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The Development and Deployment of Walkability Assessment Models for Built Environments

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Abstract: To encourage walking behavior, revising a built environment to be walkable is recognized as a necessity for influencing a broader audience while also having a long-term effect. Walkability, which indicates the friendliness of walking in a built environment, helps concerning parties to understand a urban context and make informative decisions when building walkable neighborhoods. Walkability is a fusion of different environment characteristics (e.g. sidewalk quality) influential to walking. Multiple instruments have been developed to measure perceived walkability by conducting surveys. However, this process is expensive and time-consuming. Matured GIS technologies together with extensive accessible data enable analysts to measure walkability objectively. While it is considerably inexpensive and time efficient, measuring walkability objectively has several challenging areas to tackle: the environmental characteristics to be considered, the methods to evaluate these characteristics, and the data availability to conduct the evaluation. To date, no existing model addresses those aspects appropriately.

This thesis has developed models to objectively evaluate walkability for neighborhoods and walking routes. Through examining empirical studies that explored the relationship between walking and environment characteristics, this thesis has identified a few characteristics that are influential to walking and incorporated them into the area based walkability evaluation model: population density, destination accessibility, land use mix, walking infrastructure quality, aesthetics, traffic safety and transit accessibility. The importance of these characteristics changes when targeting different walking purposes (recreational or transportation), population groups, geographic locations and cultural contexts. By weighing each characteristic accordingly, the model adapts to different study contexts. The weights should be adjusted based on expert knowledge or by benchmarking empirical studies conducted in similar contexts (e.g. similar urban setting). For evaluating walkability for walking routes, Dijkstra's algorithm is adopted to identify the walkable routes by minimizing the cost associated with the routes. This cost is defined by route distance, street type (e.g. highway, sidewalk), infrastructure quality and facilities along the routes.

As a case study, walkability is evaluated for the city of Helsinki. The implementation of the models has two purposes: 1) to provide a benchmark for analysts who intend to apply the model to other contexts, 2) to provide the environment quality information of Helsinki to concerning parties. Data processing, characteristics assessment, and walkability evaluation are described in detail to fulfill the first purpose. Secondly, a web application was developed to provide an accessible service for users to view the environment quality information including walkability. While walkability varies for individuals due to their personal preferences and needs, this service also allows customization by providing functionality to adjust weights of characteristics that are used to define walkability.

Keywords Walkability, GIS, Built Environment, Environment Characteristics, Walking, Active Transport

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List of acronyms

ACS Accumulated Cost Surface

BME Behavioral Model of Environment

DEM Digital Elevation Model

GIS Geoinfomation Science

NEWS Neighborhood Environment Walkability Scale

NEWS-A Neighborhood Environment Walkability Scale abbreviation form

OSM OpenStreetMap

PANES Physical Activity Neighborhood environment survey

PEDS Pedestrian Environmental Data Scan

WHO World Health Organization

WI Walkability Index

1. Introduction

The health benefits of physical activity have been acknowledged by healthcare professionals and the public. An active lifestyle can reduce the risk of many diseases like cardiovascular diseases, cancer, diabetes, depression, and fall-related injuries. Although these facts are well known, we are still incredibly lacking in regular physical activity, thus resulting in an astronomical 3.2 million deaths globally (World Health Organization 2017).

Many factors contribute to insufficient physical activity, such as easy access to passive modes of transportation (motorized transportation, e.g. car, motorcycle), less physical work on the job, along with more available sedentary recreational activities. Similarly, rapid urbanization has worsened this situation. Cities have been expanding at a dramatic speed while the proper urban planning failed to keep up. For example, a lack of sidewalks and recreational facilities, high-density traffic, and low air quality can all discourage physical activities to take place.

Walking is the most common form of physical activity and is recognized as the most amenable activity of influence, due to its well-established health benefits, popularity, and accessibility (Saelens et al. 2003; Owen et al. 2004; Lee & Buchner 2008). The benefits of walking go beyond its health benefits. Walking is a carbon neutral way of transport. Promoting walking to commute can reduce automobile use, which helps lower air pollution and road traffic. Subsequently, the air quality can improve, and traffic accidents can be reduced.

Due to the enormous benefits of walking, governments along with concerned communities and organizations, are making an effort to encourage the public to walk more. To achieve this goal, walking behavior is extensively studied to design effective intervention strategies. A comprehensive understanding on walking behavior is still lacking due to its complexity. This complexity stems from several areas of influence: personal value and motivation, social context, built environment and policy environment (e.g. zoning regulations). These areas are the targeting points of existing walking promotion strategies. Among the strategies, improving built environment to be more walking friendly has been recognized to impact a broader audience and have a long-term effect. Along with this recognition, the term walkability emerged to describe the ease and friendliness of walking in a built environment. Improving walkability can make walking an easy and pleasant experience for pedestrians, and encourage many to develop an active lifestyle. Many cities are constantly trying to reach such goal. This requires the officials have a good understanding of the current built environment quality regarding to its walkability. Meanwhile, improving public awareness of environmental quality can also encourage residents to take more walking trip as they can identify the areas that meet their needs for supporting walking behaviors. A walkability evaluation tool is then crucial towards reaching the goal of encouraging walking behaviors in the urban settings.

Understanding the correlations between walking behavior and built environment is one essential step towards evaluating walkability. Conceptualized from walking requirements and needs (i.e. feasibility, accessibility, safety, comfort and pleasurably), pedestrian infrastructure, street network connectivity, safety from traffic/crime, service accessibility and aesthetics are a few environmental characteristics hypothesized to be influential to walking behavior (Alfonzo 2005; Samarasekara et al. 2011). Based on those hypotheses, empirical studies have been conducted in various contexts to explore and validate the relationship between walking behavior and a built environment. While walking behavior is complex and determined by many other factors (e.g. value towards walking, socio-economic status, physical condition), the level of influence of built environment is found to be different for different study contexts (e.g.

different population groups, different locations), but some environmental characteristics constantly found to be correlated with walking (Saelens et al. 2003; Owen et al. 2004; Sugiyama et al. 2012).

Based on the established understanding of the relationship between built environment and walking, several tools were made for evaluating walkability. The majority tools rely on conducting surveys on sample population. As the environment is measured by subjective opinions, the evaluation is referred as perceived built environment/walkability. Perceived walkability is helpful to understand walking behaviors as perception highly influential to human behaviors. However, comparing objective evaluation, the perceived does not capture the true physical environment. Objective walkability is more suited to provide walkability information either to urban planners for designing urban areas to be more walkable, or to residents for identifying walkable areas/streets that meet their needs. Furthermore, matured Geoinformation technologies and massive openly accessible data (e.g. OpenStreetMap) make objective evaluating walkability inexpensive and time-efficient while perceived walkability evaluations tools are very costly to implement. Nonetheless, building an objective walkability evaluation model is still challenging because it greatly relies on: the target user group (e.g. recreational walkers, commute walkers, adults, school children, the elderly); available data and data quality; and an expert opinion of correlations between environment and walking.

This thesis aims to develop models to evaluate environment regarding to its walkability. With the knowledge and insights of correlations between environment and walking, GIS technologies, as well as open data, it is feasible to objectively evaluate walkability. Such model can benefit researchers and analysts to evaluate walkability easily, while the evaluation result can be used to study walking behavior, facilitate urban planning as well as improve the awareness of the public about the environment quality.

1.1. Background

Substantial health benefits can be achieved when conducting sufficient physical activities. The World Health Organization (WHO) provides specific recommendations addressing activity frequency, duration, intensity, type, and volume to help people achieve the adequate health benefits for an average person. The recommendations state an adult between 18-64 years old should at least perform 150-minutes moderate-intensity physical activity or its equivalence per week (World Health Organization 2010). However, around 31% of adults fail to meet this recommendation globally (Hallal et al. 2012). WHO has identified physical inactivity as the fourth leading risk for mortality, as it is responsible for around 6% (around 3.2 million) deaths globally (World Health Organization 2009).

Physical inactivity is comparably more common in high-income countries opposed to their low-income counterparts. This is due to an increased occurrence of physical labor, household chores, and a decreased availability of automated transport in low-income countries compared to others. More concerningly, the total amount of physical activity has been declining due to rapid urbanization, mechanization and transport motorization among developing countries. On the positive side, in some high-income countries, the awareness of physical activity benefits is increasing, resulting in a rising trend of physical activity in those countries (e.g. Finland, United Kingdom) (Hallal, et al., 2012). Nonetheless, physical inactivity remains as a concerning problem worldwide and there is a need to promote physical activity for the population at large (World Health Organization 2015).

Walking is one of the most common physical activities. It is accountable for the largest portion of physical activity performed among those who meet the WHO's physical activity recommendation (Lee & Buchner 2008). Compared to many other forms of physical activity walking is accessible, familiar, inexpensive, convenient, safe, flexible, and is easily incorporated into everyday life. Therefore, it is an ideal physical activity to promote universally, regardless of age, race, and social status.

1.1.1. Health benefits of walking

The effectiveness of walking as a form of physical activity has been studied extensively. When meeting the recommendation of 150-minute moderate intensity physical activity per week by walking, an adult can gain considerable health benefits while reducing the risk of type-2 diabetes (Hu et al. 1999), cardiovascular diseases (Boone-Heinonen et al. 2009), colon cancer, depression (Robertson et al. 2012), and gain greater longevity (Robertson et al. 2012; Lee & Paffenbarger 2000). For people who suffer from Alzheimer's disease, walking is also beneficial to cognitive function (Winchester et al. 2013). Performing vigorous physical activities brings more substantial benefits compared to solely walking. However, when having the equivalent energy expenditures from walking and vigorous activity, the magnitudes of some health benefits are even comparable to each other (e.g. risk reduction in type-2 diabetes, cardiovascular diseases). Considering that people with sedentary lifestyles are the ones facing serious health risks brought by physical inactivity, a cost-effective physical activity like walking can help them obtain tremendous benefits. Walking is especially helpful for the elderly, since older adults can safely perform walking in a variety of locations with little skill required (Troped et al. 2017).

Moreover, walking can also serve as an active and low-cost transportation method. Today, cities are faced with many challenges including poor air quality, traffic congestion, and the greenhouse effect. With promoting walking as transportation method instead of motorized counterparts, these issues are also addressed. Indirectly, increased pedestrian traffic can also reduce traffic accidents and better social interactions among individuals (Giles-Corti et al. 2010).

1.1.2. Physical activity and walking promotion

Considering the enormous benefits of walking as well as the concerning physical inactivity status quo, its promotion has been gaining increasing attention. Governments, concerned communities and organizations have been developing different strategies and programs to promote physical activity worldwide. These promotional approaches can be classified as follows: 1) informational campaigns which aim to raise public awareness about the values of physical activities; 2) behavioral and social support and coaching which facilitate individual behaviour changing; 3) environment and policy advances advocating for easy access to physical activities (Heath et al. 2012).

While all three approaches have individually shown progress in the alteration of physical activity, to move towards a major impact at the populous level would require incorporating different approaches simultaneously (Giles-Corti & Donovan 2002; Hoehner et al. 2003). This is due to the complex decision-making process which leads to behavior usually incorporates personal, social and environmental factors. Therefore, physical activity promotion that has comprehensive coverage of all three aspects is more likely to maximize the promotion's effect.

In the context of Finland, around 34% of adults and 20% of older adults reached the physical activity recommendation in 2013 (World Health Organization-Europe 2013). With this recognized insufficiency of physical activity, governmental organizations have been developing and launching different promotional programs to increase the amount of physical activity at the population level. In the meantime, this study also showed sitting for long periods is harmful to physical well-being even if the amount of physical activity meets the recommendation. This type of sedentary lifestyle is also commonly found in Finland. Thus, the promotional programs also aim to decrease the amount of sitting time for individuals. For example, national strategy "On the Move" is designed to promote physical activity for different age groups up to 2020 (e.g. children, working class, older adults). This national strategy covers different levels of promotion including: increasing public awareness through basic education and media promotion, forming operating culture of reducing sitting time, improving more physical activity opportunities through bettering the accessibility to indoor and outdoor facilities, and providing supporting environmental infrastructure for cycling and walking.

1.1.3. Walking behaviour in research

To develop effective strategies for walking promotion, researchers aim to understand determinants that contribute to walking behavior and further identify ones that allow intervention. There have been two research fields leading relevant studies: public health and transportation. In early research stages, there was a clear gap between these fields. Based on the end goal of promoting walking, the former studies walking as a physical activity, the latter studies walking as an active transportation method. This gap resulted in distinguishing theories and models applied to walking behavioral studies.

Typical theories used in health research include the Theory of Planned Behavior, Social Cognitive Theory, and the Transtheoretical Model which aim to identify psychological and social influences on walking behavior. Utilizing those theories often lead to intervention practices that only affect small groups of people (Sallis et al. 2006). While there is a possibility these methods are highly effective, they come with a set of challenges: a lack of financial feasibility and questionable long-term results (Berrigan et al. 2010).

In urban planning and transportation, researchers are more concerned with motivating individuals to choose an active travel mode opposed to motorized options. Consumer Choice Theory is largely applied to studying travel demand and is based on the hypothesis that individuals choose their mode of travel by maximizing their benefits or minimizing costs associated with the travel process. Taking environment characteristics as influential factors contributing to travel costs, researchers also utilize this theory to examine the relationship between built environments and travel methods (Mitra 2013). However, Consumer Choice Theory does not consider an individual's attitude and cognitive process leading to the choice of specific travel methods (Mitra 2013), exposing a weakness in establishing the cause-effect relationship between determinants and behavior. Moudon and Lee (2003) proposed the Behavioral Model of Environment (BME) based upon the interaction between one's walking/cycling behavior and environment. The underlying theorem states a physical environment is both changing human behaviors while evolving around human behaviors. Targeting walking and cycling trips, the constructs of BME include (Figure 1): 1) areas of origin and destination, 2) route characteristics, and 3) areas that provide opportunities for walking and cycling trips. Unlike the Consumer Choice Theory, BME encapsulates a physical environment's context where walking/cycling trips take place rather than considering specific environment characteristics.

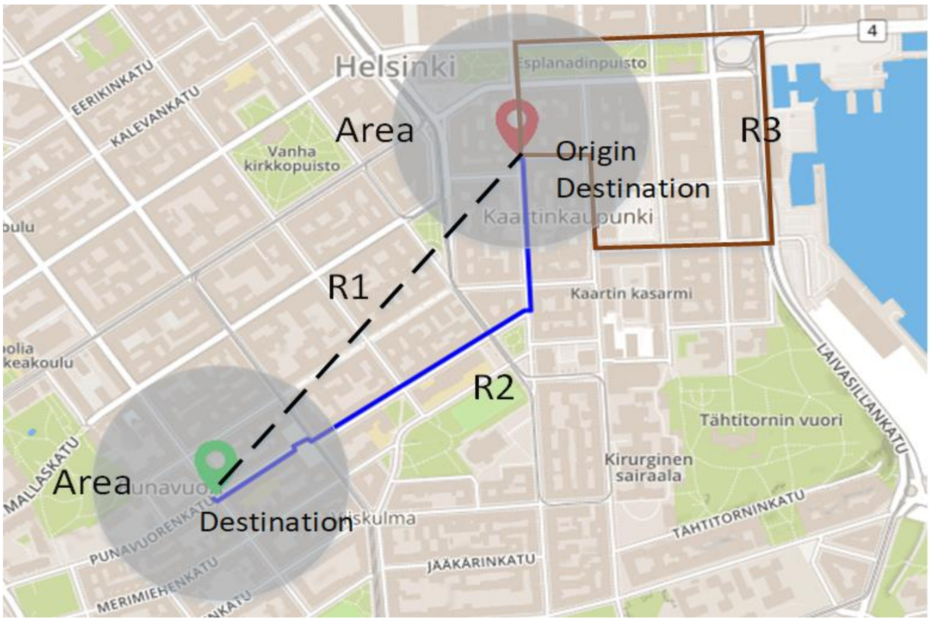


Figure 1. The basic constructs of BME: origin/destination, route, and area (Moudon and Lee 2003)

The adoption of these distinguish theories leads to the realization of a research gap that exists between each field. Upon identification of this gap, a multidisciplinary joint effort is clearly needed to study walking behavior more comprehensively. Researchers should begin to view human behavior holistically by considering not only personal characteristics, but also individual context such as social, environmental, and policy circumstances. As a result, ecological models are becoming increasingly popular in behavioral research including walking behavior. The essence of ecological models is the consideration of multiple layers of influence, including intrapersonal, interpersonal, environmental, and policy factors. Therefore, ecological models have great potential in assisting systematic explanations of walking behavior and further developing multilevel interventions to promote walking (Sallis et al. 2006; Sallis et al. 2008).

Sallis et al. (2008) proposed the following four core principles for ecological based models on behavior change: 1) health behaviors are influenced by different layers of factors, e.g. intrapersonal, interpersonal, organizational, community, and public policy; 2) factors from different layers interact with each other, and together they define human behaviors; 3) the most effective way of changing behaviors resides in multi-level intervention; 4) when guiding research and interventions, ecological models should be behavior specific (e.g. walking, cycling). For example, based on the core principles of ecological perspective, Sallis et al. (2006) proposed an ecological model of four domains of active living (Figure 2).

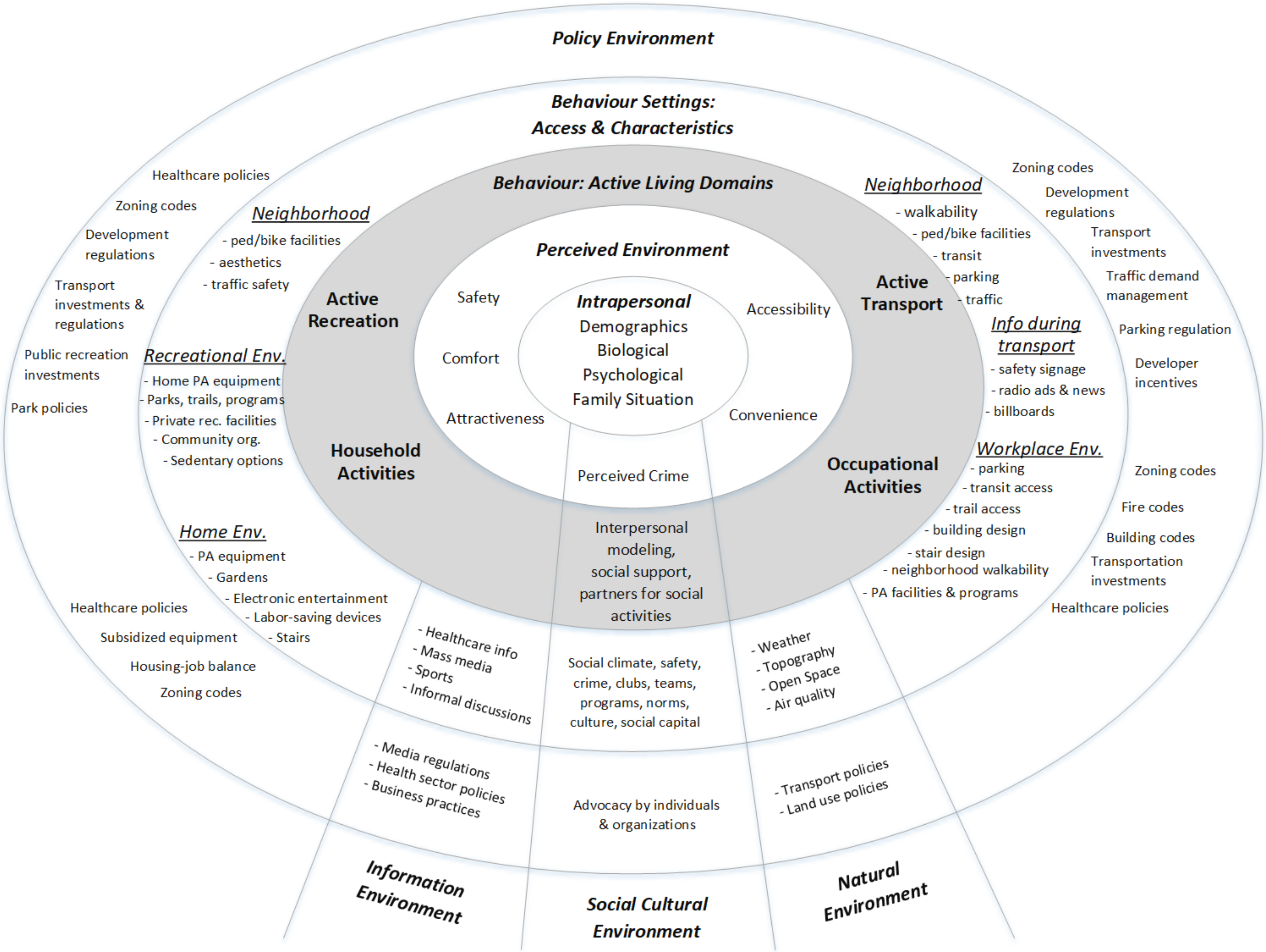


Figure 2 Ecological model for active living (Sallis et al. 2006)

1.2. Problem statement

Built environment is constantly evolving to serve its residents. Designing cities to be more walkable meets the current urban developing direction to improve public health and reduce carbon emissions. The knowledge of environment quality regarding to its walkability is essential in this process to guide proper planning and designing. While it can take decades to build a completely walkable city, citizens can utilize the walkability information to identify a residing location which meets their walking needs. Living in such locations encourages individuals to take more walking trips. Furthermore, to facilitate the increasing trend of walking trips, a routing service that provides walkable routes is in order. Such service can ensure the walking experience maximumly.

Built environment is not the only determinant of walking. Researchers are putting effort in understanding walking behavior better as promoting walking goes beyond improving physical environment. To maximize the promotion efficiency and ensure the long-term effect, other factors (e.g. value towards walking) should also be incorporated in the walking promotion strategies. Designing such promotion strategies requires a comprehensive understanding on walking behavior. However, at current research stage, walking behavior is still lack of understanding as it is complex and has multiple layers of factors (Figure 2). To fill this research gap, multidisciplinary cooperation is required to investigate the different aspects of walking behavior and its determinants, while synthesise the results and insights. An easy-to-use walkability evaluation model can be a great input for researching walking behavior, as the physical environment has significant influence on walking.

Therefore, an easy way to assess walkability is important for either practical usage or for researching purposes. However, majority walkability evaluation tools are expensive and time-consuming to implement while little walkability information is available for the public. This is because the majority evaluation tools are measuring walkability through conducting extensive surveys. Walkability Index (Frank et al. 2010) is the only tool objectively evaluates walkability by analyzing data. It integrates four different environmental characteristics: residential density, street network connectivity, retail floor area ratio, and land use mix. The limitation of Walkability Index is it neither considers other influential environmental characteristics such as aesthetics, nor the different impacts of each characteristic on different population group (e.g. the old versus young) or geographic location.

1.3. Purpose and structure of the study

Walkability information is beneficial for the officials to design walkable cities, for the citizens to choose the living and walking regions that meets their walking needs, and for the researchers to conduct research on walking behaviors. The majority of tools are evaluating walkability through conducting surveys which requires intensive resources and time. Nonetheless, extensive work has done to exploring relationship between built environment and walking. Meanwhile, matured GIS technologies and openly available data are available for comprehensive spatial data analysis. Specifically, many data sources (e.g. government entities, OpenStreetMap) provide extensive built environment information (e.g. land use, population, infrastructure information). Therefore, objectively evaluating walkability is a feasible task.

The purpose of this thesis is building walkability evaluation models to produce the walkability information that satisfies the needs of 1) decision makers and urban planners to design more walkable urban regions; 2) citizens to learn the urban context and identify the neighborhoods and routes that meet their walking requirements; 3) researchers to conduct walking behavior studies.

To reach the purpose, the models should:

1) Be elastic that it can be implemented in different geographic locations and for different population group;
2) Provide walkability evaluation based on different area units;
3) Provide walkability evaluation based on routes.

The elasticity requirement is based on the insight that in different urban contexts, for different population groups, the environmental characteristics have different levels of influence on walking. Area based walkability information can provide an overview of walkability across a large region, while route based walkability information helps identify walkable routes. It is hard to enumerate all the use cases for urban planners and the public, but both area based and route based walkability information are valuable. For example, the urban planners can utilize the area based walkability information to identify the neighborhoods that is not walking friendly while have high population density; the individuals can use route based walkability information to identify the walkable routes upon taking walking trips. For walking behavior research, only area-based walkability evaluation has been used. Therefore, in essence, this thesis aims to develop two walkability evaluation models that can evaluate walkability based on areas and routes respectively while both of then can adapt to various contexts.

