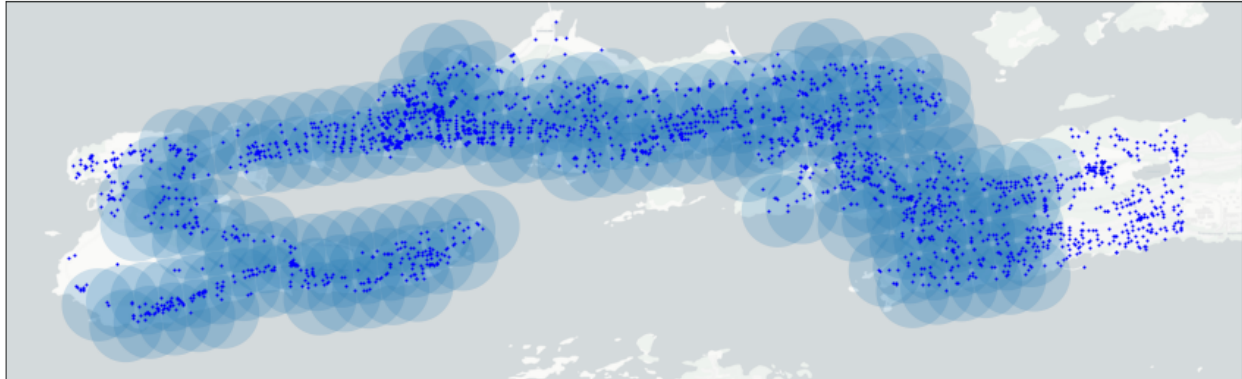
Figure 4.10: Counting number of street intersections

Listing 4.3: Counting of street intersections.

```
for gridCell in grid:
    gridCell.count = 0
    for streetIntersection in streetIntersections:
        if(intersect(gridCell, streetIntersection)):
            gridCell.count += 1
```

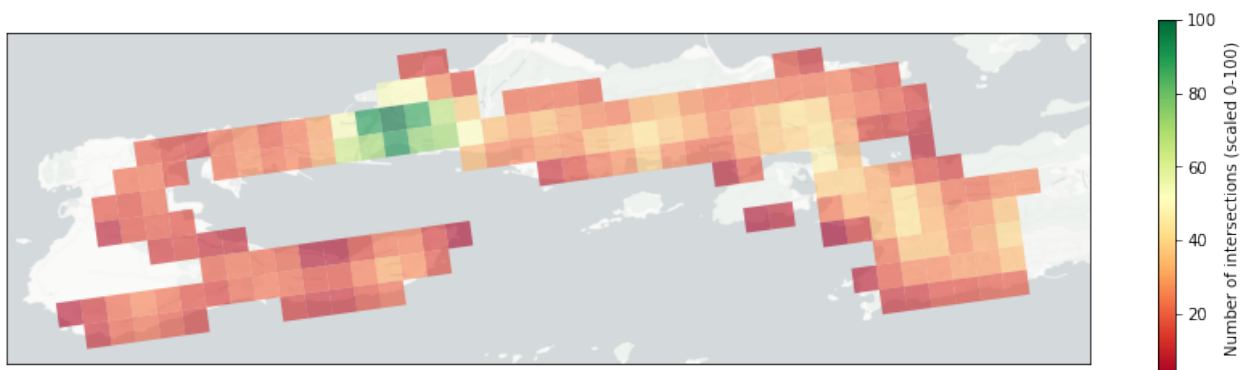after normalizing and scaling the values between 0 and 100.

Figure 4.11: Computed walkability indicator for street intersections.

4.2.6   Slope/Elevation Indicator

The elevation dataset of Møre og Romsdal county was downloaded from GeoNorge. The dataset has the EUREF89 (ETRS89) UTM Zone 33N (EPSG: 3045) projection and it is stored in a GeoTiff raster file format. For raster images to be able to cover a larger area, it was divided into tiles as previously, as shown in Figure 2.6. The Ålesund region is in between two tiles. Figure 4.12a
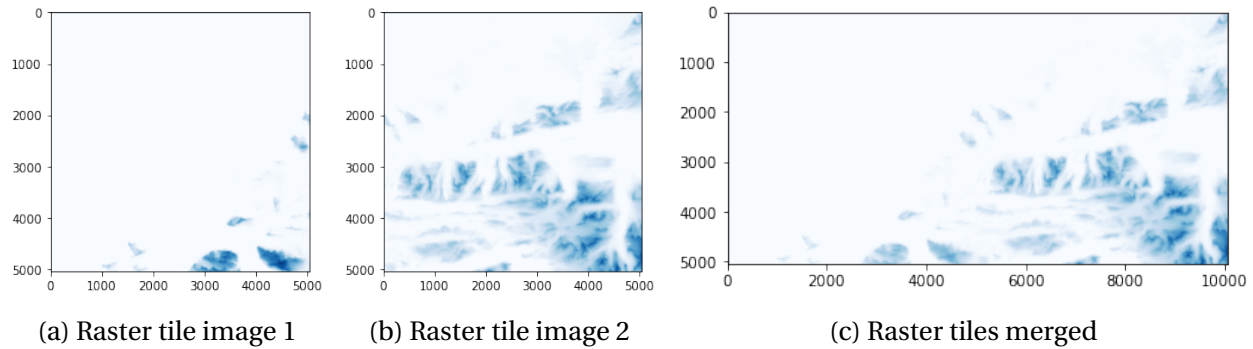
(a) Raster tile image 1   (b) Raster tile image 2   (c) Raster tiles merged

Figure 4.12: Elevation Dataset.
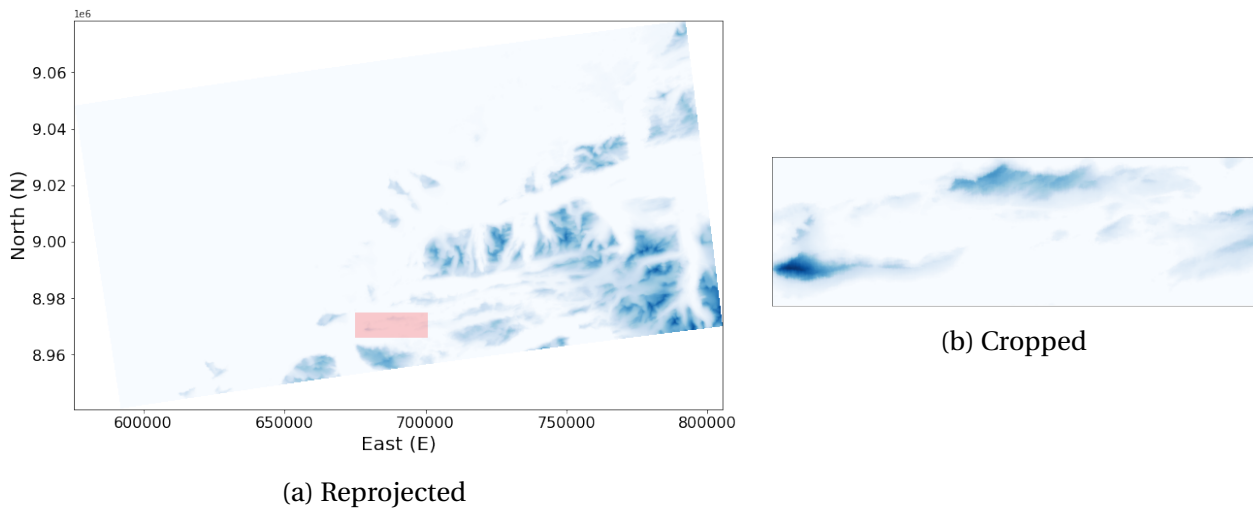

(b) Cropped

(a) Reprojected

Figure 4.13: Elevation dataset reprojected and cropped according to the area of interest.

shows the first raster tile and Figure 4.12a shows the second one. Figure 4.12c shows the two tiles merged into a single raster image.

After the image is merged, it is reprojected into the Web Mercator (EPSG: 3857) projection as shown in Figure 4.13a. The red rectangle is the AoI used when cropping as shown in Figure 4.13b.

Figure 4.14 shows the elevation data after cropped by the grid. The elevation data is inverted so the highest score is at the lowest altitude. Figure 4.15 shows the elevation data after normalizing and scaling the values between 0 and 100.

4.2.7 Speed Limits Indicator

The data acquisition related to speed limits is done in the same operation as for the street connectivity indicator, described in Section 4.2.5. Data related to streets include the geometry shapes with their coordinates and speed limit attribute used to compute the walkability index
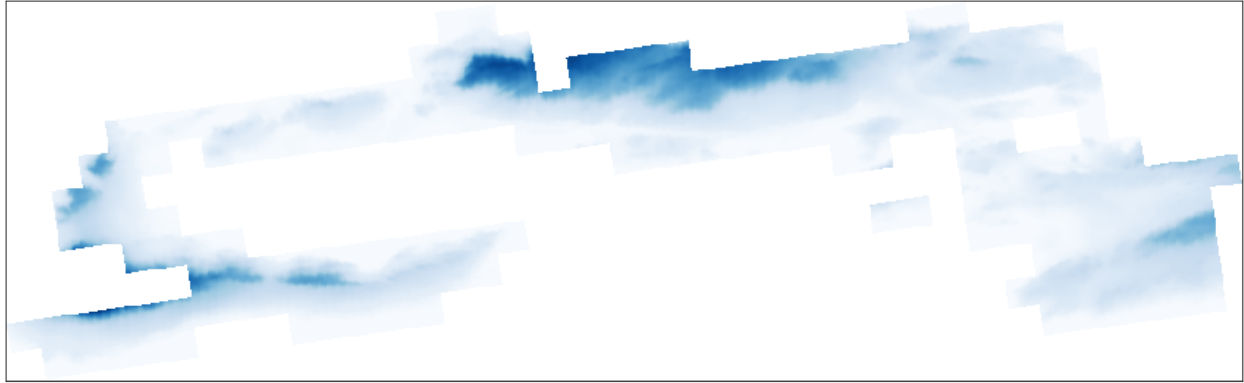
Figure 4.14: Elevation cropped grid.
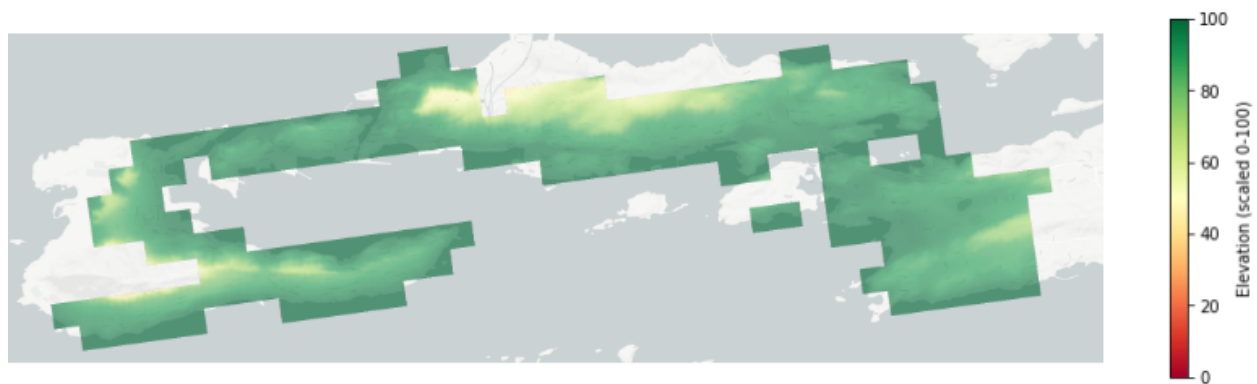
Figure 4.15: Computed walkability indicator for elevation.

for speed limits. Figure 4.16 shows the street network downloaded from Open Street map with the grid used when calculating the walkability index.