For reaching the stated goal, four steps have been taken and divided into chapters in the following parts of the thesis.

First, in chapter 2, this thesis systematically examines the empirical studies and review work based on BME. The aim of the review is to gain a holistic understanding on each aspect of environment influences on walking behavior. Specifically, the literature review focuses on the three domains proposed by BME: the origin and destination, the route of the trips, as well as the area which provides walking opportunities.

1) The origins and destinations of walking trips (Trip purposes)

Origins and destinations usually indicate the purpose of the trip. With a clear purpose, it is easier to identify the environment characteristics relevant to pedestrians. Often, walking purposes are classified into utilitarian (transportation) and recreational (leisure) formats. Utilitarian walking is about getting from place to place, while recreational walking is about leisure or exercising activity. The origin and destination of a trip is usually different in utilitarian walking, while it can be the same for recreational purposes.

2) The route characteristics of walking trips

The characteristics of routes are highly relevant to providing a safe, comfortable and pleasant walking experience. Distance, walking infrastructure, pedestrian and vehicular traffic, route designs are a few characteristics of influence. For example, distance has been identified as one major determinants for individual to decide on traveling mode for utilitarian purposes.

3) The characteristics of the area that provides walking opportunities

Areas are the environmental context which interacts with individuals. When areas have high service/facility accessibility, well connected street networks, good route availability, and multiple alternative travel methods, they provide pedestrians with various walking opportunities. While addressing the reasons why individuals participate in walking activity, the characteristics of areas are crucial to consider in estimating walkability.

Each component in BME is highly relevant to walking behavior, as they address walking opportunities, walking purposes, and supportive infrastructure. For environmental evaluation, these three aspects need to be considered comprehensively as they join together to influence walking activities. With BME, the environment characteristics that are relevant to walking can be systematically reviewed (Moudon & Lee 2003).

Second, in chapter 3, this thesis gives an overview of the GIS technologies that can be adopted into the walkability evaluation models: *Map Overlay*, *Cost Distance Analysis* and *Dijkstra's algorithm.* The area based walkability evaluation model incorporates with various environmental characteristics that are influential to walking. Indexed Map Overlay is a useful GIS analysis method to integrate quality information of different characteristics. This method allows weights assigning for different layer of information, thus it is adaptive for different modeling contexts. The route based walkability evaluation is in essence a routing tool. It provides walkable route options. Both Cost Distance Analysis and Dijkstra's algorithm are tools for solving routing problems. Cost Distance Analysis is based on the principle that there is always a cost associated when moving a distance unit on a surface. For providing walkable routes, the cost can be defined with route characteristics that are impactful to walking. Dijkstra's algorithm, on the other hand, is a solution for identifying shortest path in a graph. The street network can be viewed as a complex graph, while the weight of the edges (i.e. street segments) can be defined based on the street characteristics that are influential to walking. As a result, Dijkstra's algorithm can determine the optimal route for walking.

Third, in chapter 4, this thesis describes the development work of the walkability evaluation models and their implementation in the city of Helsinki. Utilizing the results and learnings from the review work, this thesis proposes area and route based walkability evaluation models. The models and the characteristics used are described in the chapter. Applying models to Helsinki aims to give an example for analysts when implementing the models, while provide the walkability information of Helsinki to the concerning parties. The used data and its process, as well as the way to adjust the model are presented. Furthermore, a tool is developed based on the evaluated walkability and various environment characteristics. This tool can be easily used by potential interested parties to learn the environment quality of Helsinki regarding to its walkability.

Fourth, in chapter 5, this thesis makes the final discussion and addresses the limitation of the thesis work and the future steps.

2. Literature review: the correlation between environment and walking

The relationship between environment and walking behavior has been one of the most studied topics in the field. In early researching stages, most studies focused on the influence of walking on perceived environments. Limited by unavailability of data and immaturity of GIS technologies, surveying people's perception about an environment's characteristics was a reasonable approach at the time. Built on the hypothetical correlations between environment and walking, a few frameworks, referred to as environmental audit instruments or walkability evaluation tools, attempt to standardize the assessment procedure and provide comparable results across different nations. These instruments are well defined, validated and adopted by a considerable amount of studies. Such instruments usually adopt a top-down approach, where the upper level of parameters address potential walking needs for pedestrians while lower level parameters address the environmental factors which are conceptualized from those walking needs (Samarasekara et al. 2011). Neighborhood Environment Walkability Scale (NEWS) and various modified versions of NEWS (Cerin et al. 2013), Physical Activity Neighborhood Environment Survey (PANES) (Alexander et al. 2006), Systematic Pedestrian and Cycling Environmental Scan (SPACE) (Pikora et al. 2003), Pedestrian Environmental Data Scan (PEDS) (Clifton et al. 2007) and Perceptions of the Environment in the Neighbourhood Scale (PENS) (Adams et al. 2013) are some examples of environmental audit instruments. There is a general pattern among these instruments that they have consistent upper level parameters while lower level parameters can differ from each other substantially.

To better understand how an environment influences physical activity or walking behavior and to provide actionable information for urban planners and policy makers, researchers started to call for objective measurements of built environments (Owen et al. 2004). In the meantime, more advanced GIS technologies and available open source data also enable the trend of conducting objective environmental measures. However, there is a lack of standardized practices to objectively evaluate a built environment. To date, only the Walkability Index developed by Frank et al. (2010) is adopted by some studies (Van Dyck et al. 2010; Sundquist et al. 2011; Saelens et al. 2012; Reyer et al. 2014). Other studies measure various environmental characteristics objectively but the method may differ from study to study. However, most of the objectively measured characteristics also align with perceived measurements as they are both conceptualized based on walking needs.

In the following section, different domains of built environment characteristics are introduced based on BME, using their methods of measurement, alongside various studies' results and their correlation with walking behavior among adults. In the case of perceived environmental evaluation, only NEWS-A (NEWS abbreviation form), PANES and PENS are discussed as they are the most recently developed and adopted in studies conducted across different geographic locations across the world. The goals of the literature review are: 1) identifying the environmental characteristics that are influential to walking; 2) investigating environment characteristics' influences on walking in different study contexts; 3) gathering the measuring methods of each characteristic.

2.1. Origins and destinations

2.1.1. Trip purposes

During early walking studies, the majority of research focused on absolute amount walking (total walking) which does not take the trip's purpose into consideration. While there have been correlations established between total walking and a built environment's characteristics, researchers also recognized differences in walking needs. For example, when walking for transportation, a well-connected street network is important. While for recreational walking, the aesthetics of a given area is more crucial. In order to better explain the relationship between behavior and environment, focusing on a specific walking purpose became popular among empirical studies.

Currently, utilitarian and recreational walking are the most commonly studied walking purposes. Utilitarian walking is defined as transport between destinations (e.g. commuting to and from work, walking for errands), thus also referred as transportation walking. Recreational walking is then typically considered as a leisure or exercise activity. Although walking can be defined more specifically, which can better explain the cause-effect relationship between walking and environment, there are several reasons for categorizing walking only for two purposes: 1) having more specific walking purposes (e.g. commuting to work, walking for errands) can lead to too little data for establishing a correlation with the environment; 2) while the measurement of walking is usually done through surveying or a travel diary, misclassification can be introduced due to different personal definitions on walking purposes, which could further influence correlation results.

2.1.2. Destination accessibility

The destinations of walking trips are usually what define the purpose of the trip. With more utilitarian (e.g. shops, barbers, banks) or recreational destinations (e.g. parks, beach) available and easy to access, residents have more walking opportunities. Destination accessibility, also referred to as service accessibility, is recognized as one of the most influential factors to walking in not only academic research but also commercial walkability assessment services (e.g. Walk Score[1]). Destination accessibility is a composite of the availability and proximity to different amenities. With various destinations within walking distance, individuals are encouraged to choose walking as means of travel.

Direct inquiry about the convenience of walking to various destinations is a commonly used method to measure destination accessibility among perceived environmental evaluation instruments. NEWS-A, PANES and PENS directly ask if participants can reach different types of destinations easily. For different walking purposes, the type of destination can be substantially different. Within those instruments, the survey items for services are categorized into utilitarian (e.g. grocery store, bank) and recreational (e.g. park, beach). However, when evaluating the correlations, not all empirical studies consider different types of destinations separately.

Consistent evidence indicates a significant positive correlation between destination accessibility and utilitarian walking, regardless of the geographic location or targeted population groups (Adams et al. 2013; Cerin et al. 2014; Sugiyama et al. 2014). Cerin et al. (2014) stated that this correlation is only valid when walking within a residential neighborhood opposed to other places. For recreational walking, however, the results varied. Adams et al. (2013) reported null correlation when examining the walking status among English adults, while Sugiyama et al. (2014) found a linear association by analyzing data from 12 different countries. A few studies categorized destinations into utilitarian and recreational ones to align with the travel purpose. Interestingly, Corseuil Giehl et al. (2017) found recreational

[1] Walk Score is an online service that provides score for neighborhoods regarding to their walkability. The service is primarily used to find housing locations based on "Walk Score". The service is available at: *https://www.walkscore.com/* (accessed on 5 Sep. 2017).

destination accessibility is positively correlated with utilitarian walking among the older adults in Brazil.

When measuring destination accessibility objectively, the most straightforward method is calculating the density of services within walking distance (Troped et al. 2014; Hirsch et al. 2014; Troped et al. 2017). Retail FAR (Floor Area Ratio) is another popular indicator for destination accessibility. It measures the utilization efficiency of retail/commercial land use. High Retail FAR indicates small setbacks of the retail area as well as large floor area for retail services. Diversity of the available destinations is another aspect for destination accessibility. Entropy index of land use mix is often adopted an approximation to address this aspect (Cervero and Kockelman 1997; Frank et al. 2010; Turrell et al. 2013; Koohsari et al. 2015; Christiansen et al. 2016). Ranging from 0 to 1, an entropy index with a higher score indicates that a neighborhood has a greater variance of evenly distributed land use types. This suggests the existence of a greater diversity of services available in a region.

Destination density, retail FAR and entropy index of land use mix are consistently found to be positively related to utilitarian walking and total walking (Frank et al. 2005; Lee & Moudon 2006; Turrell et al. 2013; Christiansen et al. 2016; Troped et al. 2017). For recreational walking, only a few studies have found positive correlation. Troped et al. (2017) found that neighborhoods with higher service/store density encouraged residents to take more walking trips, while Saelens et al. (2012) established a marginal positive correlation between retail FAR and recreational walking. In another study, which only focused on neighborhoods that have low socioeconomics, no relation was identified (Turrell et al. 2013).

Various reviews also observed similar results. Destination or utilitarian destination accessibility is consistently found to be positively correlated to utilitarian walking, while little evidence supports the correlation between general/recreational destination accessibility and recreational walking (Owen et al. 2004; Saelens and Handy 2008; Sugiyama et al. 2012; Van Holle et al. 2012).

Higher accessibility to different kinds of services provide more destinations for residents to reach by foot. As these services are essential parts to support our daily life, it is sensible that positive correlations between service accessibility and transportation walking exists. For recreational walking, the majority of studies found null correlation with service accessibility even when recreational services (e.g. parks, beaches) are considered separately (Sugiyama et al. 2012; Van Holle et al. 2012). The exact reasons have not been identified, but several hypotheses are proposed:

1) For recreational walkers, the availability of destinations holds less importance.
2) Individuals sometimes combine utilitarian and recreational walking which is not observable through surveying or travel diary. Therefore, errors are introduced in the correlation analysis.
3) The majority empirical studies were conducted around the participants' housing locations, while recreational walking may occur outside that area.
4) There are no existing standards for classifying recreational destinations. Some studies only consider open spaces, such as parks and beaches, while others included gyms and sport centers. Thus, when synthesizing findings, mixed recreational destination categorization can interfere results.

2.2. Route characteristics

2.2.1. Walking infrastructure

Walking infrastructure caters to different pedestrian needs for walking safely and comfortably. The existence of walking spaces (e.g. sidewalk, cross road) are often investigated in terms of their correlation with walking behavior. Well maintained sidewalks, lighting and sitting facilities provide comfort when walking. These factors are especially important for an older population (Cerin et al. 2014). Some researchers also consider a route's availability and directness to walking destinations (e.g. grocery store, school, bus stops) as part of walking infrastructure, while others combine those factors into street connectivity. Here street connectivity is considered separately. The rationale is while walking infrastructure is most concerned with the quality of a built environment to support walking behavior, street connectivity relates to the availability of route options and their directness to various destinations.

In measuring perceived infrastructure quality, NEW-A, PANES and PENS address the presence of sidewalks and their condition. NEWS and PENS also consider buffers between sidewalks and main roads, along with night-time lighting. Interestingly, in NEWS-A, crosswalks and pedestrian signals also belong under the walking infrastructure section, unlike in PENS where they are considered as traffic safety factors. This can potentially affect analysis results when determining the influence of traffic safety and infrastructure on walking.

Utilizing NEWS, Corseuil Giehl et al. (2017) emphasized the importance of well-maintained and well-lit sidewalks, as well as crosswalks in neighborhoods to encourage older Brazilian adults to walk for both leisure and transportation. Similarly, Cerin et al. (2014) reported a positive correlation between walking infrastructure and walking for transportation among the elderly in Hong Kong. However, there is no correlation found for either recreational or transportation walking in the study conducted by Saelens et al. (2012) for adults in the United States, nor Sugiyama et al. (2014), who cross examined results from 12 different countries from four different continents. Ding et al. (2013) compared PANES data across 11 different countries finding significant positive associations between the presence of sidewalks and physical activity in Colombia, Hong Kong, Japan, and Lithuania. Although, a positive but insignificant association was also identified in Canada, Norway, Sweden and the USA. Walking for transportation and leisure was also found to be positively associated with supportive infrastructure in a study done in UK using PENS (Adams et al. 2013).

Cervero and Kockelman (1997) objectively measured walking infrastructure quality in 3Ds (density, diversity and design) model using six different factors (i.e. sidewalk provisions, street light provisions, planted strips, block size, lighting distance and the amount of flat terrain). The composite walking quality factor was found to be a strong predictor of non-personal vehicle travel during non-work-related trips for residents in the San Francisco Bay Area. It is noteworthy however, that some walking quality factors relate to street connectivity (e.g. block size). As the authors adopted a composite factor, it is difficult to understand if the walking infrastructure or street connectivity is more crucial for walking. No other reviewed studies evaluated walking infrastructure objectively.

Opposed to the hypothesis that infrastructures are highly influential for walking behaviors, the result of null relationship might be caused by well-established walking infrastructures in urban environments where utilitarian walking happens often. Therefore, although walking infrastructure is an important enabler, it appears to be insignificant as it is a homogeneous feature across the studied regions. Nonetheless, considering the safety and comfort walking infrastructure provides, it is important for a walkable environment to offer well-maintained and lit sidewalks or walking trails. Furthermore, for specific groups such as older adults, it is also important to have other infrastructure (e.g. benches) to facilitate walking behavior (Cerin et al. 2014).

2.2.2. Street connectivity

Street networks provide the possibility for individuals to participate in walking. Connected streets link destinations thus enabling people to reach their desired locations. Distance has been identified as the most influential barrier for pedestrians, especially for transport-related walking (Hess et al. 1999; Saelens et al. 2012). Streets with high connectivity often have few cul-de-sacs, offer shorter routes to reach the destinations, while providing a greater number of alternative routes. High street connectivity is often found in grid-like neighborhoods, which are usually located in city centers. In contrast, suburban areas are often observed to have longer sidewalks with more cul-de-sacs.

As street connectivity has been identified as one of the most influential factors to walking behavior, the majority of instruments and empirical studies include this factor in their models.

Street connectivity is surveyed differently in different instruments. NEWS-A audits the distance between intersections and the availability of alternative routes, PANES directly queries the density of four-way intersections, while PENS addresses the completeness/continuity, as well as the connectivity between sidewalks, and presence of cul-de-sacs.

Using NEWS, Cerin et al. (2014) found a positive correlation between street connectivity and walking for transportation among the elderly in Hong Kong. With the same instrument, Sugiyama et al. (2014) reported a more complicated relationship between street connectivity and walking for recreation. While residents who live in neighborhoods with more cul-de-sacs are more likely to walk for recreational purposes, higher street connectivity increases the frequency of walking among those who participate recreationally. No correlation with either transport or leisure walking was established in the study conducted in the UK using PENS (Adams et al. 2013).

Objective measurements for street connectivity also vary. Two common practices are measuring intersection (three-way or more) density or directness to various locations (e.g. grocery stores). The directness is usually indicated by the ratio of Euclidean to network distance[2].

Through measuring intersection density, a positive correlation between street connectivity and transport walking was identified in many empirical studies conducted across different countries from various continents (Saelens et al. 2012; Turrell et al. 2013; Christiansen et al. 2016).

Lee and Moudon (2006) considers route attributes more explicitly in their 3Ds+R (density, diversity, design and route) model. In terms of street connectivity, sidewalk length and directness to grocery stores and schools were evaluated. All three factors showed correlations with total walking, with directness to schools having an inconsistent direction of correlation. Another study that aimed to evaluate the change in walking over time corresponded to changes

[2] The distance measured through the street network.

in the built environment's measured street connectivity based on its network ratio[3]. A positive association between street connectivity and total walking was identified. In the meantime, evidence also showed increasing street connectivity over time encourages more walking (Hirsch et al. 2014).

Street connectivity shows a consistent positive association with walking for transportation. This has confirmed the hypothesis that connected street networks provided more direct routes and thus catering to pedestrians' needs for shorter distances. For recreational walking, it is possible that it is less important to have direct routes, as walking for recreational purposes is more likely related to attitude and scenery. Better connected neighborhoods can also provide more alternative routes associated with different walking experiences. This can be one possible explanation for the higher frequency recreational walking observed by Sugiyama et al. (2014).

2.2.3. Safety from traffic

Traffic safety is a concerning environment characteristic. Among the studies which proactively make an effort to build an environment that supports active life, pedestrian safety is not always present as a factor. However, providing a safe and comfortable walking environment for pedestrians should always be a top priority for urban planning (Ewing & Dumbaugh 2009).

In NEWS-A, traffic speed and volume are taken into consideration. Both PANES and PENS consider overall safety from traffic, while PENS also includes the safety of crossing roads.

Adopting NEWS, Corseuil Giehl et al. (2017) found a positive association between traffic safety and transportation walking among Brazilian elderlies; in Hong Kong, Cerin et al. (2014) had an inverse finding where traffic hazards were positively related to transportation walking among older adults; Saelens et al. (2012) did not find any correlations between traffic safety and walking for either transportation or leisure purposes for adults in United States. Similarly based on the NEWS surveying results from 12 different countries, Sugiyama et al. (2014) concluded that there are no associations between traffic safety and walking recreationally. No traffic safety correlations with walking were identified in a study conducted with PANES (Ding et al. 2013) and PENS (Adams et al. 2013).

For traffic safety, most studies that objectively measured built environments omitted this element. In some research, when addressing pedestrian supporting infrastructure such as sidewalk provisions, traffic safety is indirectly considered. So far, only the classic 3Ds model explicitly considers factors for traffic safety, including average speed limits, street widths and freeways in neighborhoods (Cervero & Kockelman 1997). However, those factors are only proposed in the 3D environmental examining model but were not measured when conducting the case study in the same research.

For the general adult population, little evidence supported the influence of traffic on walking for recreational and transportation purposes. It is possible that only heavy traffic interferes with walking. In the meantime, in the majority of countries, pedestrian safety is one significant factor considered in transportation policy. This can explain why traffic is not a barrier for walking participants. However, this result may not be applicable for the elderly or youth, as traffic safety is consistently found to be related to the likelihood of walking for children and older adults (Saelens and Handy 2008; Mitra 2013).

[3] The area of a 1-mile network buffer divided by the area of a 1-mile Euclidean buffer around a participant's home.

2.2.4. Aesthetics

In modern society, functionality is only part of an urban setting. Metropolitan design is also expected to bring a pleasant experience regarding to street scenery. This is especially important for outdoor recreational activities. Corresponding to this need, aesthetics is added to environmental assessment models. Aesthetics is in nature a subjective evaluation. So far, only perceived environmental auditing instruments have incorporated this factor. Catering to different aesthetic values, street design, landscape, and environmental diversity are considered in the instruments.

Consistent evidence has shown a positive correlation between aesthetics and recreational walking, in a few studies, aesthetics was the only factor revealing a significant association (Rhodes et al. 2007; Lee and Shepley 2012; Saelens et al. 2012; Sugiyama et al. 2014). For transportation walking, however, aesthetics is less important (Saelens et al. 2012; Sugiyama et al. 2012; Van Holle et al. 2012; Liao et al. 2015).

2.3. Area characteristics

2.3.1. Safety from crime

Safety concerns are one of the major barriers for individuals to participate in walking activities, especially for women and older adults (Foster & Giles-Corti 2008).

Perceived safety from crime is measured through three items in NEWS-A, encapsulating overall crime rate, and the perceived safety during day and night. In PANES, there are two survey questions that address the impact of an area's crime rate and walking safety during day and night (Alexander et al. 2006). PENS evaluates the overall safety from crime with only one question in the survey (Clifton et al. 2007).

Although it has been considered important, environmental safety has an inconsistent correlation with walking across different countries. Studies which have adopted NEWS as a perceived environment assessment tool, found that safety during the day was positively associated with both transport-related and recreational walking for older adults in Brazil (Corseuil Giehl et al. 2017). In Hong Kong, Cerin et al. (2014) concluded that the perceived personal safety was not related to walking for transport among the elderly. Interestingly, Saelens et al. (2012) discovered a negative correlation to transportation walking for adults in the context of United States while no association was found for leisure walking. Sugiyama et al. (2014) analyzed NEWS data from 12 different countries located in Europe, America, Australia and Asia, and found a large variation among cities for perceived safety from crime (lower in Latin America and Hong Kong, higher in Europe and United States). Using this data, a positive linear relationship between perceived safety from crime and recreational walking was established. The inconsistency was also shown in studies adopted by PANES for environmental auditing. Ding et al. (2013) compared data across 11 different countries, positive associations between safety from crime and physical activity were found in Japan, Brazil, and Lithuania; while inverse result were shown in Hong Kong and Norway. In a study conducted in the UK with PENS, no relationship has been identified between safety from crime and walking for either transportation or leisure.

Safety from crime is a subjective factor and is usually not aligned with objective sources such as crime rates. To date, it is rarely evaluated in an objective manner, as perceived safety may influence walking behavior more than the objective crime rates (Alexander et al. 2006). The presence of street lighting is sometimes added in an objective environmental evaluation, but usually is considered as part of infrastructure rather than a crime-related safety factor.

Multiple review studies also reported an inconsistent association regarding personal safety and walking (Owen et al. 2004; Saelens and Handy 2008; Sugiyama et al. 2012; Van Holle et al. 2012). Specifically, the aforementioned reviews stated only a few studies showed correlation while the vast majority found null correlation for both transportation and recreational walking. Notably, most of these empirical studies were conducted in developed countries. The possible reasoning for inconsistent correlations of crime-related safety may reside in: 1) general low crime rate in the studied regions; 2) an over generalized measurement (either leading respondents to overestimate safety issue, or not directly addressing the fear of crime); 3) the lack of consideration for other confounders such as gender, ethnicity; 4) impacts on walking for other correlated characteristics such as service availability or low vehicle ownership (Foster and Giles-Corti 2008). Although in most studies, null correlation was reported, it should still be a factor considered in future studies to fully understand actual crime rate impact on walking.

2.3.2. Residential density

From the early stages of environmental correlation with physical activity, residential density has been one key element examined. This is built on the assumption that higher density neighborhoods potentially have more services available, better infrastructure, as well as provide safer environments while enabling a more active street life. Although these influences may be indirect, it is a simple indication of multiple factors and comparably easy to measure.

In both NEWS-A and PANES, residential density is estimated by types of housing in neighborhoods (e.g. single-family residences, multi-family housing). PENS does not directly address residential density (Clifton et al. 2007).

Cerin et al. (2014) hypothesized an inverted-J relationship between residential density and walking for transportation in Hong Kong, as it is an ultra-dense city and the crowdedness may hinder walking behaviors for the elderly. However, they discovered a linear positive correlation instead. Sugiyama et al. (2014) established a curvilinear relationship for residential density and walking for recreation based on NEWS data gathered in 12 different countries. In the study, substantially higher residential density was identified in Hong Kong, showed a lower amount of recreational walking compared to other countries. Therefore, it is possible that a positive correlation still exists in typical urban settings as the majority of cities do not resemble Hong Kong in their population density. In another multi-national study, Ding et al. (2013) found a positive association with total physical activity in Norway and a negative association in Japan, while in other countries, no correlations were identified.

Measuring residential density objectively is straightforward. In empirical studies, residential density is either measured through the ratio of residential area or population density.

Consistent evidence shows a significant positive association between objectively measured residential density and transportation walking (Lee & Moudon 2006; Turrell et al. 2013; Hirsch et al. 2014; Christiansen et al. 2016; Troped et al. 2017). Saelens et al. (2012) also reported the same result based on the unadjusted model, but residential density became insignificant after introducing other factors (e.g. service density, street connectivity). Furthermore, Hirsch et al. (2014) found a higher population density increases the amount of walking over time.

Residential density has been addressed in the majority of empirical studies. Although evidence supports significant association between residential density and walking, some of the studies also reported null association after introducing other factors such as facility quality and service accessibility into the environmental assessment model. However, there is a coexist pattern that when a neighborhood is a dense residential area, it is more likely to have higher service availability and better infrastructure quality. This pattern supports residential density as an evaluation of neighborhood walkability. It is also worth noticing that in Hong Kong and Japan a negative association was identified between residential density and recreational walking and overall physical activity respectively. Both regions have extremely high population density compared to other locations, indicating populous settings can be a barrier for recreational walking participation.

2.4. Summary

Overall, a built environment is important for enabling walking behaviors. As society evolves, the infrastructure in urban areas becomes well established in catering to the basic needs of residents. Recently, there is an emerging trend to build cities supporting active lifestyles beyond a day to day life routine. The factors discussed above have shown important aspects to consider when revising built environment. However, empirical studies show various results (Table A-1) when conducting research in different geographic locations and target various groups of people at different times using different measurements. Although some factors show little association with either recreational or utilitarian walking, such as safety and walking infrastructure, they are still essential for supporting walking behavior. It is possible that the qualities of such characteristics are homogeneously high across the majority of studied locations, resulting in their insignificance in walking. For regions that are less developed, these factors become more important, especially for those (e.g. older, younger) who have higher environmental requirements to participate in outdoor activities. Researchers consistently found that fewer environment characteristics are correlated with recreational walking compared to utilitarian. Recreational activities usually happen outside the neighborhood while most studies only measure characteristics around participant's residential location (Adams et al. 2013). In the meantime, recreational activities can be heavily influenced by one's attitude towards physical activities compared to a physical environment. Therefore, when targeting recreational walking, other potential determinants should also be included alongside neighborhood characteristics.

Between perceived and objective environmental evaluation, a mismatch has been observed where high environmental quality may be perceived low and vice versa. Both perceived and objective environmental associations are considered important to investigate. While perception can be used to better explain human behavior, an objective environmental association is more successful at guiding policy makers and urban planners in reforming cities to become more walkable for their residents. However, the relationship between these two environmental aspects has not been investigated thoroughly, especially for the interactions between environment and one's perception that in the end determine walking behaviors.

The literature review on the topic of correlations between walking and built environment has captured the current academic research status on the subject. To date, many relationships remain inconclusive as they vary among empirical studies. Human behavior is complex and requires a more systematic analysis. Based on ecological models, analyzing walking behavior comprehensively can potentially can shed some light on unknowns that have led to ambiguous correlations. This process will require different fields of knowledge, long-term observations and a considerable amount of resources. Nonetheless, with existing knowledge including theoretical frameworks, built environment evaluation tools, and insights from empirical studies, it is feasible to build objective evaluation models for walkability that can act as a starting point for ecological studies, a guide for policy marker and urban planners, and an educational tool for residents for learn about their physical environment. In the following section, area and route based objective walkability evaluation models are introduced and applied to the Helsinki municipality.

3. GIS technologies for walkability modeling

In the literature review, different built environmental aspects and their correlations with walking behavior were investigated. Based on the insights from different empirical studies and various reviews, objective walkability evaluation models are proposed for two different units: area and route. Before getting into the development of the models, the technologies utilized are introduced in this section: *Map Overlay*, *Cost Distance Analysis* and *Dijkstra's algorithm*.

3.1. Map Overlay

Map Overlay is a GIS method for combining information from different map layers. Each map layer usually contains one type of geographic information to be combined. The geographic information can be geometric (i.e. point, line, polygon) or non-geometric attribute (i.e. fields). Based on various types of geographic information, there can be more than 10 different ways to overlay information from different map layers (Table 1) (O'Sullivan and Unwin 2010).

Table 1. Possible combinations of different geographic information (O'Sullivan and Unwin 2010)

	Points	Lines	Areas	Fields
Points	Point/point			
Lines	Line/point	Line/line		
Areas	Area/point	Area/line	Area/area	
Fields	Field/point	Field/line	Field/area	Field/field

Therefore, the overlay operation can either indicate a geometry manipulation (e.g. intersection, union, or a basic algebraic operation (e.g. summation, multiplication). Regardless of the types of information to be combined, one prerequisite of the may overlay operation is making sure that the geographic coordinate system is the same for different map layers.

3.1.1. Geometric map overlay

The geometric attribute is the essence of geographic information. Geometry manipulation is often inevitable during a spatial analysis. In many cases, the geometries are from different map layers. For combining information, map overlay operation is a necessary step. In the context of evaluating environmental characteristics, possible operations include area over area, line over area, and point over area.

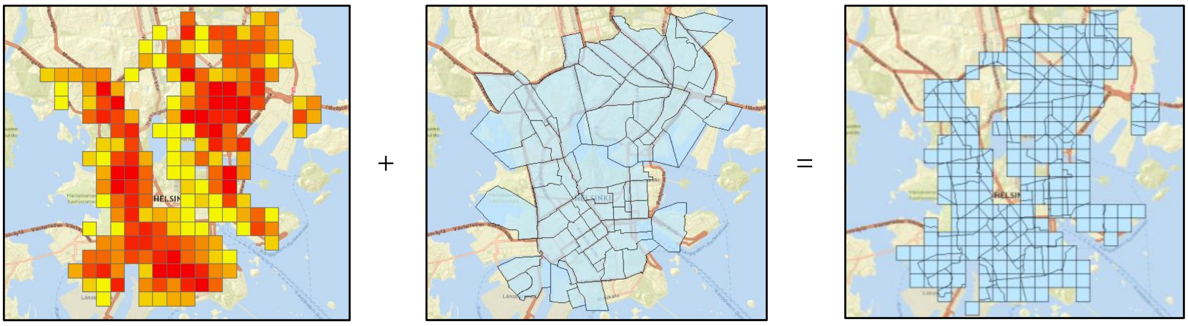
Area over area

Area over area operation is known as Polygon Overlay in GIS field. It is a common practice especially during data pre-processing. This is because data is not necessarily available at the desired resolution level.

For example, in Helsinki, the population data is available at 250m*250m grid level. When interpolating population for district level, Polygon Overlay operation is applied. Specifically, two operations are necessary for this process: intersection and union.

1) Intersection map overlay

The first step is intersecting 250m*250m girds with districts. The intersected result is an irregular polygon layer (Figure 3). The population can be estimated for the result layer through Equation 1.



a. population grids b. districts c. intersected result

Figure 3. Polygon overlay (intersection)

$$p_i = \frac{a_i}{a_j} \times p_j \qquad (1)$$

*where i is the polygon in the intersected layer (Figure 3-c), j is the grid cell corresponding to i before intersection (Figure 3-a), p_i is the estimated population for polygon i, a_i and a_j (a_j =250m*250m) are the area of the polygon i and gird j, p_j is the population of cell j.*

Equation 1. Population estimation

The estimation assumes that for each grid cell, the population density is constant. The estimated result is shown in Figure 4.

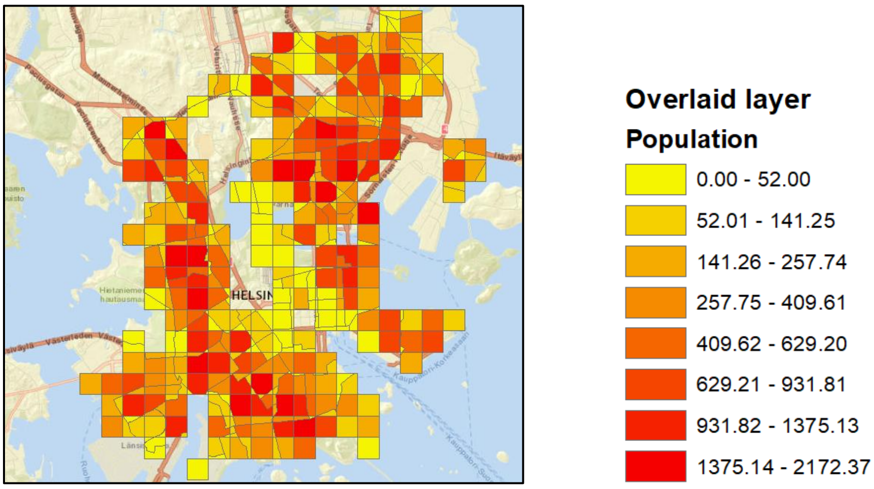
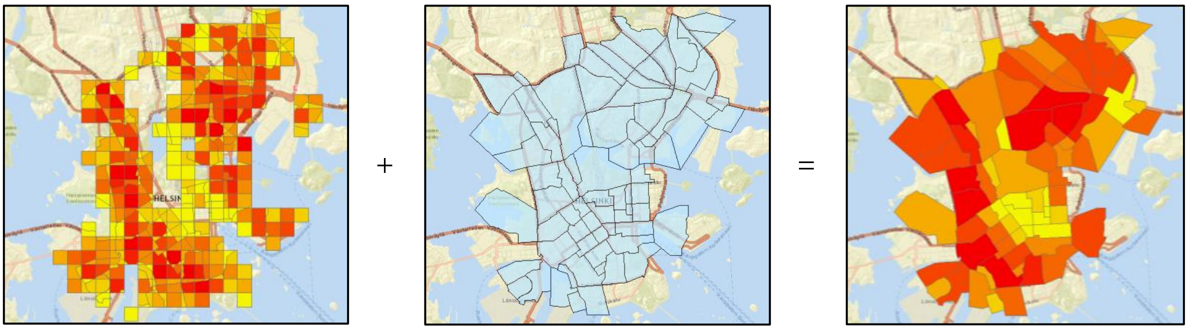


Figure 4. Population estimation for intersected polygons

2) Union map overlay

To get the population estimation for districts, union overlay is applied for aggregating the population attribute of the intersected polygons from previous step (Figure 5). As a result, all the polygons inside one district are summed up.



a. population cells b. districts c. union result

Figure 5. Polygon overlay (union)

Line over area

When assessing walkability, the sidewalks are important aspect of the built environment. One approach to estimate the sidewalk availability is calculating the length of sidewalk per unit of area, which is combining information from line and polygon features. This can be achieved by intersecting sidewalk network with districts, and then aggregating the length of sidewalks within each district.

Point over area

For point over polygon overlay, the most common operation is counting the number of points within each polygon. This is useful when, for example, calculating service density for each district. The service density can be used to indicate service availability.

3.1.2. Non-geometric map overlay

When combining non-geometric (i.e. fields) information from different map layers, basic algebraic operations are applied (e.g. summation, multiplication). Therefore, this type of map overlay is also considered as one type of map algebra operations. Non-geometric map overlay can be applied to either raster or vector map layer. Besides satisfying same coordinate system requirement for overlay operation, the map layers must have the same resolution. This is because the algebraic operation is conducted between the grid cells/features which have the same location across different map layers (Figure 6, Figure 7).

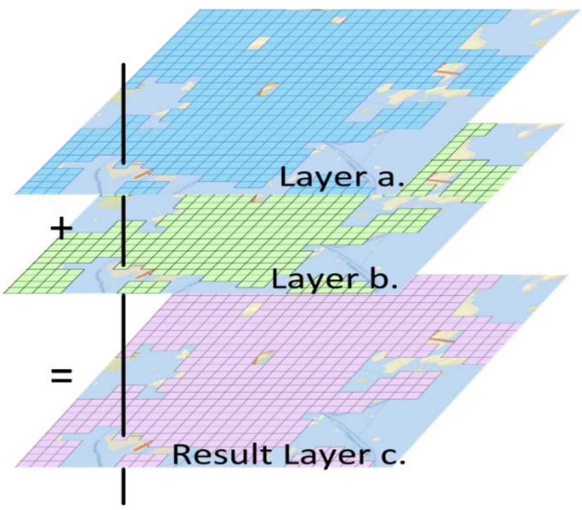


Figure 6. Non-geometric map overlay operation relationship among layers

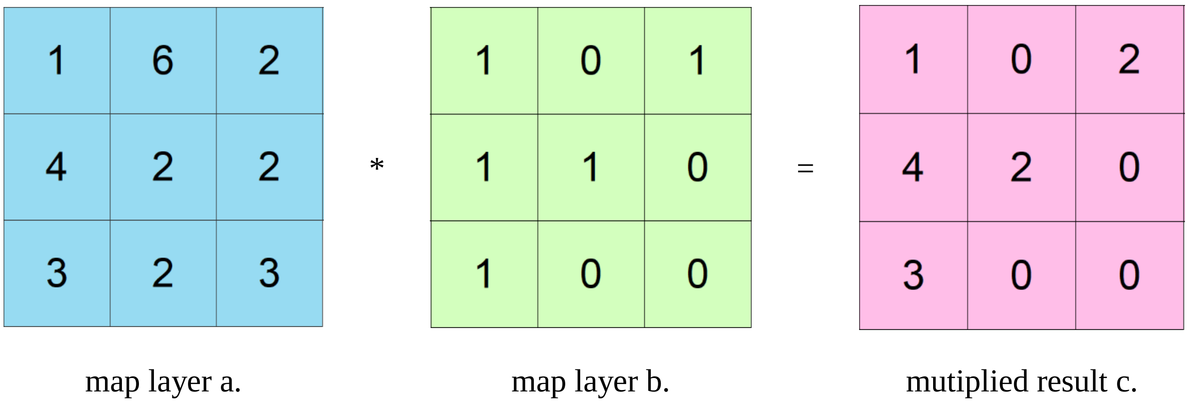


Figure 7. Map overlay for non-geometry attribute (multiplication)

Therefore, for raster map, the grid size and orientation should be the same across different layers; for vector map, the feature sets are the same across different layers. When map layers do not satisfy those requirements, resampling is needed.

Non-geometric map overlay is a necessary step when combing different evaluations for built environment characteristics. The equation to combine information is referred as favorability function by O'Sullivan and Unwin (2010) (Equation 2). This operation produces an overall index as the overlaid result, thus the process is called an *indexed overlay*.

$$F = \sum_i w_i \, x_i \quad (2)$$

where w_i stands for the weight of map layer i, x_i stands for the information to be integrated from map layer i

Equation 2. Indexed Map Overlay operation

In the favorability function (Equation 2), there are three components: the information to be combined (x_i), the weights assigned to the map layers (w_i) and the map layers (i). These three components suggest the prerequisites for a valid indexed overlay:

1) The summation of different types of information should be meaningful.

The favorability function is based on the summation operation. Therefore, the information to be added needs to have the same unit so that the operation is sensible. For example, adding the number of people per square meter and the number of services per square meter does not provide meaningful result. To apply summation for these types of information, a normalization operation should be applied beforehand. It means the map layers are indexed before applying indexed overlay.

2) The levels of importance should be examined for each map layer.

Each map layer is assigned to a weight. For walkability, different environmental characteristics have different levels of importance. For example, service accessibility is found to be significantly correlated to utilitarian walking while population density is less influential. After gaining the understanding on the importance, the weight can be properly assigned for each factor, thus making indexed overlay producing a meaningful result.

3) The map layer should be relevant to produce the favorability.

In the context of evaluating walkability, many environmental characteristics are examined by empirical studies (e.g. service accessibility, population density, safety from crime). Not all characteristics are found to be correlated with walking (e.g. safety from crime). The map layers to be combined need to have valid basis for their relevance for desired result.

A knowledge based approach can be applied for ensuring the validity of indexed overlay. The knowledge is accessed either through experts or empirical studies. For example, in the case of walkability, knowledge can be gained through examining research that studied built environment characteristics and their correlations to walking. As a result, the relevant environmental aspects and their importance to walking can be used to produce an overall index for walkability.

3.2. Cost Distance Analysis

Cost Distance Analysis is a tool for solving routing problems. This analysis is based on the principle that there is always a cost associated when moving a distance unit on a surface. For a given origin-destination pair, it finds the least costly route (De Smith et al. 2007). The most commonly used costs are travel time and network distance. Cost can also be a composite calculation (e.g. distance and slope) based on route characteristics. Route based walkability modeling aims to provide the most walkable routes when provided with an origin and destination. Via incorporating walking related environmental characteristics into the cost definition, Cost Distance Analysis can identify the most favorable routes between the origin and the destination.

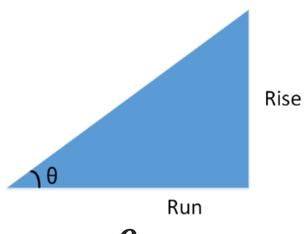
3.2.1. Defining a cost surface

The first step of cost distance analysis is defining a cost surface. The cost surface is a raster map layer while each grid cell has a cost associated with it. High cost cells have low favorability to move across. Usually, the cost is defined based on the cell properties (e.g. land cover, congestion) and the characteristics of the traveller (e.g. automobile, pedestrian). When solving the routing problem to provide the most walkable routes, the cost is associated with the environmental characteristics that are influential to walking.

For example, when solving a routing problem for pedestrian walking with a stroller, flat terrain and paved streets are hypothesized to be the most important factors to consider. To produce a cost surface for this scenario, the following steps are taken:

1) Produce a cost surface for moving on different degrees of slope

Slope is a barrier for walking with a stroller. For getting a cost surface for slope, the elevation data is needed. Elevation data is usually available as a Digital Elevation Model (DEM). DEM can be either a raster dataset where the value of the cell indicates the elevation, or a vector dataset such as Triangular Irregular Network. Slope is defined as amount of rise over run (Equation 3).



$$tan\theta = \frac{Rise}{Run} \quad (3)$$

Equation 3. Slope (θ) in degrees

Many tools are available for evaluating the slope based on DEM (e.g. ArcMap[4] Slope tool). The most common practice for evaluating slope is by incorporating the rate of the change horizontally and vertically.

$$S_t = tan^{-1}\left(\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}\right) \tag{4}$$

where S_t is the terrain slope in radians, $\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial y}$ are the rates of the change in x- and y-direction respectively

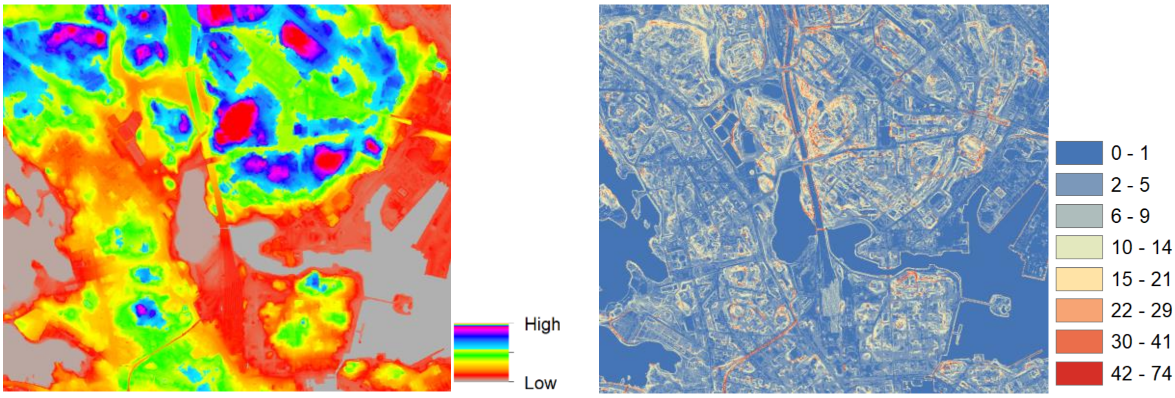
Equation 4. Slope estimation function

In ArcMap, the slope calculation utilizes the approximation for rate of change based on 8 adjacent cells in a raster DEM (Horn 1981) (Equation 5). Figure 8 shows the slope evaluation result based on raster elevation model of Helsinki in ArcMap (source: National Land Survey of Finland; grid size: 2m * 2m).

$$\begin{aligned} \frac{\partial z}{\partial x} &= \frac{(z_{1,1} + 2z_{1,0} + z_{1,-1}) - (z_{-1,1} + 2z_{-1,0} + z_{-1,-1})}{8\Delta x} \\ \frac{\partial z}{\partial y} &= \frac{(z_{1,1} + 2z_{0,1} + z_{-1,1}) - (z_{1,-1} + 2z_{0,-1} + z_{-1,-1})}{8\Delta y} \end{aligned} \tag{5}$$

where $z_{i,j}$ is the elevation for cell (i, j). Δx and Δy are the cell size in x- and y- direction respectively.

Equation 5. Approximation Rate of change in x- and y-direction



a. Elevation data of Helsinki (source: National Land Survey of Finland)

b. Terrain slope (in degrees)

Figure 8. Slope evaluation based on DEM (Processing tool: ArcMap)

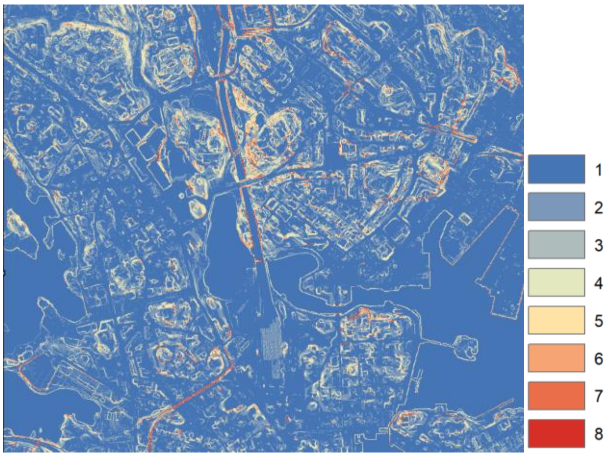
The cell value of the result raster layer indicates the degree of the slope at the corresponding location. To produce a cost surface, the slope needs reclassification for presenting the cost when crossing certain degree of slope (Figure 9).

---

[4] ArcMap is part of ArcGIS Desktop solution developed by Esri Inc. It has comprehensive spatial data processing and analysis tools.

Slope degrees	Cost
0-4	1
4-8	2
8-12	3
12-18	4
18-24	5
24-32	6
32-40	7
40-74	8
No Data	No Data

a. Value reclassification



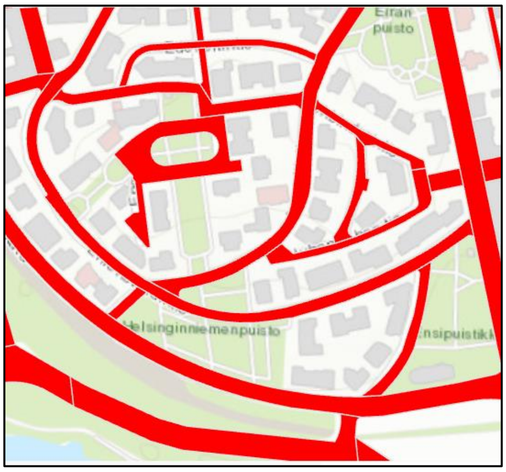
b. Cost surface based on slope

Figure 9. Produce cost surface based on slope data

2) Produce a cost surface for street network

The street network data is often available as a vector dataset. Depending on the data source, it can either be line or polygon features. Usually, the line based street network is more complex and detailed (Figure 10).

a. Line based street network (source: OpenStreetMap)



b. Polygon based street network (source: City of Helsinki)

Figure 10. Street Network Types

Polygon street network is more appropriate for rasterizing as it contains width of roads by default and resembles the real world more. The purpose for rasterizing street network data is to produce corresponding cost surface and combine the slope based cost surface generated in the previous step. Therefore, the street network raster layer should have the same grid size with the slope based cost surface so that the map overlay operation can be conducted. After rasterizing street network, the cost should be assigned for each cell in the raster layer. The cost for crossing the street network is considered constant (i.e. 1 unit of cost), while the areas with no streets coverage are assigned with *NoData* (Figure 11). The cells with *NoData* are prohibited to cross over.