Figure 4.16: Streets in Ålesund from Open Street Map with overlaying grid.

Figure 4.17 shows the speed limits for each street. The walkability index score is calculated by taking an average of each speed limit intersecting each grid cell. Since a lower speed limit should give a higher score, the speed limits are first inverted and scaled from zero to one hundred as

Figure 4.17: Speed limits in the Ålesund area.
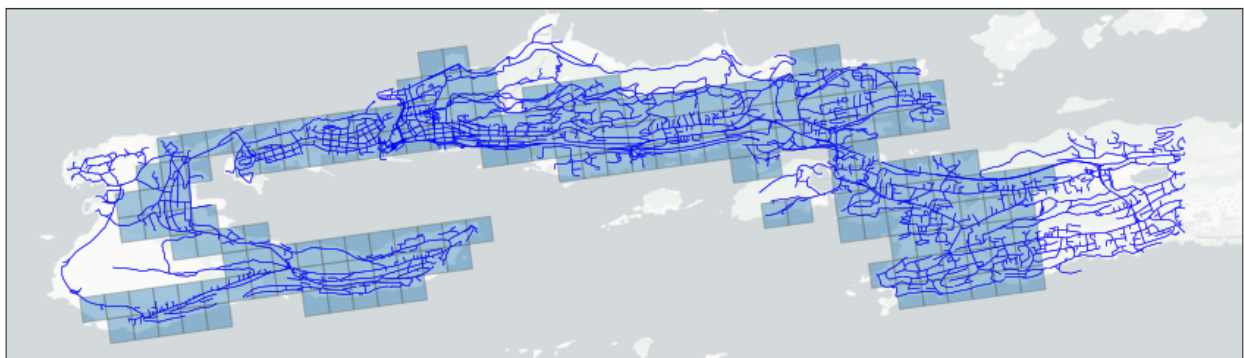
Listing 4.4: Inverting and scaling speed limits.

```
maxSpeed = streets.speedLimit.max()
for street in streets:
    street.speedLimit = ((maxSpeed - street.speedLimit)*100)/maxSpeed
```

shown in Listing 4.4. In this case, zero corresponds to 80km/h and one hundred corresponds to 0km/h. Next, a spatial join is performed to get a reference to each street that intersects with each grid cell as shown in Listing 4.5.

The inverted and scaled speed limits are summed up for each grid cell and then divided by number of streets to calculate the average as shown in Listing 4.6. Figure 4.18 shows the computed walkability indicator for speed limits.

4.2.8 Pedestrian Crossings Indicator

Figure 4.19 shows the user interface from "Statens Vegvesen" displaying the pedestrian crossings in the Ålesund city region.[7] The dataset was downloaded by zooming in on the area and typing in "gangfelt" (pedestrian crossing) in the search box and clicking on the SOSI link. After the file

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[7]https://vegkart.atlas.vegvesen.no/ (As of June 2021).

Listing 4.5: Spatial join between grid and streets.

```
for gridCell in grid:
    gridCell.streets = []
    for street in streets:
        if(intersect(gridCell, street)):
            gridCell.streets.append(street)
```

Listing 4.6: Average speed limit score calculation.

```
for gridCell in grid:
    gridCell.numberOfStreets = 0
    gridCell.totalScore = 0
    for street in gridCell.streets:
        gridCell.numberOfStreets += 1
        gridCell.totalScore = street.speedLimit
    gridCell.score = gridCell.totalScore/gridCell.numberOfStreets
```
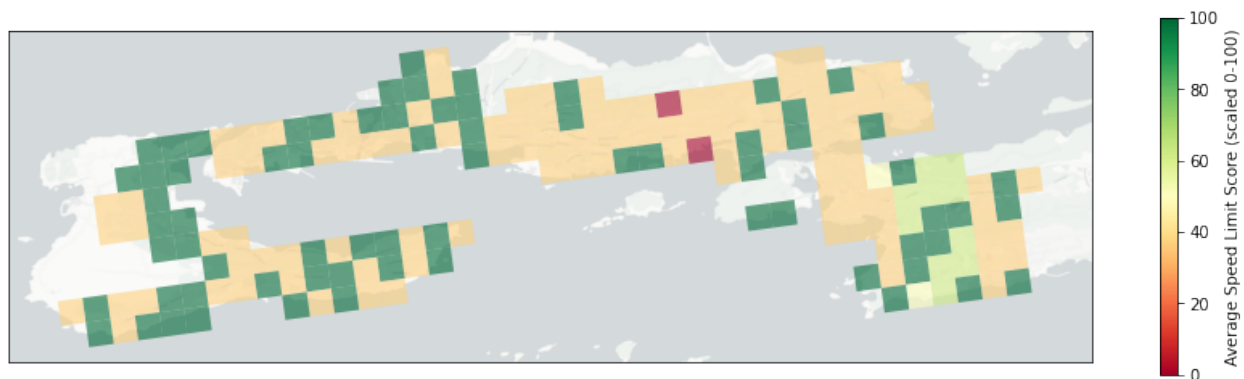

Figure 4.18: Computed walkability indicator for speed limits.

was downloaded, the online tool "SOSI to Shape" converter[8] was used to convert it into a shape file.

The dataset has the EUREF89 (ETRS89) UTM Zone 33N (EPSG: 25833) projection and it was reprojected into the Web Mercator (EPSG: 3857) projection. The data was then cropped out by the AoI as shown in Figure 4.20.

The walkability index computation is done in a similar way as for the "Distance to park areas" indicator. A spatial join is performed to get a reference to each pedestrian crossing that intersects within the walking distance of each grid cell as show in Listing 4.7.

A walkability index score is calculated by measuring the distance to the closest pedestrian

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[8]https://geodata.no/geodataprodukter/sosi-shape (As of June 2021).

Listing 4.7: Spatial join between grid with radius and the pedestrian crossings

```
for gridCell in grid:
    gridCell.pedestrianCrossings = []
    for crossing in pedestrianCrossings:
        if(intersect(gridCell,crossing)):
            gridCell.pedestrianCrossings.append(crossing)
```

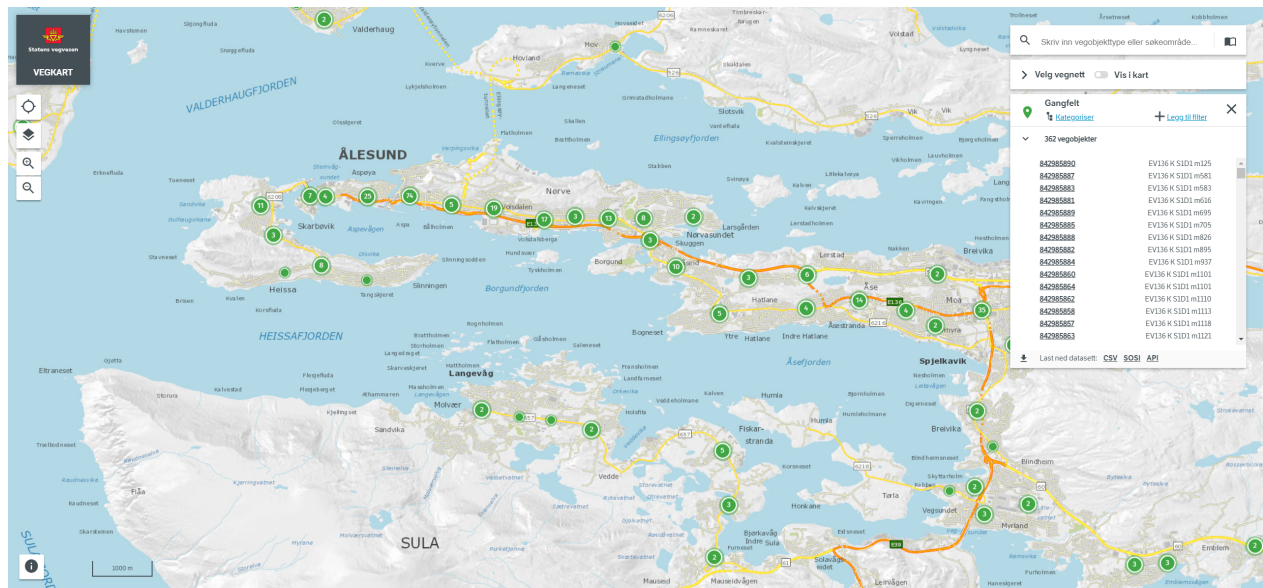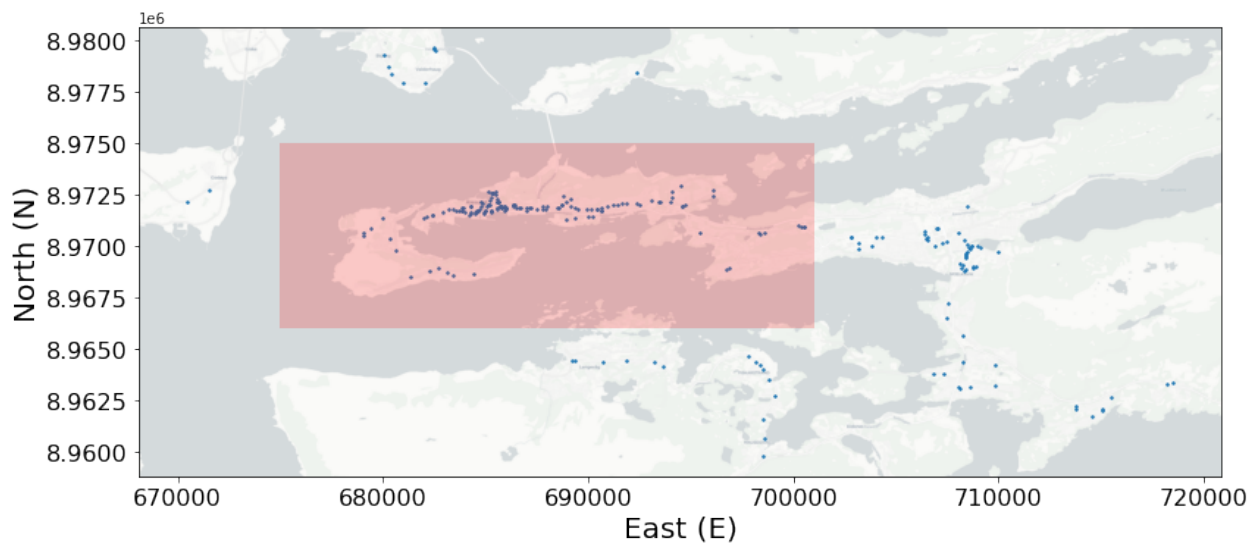Figure 4.19: Overview of data related to pedestrian crossing points in the Ålesund area.

Figure 4.20: Pedestrian crossing data.

crossing as shown in Listing 4.8. It will give a score of zero if there is no pedestrian crossing within the walking distance and full score if the distance is zero. Figure 4.21 shows the computed walkability indicator for pedestrian crossings after normalizing and scaling the values between 0 and 100.

Listing 4.8: Distance to nearest pedestrian crossing

```
for gridCell in grid:
    gridCell.score = 0
    for crossing in gridCell.pedestrianCrossings:
        newScore = radius – distance(gridCell.centroid, crossing)
        If newScore > gridCell.score:
            gridCell.score = newScore
```
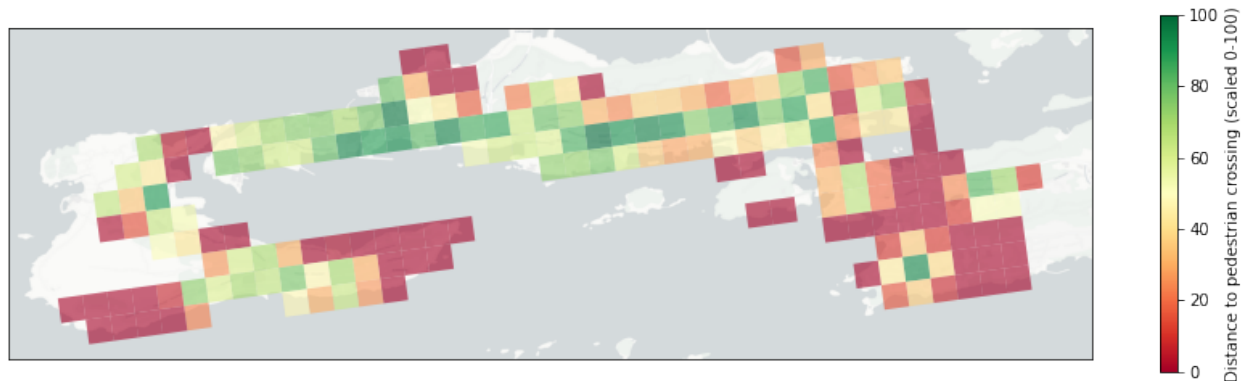

Figure 4.21: Computed walkability indicator for pedestrian crossings

4.3 User Interface

Figure 4.22 presents an overview of the user interface. At the upper right corner of the menu (region labeled with 1), there is a slider button, which defines if the menu will be shown or hidden. At the top (label 2), there is a button that allows users to open and hide the configuration window for the walkability calculation. In the center (label 3), there is a map area that presents the Ålesund region. At the bottom, there are some options related to the map view and the camera mode (labels 4, 5, and 6):

- By clicking on the toggle camera mode button, it is possible to switch between the 2D and 3D view (label 4).

- Different map layers can be selected from the drop-down menu (label 5).

- It is also possible to select between flat terrain and terrain with elevation (label 6). Figure 4.23 displays the map in 3D with elevation and the satellite layer selected.

Figure 4.24 displays the different map layers available. It is possible to select between Street Layer (Figure 4.24a), Outdoor Layer (Figure 4.24b), Dark Layer (Figure 4.24c), Light Layer (Figure 4.24d), and Satellite Layer (Figure 4.24e).
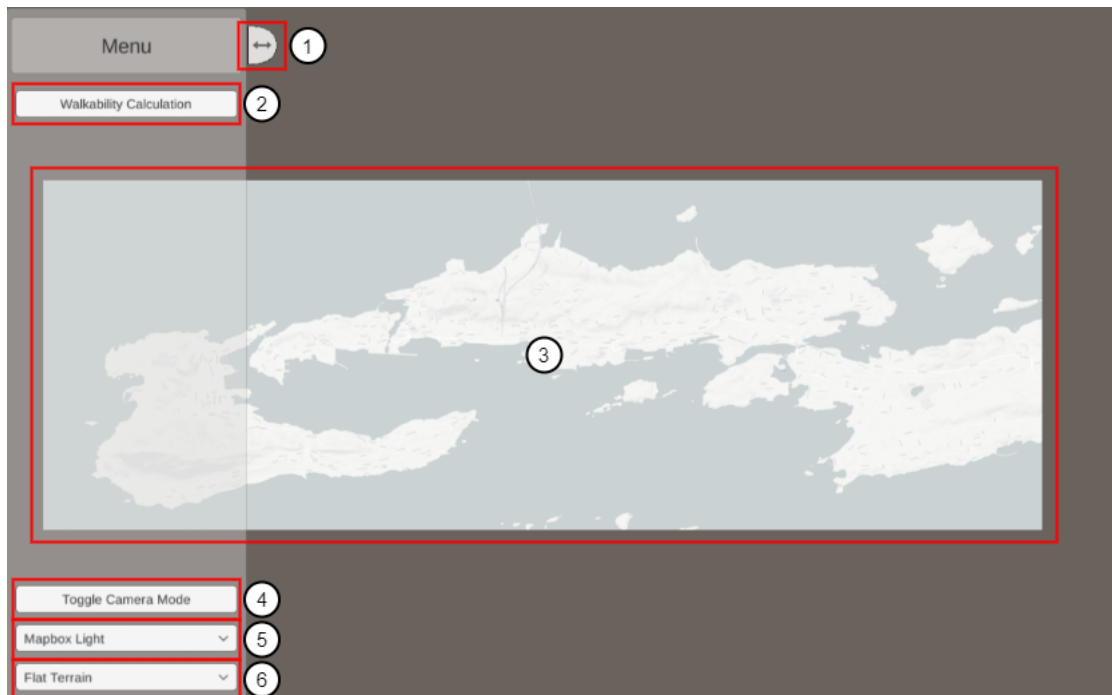
Figure 4.22: Overview of the user interface.

Figure 4.23: Map visualization in 3D.
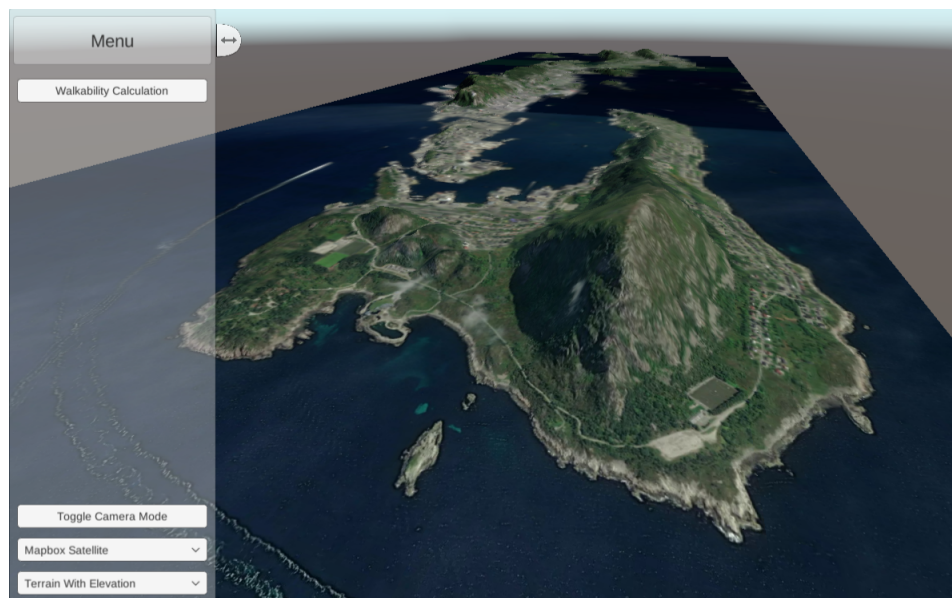
In both camera modes, it is possible to pan and zoom in with the mouse and keyboard. The left mouse button or the arrow keys can be used to pan and the mouse scroll wheel, to zoom in and out. In the 3D view, the user could also rotate by holding down the right mouse button and drag.