Figure 11. 2m*2m raster street network

3) Combine the slope and street network based cost surfaces

When cost surfaces are prepared for all the relevant factors, they are combined to produce one single cost surface. In this case, the slope and street network based cost surfaces are multiplied to fulfil the purpose (Figure 12).

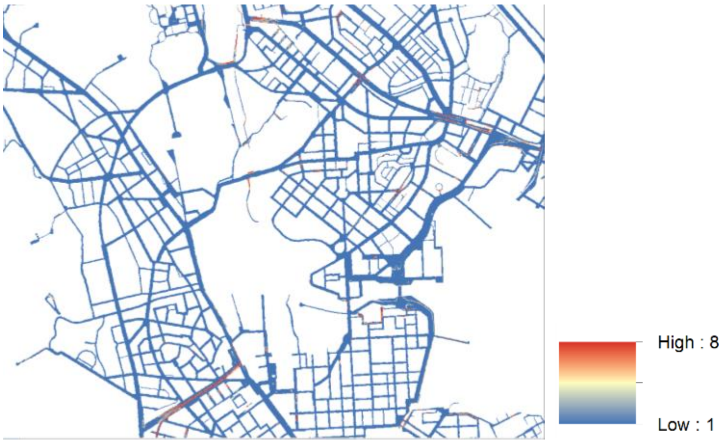
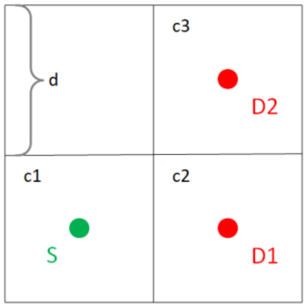


Figure 12. Cost surface based on street network and slope

3.2.2. Accumulated cost surface and least cost path

Using the cost surface together with a defined origin, Accumulated Cost Surface (ACS) algorithm is applied (De Smith et al. 2007) to produce a raster map layer with the value of each cell indicating the least accumulated cost when moving from origin to the cell.

ACS is a spread algorithm that it starts at the origin, then calculates the least accumulated costs for its adjacent cells in all directions and gradually move outwards. The most common implementation of ACS calculates the accumulated cost based on the 8 adjacent cells (i.e. Queen's move). As shown in Equation 6, the accumulated cost considers the cost and distance when moving across the surface. This implementation of ACS has two issues: calculating costs for only 8 adjacent cell movement, assuming the origins and destinations are in the center of the cells.



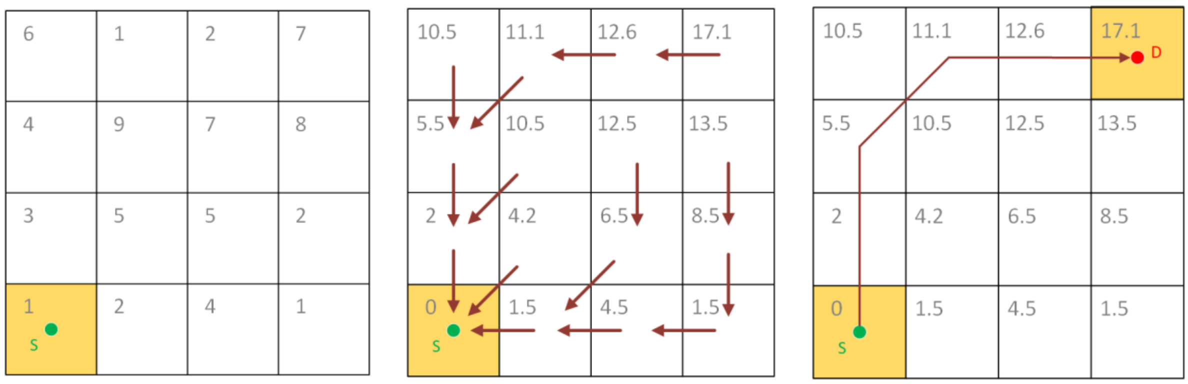
$$a1 = d * \frac{c1 + c2}{2}$$

$$a2 = \sqrt{2}d * \frac{c1 + c3}{2} \qquad (6)$$

where c1, c2, c3 are the costs associated with the girds, d is the raster resolution (i.e. cell length), S is the starting point, D1 and D2 are two different destinations, a1 and a2 are the accumulated costs moving from S to D1 and D2 respectively

Equation 6. Accumulated cost calculation

Based on Equation 6, the accumulated cost surface for an origin can be produced. In the accumulated cost surface, each cell has the least accumulated cost when moving from the origin. When recording the movement that yields the least cost, with a given destination, the optimal (least cost) path can be identified (Figure 13).



a. Cost surface and origin (S)

b. Accumulated cost surface for origin (S) and movement track

c. Least cost path between origin (S) and destination (D)

Figure 13. Applying Accumulated Cost Surface algorithm

Following the example in the previous section for identifying optimal walking route, an accumulated cost surface is produced for an origin, while the least cost path between origin and destination is identified (Figure 14) (processing tool: ArcMap).

Figure 14. Accumulated cost surface and the least cost path

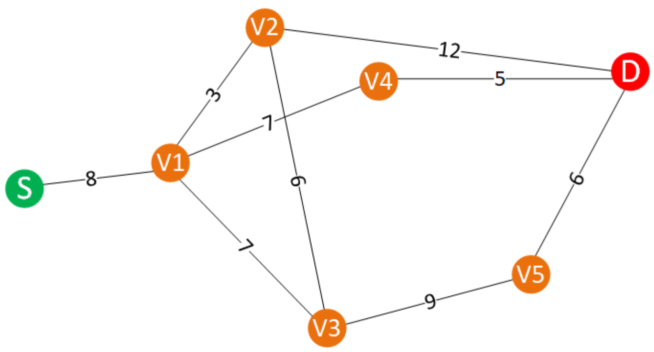
The cost distance analysis is a combination of defining cost surface, calculating accumulated cost surface and identifying least cost path. A simple example is introduced for solving routing problem when only considering the street network and slope. Same principle applies for identifying the most walkable routes. When the cost surface is defined by all the characteristics that are influential to walking, the most preferable walking path will be produced by using cost distance analysis.

3.3. Dijkstra's algorithm

Dijkstra's algorithm is known for solving the shortest path problems: determine the shortest (least cost) path between two vertices when provided with a set of edges. Unlike cost distance analysis, the processing data is vector based (i.e. graph). The algorithm scans through all the nodes in the graph while storing the shortest distance (cost) from the source node to each vertex (De Smith et al. 2007).

3.3.1. Algorithm logic

An example is shown in this section to present the logic for the Dijkstra's algorithm.

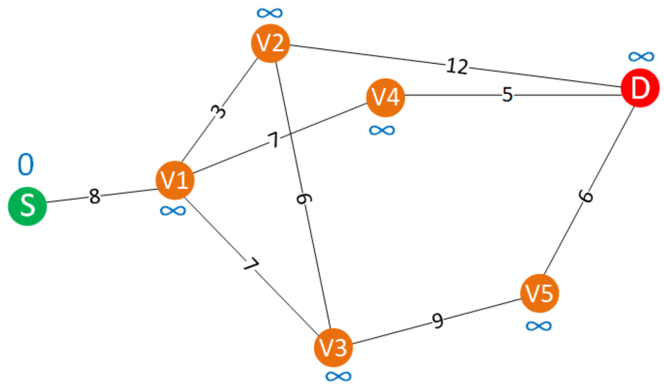


where S is the source node (origin), D is the destination node, Vi is a vertex in the graph, the numbers are the weights of the edges

Figure 15. An undirected graph

The following steps are taken to find the shortest path between S and D in Figure 15.

1) Initializing the distance from the source node to each node in the graph. The distance is 0 from the source node to itself (denoted as d(s) = 0), and infinity to other nodes (denoted as d(Vi) = ∞) (Figure 16).



where the blue text indicates the distance between the source node (S) to the corresponding node

Figure 16. Initialize distance from the source node (S) to other vertices

2) Categorizing the nodes into three different sets: visited, unvisited and active. The visited set has nodes that have been determined with the lowest distance moving from the source node; the unvisited set has the nodes with a distance that may not be the shortest; the active set have one node that is used for calculating the distance for the unvisited nodes. Right after initializing the distance stated by step 1), the source node is categorized as the active node while others are the unvisited ones.

3) Calculating the distances from the active node to its adjacent nodes that are unvisited. In Figure 17, the current active node is S, thus the distance is calculated for its adjacent node V1.

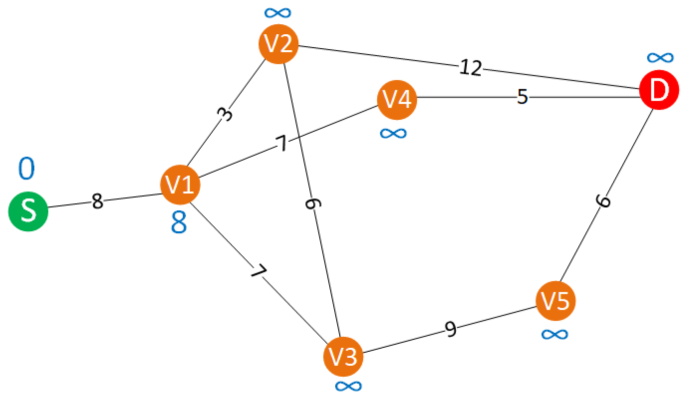


Figure 17. Calculate distance for V1 from S (active node)

4) Confirming the shortest distances calculated in step 3), choosing the unvisited node which has the shortest distance to be the new active node while the old is assigned as visited. In Figure 18, d(V1) is confirmed to be the shortest distance from S, thus updating V1 as the current active node while S as a visited node.

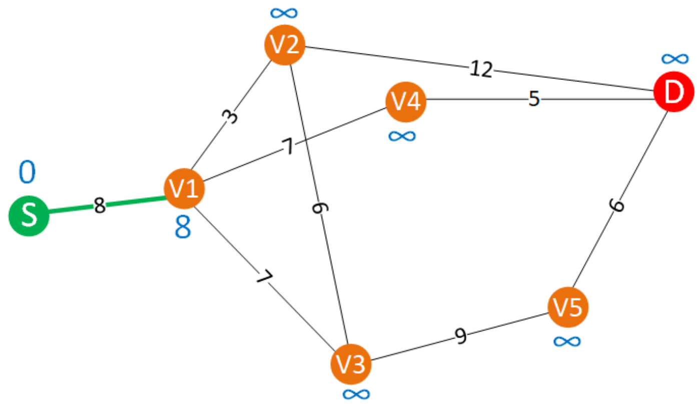


Figure 18. Assign V1 as the active node, S as a visited node

5) Iterating step 3) and 4) till the destination node is active or visited. The iteration process is presented through Figure 19 for solving the shortest path for the graph in Figure 15.

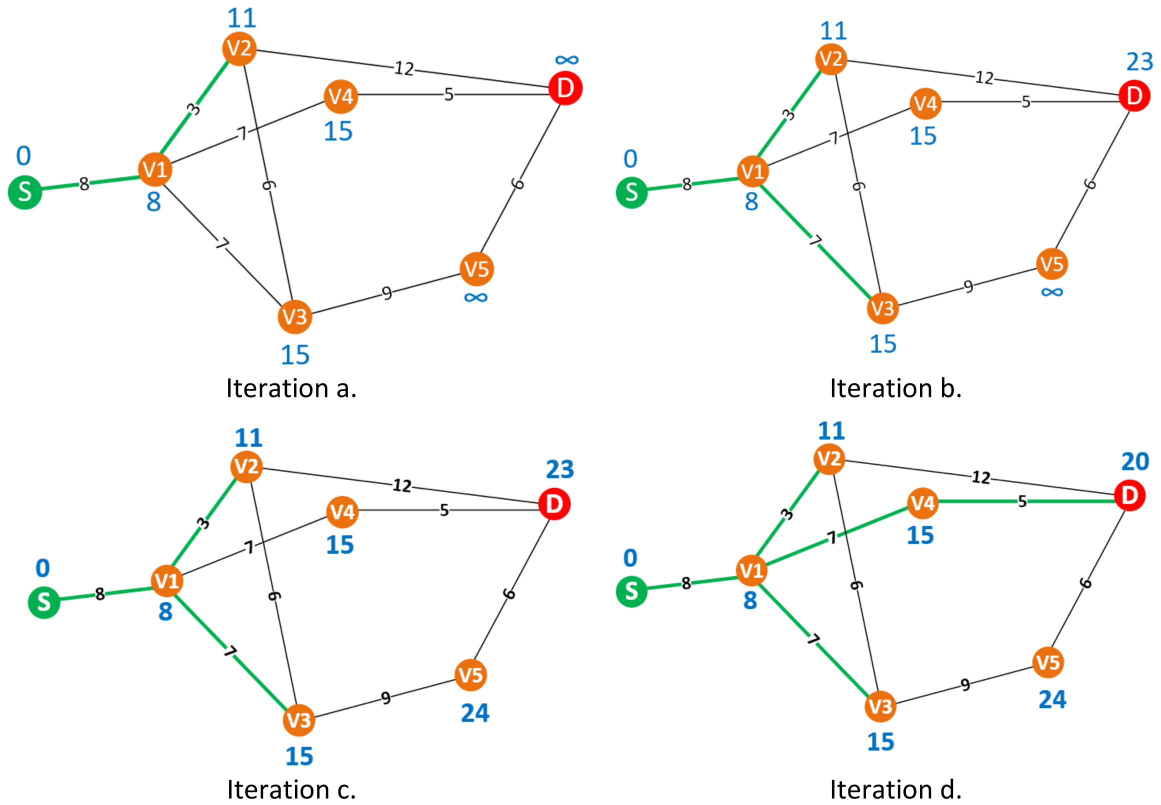


Figure 19. Dijkstra algorithm implementation (scanning nodes for obtaining the shortest path)

Iteration a: Calculate d(V2), d(V3) and d(V4) based on active node V1. While d(V2) = 11 is lowest distance for all the unvisited nodes, it is updated to be the new active node while V1 is assigned as a visited node.

Iteration b: Calculate d(V3) and d(D) based on active node V2. The newly calculated d(V3)=17 is longer than existing d(V3)=15, thus d(V3) remains as 15. d(D) is updated to be 23 as it is smaller than infinity. Both d(V4) and d(V3) have the current lowest distance among the unvisited nodes. Because there is only one node being active, only V3 is updated as the new active node while V2 is assigned to be a visited node.

Iteration c: Calculate d(V5) based on V3. d(V5) is updated to be 24. The current lowest distance for unvisited nodes is d(V4) = 15. Therefore, V4 is updated to be the active node, while V3 is assigned to be visited.

Iteration d: Calculate d(D) based on V4. Newly calculated d(D) = 20 is shorter than existing d(D) = 23. Therefore, d(D) is updated to be 20. The current lowest distance for unvisited nodes is d(D) = 20. Therefore, D is updated to be the active node, while V4 is assigned to be visited. As the shortest distance for Destination is determined, the Dijkstra algorithm is completed. From the source node (S) to the destination node (D), the shortest path is S→V1→V4→D, while the distance is 20.

3.3.2. Cost Definition

When having the street network as a vector dataset, Dijkstra's algorithm can be used for finding the shortest (least cost) path. In the case for identifying the most walkable route, each street segment can be assigned with a cost that is defined by street characteristics that are influential to walking (e.g. length, pedestrian infrastructure).

The process of assigning the cost of each street segment then requires map overlay operation. Given that one aims to find the route with the decent amount of points of interest, the cost for each road segment should be assigned based on the amount of points of interest available along the road and its length. To define the cost for this scenario, the following steps are taken.

1) Determine the points of interest per kilometer for each road segment

The street network data is available as line features. Point over line map overlay is used for calculating the amount of points of interest are reachable for the street segments. The points within 50 meters are considered reachable for streets. After determining the number of point of interest are reachable for each road segment, the density of point of interest (i.e. amount of points of interest per kilometer) is evaluated (Figure 20).

Street network (source: City of Helsinki) and points of interest (Source: Helsinki Regional Transport Authority)

Figure 20. Points of interest density for street network

2) Integrate point of interest density and length property to be the cost of the road segment

To meaningfully combine the point of interest density and length property, the density can be normalized with Equation 7.

$$n = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{7}$$

Equation 7. Normalization equation

The cost is then defined as Equation 8, which means the long road segments with low point of interest density will cost more to cross over.

$$Cost = \ d \times (1 - n(point\ of\ interest\ density)) \tag{8}$$

Equation 8. Cost definition for routing when considering point of interest reachability

4. The development and implementation of walkability models

In the literature review (Chapter 2), different built environmental aspects and their correlations with walking behavior were investigated. Based on the insights from different empirical studies and various reviews, objective walkability evaluation models are proposed for two different units: area and route.

The models can be adjusted to cater to the needs of different population groups (e.g. children, women, older adults) and the values of different cultures. The goal of the proposed models is guiding future studies to evaluate walkability objectively based on a target population or geographic location. The models can be easily applied to larger geographic regions while requiring little resource. This step can be crucial when conducting ecological studies or promoting physical activity/walking at large, as both operations need extensive time and resource, as well as delicate planning.

In this section, the development and implementation of area and route based walkability models are presented. The purpose of implementation of the walkability models are: 1) providing an example for the analysts to apply the proposed walkability models in other contexts; 2) provide the information to the policy makers and urban planners to make informative decisions on designing urban areas, 3) helping individuals learn about their environmental context and identify the most walkable route for themselves. To reach this goal, the models are applied to the Helsinki municipality and implemented as a web application[5]. Through this web application: 1) policy makers and urban planners can identify regions of interest as well as different built environment characteristic evaluations; 2) residents can find the areas/routes that meet their own criteria of walkability.

The structure of this chapter is:

1) The description of the area based walkability evaluation model

The general walkability evaluation model is introduced in the beginning of this section. All the environmental characteristics (i.e. population density, destination accessibility, land use mix, infrastructure quality, street connectivity, aesthetics, traffic safety) considered in the model are detailed described later, including the rationale and evidence for their inclusion, as well as the quantifying methods.

2) The implementation of area based walkability evaluation model in the Helsinki municipality

In this section, the data used to make the evaluation are described, including their sources and the rationale of using particular dataset (e.g. OpenStreetMap). Furthermore, the measuring procedure and evaluated result of destination accessibility, land use mix and infrastructure quality are also described. The reason for only presenting three characteristics is that these three have more complex quantifying procedure compared to others. Lastly, walkability evaluation process for Helsinki region, the result and the validation of the result are presented in the end of this the section.

3) The description of the route based walkability evaluation model

Dijkstra's algorithm is used to evaluate walkability for different route choices in the model. The general equation of cost used to evaluate walkability is introduced in the beginning of this

[5] The application is now available at *http://13.74.165.167* (access date: September 5th, 2017)

section. Next, the route characteristics (i.e. route distance, street type and quality, and the facilities along the route) that are used in the cost definition are detailed described, including the rationale and evidence for their inclusion, as well as the quantifying methods.

4) The implementation of route based walkability evaluation model in the Helsinki municipality

In this section, the data used to make the evaluation are described, including their sources and the rationale of using particular dataset (e.g. OpenStreetMap). Next, the way to quantify street type, street quality and the facilities along the route are explained as they are part of the cost definition. Lastly, a few cost definitions are made and the result of Dijkstra's algorithm is presented. With the different cost definitions, Dijkstra's algorithm can identify the shortest route, the route with good infrastructure facility, the route with more total, utilitarian or recreational services in Helsinki region.

5) The features and potential use cases of the walkability web application

The web application includes both area and route based walkability evaluation for Helsinki. In this section, the features and potential use cases of the web application are introduced. In the end of this section, the advantages of the web application are discussed.

4.1. Objective walkability evaluation for area unit

Area is a basic evaluation unit for walkability. The existing walkability evaluating instruments as well as all of the empirical studies use a neighborhood as their primary unit. The majority of studies considered the buffer area ranging from 1 to 2 kilometers around the participants' home addresses, while a few used administrative units. As this model is an overall walkability evaluation without any target participants, the recommended neighborhood areas are administrative units or grid cells (e.g. 250m*250m grids). Furthermore, it is most likely that the essential data needed to assess environmental characteristics is available in administrative units and different grid levels.

The Indexed Map Overlay is adopted to evaluate the walkability for areas. The overlay method for different environmental characteristics is presented in Equation 9. Each characteristic is normalized with z-score (Equation 10). The weights should be adjusted according to the study's context as well as data availability.

$$\begin{aligned} Area\ Walkability &= w_1 \times z(destination\ accessibility) + w_2 \times z(land\ use\ mix) \\ &+ w_3 \times z(infrastructure\ quality) + w_4 \times z(traffic\ safety) \\ &+ w_5 \times z(street\ connectivity) + w_6 \times z(population\ density) \\ &+ w_7 \times z(aesthetics) + w_8 \times z(transit\ accessibility) \end{aligned} \tag{9}$$

where w is the assigned weight; z stands for z-score normalization

Equation 9. Area walkability evaluation

$$z_i = \frac{x_i - \mu}{\sigma} \tag{10}$$

where μ is the mean value; σ is the standard deviation

Equation 10. Z-score normalization

4.1.1. Population/Residential density

Population density is important not only because of its indication for service availability and social activeness, but also because it can guide the policy makers to prioritize higher populated neighborhoods that have a poor walking environment. Population density is measured by calculating the population per area unit.

$$Population\ density\ =\ population/area \tag{11}$$

Equation 11. Population density calculation

Residential density sometimes is used as an equivalent measurement. It stands for residential land use ratio of an area. However, areas that have high residential density are not necessarily highly populated.

$$Residential\ density\ = residential\ land\ use\ area/total\ area \tag{12}$$

Equation 12. Residential density calculation

4.1.2. Destination accessibility

Destination provides the basic purpose for walking trips. As discussed in section 2.1.2. , destination accessibility, or sometimes referred as service accessibility, consistently has proven to be positively correlated with utilitarian walking. For recreational walking, although destination is considered less important, it can potentially encourage some people to take walking trips when there are good quality recreational destinations such as parks or beaches. Calculating the destination density is the most commonly adopted objective evaluation for destination accessibility. In this model, the destination accessibility is assessed via weighted destination density. The adoption of weights is because of the different importance levels destinations have. For example, a close by grocery store may encourage more walking trips than a pharmacy. Therefore, weight is defined according to approximate visiting frequency to one type of destination (e.g. high frequency for grocery stores, low frequency for furniture stores).

$$Destination\ Accessibility = \sum_i (destination_i\ *\ w_i)\ /area \tag{13}$$

where $destination_i$ is the number of service i (e.g. 10 grocery stores, 2 pharmacies) within the area under evaluation, w_i is the weight assigned to service i based on its popularity or visiting frequency (e.g. 5 for grocery store, 2 for pharmacy)

Equation 13. Destination accessibility evaluation

Destination accessibility has two pillars of construct: the specific services/amenities considered as destinations and the visiting frequency to those destinations. Whether some types of services or amenities should be included and how to define their visiting frequency depend on the types of walking, the target population, season and local culture.