When clicking on the Walkability Calculation button seen in Figure 4.25 (region labeled with

(a) Mapbox Streets

(b) Mapbox Outdoors

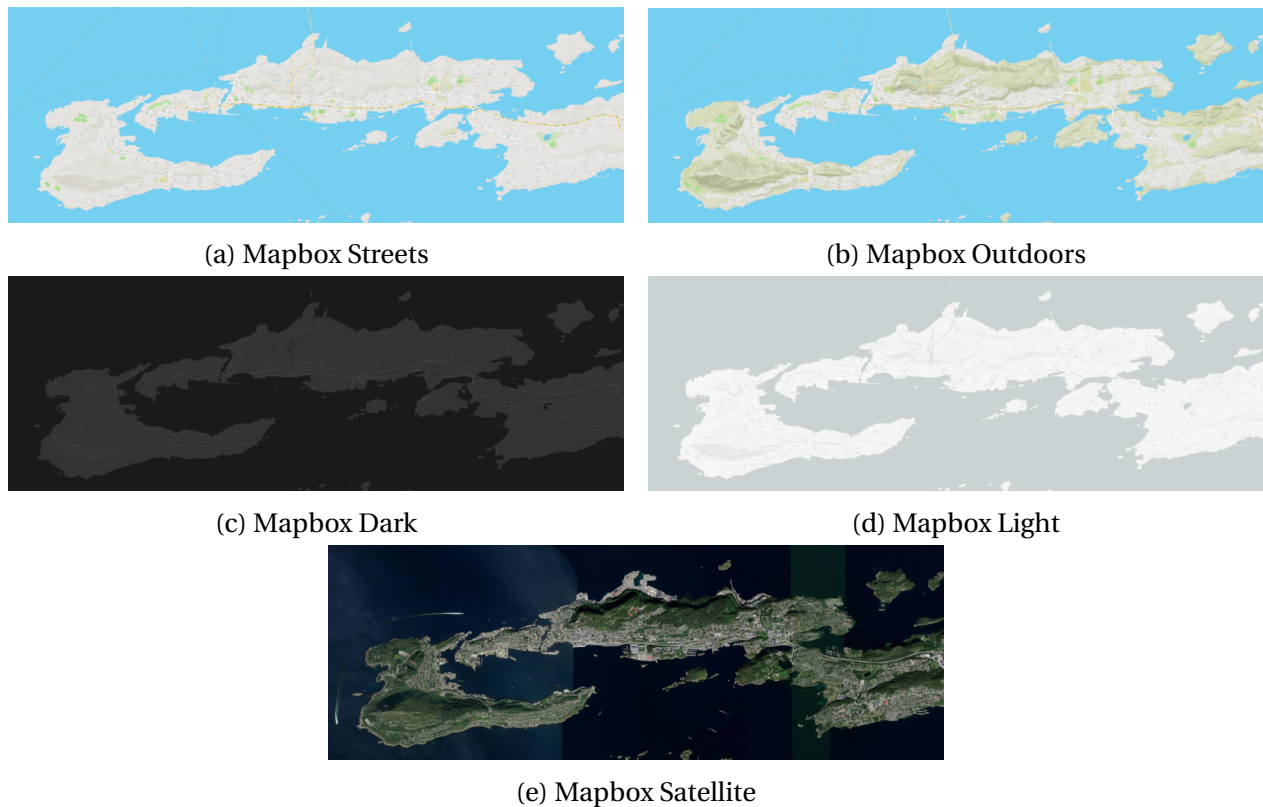(c) Mapbox Dark

(d) Mapbox Light

(e) Mapbox Satellite

Figure 4.24: Map layers available in the tool. Their implementation is based on Mapbox libraries.

1), a new window will appear (label 2). The walkability calculation window has four pages: Indicator Overview, Select Aggregator Function, Select Indicators, and Select Categories.

Figure 4.26 shows the Indicator Overview page. At the top, we have the page header (region labeled with 1) and the close window button (label 2). The indicators (label 4) are listed under underneath their category (label 3). A tooltip displaying information about the category (label 5) or indicator (label 6) is shown by hovering over the info symbol. The "Select Aggregator Function" page is entered by clicking the "Next" button (label 7).

Figure 4.27 shows the Select Aggregator Function page. The indicators could either be aggregated by weighting the indicators individually or by weighting the indicators by category (region labeled with 1). The specific aggregator function is enabled by selecting the radio checkbox (label 2). A tooltip displaying information about the function is shown by hovering over the info symbol (label 3). By clicking on the "Previous" button (label 4), users are sent back to the Indicator Overview page. By clicking on the "Next" button, users go to the page linked to the selected function (label 5).

Figure 4.28 shows the Selection Indicators page. It is possible to select which indicator to be included into the walkability calculation (region labeled with 2) and to define the weight assigned to indicators (label 1). If more than one of the indicators are selected, the assigned
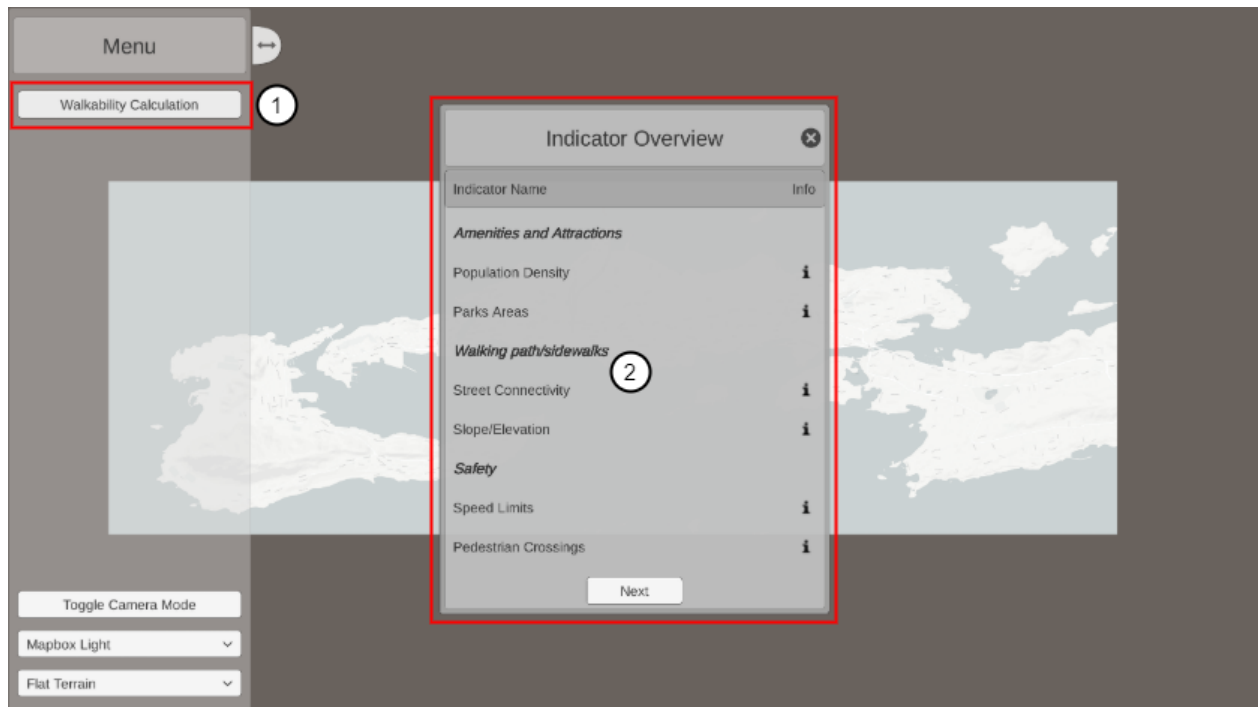
Figure 4.25: Configuration window for walkability calculation.

weight is used as a weighted ratio between them. By clicking on the "Previous" button (label 3), users go back to the Select Aggregator Function page. By clicking on the "Compute" button (label 4), users asks the system to compute the walkability score, whose computation results are displayed as a grid.

Figure 4.29 shows the Selection Categories page. It is possible to select which category to be included into the walkability calculation (region labeled with 2). If more than one of the categories are selected, the assigned weight is used as a weighted ratio between them (label 1). By clicking on the "Previous" button, users move back to the Select Aggregator Function page. Clicking on the "Compute" button, in turn, starts the computation of the walkability score, which is displayed as a grid.

Figure 4.30 displays examples of tooltip available for indicators (Figure 4.30a), categories (Figure 4.30b), and aggregators (Figure 4.30c).

Figure 4.31 shows the result of selecting all indicators using equal weights as a ratio between them. A colored grid is layed on top of the map to visualize the walkability score for each region. A color bar is shown to the right indicating green as the highest score and red as the lowest.
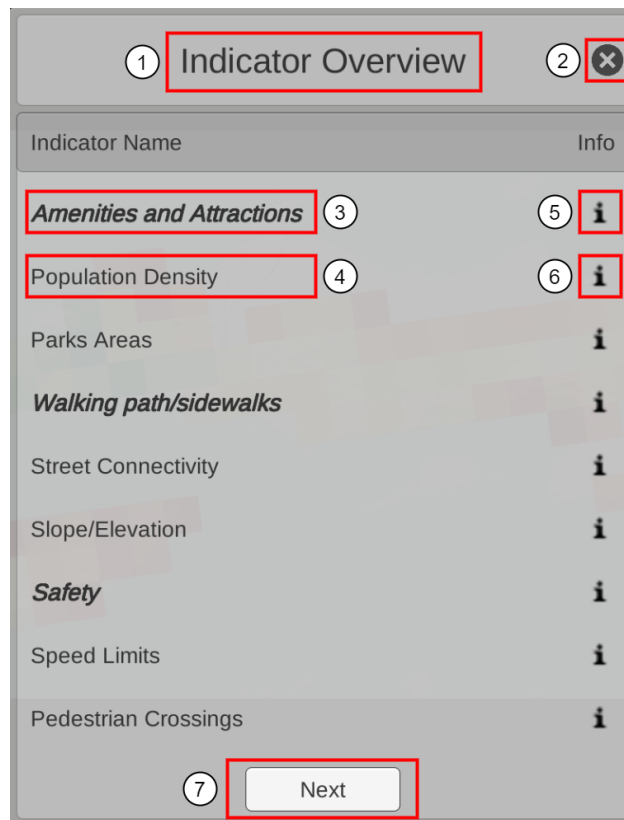
Figure 4.26: Walkability calculation – Indicator Overview.

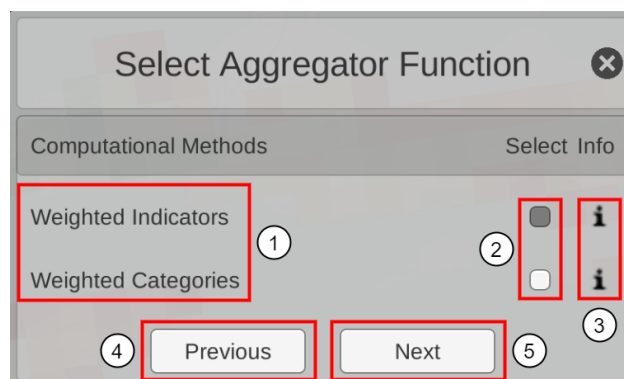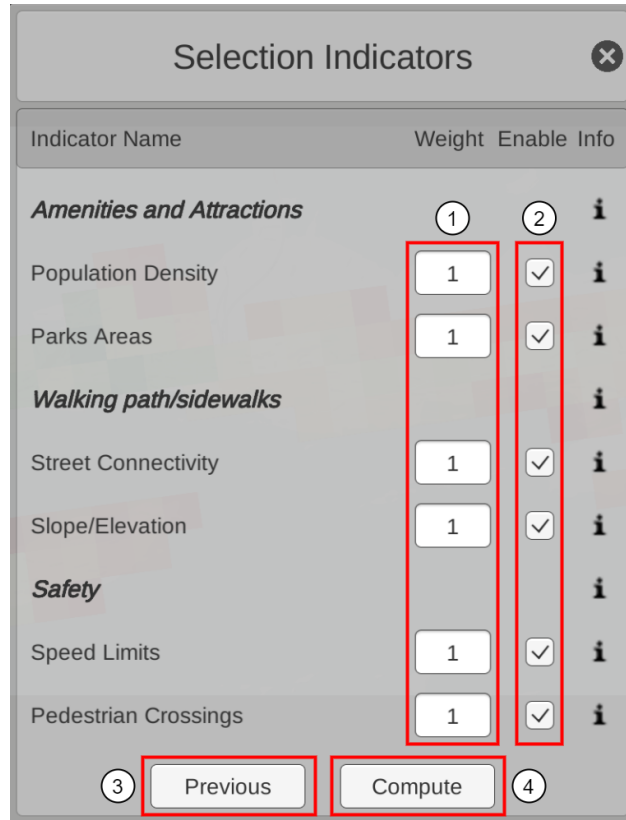Figure 4.27: Walkability calculation – Aggregator Function.

Figure 4.28: Walkability Calculation - Indicator Selection & Weight Assignment

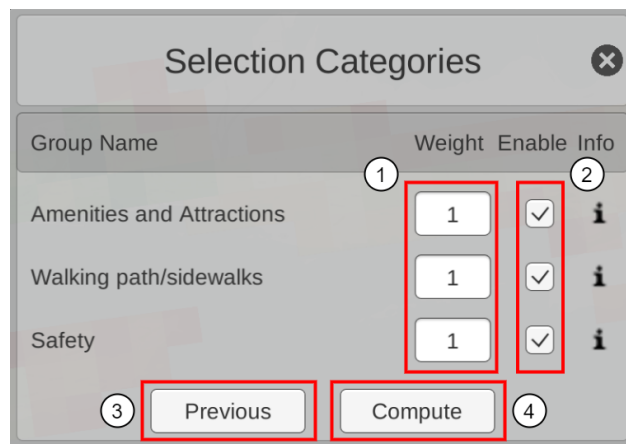Figure 4.29: Walkability calculation – Category Selection & Weight Assignment.

(a) Indicator Tooltip   (b) Category Tooltip   (c) Aggregator Tooltip

Figure 4.30: Examples of tooltips.
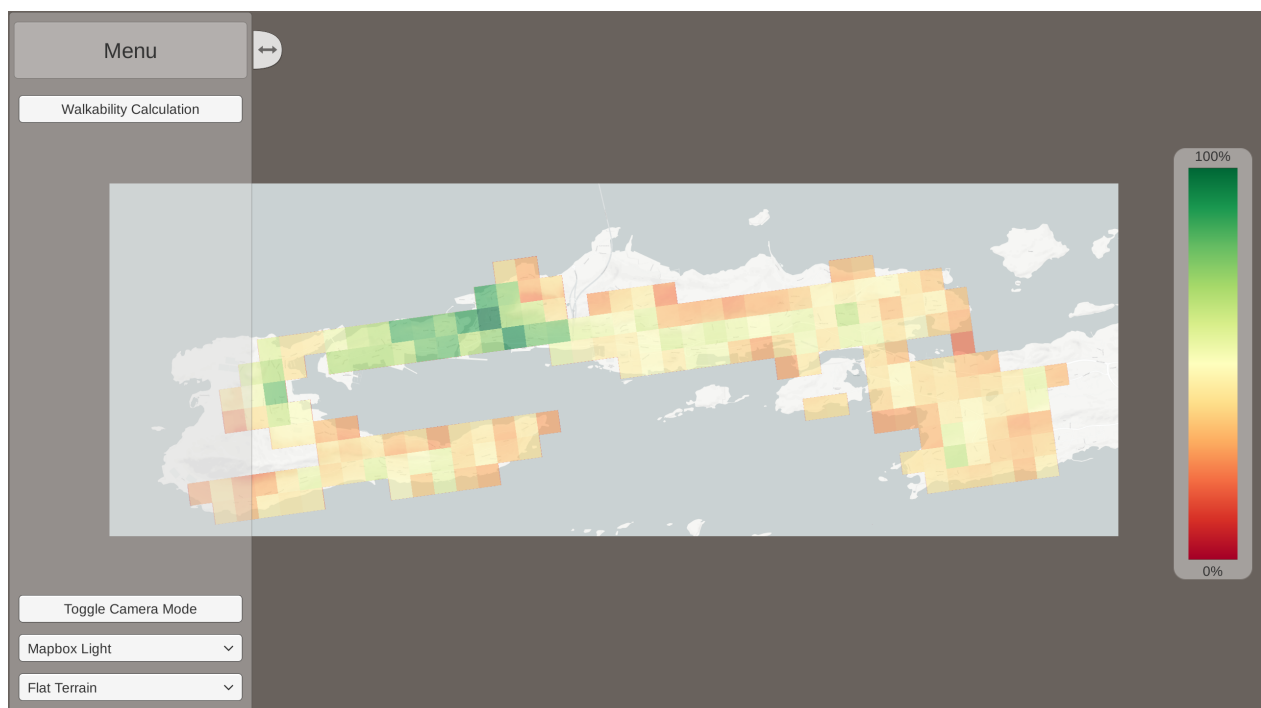
Figure 4.31: Screenshot illustrating walkability calculation results.

Chapter 5

Evaluation and Discussion

This chapter describes the conducted case study aiming to evaluate the developed generic architecture in the context of the assessment of the walkability in the Ålesund municipality (Section 5.1). The results from the research of the case study and the limitations of the implementation are discussed in Section 5.2.

5.1 Evaluation

The evaluation concerns the assessment of the user interface by taking into account the definition of parameter values (configuration) and visualization of results, and the analysis of the overall experience of users with regard to the computation of walkability indicators associated with the Ålesund municipality. This evaluation counted on the participation of a set of volunteers, and it is divided into two rounds, one during development and one after.

5.1.1 Evaluation Protocol

The evaluation framework DECIDE described in Section 2.4 is used as a guideline in the performed evaluation. This section explains the details of each item adopted in the evaluation protocol.

Determine the goals: This experiment aims to evaluate the graphical user interface of the digital twin walkability application of the Ålesund Municipality. It is expected that evaluators understand how this application works and its purpose, as well as find it user-friendly and with a consistent design. Finally, we aim to assess whether the available interaction mechanisms are easy to identify and perform.

Explore the questions: The conducted user study aims to address the following research questions:

- Does the user understand how the application works?

- How difficult is it to perform different tasks related to the computation of walkability indicators?

- How easy is it to identify the supported interaction mechanisms and to understand the provided visualizations?

Some open questions were also added so the users could provide their subjective suggestions and comments about the application.

Choose the Evaluation Paradigm and Techniques: An online Google Form, composed of linear scale ratings, multiple selection options, and free text fields, was used to collect the feedback from evaluators.

Identify the Practical Issues:

- **Users:** A set of volunteers from Ålesund Kommune (Ålesund Municipality), Møre & Romsdal Fylkeskommune (Møre & Romsdal County Municipality), and from the United Future Lab Norway were invited to both evaluations. Nine participants responded to the first evaluation. Unfortunately, no participants responded to the second evaluation due to their summer holiday.

- **Equipment:** The evaluators could use their own computer since all the material was accessible using a web browser.

- **Material:** The material used in this evaluation includes:

  - User invitation: An invitation was sent out to the participants by email. The email contained information about the relevance between this project and their own Smart Plan project, a short description about the survey, the estimated time, and a URL link to the Google form.

  - User instructions: The evaluation was divided into sections. For each section the user was given instructions before performing tasks and answering questions. It was also given a short description about the walkability concept and about the aggregation functions, categories, and indicators implemented.

  - Videos: Three videos were made available to give a visual and audible description about the application, two for the first evaluation and one for the second. The first video[1] provides an overview of the application, while the second one[2] presents a more detailed description in how to perform a walkability computation. The third video[3] refers to the description of updates to the user interface and new features added since the first evaluation.

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[1] https://youtu.be/qAGqTNSr9WO (As of June 2021).
[2] https://youtu.be/4-Qujt9xt8Q (As of June 2021).
[3] https://youtu.be/-gpVqUdMYnw (As of June 2021).

– Evaluation form: The predefined questions used when collecting answers from users.

– Application website: An online link to the application was provided to let the user test the application and perform the user tasks[4].

Decide how to deal with the ethical issues: The responses to this survey were collected anonymously. This was explained in the user invitation.

Evaluate, Interpret, and Present the Data: The participants received instructions for each task. They were then expected to perform some tasks and to provide feedback. Responses were collected by using linear scale ratings, multiple selection options, and free text. This will be used to generate bar charts, counter plots, and list of items that could be presented and used for further analysis.

5.1.2 Evaluation Forms

As mentioned in the beginning of Section 5.1, the evaluation was divided into two rounds, one during development and one that was supposed to be done after. The first evaluation was divided into four parts while the second evaluation had only one.

Evaluation 1 - Profile

In the first part of the first evaluation, a profile form was used to collect anonymous information about the participants. The first question was to obtain information about the level of education of the participants. The next three questions focus on the characterization of evaluators' profiles by taking into account their previous experience with related technologies. These questions are:

- How familiar are you with map-based applications (e.g., Google Map, Bing Map, Mazemap, etc.)?

- How familiar are you with geographic information systems (GIS)?

- How familiar are you with information visualization approaches (i.e., approaches used to represent data in a visual and meaningful way so that a user can better understand it)?

To answer these questions, a linear scale with five steps from 1 to 5 was used to indicate their familiarity. In the scale: 1 means not at all; 2, less familiar; 3, medium; 4, familiar, and 5 means very familiar. Finally, the last question aimed to obtain information about how familiar they were with the walkability concept. This was answered by using the same scale as the previous questions.

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[4]http://bjornarlongva.no/Walkability/ (As of June 2021).

Evaluation 1 - Application Task 1

In the first evaluation task, a user was expected to find and select walkability indicators, select an aggregation function, and visualize results. A video was provided to demonstrate each step of the process. After watching this video, participants had to answer the following questions:

- After watching this video, how do you rate your understanding about how this application works?

- How do you rate the degree of difficulty for performing Task 1?

- How easy is the identification and selection of walkability indicators?