4.1.3. Land Use Mix

The level of mixed land use represents the degrees of integration for different functionalities in the area. Land use mix is frequently examined and positive correlations have been observed by many studies, which prove being in a diverse environment encourages walking behavior. Entropy index is a standard practice to evaluate land use mix in the field.

$$Entropy\ index\ = -\frac{\sum_i (p_i \ln p_i)}{ln\ N} \tag{14}$$

where i is the land use category, p_i is the proportion of the land area covered by land use i, N is the number of the categories considered in the model

Equation 14. Entropy index calculation

4.1.4. Infrastructure quality

Infrastructure quality (e.g. presence of sidewalks, lights, benches) is not always found to be correlated with either utilitarian or recreational walking. However, for some regions (e.g. less developed areas), seasons (e.g. winter) or population groups (e.g. older population) the quality of infrastructures can be considerably influential.

$$\begin{aligned} &Infrastructure\ quality \\ &\quad = w_1 \times z\ (sidewalk\ length\ \ / \ area) \\ &\quad + w_2 \times z\ (number\ of\ benches\ /area) \\ &\quad + w_3 \times z\ (number\ of\ lights\ \ /area) \end{aligned} \tag{15}$$

where: w_i is the assigned weight; z stands for z-score normalization

Equation 15. Infrastructure quality evaluation

4.1.5. Street connectivity

Street networks provide the possibility for individuals to participate in walking. Connected streets link destinations thus enabling people to reach their desired locations. Streets with high connectivity often have few cul-de-sacs, offer shorter routes to reach the destinations, while providing a greater number of alternative routes. Street connectivity shows a consistent positive association with walking for transportation. For recreational walkers, better connected street network can encourage exploration for different route choices. The common practice for evaluating street connectivity is by calculating intersection (more than 3-way intersection) density and cul-de-sacs density.

$$\begin{aligned} &Street\ connectivity \\ &\quad = w_1 \times z\ (number\ of\ intersections\ /\ area) \\ &\quad - w_2 \times z\ (number\ of\ cul\ de\ sacs\ /area) \end{aligned} \tag{16}$$

where: w_i is the assigned weight; z stands for z-score normalization

Equation 16. Infrastructure quality evaluation

4.1.6. Aesthetics

Aesthetics is a subjective characteristic. In the domain of researching correlations between built environment and walking behavior, no previous studies have evaluated aesthetics objectively. Aesthetics showed its significant influence on recreational walking through various empirical studies. Therefore, an objective way of evaluating aesthetics should be developed to ensure the validity of the objective evaluation on recreational walkability. As web technology is maturely developed, many online platforms are available to provide aesthetics information. For example, photo hosting services such as Flickr provide geotagged pictures that address how people perceive the environment (Figueroa-Alfaro & Tang 2017). Another possible evaluation can be done through geotagged review data for points of interest. However, at the moment, there is no aggregated review data available. Therefore, in this context, aesthetics is evaluated by photo density.

$$Aesthetics\ = number\ of\ photos/area \quad (17)$$

Equation 17. Aesthetics evaluation

4.1.7. Traffic safety

Traffic safety has not been evaluated in any objective walkability evaluation models. As traffic safety is a top priority in an urban design, as well as a concern for the young and old when walking, it should be present in walkability evaluation. In this study, traffic safety is estimated by the traffic accident density per year.

$$Traffic\ safety = -number\ of\ accidents/year/area \quad (18)$$

Equation 18. Traffic Safety evaluation

4.1.8. Transit accessibility

Few studies have included transit accessibility into their environmental evaluation model. Hypothetically, areas that have higher transit accessibility can encourage residents to take public transportation. Such action eventually contributes to more transportation walking. Currently, there is a trend to build sustainable cities. Meanwhile, people are more aware of the benefits for taking public transportation over self-owned motorized vehicles. Therefore, transit accessibility can be an important indicator for environmental auditing. In this study, transit accessibility is assessed with bus line density.

$$Transit\ accessibility\ = number\ of\ bus\ lines/area \quad (19)$$

Equation 19. Transit Accessibility evaluation

4.2. Area walkability evaluation in Helsinki

When applying the walkability evaluation in Helsinki, two different area units are used: the smallest administrative unit defined by the city of Helsinki and 250m*250m cell in grid system. The model presented in the section 4.1. is utilized. The data used in the model is from city of Helsinki as well as other open sources (e.g. OpenStreetMap). The pre-processing of data is done in ArcGIS Desktop[6].

For administrative units, the environment characteristics assessed are: street network connectivity, service accessibility, infrastructure quality, population density, land use mix, traffic safety and public transit accessibility. For grid system, in addition to the characteristics mentioned above, aesthetics is also assessed by calculating the photo (from Flickr) density. Aesthetics is only evaluated for grid cells due to technical difficulties in querying Flickr photos based on irregular boundaries of administrative units.

Majority environment characteristics are evaluated based on density, which is straightforward to calculate. Therefore, only service accessibility, infrastructure quality and land use mix are explained in detail as they require context based data pre-processing. Table 2 shows the data sources for evaluating different environment characteristics. In this section, the evaluation results for environmental characteristics and walkability are presented as thematic maps and put in Appendix C unless the results are content-relevant.

[6] ArcGIS Desktop: GIS software developed by Esri Inc. It contains ArcMap, ArcCatalog and ArcScene. The software provides comprehensive spatial data process and analysis tools.

Table 2. Data sources for environment characteristics evaluation

Evaluated characteristics	Data source
Street network connectivity	Street network: OpenStreetMap PBF format downloaded from Mapzen for Helsinki Region *(available at https://mapzen.com/data/metro-extracts/metro/helsinki_finland/, accessed on 5 Sep. 2017)*
Destination accessibility	Amenities: OpenStreetMap Shapefile downloaded from Mapzen for Helsinki Region *(available at https://mapzen.com/data/metro-extracts/metro/helsinki_finland/, accessed on 5 Sep. 2017)*
Infrastructure quality	Paved pedestrian paths, benches, lights: City of Helsinki open data service *(available at http://kartta.hel.fi/, accessed on 5 Sep. 2017)*
Population density	Population grid *(available at http://www.hri.fi/en/dataset/vaestotietoruudukko, accessed on 5 Sep. 2017)* Author: Helsingin seudun ympäristöpalvelut HSY
Land use mix	Area land use: OpenStreetMap Shapefile downloaded from Mapzen for Helsinki Region *(available at https://mapzen.com/data/metro-extracts/metro/helsinki_finland/, accessed on 5 Sep. 2017)*
Traffic safety	Traffic accidents 2000-2015 *(available at http://www.hri.fi/en/dataset/liikenneonnettomuudet-helsingissa, accessed on 5 Sep. 2017)* Author: Helsingin kaupungin kaupunkisuunnitteluvirasto
Public transit	Helsinki Region Transport public transport lines *(available at http://www.hri.fi/en/dataset/hsl-n-linjat , accessed on 5 Sep. 2017)* Author: Helsingin seudun liikenne HSL
Aesthetics	Geotagged photos *(available at https://www.flickr.com/services/api/flickr.photos.search.html , accessed on 5 Sep. 2017)*

4.2.1. Destination accessibility

Currently, many online platforms (e.g. Google places, Yelp, Foursquare[7]) provide amenity information based on locations. Within these platforms, the amenity information is usually relatively complete and updated. However, the aggregated amenity data is not freely available through those platforms. OpenStreetMap (OSM) also provides such information while being an open source. As OSM is a popular crowdsourcing platform, the data is usually updated but may contain some other errors. In OSM, there are more than hundreds of different types of amenities. As the destination accessibility evaluation is made for the general adult population, all different types of amenities are included in the evaluation. They are categorized into different groups: retail, entertainment, service, nature, tourism/culture and sport. In the calculation of destination accessibility (Equation 13), amenities are weighted based on visiting frequency: 6 (*very frequently*), 5 (*somewhat frequently*), 4 (*often*), 3 (*occasionally*), 2 (*somewhat infrequently*) and 1 (*very infrequently*). Thus, the approximate visiting frequency is also included for categorization (Table B-1 to Table B-6).

Based on the categorization, the destination accessibility is evaluated for all destinations (Figure C-1, Figure C-4), utilitarian destinations (i.e. retail, service, entertainment) (Figure C-2, Figure C-5), recreational destinations (i.e. nature, tourism, sport) (Figure C-3, Figure C-6).

[7] Google places, Yelp and Foursquare are popular location-based services that provide detailed amenity information. Such services also allow user to rate the amenities.

4.2.2. Land Use Mix (entropy Index)

Zoning data from the government entity usually is a good source for land use mix evaluation. However, zoning data was inaccessible to the public in the case of Helsinki. While area elements in OSM have land use property, OSM data is used for calculating the entropy index. Forty-nine different land use types are extracted from OSM within Helsinki region. For entropy calculation, different land use types are recategorized into commercial, green space, industrial, institutional, residential and others (Equation 20, Table 3, Figure 21). While industrial land use is considered irrelevant to walking, it is omitted when calculating the entropy index. For grid system, 250m*250m is considered too small to have different types of land use. Therefore, for each grid cell, entropy index is calculated together with its eight adjacent cells. The evaluation result of land use mix for Helsinki can be found in Figure C-7 and Figure C-8.

$$p_i = \frac{a_i}{area}$$

$$Entropy\ index\ = -\frac{\sum_i (p_i \ln p_i)}{ln\ 6} \qquad (20)$$

where i is the land use type (i.e. commercial, green space, industrial, institutional, residential and others), a_i is the land area of land use type i, p_i is the proportion of the land area covered by land use i

Equation 20. Entropy index calculation for Helsinki

Table 3. Land use categorization based on OSM data

Commercial	Green space	Industrial	Institutional	Recreational	Residential	Others
commercial	allotments	generator	hospital	cinema	residential	barracks
retail	cemetery	industrial	heath	golf course		common
	farm	fuel	college	pitch		quarry
	farmland	substation	library	playground		footway
	farmyard		place of worship	recreation ground		parking
	forest		school	sports centre		pedestrian
	garden		university	theatre		pier
	grass			stadium		railway
	hedge					
	island					
	meadow					
	nature reserve					
	orchard					
	park					
	plant					
	scrub					
	village green					
	wetland					
	wood					

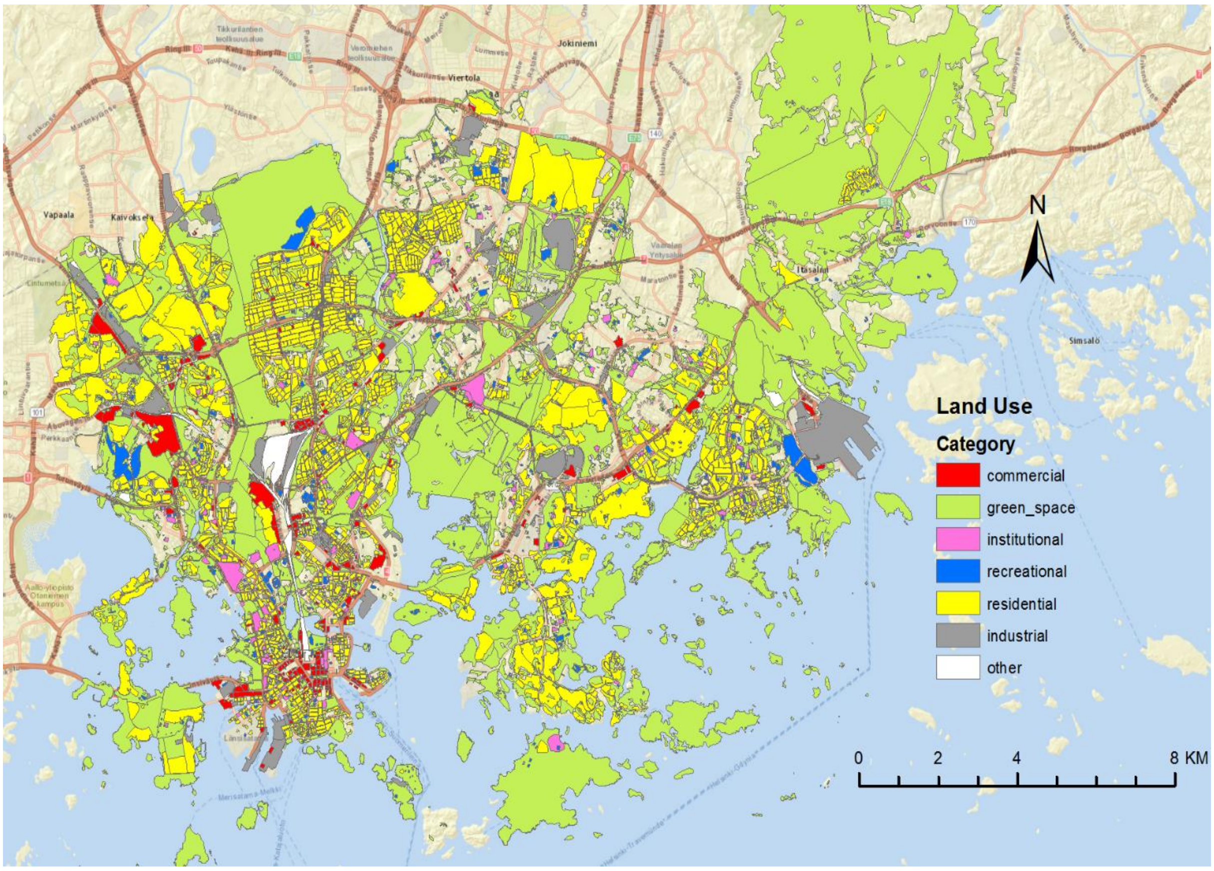


Figure 21. Recategorized OSM land use in City of Helsinki

4.2.3. Infrastructure quality

The infrastructure in Helsinki is well established. Pedestrian path availability is high and homogeneous across the region. Therefore, in normal conditions, sidewalks would not make any impact on walking. However, the weather condition changes dramatically during the winter time in Helsinki (e.g. heavy snow, short daylight). Well maintained sidewalks and presence of street lights become high priority when considering walking trips during winter. As the maintenance data is not available, paved walking paths are hypothesized to be walkable for winter time. Thus, the walking paths quality is estimated with the following equation during winter.

$$Infrastructure\ quality = 0.5 \times z\ (paved\ walking\ path\ length/area) + 0.5 \times z\ (number\ of\ lights/area) \quad (21)$$

where z stands for z-score normalization

Equation 21. Infrastructure quality evaluation

4.2.4. Walkability calculation

For the general population during normal weather condition, the following walkability calculation are proposed.

$$\begin{aligned} Utilitarian\ walkability \\ &= 2 \times z(utilitarian\ \ destination\ accessibility) + z(land\ use\ mix) \\ &+ 0.8 \times z(Intersection\ density) - \ 0.2 \times z(cul\ de\ sac\ density) \\ &+ z(population\ density) \end{aligned} \quad (22)$$

where z stands for z-score normalization

Equation 22. Utilitarian walkability evaluation for Helsinki

$$\begin{aligned} Recreational\ walkability \\ &= z(recreational\ \ destination\ accessibility) + z(land\ use\ mix) \\ &+ 0.8 \times z(Intersection\ density) - \ 0.2 \times z(cul\ de\ sac\ density) \\ &+ z(population\ density) + z(aesthetics) \end{aligned} \quad (23)$$

where z stands for z-score normalization

Equation 23. Recreational walkability evaluation for Helsinki

In the evaluation equations (Equation 22 & Equation 23), not all measured environmental characteristics are included.

For utilitarian walkability assessment, infrastructure quality, traffic safety and transit accessibility were all weighted at zero. Pedestrian safety is considered as the top priority in the Finnish transportation policy. Helsinki provides an appropriate traffic order and well-established walking infrastructure across urban areas. As discussed in the literature review section, when an environment characteristic is homogenous in the built environment, its influence on walking becomes insignificant. Furthermore, in the majority of empirical studies conducted for average adults in cities which resemble Helsinki, neither infrastructure quality nor traffic safety were found to be correlated with utilitarian walking (Saelens and Handy 2008; Sugiyama et al. 2012; Van Holle et al. 2012). While the transit accessibility was proposed as an important factor to consider when it comes to transportation walking, no available evidence supports the hypothesis. Further research is required to investigate the correlation between transit accessibility and walking behavior, based on which transit accessibility can be re-weighted in the model.

In the case for recreational walkability evaluation, recreational destination accessibility, land use mix, street connectivity and aesthetics are incorporated. Helsinki is not a populous city. Residential areas are dispersed across urban regions (Figure 22), while well connected streets (Figure 23), high mixed land use (Figure 24), as well as recreational destinations (Figure 25) are clustered in the downtown area. These factors are included in the assessment because they have shown relevant to leisure walking in multiple empirical studies, and appear to be heterogenous in the study region (Hirsch et al. 2014; Reyer et al. 2014; Sugiyama et al. 2014).

The results for walkability evaluation are shown in Figure C-11(utilitarian walkability in district level), Figure C-12 (recreational walkability in district level), Figure C-13 (utilitarian walkability in grid level) and Figure C-14 (recreational walkability in grid level).

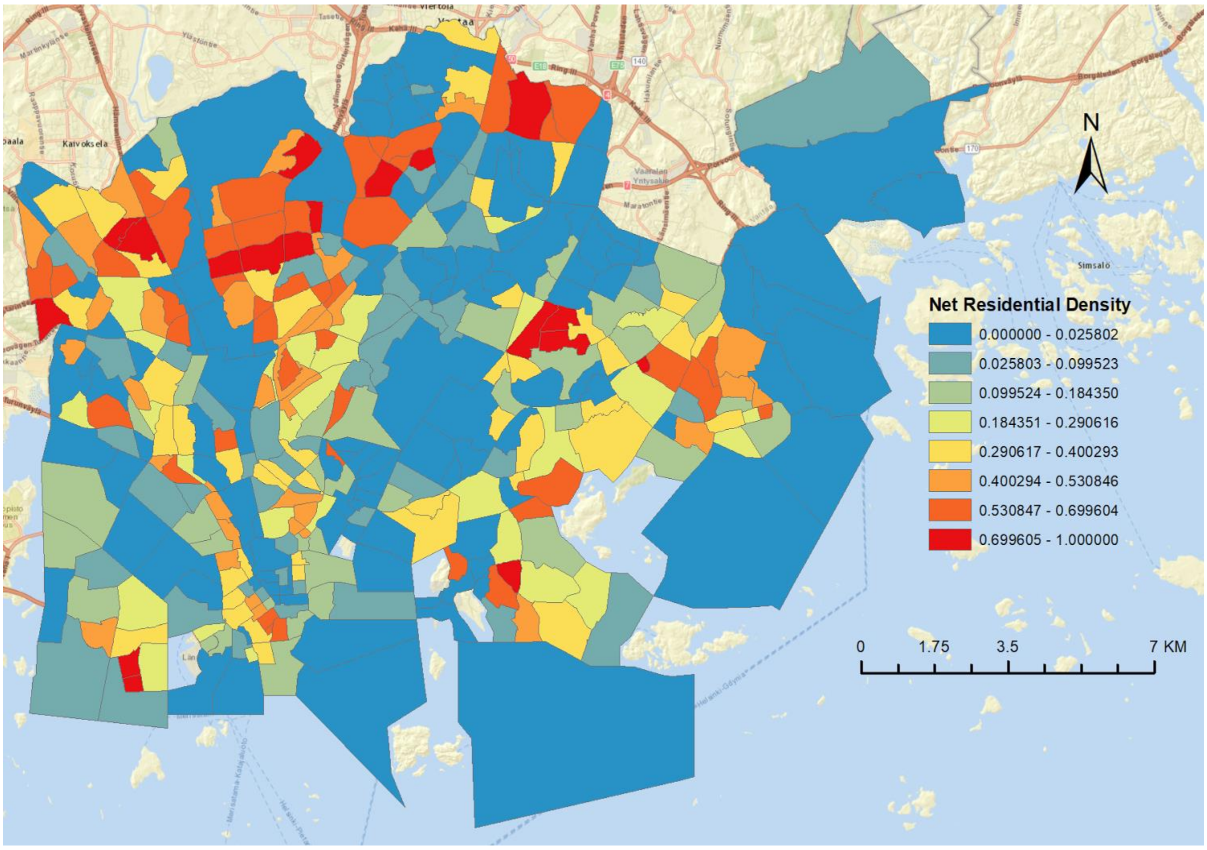


Figure 22. Net residential density in Helsinki

S

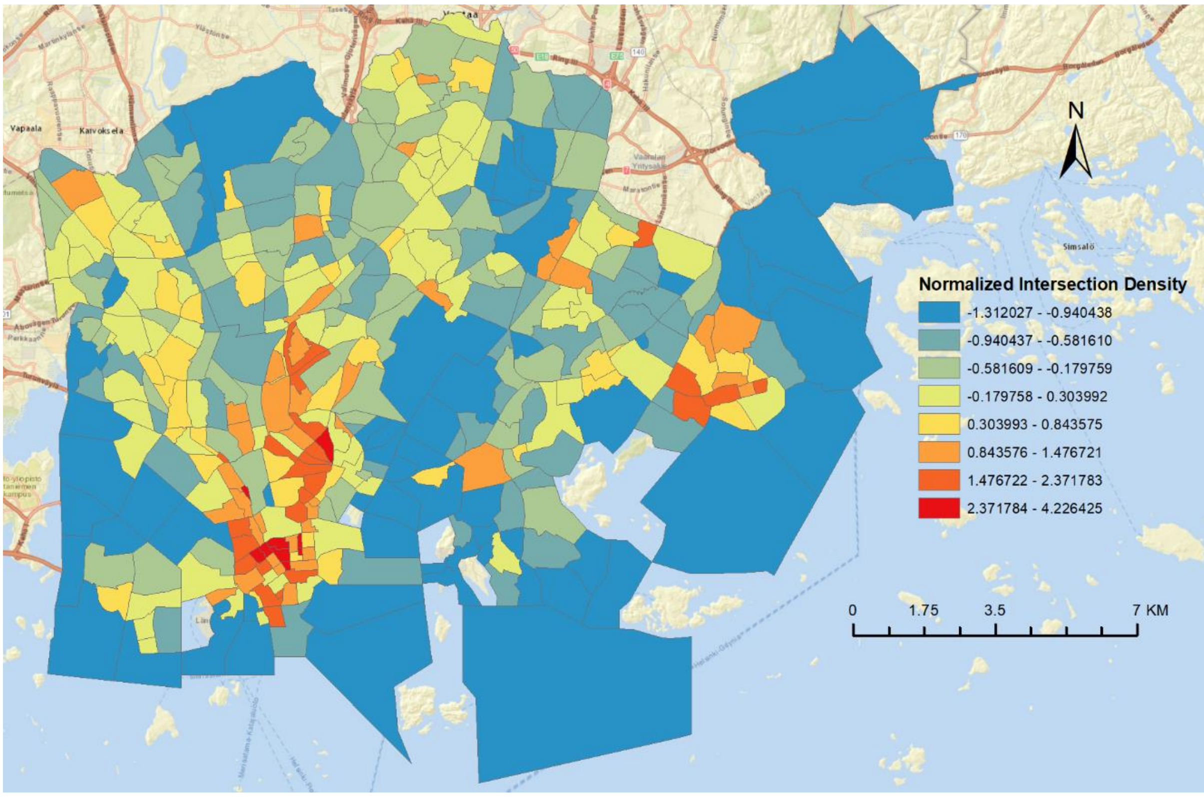


Figure 23. Normalized (z-score) intersection density based on administrative units