- How easy is the identification and selection of the walkability indicator aggregation function?

- How easy is the identification of regions and their associated walkability scores?

To answer these questions, a linear scale with five steps from 1 to 5 was used to indicate their degree of difficulty. In the scale: 1, very difficult; 2, difficult; 3, medium; 4, easy; and 5 means very easy. The participants were also provided with an open question where they could give suggestions or comments related to the use of the envisioned application for Task 1.

Evaluation 1 - Application Task 2

In the second evaluation task, a user was expected to find and select walkability indicators, assign different weights to different walkability indicators (which represent their relevance), select an aggregation function, and visualize results considering different weight assignments. A video was provided to demonstrate each step of the process. After watching this video, participants had to answer the following questions:

- How do you rate the degree of difficulty for performing Task 2?

- How easy is the assignment of different weights to walkability indicators?

- How easy is the identification of the impact of changing the weights associated with different walkability indicators?

To answer these questions, a linear scale with five steps from 1 to 5 was used to indicate their degree of difficulty. In the scale: 1, very difficult; 2, difficult; 3, medium; 4, easy; and 5 means very easy. The participants were also provided with an open question where they could give suggestions or comments related to the use of the envisioned application for Task 2.

Evaluation 1 - Final Questions

After performing the two tasks, the participants were asked three final questions. The first question aimed to asses if they have increased their knowledge regarding how the application works. They were asked how they rate their understanding about how this application works before and after performing the tasks. The same scale as the last time was used.

In the second question, participants were asked to select indicators from a predefined list which would be valuable to compute the walkability of a specific region/road/street. As a last option to this list, participants could select "Other" and write their own suggestion of a relevant indicator. The indicators available in the list were:

- Population density: Number of people living in areas

- Street connectivity/intersections: Feasibility of walking from one point to another

- Green areas: Parks within a ten minutes walk

- Woods/forest

- Land use mix - Restaurants and workplaces are co-located to the neighborhood

- Lighting - Street lights

- Crossing availability

- Speed limits: Average speed limits in area

- Car traffic volume

- Potential for vehicle conflicts

- Sidewalk presence

- Sidewalk quality

- Sidewalk width

- Bus stops: Public transport available

- Fixed furniture: presence of benches and other places to rest

- Tree/plants presence

In the last question, the participants were also provided with an open question were they could give suggestions or comments about the application.

Evaluation 2

In the second evaluation the users were invited to watch one short video that demonstrate the updated functionality of the tool since the previous evaluation, and to provide some answers. In the previous evaluation the participants were asked to answer questions after only watching a video. In this evaluation the participants were expected to use the application themselves.

In the first question, participants were asked if they took part in the first evaluation with a yes or no answer. The next questions had to do with the difficulties of identifying and performing the operations. They had a linear scale with five steps from 1 to 5 was used to indicate their degree of difficulty and were listed as follows:

- How easy is the identification of walkability indicators?

- How easy is the identification of categories?

- How easy is the identification and selection of the walkability indicator aggregation function?

- How easy is the selection of walkability indicators and the assignment of weights to indicators?

- How easy is the selection of categories and the assignment of weights to categories?

Next, participants were asked which aggregator function they found most useful. Here, they could select between the functions associated with weighting indicators or weighting categories.

The next questions use the linear scale with five steps from 1 to 5 to indicate their degree of rating and were listed as follows:

- Would this tool lead to an effective assessment of walkability for the Ålesund region?

- After using the application, how do you rate your understanding about how this application works?

The last two were open questions:

- Are there other indicators or categories that you see could be included?

- Would you have suggestions or comments related the use of the envisioned application for?

5.1.3 Evaluation Results

In the first evaluation, nine users participated in the survey. All questions were required to be answered except for the open questions.

Evaluation 1 - Profile

The profile form is used to provide general information that might be relevant about the participants. The first question aims to obtain information about theirs level of education. Figure 5.1 shows the results. We can observe that all nine participants have a higher level of education; they hold either master's or PhD degree.
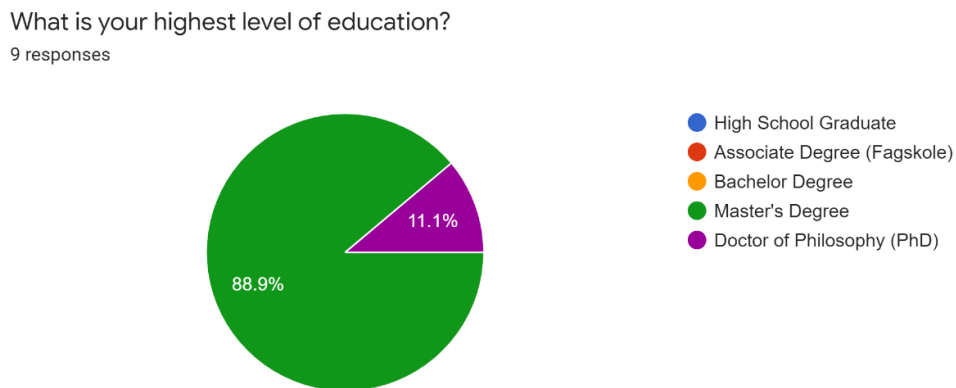

Figure 5.1: Information on education of participants.

Figure 5.2a shows that most participants are familiar with map-based applications. One participant is very familiar, six are familiar, and two are at medium level. Figure 5.2b shows that most participants are also familiar with visualisation approaches. One participant is very familiar, five are familiar, two are at medium level, and only one is less familiar.

Figure 5.3a shows that the participants have varying knowledge about GIS. Two participants are very familiar, two are familiar, two are at medium level, and three are less familiar. Figure 5.3b shows that most participants are lacking knowledge about the walkability concept. Two of them are familiar, one is at medium level, five are less familiar, and one is not at all familiar. According to Figure 5.2 and Figure 5.3, we could say that the participants have a medium level of knowledge about the main technologies employed in the implementation of the application.

Evaluation 1 - Application Task 1

Figure 5.4a shows that participants have a good understanding about how the application works. Three participants think it was very easy, four believe that the tool was easy, and two, at a medium level. Figure 5.4b shows that the participants found that performing Task 1 was easy. Five participants think it was very easy; three, easy; and one provided an intermediate assessment.
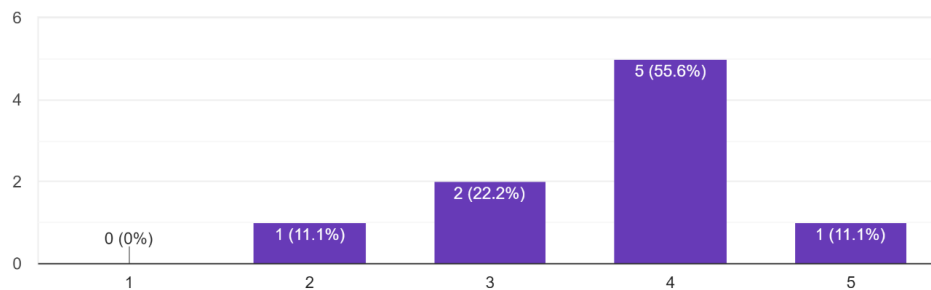
Figure 5.5a shows that most participants managed to identify the selection of walkability indicators. Four participants think it was very easy, three, easy, and one at a medium level. Only

How familiar are you with map-based applications (e.g., Google Map, Bing Map, Mazemap, etc.)?
9 responses
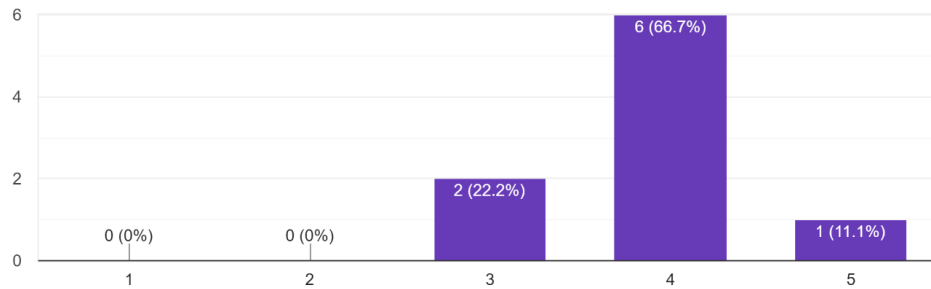
(a) Map-based applications

How familiar are you with information visualization approaches (i.e., approaches used to represent data in a visual and meaningful way so that a user can better understand it)?
9 responses


(b) Visualization approaches

Figure 5.2: Familiarity with map-based applications & visualization approaches.

one think it was difficult. Figure 5.5b shows that most participants managed to identify the selection of walkability indicator aggregation function. Three participants believe think it was very easy, four, easy, and one at a medium level. Only one think it was very difficult. Figure 5.5 shows that most participants managed to identify the regions and their associated walkability scores. Five participants think it was very easy, while two, easy and one, at a medium level. Again, only one think it was difficult. In summary, the feedback from the users is positive regarding the use of the tool for walkability computation in terms of the provided visualization and interaction approaches.

Participants were asked if they had any suggestions or comments related the use of the envisioned application for Task 1. The first comment was that it would have been better if the survey was in Norwegian and not in English. This could have made it easier for some people to express

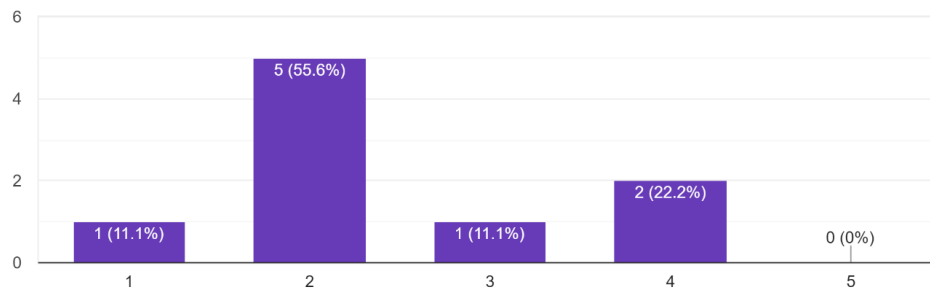How familiar are you with geographic information systems (GIS)?
9 responses
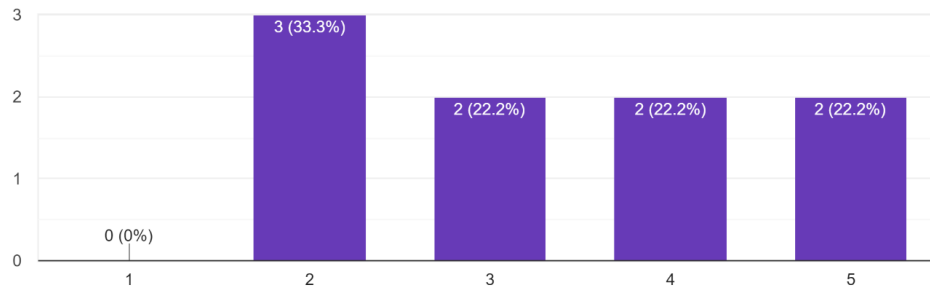
(a) Geographic information systems (GIS)

How familiar are you with the walkability concept?
9 responses

(b) Walkability concept

Figure 5.3: Familiarity with GIS and the walkability concept.

their opinions related to the walkability concept and application. There were some comments about how the indicators were measured and that it should be described in more detail to the user. For example, the calculation of the speed limit indicator is using the average speed in the area instead of the lowest speed available. According to an evaluator, that should be changed.