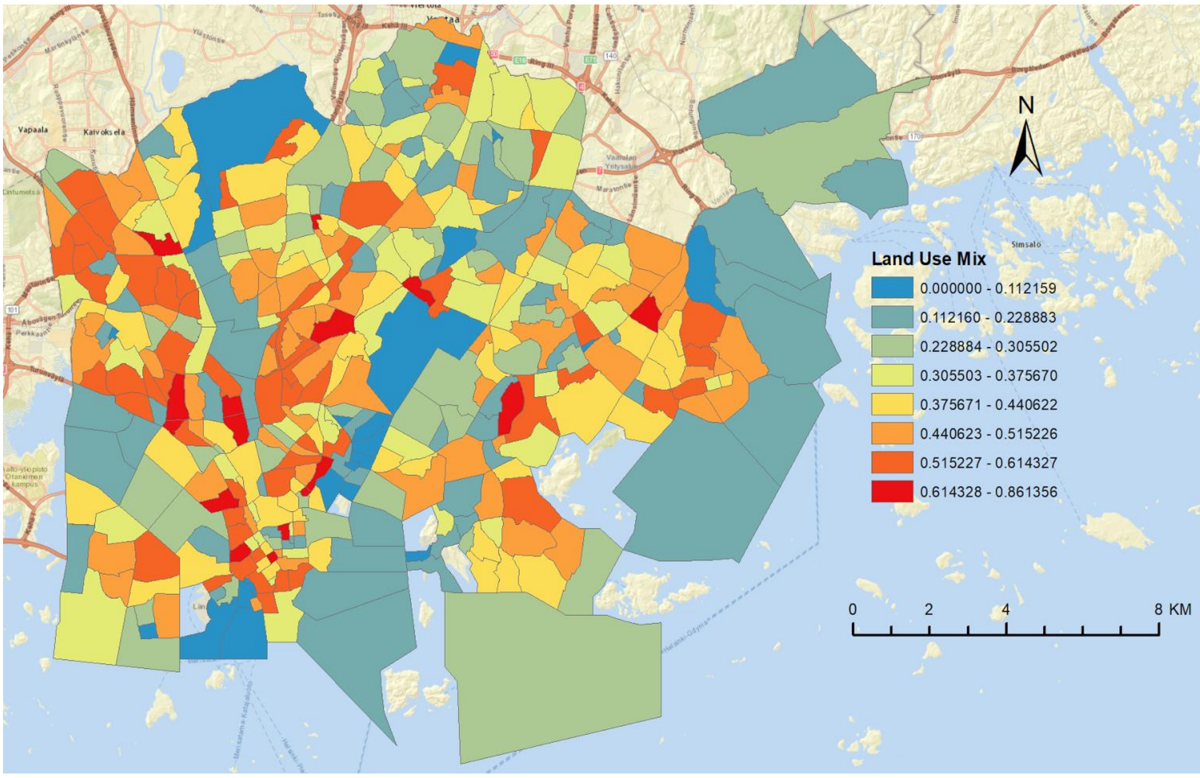


Figure 24. Entropy index for land use mix based on administrative units

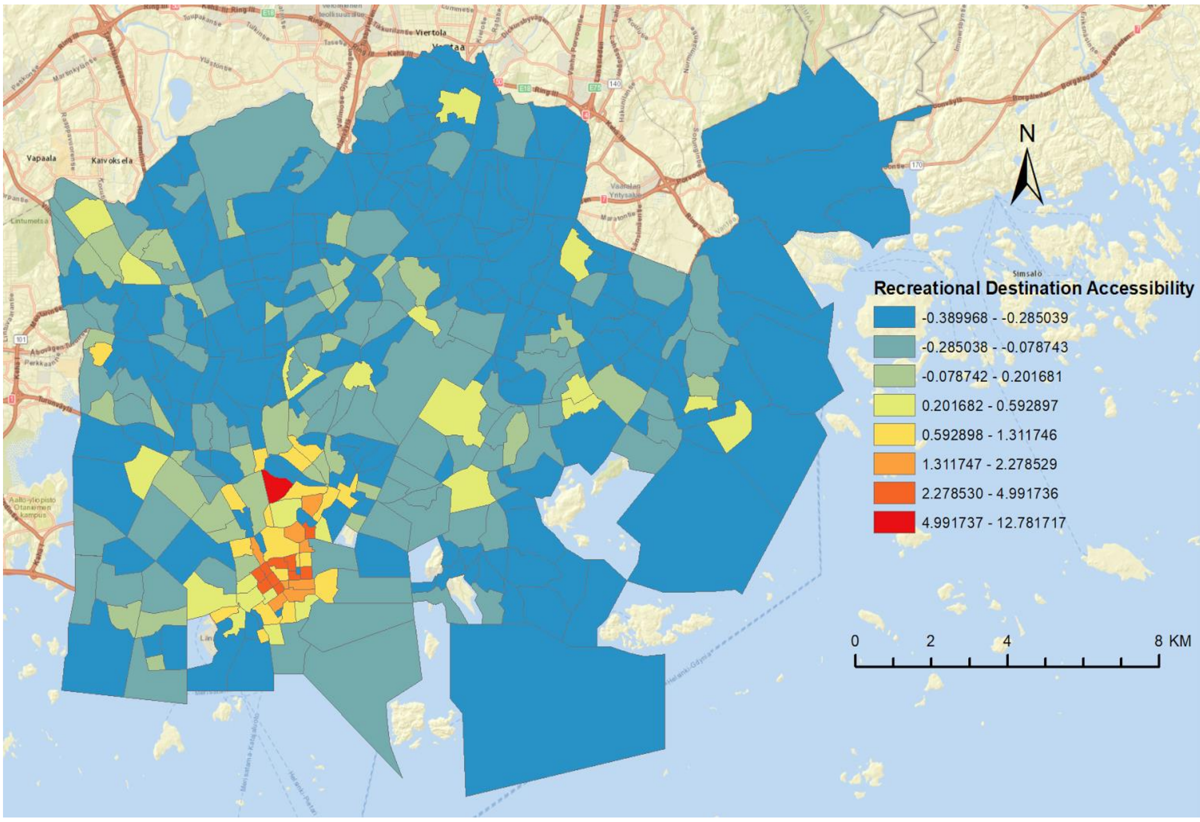


Figure 25. Normalized (z-score) recreational destination accessibility based on administrative units

4.2.5. Validation with Walkability Index

Walkability Index (WI) is an objective measurement that evaluates transportation walkability (Frank et al. 2010). Up till now, WI is the only widely adopted objective walkability measurement. Although WI is developed only for assessing transportation walkability, several studies observed that WI is positively correlated with both utilitarian and recreational physical activities (Saelens et al. 2012; Van Dyck et al. 2010; Reyer et al. 2014). However, this correlation with utilitarian walking is considerably more significant than recreational.

Four different environment characteristics are used to define WI: net residential density, retail FAR, intersection density and land use mix (Equation 24).

$$\begin{aligned} &Walkability\ Index \\ &\quad = 2 \times z(Intersection\ density) + z(net\ residential\ density) \\ &\quad + z(retail\ floor\ area\ ratio) + z(land\ use\ mix) \end{aligned} \tag{24}$$

where z stands for z-score normalization

Equation 24. Walkability Index

Retail FAR is representing the efficiency of retail land usage. The higher the ratio is, the smaller setbacks and surface parking lots are. Both setbacks and surface parking in retail area are considered barrier for pedestrians to access services. Therefore, retail FAR is included in walkability index. Low retail FAR is more commonly found when an area is designed for motorized vehicles to access. In a European context, urban areas are usually compact thus presumably setbacks and surface parking have less influence on walking behavior. Considering retail FAR may have a smaller impact on walking in Helsinki, at the same time, no proper data source is available to measure this factor, retail FAR is omitted in the calculation. Similarly, one study conducted in Belgium also excluded retail FAR in their WI model (Van Dyck et al. 2010). For Helsinki, the WI is calculated as Equation 25.

$$\begin{aligned} &Walkability\ Index \\ &\quad = 2 \times z(Intersection\ density) + z(net\ residential\ density) \\ &\quad + z(land\ use\ mix) \end{aligned} \tag{25}$$

where z stands for z-score normalization

Equation 25. Walkability Index adopted for Helsinki

The goal of applying WI in Helsinki is using an established walkability audit tool to validate the environmental evaluation for the Helsinki region. Both intersection density and land use mix were evaluated in the previous section. The residential land use is derived from OpenStreetMap to evaluate net residential density (Figure 22). The WI evaluation result for Helsinki can be found in Figure C-15 (for district units) and Figure C-16 (for grid units).

The correlation coefficient between WI and utilitarian/recreational walkability is calculated as 0.80 and 0.78 respectively in the district model, and 0.78 and 0.69 in the grid model. This result suggests that this Helsinki specific walkability model is a plausible equivalent for WI. Compared to WI, data required in applying the walkability model is easy to access. All environmental characteristics measured can use OpenStreetMap as a data source except population density. However, net residential density, the equivalent measurement of population density, can also be assessed using OpenStreetMap land use information.

While there is a demonstration on data processing and measuring various environment characteristics, the model can be easily migrated to different geographic locations and demographics.

4.3. Objective walkability evaluation for route unit

In modern society, an enormous number of streets are built to satisfy various transporting purposes. The complex nature of street networks prevents evaluating route walkability similarly to areal evaluation. Unlike in a small amount of defined neighborhoods in a city, there can be thousands of route choices. Evaluating each route combination is neither feasible, nor meaningful as their evaluations are not comparable. Furthermore, pedestrian behavioral data on a route level is challenging to gather.

Nonetheless, routes are where walking takes place and its quality directly influences pedestrian experience. Evaluating walkability can help pedestrians to choose preferable routes when walking. This goal can be achieved when having a defined origin-destination pair. While the number of sensible route choices are limited, routes quality is also comparable when they have the same origin and destination.

Two different technologies can be used to determine the most walkable routes: Cost Distance Analysis and Dijkstra's algorithm. One of the major differences between two technologies are the data to be processed. Cost Distance Analysis is solving routes based on raster dataset, while Dijkstra's algorithm utilizes vector dataset.

In this thesis, Dijkstra's algorithm is used to identify most walkable routes. The rationales are 1) the results have better accuracy compared to raster data processing; 2) OpenStreetMap is freely available and a good source of data for conducting Dijkstra's algorithm; 3) existing tools (e.g. PGRouting) allows easy implementation of a routing service based on Dijkstra's algorithm.

When defining cost of street segments for walkability evaluation, street type and quality, and facilities along the route are introduced as they are factors concerning walkability. Through minimizing the route cost, the most walkable routes for defined origin-destination pairs can be identified.

The route cost is defined in Equation 26, while the normalization is calculated as Equation 7.

$$Cost = d \times p + \sum_i d(1 - n_i) w_i \tag{26}$$

where d is distance of the route; p is the street priority; i stands for the type of the facility; n_i *is the normalized facility quantity,* w_i *is the weight for facility.*

Equation 26. Cost equation for route

4.3.1. Route distance

Distance has been identified as the primary barrier for walking behavior, thus its inclusion is a necessity. All reasonable route choices should be calculated based on distance so that the walking length is not unnecessarily long for pedestrians.

4.3.2. Street priority (street type and quality)

All street networks include different types of roads to support various transportation methods (e.g. highway, sidewalk). Therefore, it is important to examine the type of road to ensure it provides a safe and comfortable walking environment. Usually, street network data includes the street type and if they allow pedestrian presence. For introducing route type into the cost definition, each street type can be assigned with a priority index. For example, sidewalks can be assigned a high priority, while highways assigned as low. High priority indicates low cost thus should be assigned with a smaller number. For example, walking on sidewalks costs 1 unit of distance while on highways costs 5 units of distance.

Street quality is associated with surface quality and its maintenance. This information can be crucial for certain weather conditions (e.g. snow, rain) and some population groups (e.g. the old). The quality of information can be integrated into street priority together with street type (e.g. paved sidewalks have higher priority than unpaved ones).

4.3.3. Facilities along the route

Facilities along the road include basic infrastructure such as lights and benches, as well as the services such as parks, grocery stores.

The infrastructure type of facilities can improve walking experience when, for example, walking during the night or for long distances. Such information sometimes is included in the street network data (e.g. OpenStreetMap lit property for roads). However, for standardization, the route infrastructure facilities are calculated based on the amount of facilities within a buffer around the route. Therefore, a separate data source that contains facility information is required.

Services, on the other hand, might be less important for pedestrians when having a defined origin and destination. In BME, services are considered as destinations, while for route walkability assessment, the destination is defined. Nevertheless, high service availability can positively influence walking experience by providing diversified street landscapes, active street life. Moreover, streets that have more services can potentially encourage detours. Services along the route can be calculated as the weighted sum, while the weight indicates approximate visiting frequency. Similar to area evaluation, services can also be grouped into recreational and utilitarian ones, as people may prefer nature or built street view.

4.4. Route walkability evaluation in Helsinki

For a route's walkability evaluation, the most essential data is street networks. For the city of Helsinki, OpenStreetMap is a good data source. OSM is both open source and has relatively updated and complete street network, including small pathways that are not usually included in other sources (e.g. Digiroad[8]). Each road segment inside OSM is tagged with specific street types (e.g. sidewalk, cycleway) and surface types (e.g. solid, soft). OSM provides detailed documentation about the tagging rules in different countries. For Helsinki, "WikiProject Finland[9]" is used a guideline to examine the tags in the dataset. In addition, the facilities along the routes are also incorporated in the evaluation. Table 4 shows the data used in route walkability evaluation.

To calculate cost for different route choices, each street segments needs to have relevant attributes: length, priority, and weighted facility quantity. Therefore, following attributes are added for each road segment:

- Distance: road segment length in meters.
- Priority: for walking purpose, prioritizing the roads based on their types
- Priority with road quality: for walking purpose, prioritizing the roads based on their types and quality

[8] Digiroad database includes Finnish street network. It is published by Finnish Transportation Agency and available online: *https://extranet.liikennevirasto.fi/extranet/web/public/latauspalvelu* (access date: September 5th, 2017).
[9] WikiProject Finland is a wiki page provided by OpenStreetMap. The page contains information related to mapping activity that is specific to Finland. It is available at: *http://wiki.openstreetmap.org/wiki/WikiProject_Finland* (access date: September 5th, 2017).

- Number of lights within 20-meter buffer
- Number of benches within 20-meter buffer
- Weighted sum of services within 20-meter buffer
- Weighted sum of recreational services within 20-meter buffer
- Weighted sum of utilitarian services within 20-meter buffer

Table 4. Data sources for route characteristics evaluation

Evaluated characteristics	Data source
Street network	Street network: OpenStreetMap PBF format downloaded from Mapzen for Helsinki Region *(available at* https://mapzen.com/data/metro-extracts/metro/helsinki_finland/*, accessed on 5 Sep. 2017)*
Facility	Benches and Lights: City of Helsinki open data service *(available at* http://kartta.hel.fi/*, accessed on 5 Sep. 2017)* Amenities: OpenStreetMap Shapefile downloaded from Mapzen for Helsinki Region *(available at* https://mapzen.com/data/metro-extracts/metro/helsinki_finland/*, accessed on 5 Sep. 2017)*

4.4.1. Priority

Priority is defined based on the street type. In OSM, the properties of each route are indicated by tags which are key-value pairs. The street type is included in the property information.

OSM data example[10]: Clipstone street, a one-way residential street

```
<way id="5090250" visible="true" timestamp="2009-01-19T19:07:25Z" version="8"
changeset="816806" user="Blumpsy" uid="64226">
  <nd ref="822403"/>
  <nd ref="21533912"/>
  <nd ref="821601"/>
  <nd ref="21533910"/>
  <nd ref="135791608"/>
  <nd ref="333725784"/>
  <nd ref="333725781"/>
  <nd ref="333725774"/>
  <nd ref="333725776"/>
  <nd ref="823771"/>
  <tag k="highway" v="residential"/>
  <tag k="name" v="Clipstone Street"/>
  <tag k="oneway" v="yes"/>
 </way>
```

where way, nd and tag are OSM elements indicating line/area feature, point feature and feature property.

The key *"highway"* is used to indicate the type of the street. For the city of Helsinki, the following values are identified, and assigned with different priorities based on their functionalities (Table 5). OpenStreetMap provides detailed description for each type of road based on different value of *"highway"* which is used as guide on assigning priority[11].

[10] OpenStreetMap data example for road element. The example is from http://wiki.openstreetmap.org/wiki/Way (access date: September 5th, 2017).

[11] The description of different types of street is available at http://wiki.openstreetmap.org/wiki/Key:highway (access date: September 5th, 2017).

Table 5. OpenStreetMap highway values and their priority

Highway Tag Value	Priority
pedestrian	1
footway	1
steps	1.2
track	1
path	1
crossing	1.2
cycleway	1.5
living street	1.5
residential	2
service	5
bridleway	5
tertiary link	5
tertiary	5
unclassified	5
secondary link	5
secondary	5
primary link	5

The "*Priority with road quality*" attribute of each road segment is an integration of the type of the road and its maintenance information. In OSM, no maintenance data is available. Therefore, the surface type of the road segment is considered as an approximation of the quality information. The surface type information is from another tag key *"tracktype"* in OSM. The "*Priority with road quality*" is calculated with *"Priority"* multiplies *"Surface quality"* (Table 5 & Table 6).

Table 6. OpenStreetMap road cover types and their quality information

Tracktype	Description	Surface quality
grade1	Solid	1
grade2	Mostly solid	1.2
grade3	Even mixture of hard and soft materials	1.5
grade4	Mostly soft	2
grade5	Soft	2

4.4.2. (Weighted) Sum of different facilities

A 20-meter buffer is used to estimate the facilities along the road. The estimated facility includes lights, benches, total services, recreational services and utilitarian services. As with area walkability evaluation, the service data is derived from OpenStreetMap. Tables (Table B-1 to Table B-6) show the categorizations (i.e. retail, service, entertainment, nature, tourism and sport) and weights for different amenities. The utilitarian services include retail, service and entertainment categories, while recreational include nature, tourism and sport.

4.4.3. Cost definition

Based on the attributes of routes, several cost calculations are made in order to provide different route choices (Equation 27): shortest route (c1), the route with good infrastructure facility(c2), the route with more total/utilitarian/recreational services (c3, c4, c5).

$$c_1 = d \times p$$
$$c_2 = d \times p + d * (1 - n[bench] \times 0.2 + d \times (1 - n[light] \times 0.5)$$
$$c_3 = d \times p + d * (1 - n[service]) \quad (27)$$
$$c_4 = d \times p + d * (1 - n[utilitarian\ service])$$
$$c_5 = d \times p + d * (1 - n[recreational\ service])$$

where d is distance of the route; p is the street priority; n stands for normalization

Equation 27. Cost equation for routes in the context of Helsinki

With a defined origin and destination, a few route choices are calculated by using Dijkstra's algorithm (Figure 26). Unfortunately, there is no established instruments to evaluate route walkability. The viable validation options are field surveying and by interviewing pedestrians who have adopted the route options provided by this model. However, those options are out of the scope of this research work.

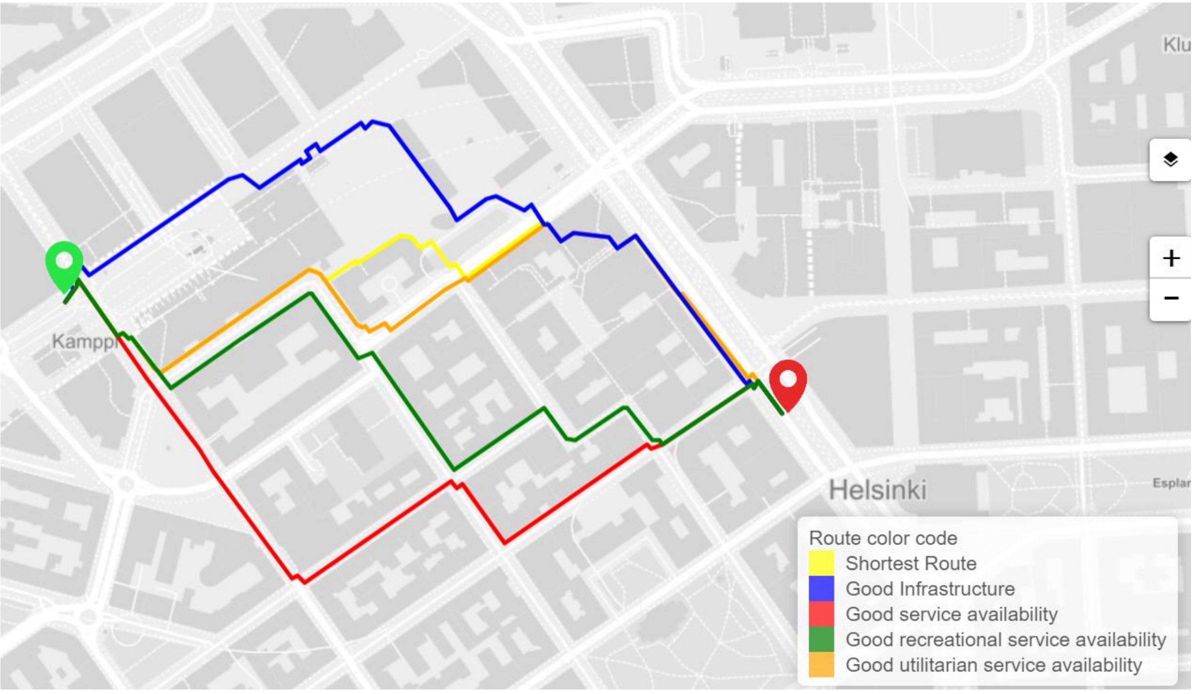


Figure 26. Five different routes are calculated by Dijkstra's algorithm

4.5. Walkability in Helsinki web application

Currently, very few walkability research results are accessible to the public but limited within academia or government institutions. However, promoting physical activity/walking behavior is about not only designing supportive neighborhoods but also raising residents' awareness of the environmental context. A walkability web application is implemented to address both aspects. This tool can help policy makers and urban planners to select the places of interest for future development, as well as help individuals to identify the locations that meet their walking preferences. All the environmental characteristics and evaluated walkability presented in section 4.2. and 4.4. are presented in the web application. The web application is developed with NodeJS[12], Leaflet[13], PostgreSQL[14], PostGIS [15] and PGRouting[16].

With the application, user can 1) view the areal environmental quality by individual characteristics, utilitarian walkability, recreational walkability, 2) define and view areal walkability by assigning customized weights to each characteristic, 3) view most walkable routes (i.e. shortest route, route with good infrastructure, route with good service accessibility) when providing a pair of origin and destination, 4) define and view the route walkability by assigning customized weights to each characteristic.

There are four different views in the application, 1) district view (Figure 27): environment characteristics and walkability in districts; 2) grid view (Figure 28): environment characteristics and walkability in 250*250 grids; 3) neighborhood view (Figure 32): environment characteristics and walkability for neighborhood (two-kilometer radius) based on 250m*250m grid; 4) route view: routing tool based on walkability. Characteristic evaluations including walkability are either a sensible indicator such as density (e.g. population per 100 m^2) or a normalized value within 0-100 range.

4.5.1. District and grid view

District and grid-view aim to provide an overview of the environment quality in the city scale (Figure 27 & Figure 28). In both views, the evaluation for environmental characteristics as well as walkability can be presented as a thematic map. By choosing a characteristic in the list (Figure 27-a), users can activate the thematic map for a chosen characteristic. Each areal unit is associated with a number to indicate the quality of the chosen characteristic. This number is a normalized value of the characteristics evaluation. It is used to define the color of the unit, while also shown when hovered over (Figure 27-b). While meaning of this number is not always clear to the users, the average is provided as a reference (Figure 27-b, c).

Each areal unit also contains detailed information about all the evaluated characteristics and its walkability. The information is shown in a pop-up window when user clicks on an interested district or grid cell (Figure 27-d). There are a few more environment characteristics evaluated in grid view because of higher data availability in the 250*250 grid system.

Utilitarian and recreational walkability are evaluated with Equation 22 and Equation 23. As the weights applied in the model are based on synthesized learnings from empirical studies, the final evaluation represents the value of an average adult rather than specific individuals. However, as the application is also targeting individual users, it is important to allow customization so that the users can get personalized walkability information that is more relevant to themselves (Figure 29 and Figure 30). In essence, the model remains the same (Equation 9) while the weights can be adjusted based on user's preferences.

In the gird-view, the number of grids in Helsinki introduces difficulties in comparing neighborhoods regarding their environment quality. However, being able to compare walkability is considered important for some target users. To allow easy comparison, grids can be filtered based on the administrative districts in the grid-view (Figure 31).

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[12] NodeJS is a JavaScript based server-side framework. It is a popular framework to build web application.

[13] Leaflet is a JavaScript library for building web map application.

[14] PostgreSQL is a database management system.

[15] PostGIS is an extension of PostgreSQL that enables the management of spatial data in PostgreSQL.

[16] PGRouting is an extension of PostgreSQL that provides routing functionalities.