It was also mentioned that that the population density indicator computation should take into consideration the floor area ratio in buildings. One important comment referred to possible limitations related to the use of videos in the assessment procedure: *"It is a bit hard to rate from only the video itself, but it seems quite straightforward. Getting to know the different outputs from the different indicators could also require some interpretation practice. Regarding identification of regions it is a bit hard to judge from the video."*

After watching this video, how do you rate your understanding about how this application works.
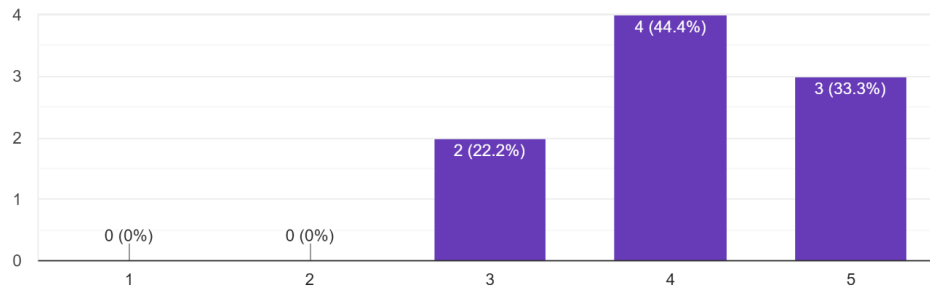
9 responses

(a) User Task 1 - Understanding about how this application works

How do you rate the degree of difficulty for performing Task 1?

9 responses
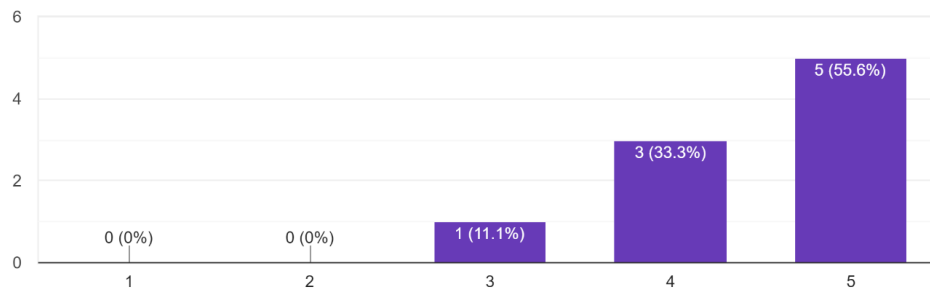
(b) User Task 1 - Degree of difficulty for performing Task 1

Figure 5.4: Task 1 - Understanding the application and difficulties in performing Task 1.

Evaluation 1 - Application Task 2

Figure 5.6a shows that most participants have a good understanding about how to perform Task 2. Three participants think it was very easy, while six think it was easy. Figure 5.6b shows that it was easy to understand the assignment of different weights to walkability indicators. Three participants think it was very easy, four, easy, and one, at a medium level. One participant think it was difficult. Figure 5.6c shows that the identification of the impact of changing the weights associated with different walkability indicators was easy to understand. Similar results to the ones observed for the previous question were achieved.

Participants were asked if they had any suggestions or comments related to the use of the envisioned application for Task 2. Only one comment was given regarding the definition of weights. According to the evaluator, the assignment of different weights is probably not so easy

for ordinary people who may not have enough background knowledge about this weighting scheme. The evaluator suggested the inclusion of a default recommendation.

Evaluation 1 - Final Questions

Figure 5.7 shows that most participants have a good understanding about how the application works. Two participants think it was very easy, while seven think it was easy. Compared with the rating given before the two tasks, shown in Figure 5.4a, we see that scores had increased a bit.

Participants were asked about which indicators would be valuable to compute the walkability of a specific region/road/street. Figure 5.6 shows that street connectivity, green areas, crossing availability, and sidewalk presence were the four most valuable indicators according to users.

At last, the participants were asked if they had any suggestions or comments about the application. Three responded to this question. The first one repeated what she/he had said earlier about the indicator used for speed limits: *"If other measurements than average can be used or one can make sure that irrelevant high speed roads don't affect the result, I think speed limit would be a very relevant indicator."* The second comment referred to the use of slope information in the walkability computation. The third comment was a summary of the evaluator's understanding regarding the tool and how this tool could be relevant in practice: *"From what I have seen and understood, I see this application as a tool for registration and grading of accessibility on a plane level (overall level). The application can help administration and politicians to make overall decisions such as choice of focus areas (geography, theme, time, coordination, requirements for regulation and development / rehabilitation ...), general annual financial allocations, ordering detailed registrations and preparation / realization of concrete / plans / measures."*

5.2   Discussion

This section discusses some of the findings during the development of the digital twin walkability application, some of the choices made, some of the evaluation feedback, as well as some of the limitations.

The walkability concept is something that is important for the future wealth, health, and sustainability. Ålesund is a city that is focusing on smart innovation and digital technology and has been part of United Nations Smart Cities program. They have their own organisation, United Future Lab Norway,[5] that works with the challenges of becoming a smarter and more sustainable society. Ålesund has established a plan to provide better conditions for both cycling and

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[5]https://www.unitedfuturelab.no/prosjekt/smart-plan---planlegging-gjennom-visualisering-og-simulering/ (As of June 2021).

walking.[6] Some of the participants that took part in the evaluation are involved with such initiative.

The walkability application framework is based on a server client solution. This allows the application to have several clients connected at the same time. The server takes care of the processing, while clients deal with visualization and interactions. The server uses an API that makes it possible to access the data through an URL using different devices. The walkability processing server is developed using Python programming language which has several packages to support GIS processing. These included many of the functions needed in the process of computing the walkability index. In this thesis, Unity has been used to create the visualization which is deployed as web application. One benefit of using Unity is that it is possible to deploy the application to several devices. With small adjustments to the Unity project, it would have been possible to access the same data on VR- and mobile devices. The downside of using Unity was that it was harder to create user interface menus compared to how it is done developing a regular websites using HTML, CSS, and JavaScript.

A lot of datasets could be found that could be used to compute a walkability index for specific indicators, but not all of them were complete. Data on sidewalks in Ålesund, for example, was limited in the API provided by Nasjonal Vegdatabank, and it was only available for the main high way street. The existence of more data available would be valuable for the walkability application. The data provided by Open Street Map is built on the users' own initiative (similar to Wikipedia). Everyone could create an account and edit the maps, which means that there is a risk of the data not being reliable or missing. Available data related to the streets seem to be enough for the proper computation of indicators, but the existing data on park areas is incomplete.

The grid used for the calculation and visualization is based upon the grid that was included the population density dataset. The reason behind this choice was to drive all computations according to the possibilities of walking from the perspective of residence locations. However, the software was developed in such a way that the common grid can be easily replaced. The resolution of the raster image used for visualization purposes might also be too low if zooming-in operations are performed. In this case, it is possible to adjust the tool to cope with different resolutions, but this implementation will require more data storage and may demand more time to compute and transfer raster images.

The feedback from the evaluation was in general positive. After the evaluation, two indicators were added based on feedback. The slope indicator was requested in the open comments and the pedestrian crossings was among the top four most valuable indicators according to participants. The sidewalk presence was also among the top four, but available data to support its computation are insufficient. The indicators were also divided into categories and it was now

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[6]https://www.vegvesen.no/vegprosjekter/prosjekt/bypakkealesund/ (As of June 2021).

possible to assign weights based on each individual indicator or by category. The description in tooltip of aggregating function, categories and indicators were improved with more details. The speed limits indicator could have been calculated differently or it could have been an option to select between the average or the lowest speed. Since the first evaluation, based on videos, was a bit hard to judge, the application was made available for the planned second evaluation.

How easy is the identification and selection of walkability indicators?
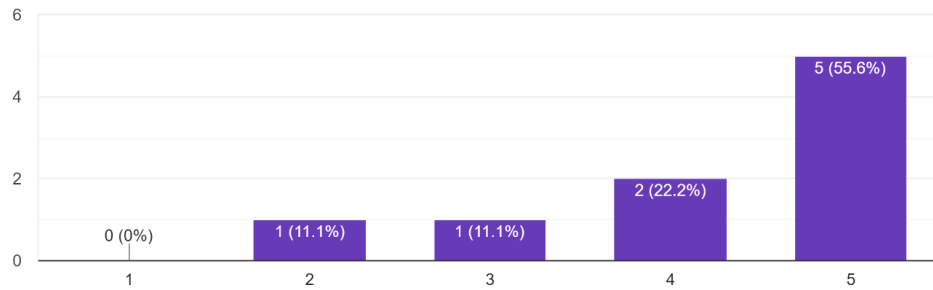9 responses
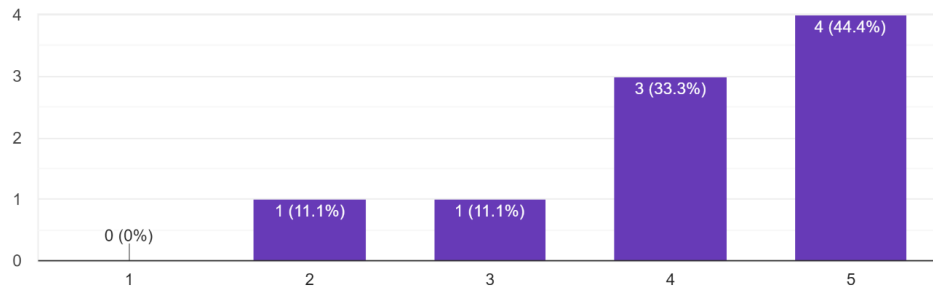
(a) User Task 1 - Identification and selection of walkability indicators