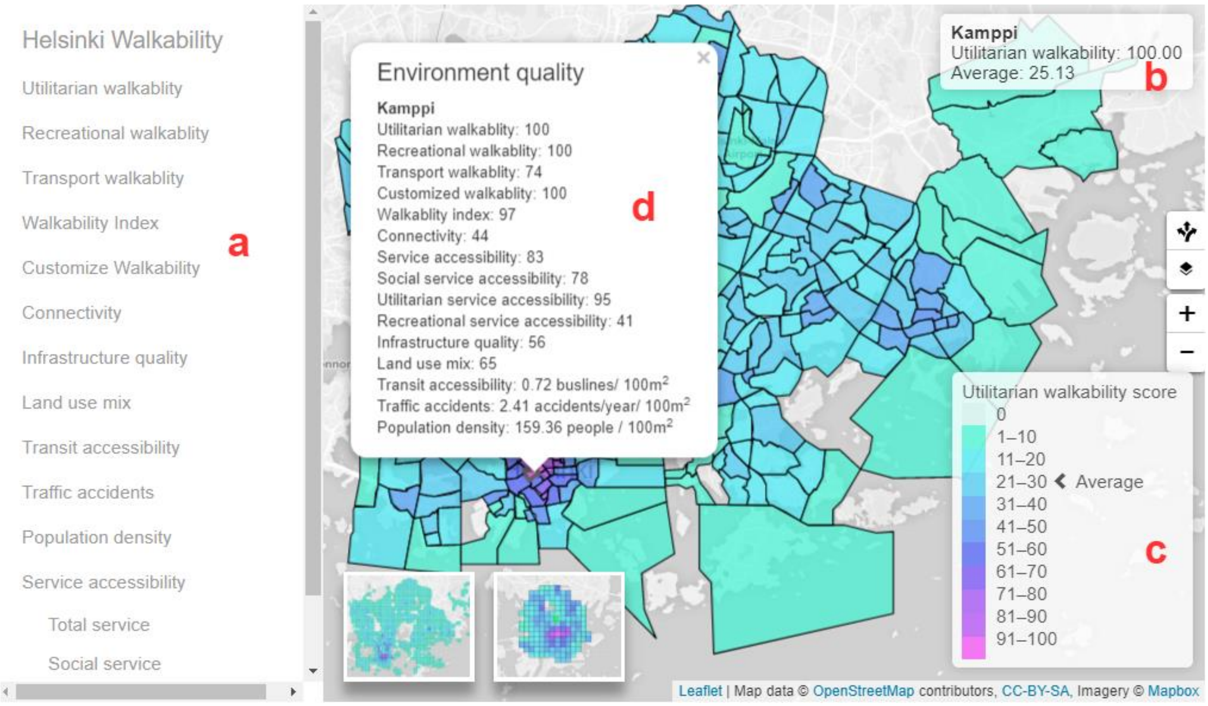

Figure 27. Utilitarian walkability in City of Helsinki (district view)

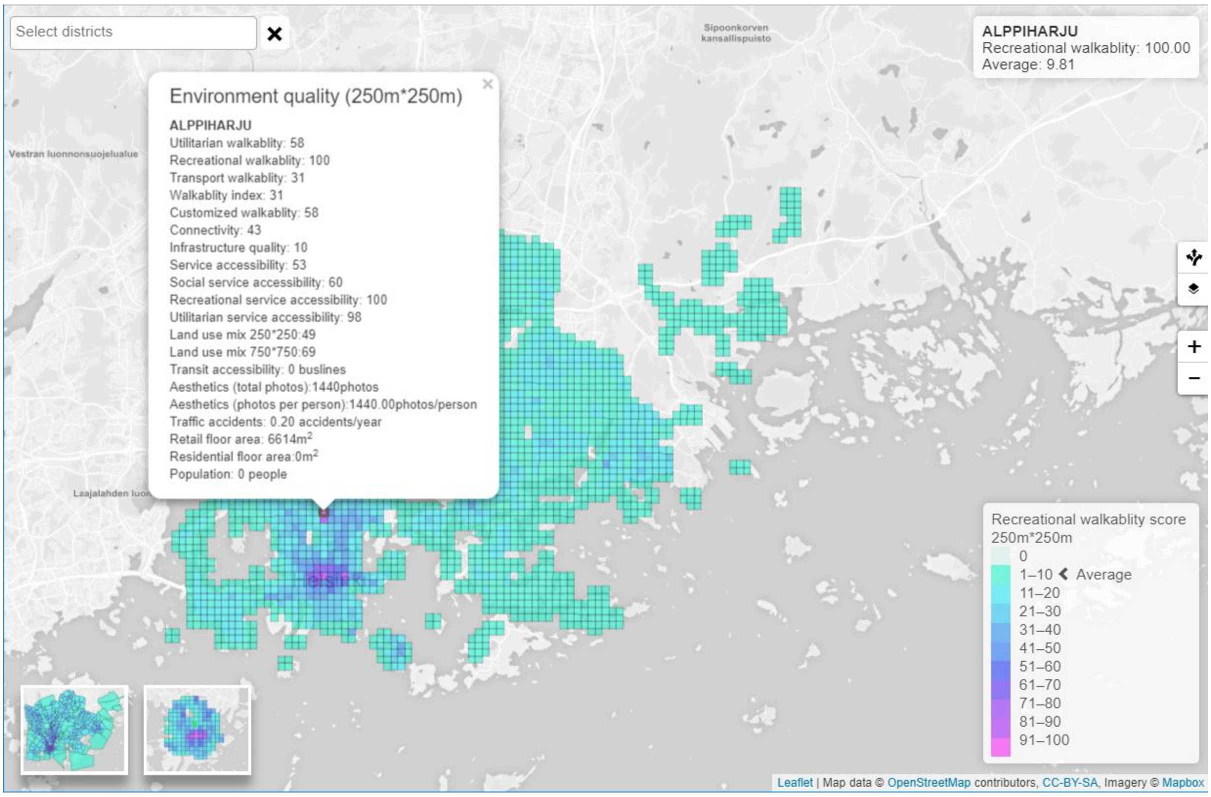

Figure 28. Recreational walkability in City of Helsinki (grid view)

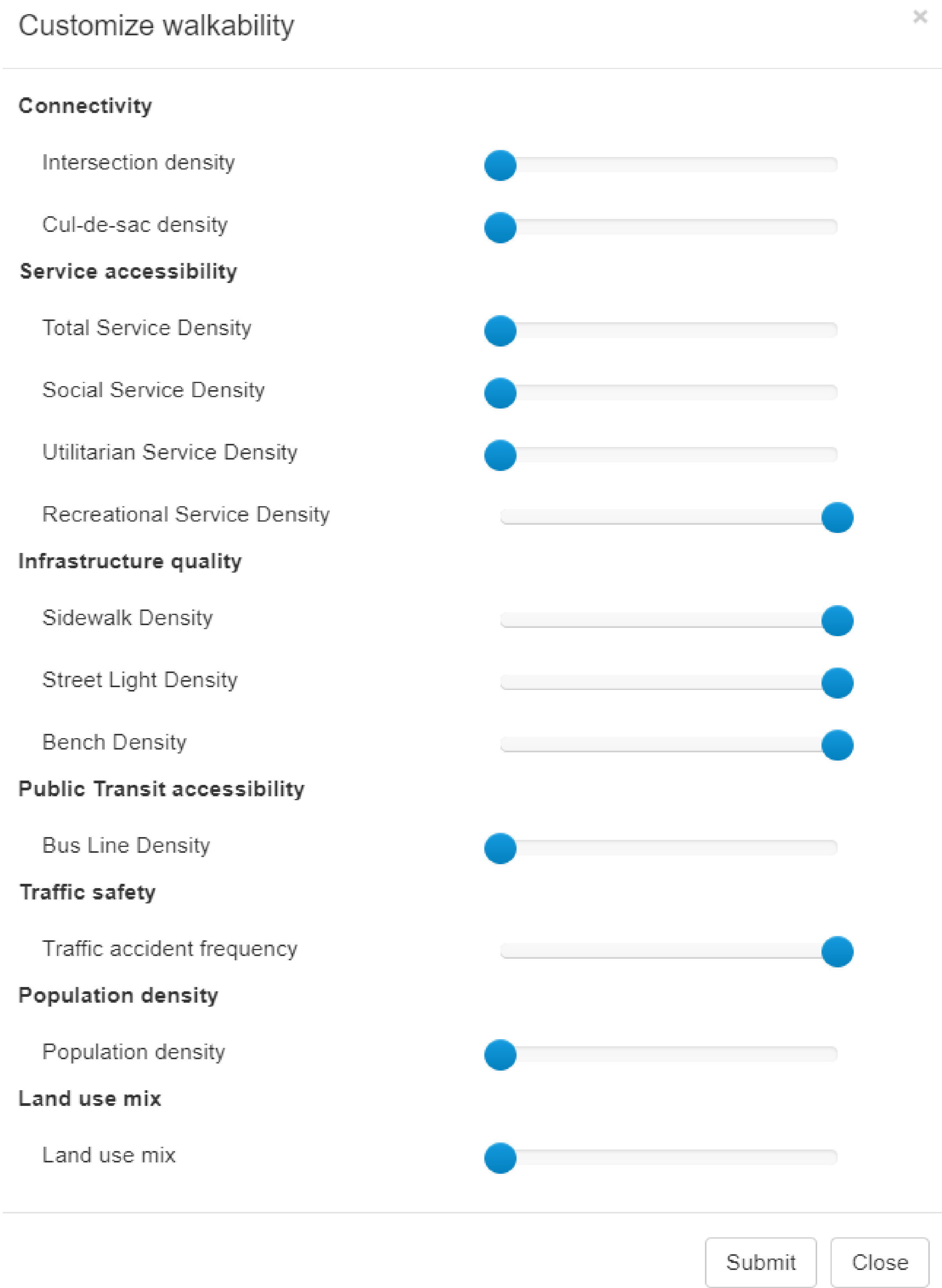

Figure 29. Customization form for walkability in the district view

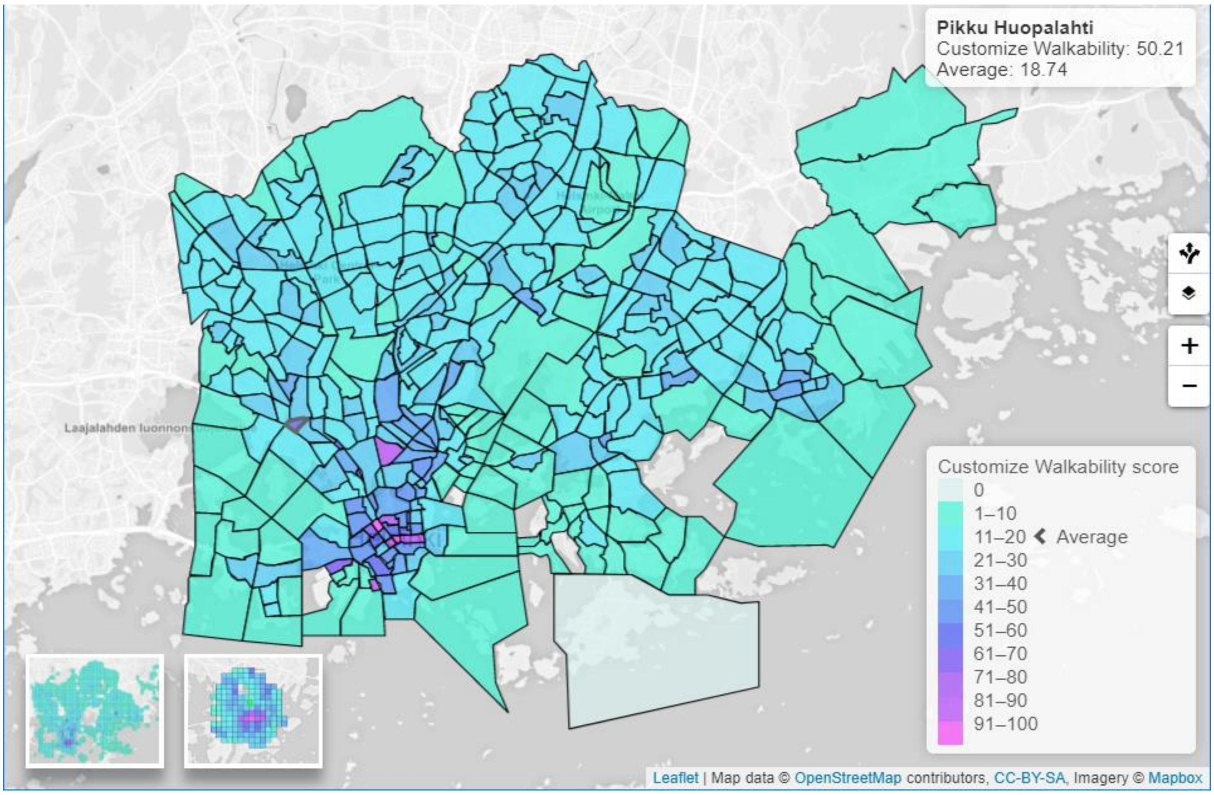

Figure 30. Customized walkability in City of Helsinki (district view)

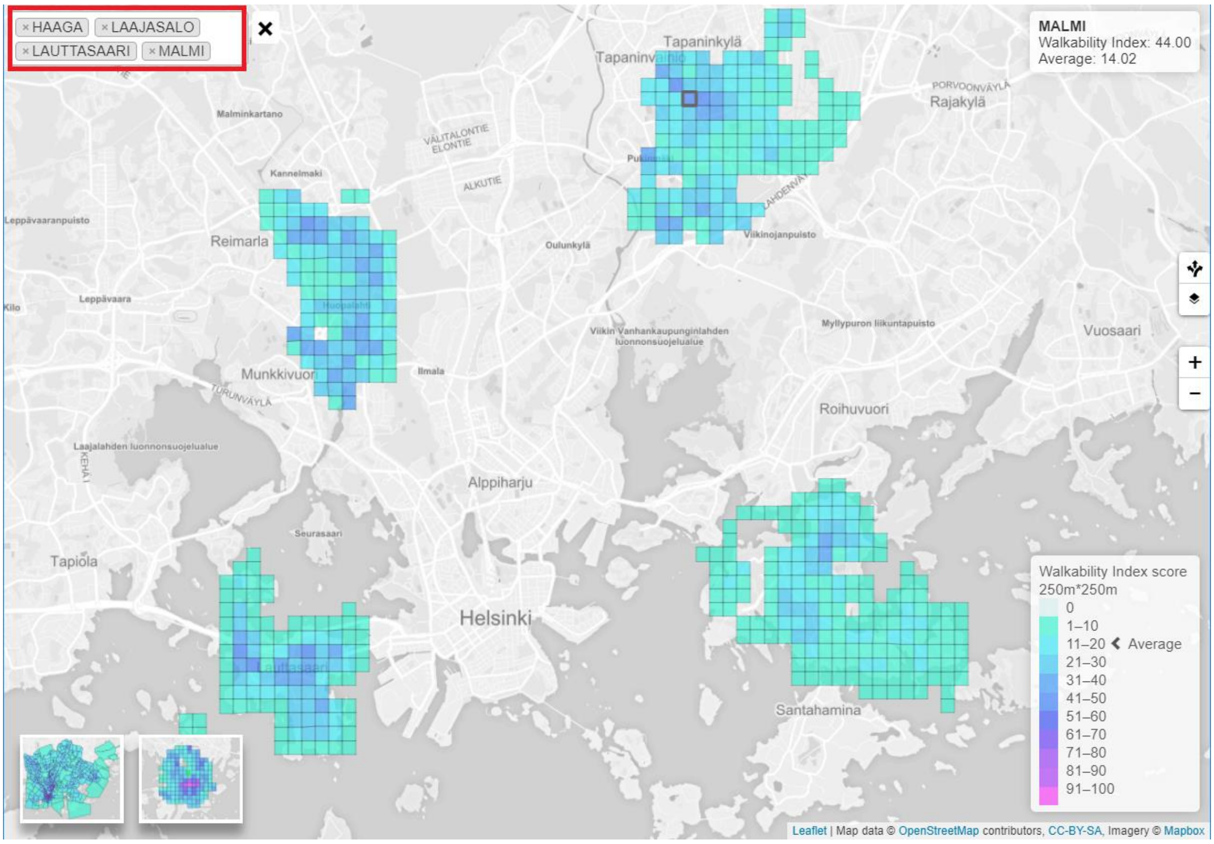

Figure 31. Walkability Index for districts Haaga, Laajasalo, Lauttasaari and Malmi (grid view)

4.5.2. Neighborhood view (2-kilometer buffer)

For individuals, walkability at the city scale is not always relevant. A neighborhood view is implemented where user can get environment quality within 2-kilometer buffer around any location within Helsinki region.

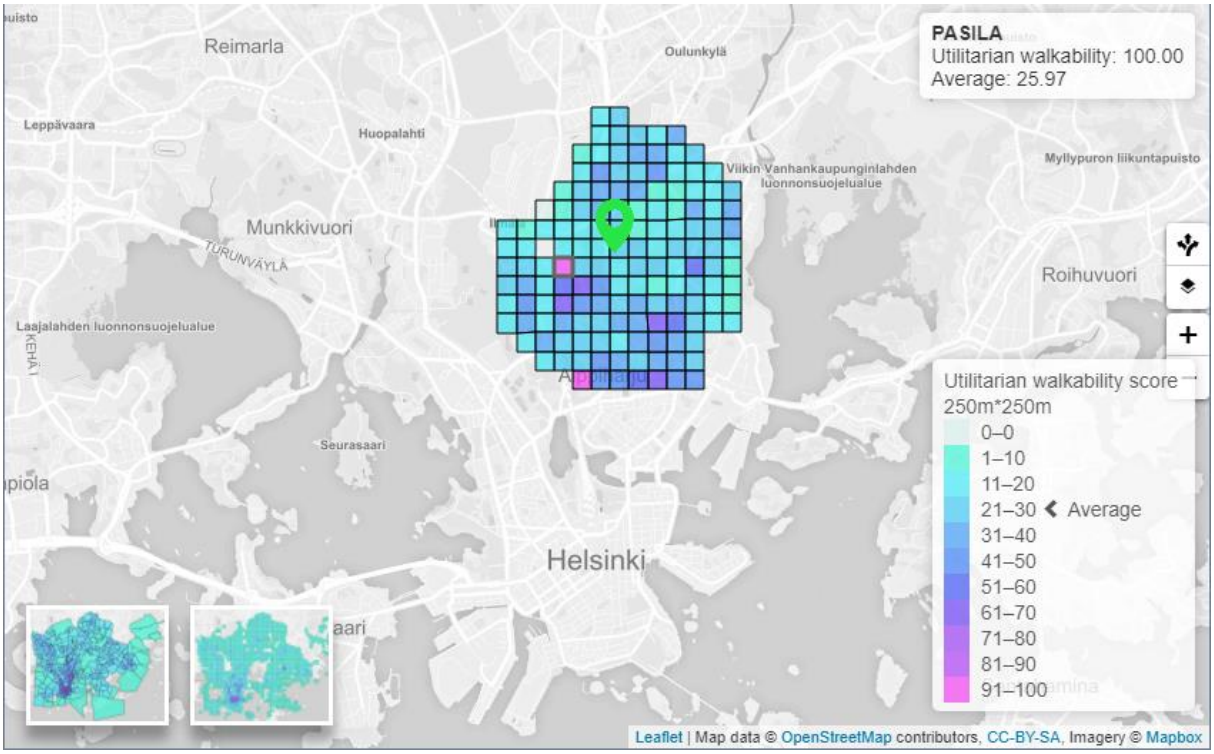

Figure 32. 2-kilometer utilitarian walkability around targeted location (Isonniitynkatu Helsinki)

4.5.3. Route view

Route view provides users with the functionality to get walking paths that are shortest, have good infrastructure, have preferable services, or have other customized features when provided with origin and destination. The customization is done through assigning weights for different route characteristics (Figure 33). Each route choice contains information regarding its length and facilities along the route (Figure 34).

4.5.4. Summary

To date, there are very few walkability applications available in limited locations. The most famous walkability application is Walk Score which is primarily used to find suitable housing locations. This service is only available in the U.S. while walkability is assessed based on public transit accessibility and proximity to people and places. Others are developed based on the concept of crowdsourcing, where users rate each street based on their own walking or cycling experience (e.g. Walkonomics). Compared to these applications, the advantages for "Walkability in Helsinki" are: 1) providing various ranges of walkability from city-scale to neighborhood-scale; 2) presenting evaluations for different environmental characteristics; 3) allowing customization to meet users' preferences; 4) providing various route choices for walking. While it can benefit from rating information of the streets to refine the walkability model, within the scope of this thesis, it is challenging to gather such information.

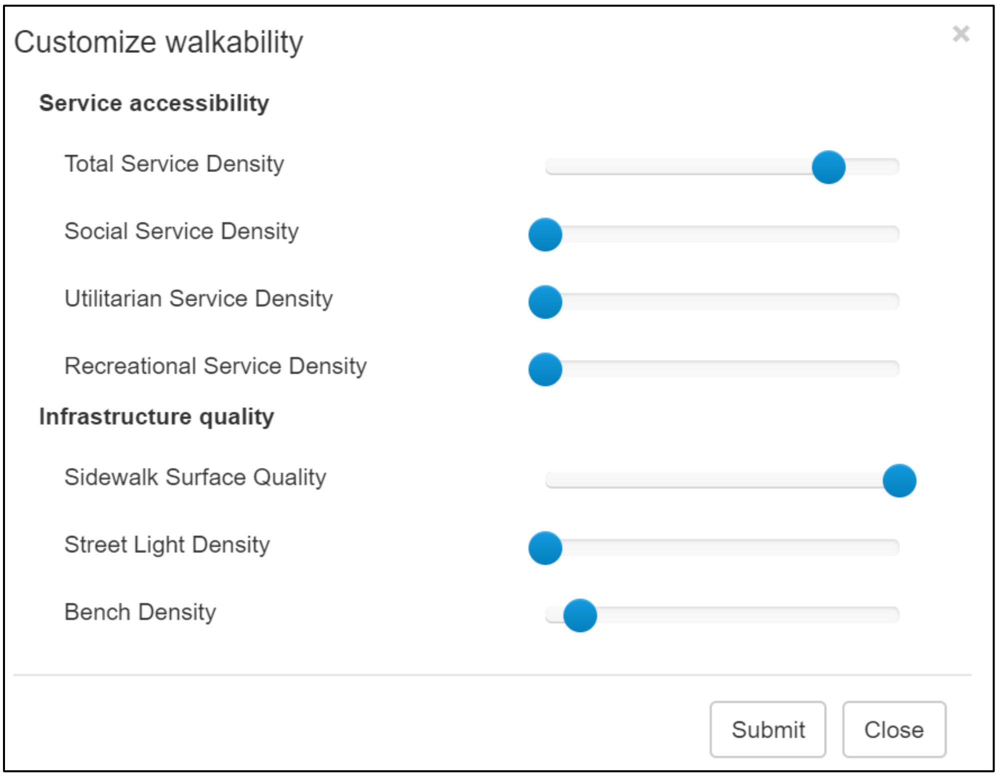

Figure 33. Customization form for walkability in the route view

Figure 34. Four different route options provided based on user defined origin and destination

5. Discussion

We are in an era where population largely lacks adequate exercise resulting in physical inactivity being one of the leading risk factors of death. As society evolves, physical and mental well-being have become a top priority for individuals, communities, and societies. Walking, a form of physical activity that is inexpensive, familiar, easy, and ready to be incorporated into everyday life, has been proven to provide health benefits physically and mentally. Therefore, walking promotion has been a widely adopted strategy to improve public health. Furthermore, faced with severe damages brought by climate change, sustainable development is called for global attention. Answering to this call, many cities aim to reduce carbon emissions and even become carbon neutral within next few decades. Encouraging citizens to take active and public transportation is one action taken to reach that goal.

Since walking, either as a physical activity form or transportation means, brings massive benefits to the society, it has gained attention from different parties including concerning communities, governments as well as academia. While communities and governments design different promotional programs to encourage active participation in walking, researchers aim to identify the efficient ways to facilitate the design process to maximize the promotion of efficiency. It leads to extensive research on walking behavior. Not until recently, the ecological model is proposed to study such behavior thoroughly by considering intrapersonal, interpersonal, social, environmental, and policy factors. Applying the model into practice, however, requires extensive resources, time, and various fields of knowledge. Objectively evaluating the built environment regarding its walkability can set up the groundwork for this process by identifying the areas of interest. Meanwhile, as the environment is an important enabler of walking behaviors, it is also incorporated in the ecological model. Therefore, the evaluation can be directly utilized when applying the model into practice. Moreover, based on existing findings of environmental influence on human behaviors, policy makers, urban planners and transportation professionals can make informative decisions when provided with environmental evaluations. Finally, while the supportive environment is only meaningful when people start to make use of it, it is also important to improve society's awareness of regions that are walkable.

With respect to walkability, an environment should be evaluated based on the characteristics that have impacts on walking behaviors. Through conducting empirical studies across different geographic locations and targeting different user groups, various characteristics are identified to be influential: safety from crime, safety from traffic, walking infrastructure, street connectivity, service/destination accessibility, land use mix, population/residential density and transit accessibility and aesthetics.