How easy is the identification and selection of the walkability indicator aggregation function?
9 responses
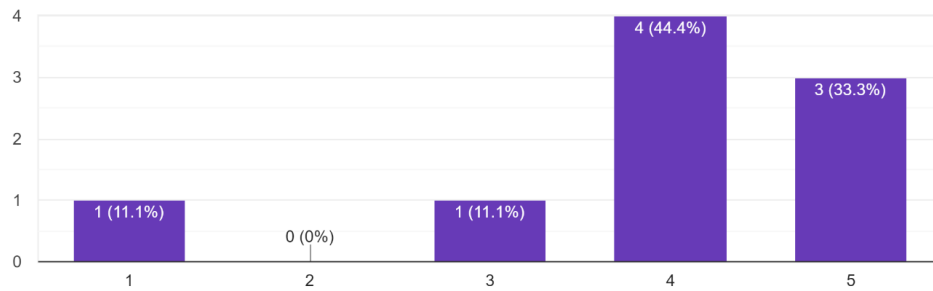
(b) User Task 1 - Identification and selection of the walkability indicator aggregation function

How easy is the identification of regions and their associated walkability scores?
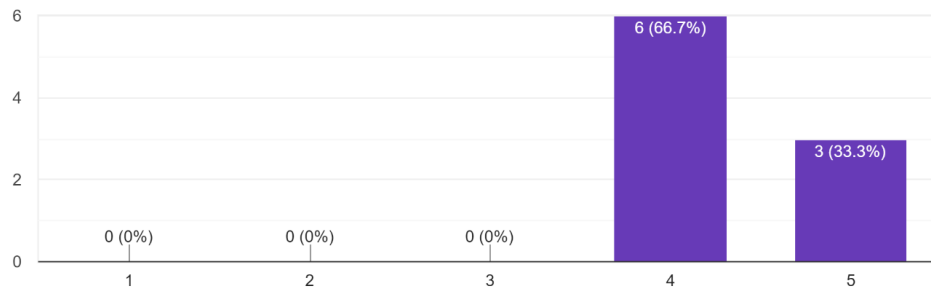9 responses

(c) User Task 1 - Identification of regions and their associated walkability scores

Figure 5.5: Task 1 - Visualization and interaction.

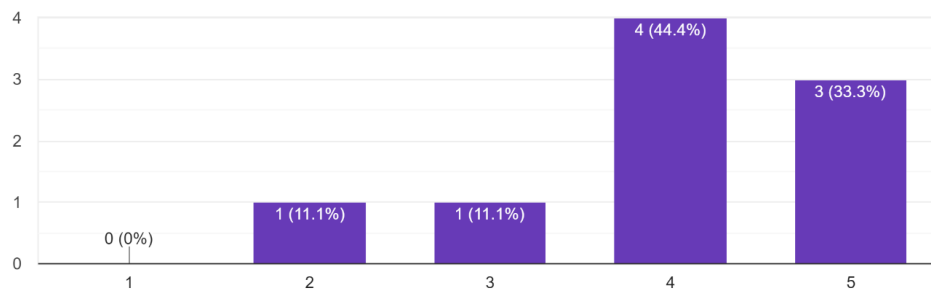How do you rate the degree of difficulty for performing Task 2?
9 responses

(a) Task 2 - Degree of difficulty for performing Task 2

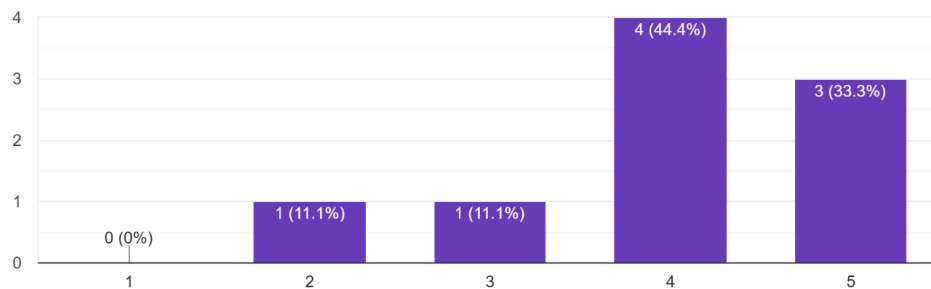How easy is the assignment of different weights to walkability indicators?
9 responses

(b) User Task 2 - Assignment of different weights to walkability indicators

How easy is the identification of the impact of changing the weights associated with different
walkability indicators?
9 responses

(c) User Task 2 - Identification of the impact of changing the weights

Figure 5.6: Task 2 - Results

After performing the two tasks, how do you rate your understanding about how this application works?
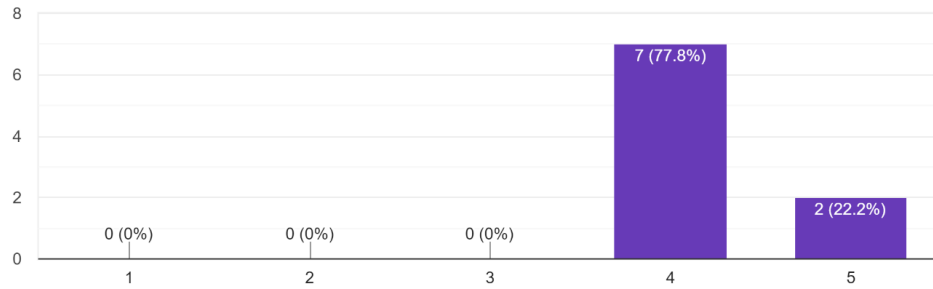
9 responses

Figure 5.7: Final Question - Understanding about how this application works.

Which indicators would be valuable to compute the walkability of a specific region/road/street?
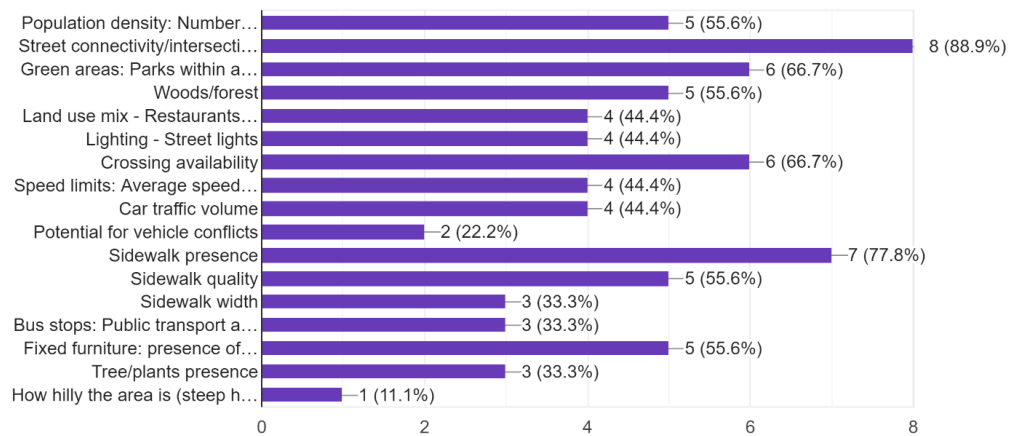
9 responses

Figure 5.8: Final Question - Most valuable indicators selected.

Chapter 6

Conclusions

This chapter outlines the main contributions of this thesis in Section 6.1, by addressing the raised research questions. Potential future work is discussed in Section 6.2.

6.1 Contributions

A generic framework for walkability assessment to support the planning process has been introduced. This framework was used to develop a digital twin application, used to perform an assessment of walkability for the Ålesund region. The design, development, and validation has been performed with the goal of addressing the following research questions:

- **RQ1:** How to construct a generic framework for walkability assessment to support the planning process?

  A generic framework was constructed in Chapter 3 for walkability assessment to support planning processes. The architecture is based on a client server architecture with four layers. Each layer in the server has their separate tasks independent of each other. The communication and transferring of data between the server and client is done using a web API. This makes it possible to visualize the results and to interact with the server using different types of devices. The generic framework was verified and proven to be successful when developing the application for walkability assessment for the Ålesund region, as described in Chapter 4. The framework is configurable in such a way that it could be applied for any city.

- **RQ2:** Would this framework lead to effective assessment of walkability for the Ålesund region?

  The generic framework constructed in Chapter 3 was used when developing the application for walkability assessment for the Ålesund region, as described in Chapter 4. The

evaluation was divided into two rounds, one during development and one that was supposed to be done after. In Chapter 4, the results of the first evaluation were analysed and the application was updated based on feedback. The second evaluation would have given a more advice in answering this question. Unfortunately, there was no time to receive answers to the second evaluation due to summer vacation. Based on the results of the first evaluation and personal communications, the framework could, with further development, potentially lead to an effective assessment for the Ålesund region.

6.2 Future Work

Since the use of walkability assessment tools is a relevant topic for Ålesund Kommune, both NTNU and the municipality are expected to continue working and investigating it further. The framework and application developed have a great potential, and with more improvements it could be a useful tool to support the planning process in Ålesund.

The conducted design, development, and validation opened possibilities for future investigation, which are summarized next:

- Adding more indicators would lead to a better result of the walkability computation. More research should be done to find and collect data that could be used to compute walkability indicator indices that may be more relevant to a given region of interest. Some examples of other indicators include sidewalks, bus stops or street lights.

- To be more organized, the use of a database management system could be explored to store the geospatial data. As it is now, the files are organized into folders and subfolders for raw, preprocessed, and processed data.

- Another enhancement refers to updating the framework to support more configuration options associated with indicators to be selected by users. For instance, the tool could make it possible to adjust the length of the radius corresponding to walkable distance used when computing some of the indices. Also, as mentioned in the evaluation discussion, the tool could make it possible to select between average and low speed when computing the index for the speed limit indicator.

- The area of interest, grid area, grid resolution, and color map are configurable on the server, but those settings are not possible to be changed by the client. For example, if the server has raw data for a large area, it could be useful to allow users to select a smaller area within the limits of the larger area. Therefore, the walkability calculation would be based on the selected area and resolution, and the colors would be based on the selected color map.

- If the graphical user interface is preferred to be only web based, a recommendation would be to maybe change the client solution developed in Unity to a more common web application, for example based on the use of HTML, CSS, and JavaScript. Although Unity is a versatile platform that could be deployed to many devices, it is not that easy to generate more complex menu systems. On the other hand, since Unity has been used the application could be extended to be explored on AR and VR devices.

- Another important direction refers to the assessment of new implemented features with target users.

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