Although those characteristics are aligned with the needs required to motivate walking, not all empirical studies found correlations between the characteristics and walking. Despite all the disagreements of the results among various studies, service/destination accessibility, land use mix, and street connectivity are the ones constantly found to be correlated with utilitarian walking, while aesthetics for recreational walking. Nevertheless, other characteristics are crucial as they act as prerequisites for taking any walking trips. There is a pattern among the results from empirical studies, safety, and infrastructure are more likely to be found correlated with walking in less developed cities, or when targeting population groups that have high requirements for safety and infrastructure quality. Therefore, when evaluating walkability, the characteristics, as well as their importance, should be examined on a case to case basis regarding specific geographic locations and targeted population groups. Currently, there is no objective evaluation considering those differences. While there is an aim to create a one-size-fits-all solution, it is not feasible when provided with evidence of inconsistency among empirical studies. A better solution is a model that encapsulates various walking-related environmental factors while providing guidance on adjusting the model based on the context of the study.

Evaluating individual characteristic objectively is no longer a challenge compared to several years ago. Matured GIS technologies and open data movement enable researchers and analysts to measure desired environmental feature easily. With OpenStreetMap data solely, it is feasible to measure walking infrastructure quality, street connectivity, service/destination accessibility, land use mix and residential density. Among the characteristics related to walkability, safety from crime and aesthetics are comparably challenging to quantify. Crime rate can be one indicator for safety. However, it is not necessarily correlated with people's perception of safety. For example, several terrorist attacks happened in Europe recently and it created a fear for some to be present in populous places even though crime rates remain low. Aesthetics is by nature subjective. Up till now, there is no previous study measuring aesthetics objectively. Photo density is used to indicate aesthetics for the average population in the proposed model. However, it has drawbacks. For example, highly populated places will have more photos taken while it does not necessarily mean those places are more aesthetically pleasing. In the final model, population density, destination accessibility, land use mix, infrastructure quality, aesthetics, traffic safety, and transit accessibility are included. Using existing empirical studies as benchmarks, together with the understanding towards Helsinki's urban form, different weights are applied to each characteristic to measure utilitarian and recreational walkability. Clearly, highly walkable areas are clustered in the downtown region (Figure C-11 to Figure C-14), while residential areas are dispersed around the outer ring of Helsinki (Figure 22). Utilizing this type of information, policy makers, and urban designers can make informed decisions for forming a more walkable built environment.

While walkability or environmental evaluation for areas can provide general quality information for concerning parties, route evaluation gives more detailed and actionable knowledge for individuals, especially upon taking walking trips. Currently, no studies exist analyzing walkability specifically for routes while there are only a few services available for rating individual street segments to provide route quality information. However, since there is a movement encouraging individuals to take more walking trips either for transportation or recreation purposes, a corresponding routing service that helps to identify walkable paths should be provided. As there is no benchmark for route evaluation, street type, infrastructure quality and facility availability included in the model based on the insights from neighborhood environmental evaluation. While OpenStreetMap provides complete street networks, along with detailed attributes of each road segment and facilities information, it is a good source to conduct route evaluation. Furthermore, many freely available tools are built to process OpenStreetMap street network data, making OpenStreetMap more favorable than other sources. Because of the complexity of street networks, only routes with defined origins and destinations are proposed to evaluate. Defining cost with distance, street type, infrastructure quality and facility availability, Dijkstra's algorithm can be used to identify the most walkable route for a given origin-destination pair.

The proposed walkability model can help researchers and analysts evaluate area and route based walkability. The example of applying the model to the Helsinki municipality gives guidance about measuring and weighing individual environment characteristic. Additionally, when measuring walkability in other contexts, benchmarking the studies conducted in similar urban form or similar population group and gathering local knowledge are also essential steps.

While the proposed model, as well as its implementation to Helsinki, provides professionals the necessary information and examples to measure walkability in different scenarios, for those (e.g. policy makers, urban planners, residents) who need an evaluated environment for other purposes, it is more sensible to have an easily accessible service for checking information while connecting academic research and real-life practices. “Walkability in Helsinki” is a service that anyone can view the quality of all environmental characteristics as well as utilitarian and recreational walkability for Helsinki on a thematic map. It is also customizable enough that user can define walkability that caters to their preferences or needs. The service also includes a routing tool to provide a few sensible route choices (e.g. shortest, have good infrastructure quality, have high service availability). The routing tool is developed based on Dijkstra’s algorithm.

The best way to validate walkability evaluation is gathering walking data in Helsinki and establish the correlation between them. However, there is no walking data accessible while conducting surveys is out of the scope of this thesis work. Therefore, the validation is only done for area-based utilitarian walkability evaluation for the Helsinki region with the Walkability Index. At the moment, only the Walkability Index is widely adopted for objective walkability measurement. Walkability Index is developed in the context of the U.S. for measuring walkability for transportation purpose targeting average adults. It incorporates land use mix, street network connectivity, retail FAR, and residential density into the calculation. A few studies conducted in Europe found that Walkability Index is positively correlated with transportation walking. Therefore, using Walkability Index to test against the utilitarian walkability is a sensible way to examine the validity of the proposed measurements. The correlation coefficient between Walkability Index and measured utilitarian walkability is 0.8, suggesting the measurement is a good substitution for Walkability Index.

Comparing WI, proposed walkability assessment has a higher adaptability. Existing studies proved that in different contexts, walkability varies. WI has been only applied in a U.S. context, and a few European cities targeting average adults. Therefore, its validity is still questionable when migrating this entire model to a city that is less developed or targeting a different population group. Furthermore, retail FAR is considerably harder to measure because of a lack of data source (Van Dyck et al. 2010; Sundquist et al. 2011; Reyer et al. 2014). Measuring retail Far requires the total retail building square footage. In modern cities, buildings usually have multiple purposes. Accessing the total square meters of the commercial parts of buildings is challenging.

5.1. Limitations

This thesis work still has several limitations regarding the evaluation accuracy, model design, validation, and application usability.

5.1.1. The evaluation of environment characteristics

The evaluation of environment characteristics is the basis of this thesis work. With high data availability, well-established evaluation methods, and matured technology, qualifying environmental characteristics is no longer difficult. However, there are still some aspects influencing the accuracy of the evaluation.

Source data

Nowadays, data availability has reached its highest point. Massive datasets are published by the public and private sectors, as well as various volunteer groups. When producing data, uncertainties cannot be eliminated. Inheritably, the published data will have a certain level of inaccuracy. Not all the entities have quality information published along with the data, leading the user of this data unaware of the potential quality issues. In this thesis work, when evaluating environment characteristics for Helsinki, the data published by government entities, Flickr and OpenStreetMap.

Government entities produce different types of data regarding public facilities, demographics and other various datasets related to government responsibilities. However, it is not guaranteed that authorities produce high-quality data when quality information is not accessible. The data used to assess environmental characteristics in this thesis, the population data, for example, does not include children who are under 5 years old. Furthermore, government entities usually publish data periodically instead of keeping it up to date. The latest available population data for Helsinki is from 2015, while traffic accident data is from 2000-2015, and paved pedestrian connections from 2014.

OpenStreetMap is a crowdsourcing platform that allows individuals to upload and edit features. Currently, it has a large community that contributes to data across the world. However, considering the way OSM operates, it ought to have human errors. One of these more apparent errors lies within facilities no longer operating while not shown as such in OSM data. In OSM, street networks have high accuracy because 1) GPS trajectories are used to update street networks, 2) in the majority of cases only new streets are built while the existing ones are rarely updated. However, amenities are not as updated and contain some minor errors.

Flickr is a free service for image and video hosting. As standardized metadata (e.g. timestamp, geotag) is stored in image files, the queried data does have good quality. However, the completeness of the data is still questionable, while not all photos are geotagged, photos from Flickr are only one fraction of produced photos. In this thesis, the images uploaded to Flickr are assumed to be a representative sample of quality photos.

Pre-processing error

While high data availability enables interested parties to access desired information, a considerable amount is not in ready-to-use forms. Pre-processing is usually an inevitable step for any data analysis. During this process, uncertainties may get introduced to the result.

The population data of Helsinki retrieved is based on a 250m*250m grid system. For calculating population density, the data is used to estimate the population in each district. While not all of the grids are completely within the districts, those on the boundaries are divided based on the area ratio. The population within districts is estimated with Equation 28. Since the population is not evenly distributed across the grid, the calculation is an approximation.

$$p = \sum \left(\frac{a_i}{250 \times 250} \times p_i\right) \tag{28}$$

where p is the population district, i is one grid within the district, a_i is the area of the grid i within the district, p_i is the population within the gird i

Equation 28. District population estimation

In OSM, there are 49 different land use types within the Helsinki region. For calculating land use mix, it needs recategorization. The basis for recategorizing land use types rely on their description of each type and intuitions. Amenities suffers from the same problem. There is no basis on categorizing amenities into different groups except for common sense and experience, which is not necessarily capturing average population behaviors. In the recategorizing process, uncertainties are naturally introduced.

Inaccurate calculation

Among the environmental characteristics evaluated, some of the evaluation methods are well established and proven to capture the essence of these characteristics (e.g. entropy index for land use mix, weighted density for destination accessibility). However, for aesthetics and transit accessibility, there are no prior examples of objective evaluation.

Aesthetics is evaluated by photo density. This method has two potential issues: 1) the photos do not represent aesthetic values of the public; 2) while a highly populated area has more photos taken, it does not equal to a higher appreciation of its aesthetic value.

Bus line density is used to indicate transit accessibility. However, the frequency of the bus lines is not taken into consideration. There is an established method to evaluate transit accessibility, which is measuring a thirty-minute travel area via public transit. Although it is a better indicator for transit accessibility, due to calculation difficulties as well as the unknown importance of transit accessibility in encouraging walking behavior, this evaluation method was dismissed

5.1.2. The walkability calculation

Based on extensive literature research, it is evident that for different contexts, walking behavior is influenced by different environmental characteristics. Therefore, when calculating walkability, the importance of different characteristics should be carefully examined. There has been no previous work done to facilitate the examination process. The proposed method in this thesis are benchmarking from studies conducted in similar contexts and adopting expert knowledge. However, this method may lead to ambiguity and confusion when implementing the proposed walkability evaluation models. Providing a clear instruction on weighing characteristics in different contexts is necessary for standardizing the implementation of the proposed models. This thesis work failed to achieve it. At the current stage of research, only a general guideline derived from literature review are provided to facilitate the weighing process: targeted population group, walking purpose, the socioeconomic development of the city, the compactness of the urban area, society values on physical activities and public transportation are important aspects to examine prior to walkability evaluation (e.g. in developed cities, destination accessibility, street connectivity, land use mix, and aesthetics are more influential for walking; for less developed cities, infrastructure quality, safety are also important factors).

5.1.3. Validation

This thesis work lacks validation work for the walkability evaluation model. Although the model encapsulates all the environmental characteristics that are influential to walking behavior, the validation procedure is required to ensure the model truly captures the walkability of a built environment. As there is no previous walkability evaluation that achieved this goal, while the proposed model has not been adopted to make the evaluation in other contexts, the validation at this stage is not achievable.

The area based walkability evaluation in Helsinki is validated through Walkability Index, as WI has been applied to various contexts and proved to be credible. However, the more suitable way of validation is gathering walking behavior data and test against the evaluation. This practice has been adopted to a majority of empirical studies. In those studies, besides evaluating environmental quality, they also conducted extensive surveys to log the amount of physical activity. Through calculating the correlations, researchers can identify the important aspects of the environment that influences human behavior, and validate walkability evaluation. Limited by the resources and time frame of this thesis work, the validation by gathering walking behavior data was not carried out.

5.1.4. Usability of the environment/walkability evaluation

There were several goals for developing a walkability evaluation model. The first goal was to set up the groundwork for the future ecological research to focus on specific regions that need more attention for walking promotion. The ecological model incorporates intrapersonal, interpersonal, social, environmental and policy factors. Applying ecological model into real practice surely requires extensive resources, time, and various fields of knowledge. Narrowing down the scale of research by targeting specific geographic locations and population groups of interest can improve the cost efficiency of the work. The environmental evaluation model can facilitate the process of identifying these locations and population groups. However, the environmental quality is not the only determinant for this process. For example, policy and demographics can also have a significant impact. The secondary goal was providing an objective evaluation on the environment to be incorporated into the future ecological research of walking behavior. The benefit of the ecological model is that it considers the entire ecosystem of walking behavior. Environmental factors are only part of the construct. Furthermore, there is also an emphasis on interactions among factors across different layers (e.g. psychosocial and environmental factors). The way to incorporate environmental evaluations into ecological model requires the understanding of the entire ecosystem, which is unclear in the scope of this work.

The third and fourth goals were about providing environmental quality information to interested parties (e.g. policy maker, urban planners, residents). To achieve these goals, a web application was developed to provide an interactive service for users to view the environment quality information, customize walkability evaluation, as well as get route choices that excel in certain aspects. However, the usability of the application is still questionable. No feedback is gathered from potential user groups. While the functionalities mentioned in the previous section are implemented, the usability is unknown.

5.2. Conclusion and future work

With literature review, it is clear that to either improve public health or build sustainable urban environments, adjusting current urban settings to support active lifestyles is a necessary step. Understanding walking behaviors and assessing built environmental quality regarding its ability to encourage walking can facilitate relevant parties to achieve this goal. With existing knowledge about the environmental influences on walking behavior, well-developed technology, and available public data, it is feasible for researchers and analysts to evaluate various environment characteristics and walkability objectively. Walking infrastructure, street connectivity, land use mix, population/residential density, destination/service accessibility, safety, and aesthetics are a few factors that have been conceptualized from walking needs and considered to be related to walking behaviors. However, due to the differences in study context, empirical studies which aimed to validate these relationships have had inconsistent results. To date, there is no clear explanation for the inconsistency.

The challenge is that human behavior is determined by a complex decision-making process that is influenced by various factors, while the physical environment is only part of them. The ecological model can be used to analyze walking behavior because of its comprehensive coverage on behavioral determinants. The existing ecological studies on walking behavior only focus on part of the ecological model (e.g. specific layer of influence, interactions across two different layers). To reach the goal of understanding walking behavior, researchers still need to design a clear study procedure to guide the future ecological studies to analyze walking behavior thoroughly. Objectively assessing environmental quality can be the first step towards a comprehensive ecological study. It is the least costly analysis and most beneficial for narrowing the geographic scale of the study or identifying the areas of interest.

Regarding environmental influence on walking behavior, there is some consensuses regardless of the inconsistent relationships observed: 1) for different walking purposes, different population groups the influential factors are different; 2) when the quality of one factor is homogeneous across the study region, this factor has little influence on walking behavior. Based on these learnings, as well as the synthesized insights from previous empirical work, this thesis work provides a standardized objective evaluation procedure which incorporates all the environmental factors that are influential to walking, while emphasizing the importance in adjusting the weights based on the study contexts. The weights can be adjusted by using expert knowledge or benchmarking previous empirical studies which are conducted in a similar context.

The Finnish government is a pioneer in the open data movement by providing online data downloading services. Together with freely available data from the private sector and volunteering communities, it is feasible to evaluate the environmental quality of the Helsinki municipality with GIS technology. While the quality information is valuable for various parties (e.g. citizens, urban planners, transportation experts), the evaluation is presented in an online web map service to enable easy access. Furthermore, this service narrows the gap between research and real practices.

The future work can be addressed in several aspects:

Improve the usability of the web map application

The application was implemented for providing easily accessible environment quality information to concerning parties. However, no user test has been conducted. It is still unknown if the functionalities provided by the application are necessary and if the information presented is understandable and beneficial for the user. By conducting user test, the application can be improved through adopting user feedback.

Furthermore, walkability evaluation is made for average adults in normal weather conditions. Although the service allows customization, it is plausible to add quality information for other contexts. For example, the routing service can provide the safest route choice. It is a known need for young students to have a safe walking environment. Established communities are working to provide safe walking routes for students to commute between home and school. For young students, the safest routes are the most walkable ones. Therefore, the current service can add the safest route choice among others to cater to this need. Similarly, the service can be expanded to target other population groups, or other weather conditions (e.g. snow).

More accurately evaluate environmental characteristics and walkability of the Helsinki Municipality

The current evaluations of environmental characteristics and walkability of Helsinki are based on the learnings from previous studies. For environment characteristics, the majority have validated evaluation methods such as the entropy index for land use mix. However, aesthetics and transit accessibility are evaluated by newly proposed calculations. Therefore, those evaluation methods should be validated and improved. Aesthetics evaluation can be validated by surveying perceived aesthetics, while transit accessibility needs to be tested against a travel matrix. Similarly, both utilitarian and recreational walkability evaluations should be validated in the context of Helsinki. This requires walking behavior data from a sample population. After examining the relationship between walking and a built environment in Helsinki, the weights can be adjusted to build a more suitable evaluation model for walkability in Helsinki.

Provide guidelines for utilizing walkability model

Due to the inconsistent findings of the relationship between environment characteristics and walking behavior, providing weights for all factors considered in the model was not feasible. However, based on the results from the previous empirical studies, there are some patterns that show, in certain context, that some characteristics are more influential than others. Therefore, it is possible to provide guidelines to pre-examine the study region, targeting population group and other relevant aspects. This is aiming to facilitate analysts to weigh each environmental characteristic in the walkability evaluation model more accurately.

Conduct ecological study in Helsinki

An ecologic model is considered to be the most comprehensive and suitable tool to study human behavior. Aligning with the goal of encouraging walking behaviors and decreasing the sedentary time for citizens, it is beneficial to learn the determinants of walking behavior in the context of Helsinki. This study can identify intrapersonal, interpersonal, environmental and policy determinants as well as influential interactions between different factors of walking. In the end, it is possible to design a comprehensive intervention program that encourages walking behavior from multiple layers. This type of intervention has been proven to be most effective and have a long-term effect.

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Appendix A: Correlations between environment characteristics and walking

Table A-1. Correlations between environment characteristics and walking

Instrument	Author	Factors considered	Transportation walking	Recreational walking	Total walking	Region	Target group
P. * (PENS)	Adams et al. (2013)	Safety from traffic Safety from crime Street connectivity Service accessibility Infrastructure Environment quality	Null***** Null Null +***** + +	Null Null Null Null + Null	NA*****	UK	Adults
P. (NEWS-Modified for Chinese Seniors)	Cerin et al. (2014)	Residential density Land-use mix Service accessibility Street connectivity Infrastructure Presence of people Crowdedness Safety from crime Safety from traffic Sitting facilities Perceived barriers	+ + + Null + Null + Null Null + Null	NA	NA	Hong Kong	Older Adults
P. (NEWS & NEWS-A)	Sugiyama et al. (2014)	Residential Density Service accessibility Street connectivity Infrastructure Personal safety Aesthetics Safety from traffic No major barriers Proximity to parks	NA	Curvilinear (+ --> -)***** + + Null + + Null Null +	NA	Australia, Belgium, Brazil, Colombia, Czech, Denmark, Hong Kong, Mexico, New Zealand, Spain, UK, U.S.	Adults

Table A-1. Correlations between environment characteristics and walking (continued)

Instrument	Author	Factors considered	Transportation walking	Recreational walking	Total walking	Region	Target group
P. (NEWS)	Saelens et al. (2012)	Infrastructure Aesthetics Safety from traffic Safety from crime Recreation facilities accessibility	Null Null Null Null Null	Null + Null Null3 Null	NA	U.S. King county, Baltimore-Washington DC	Adults
P. (IPAQ environmental module)	Liao et al. (2015)	Residential density Service accessibility Transit accessibility Walking infrastructure Recreational facilities accessibility Safety from crime Safety from traffic Active neighbourhood Aesthetics Connectivity	Null + + + Null Null + Null Null +	NA	NA	Taiwan	Adults
P. (Modified NEWS)	Corseuil Giehl et al. (2017)	Walking infrastructure Personal safety Recreational facilities Traffic related safety	+ + + Null	+ + Null Null	NA	Brazil	Older Adults
P. (IPAQ environmental module)	Lee and Shepley (2012)	Service accessibility Aesthetics Safety from traffic Safety from crime	NA	Null + Null +	NA	Korea	

Table A-1. Correlations between environment characteristics and walking (continued)

Instrument	Author	Factors considered	Transportation walking	Recreational walking	Total walking	Region	Target group
O.*	Saelens et al. (2012)	Residential density Land use mix Street connectivity Retail FAR Park accessibility Recreational facilities accessibility (e.g. gym)	Null Null + + Null +	Null Null Null + Null Null	NA	U.S. King county, Baltimore-Washington DC	Adults
O.	Reyer et al. (2014)	Walkability Index Walking Score (service accessibility)	NA	+ +	NA	Germany Stuttgart	Adults
O.	Sundquist et al. (2011)	Walkability Index	+	+	+	Sweden Stockholm	Adults
O	Van Dyck et al. (2010)	Walkability Index	+	+	+	Belgium	Adults
O.	Christiansen et al. (2016)	Net residential density Land-use mix Connectivity Park density	+ + + +	NA	NA	Australia, Belgium, Brazil, Colombia, Czech, Denmark, Mexico, New Zealand, UK, U.S.	Adults
O.	Frank et al. (2005)	Street connectivity Land use mix Residential density Walkability Index	NA	NA	+ + + +	Metropolitan Atlanta (U.S.)	Adults

Table A-1. Correlations between environment characteristics and walking (continued)

Instrument	Author	Factors considered	Transportation walking	Recreational walking	Total walking	Region	Target group
O.	Hirsch et al. (2014)	Population density Retail area Residential area Service accessibility Transit accessibility Street connectivity	Null + -* + + +	Null + Null + Null Null	NA	U.S.	Adults
O.	Turrell et al. (2013)	Street connectivity Land use mix Residential density	+ + +	NA	NA	Australia, Brisbane	Mid-aged adults (40-65)

P.* **perceived environmental evaluation**
O.* **objective environmental evaluation**
NA* **not applicable**
Null* **null correlation between walking and environment characteristic**
+* **positive correlation between walking and environment characteristic**
-* **negative correlation between walking and environment characteristic**
Curvilinear (+ --> -)* **curvilinear relationship between walking and environment characteristic, from positive to negative**

Appendix B: OpenStreetMap amenities categorization

Table B-1. Retail - Amenities categorization

Very frequently	Somewhat frequently	Often	Occasionally	Somewhat infrequently	Very infrequently
supermarket	kiosk	bakery	books	baby	blinds
convenience		meat	clothes	bag	bathroom accessories
		deli	cosmetics	bicycle	boats
		fast food	department store	computer	cloth rental
		ice cream	boutique	craft	construction supply
		food court	design	DVD	disabled
		candy	Flea market	electronics	dressmaker
		alcohol	florist	games	fabric
			gift	hifi	fishing
			laundry	jewellery	frame
			mall	kitchen	glass
			pharmacy	lighting	gun
			second hand	mobile phone	hat
			shoes	office supply	carpet
			variety store	optician	furniture
				organic	erotic
				outdoor	equestrian
				photo	karting
				pet	lab supply
				print	locksmith
				souvenir	music
				sports	plumber
				tobacco	rug
				stationery	sewing
				toys	trophy
				video	tubes
				hardware	TV repair
					yarn
					interior decoration
					funeral directors

Table B-2. Tourism/culture - Amenities categorization

Often	Occasionally	Somewhat infrequently
attraction	monument	archaeological site
arts centre	plaza	memorial
artwork	fountain	grave
gallery		ruins
museum		tomb
		cannon

Table B-3. Services - Amenities categorization

Somewhat frequently	Often	Occasionally	Somewhat infrequently	Very infrequently
restaurant	hairdresser	beauty	bicycle rental	courthouse
cafe	bar	library	clinic	driving school
	nightclub	massage	dentist	estate agent
	pub		doctors	embassy
	club	dance	convention centre	laboratory
		community centre		Lawyer
		post box	police	Tattoo
		mobile library	co-working space	pawn
		place of worship	hospital	self-storage
		post office	sauna	training
		preschool	Social facility	veterinary
		school	Travel agency	scouting
		ATM	casino	carpet washing
		bank		hackerspace
				music rehearsal place
				strip club

Table B-4. Entertainment - Amenities categorization

Often	Occasionally	Somewhat infrequently
cinema	miniature golf	aquarium
theatre		theme park
		zoo

Table B-5. Nature - Amenities categorization

Often	Occasionally	Somewhat infrequently	Very infrequently
park	bay	cape	bunker
	beach	dog park	campsite
	bird hide	dog spa	giants kettle
	picnic site	dog swim	
	viewpoint	ferry terminal	
	water	firepit	
		fort	
		garden centre	
		marina	
		peak	

Table B-6. Sport - Amenities categorization

Somewhat frequently	Often	Occasionally	Somewhat infrequently	Very infrequently
gym	sports centre	fitness station	hunting stand	boating
		ice rink	volleyball	disc golf course
		swimming	swing	gymnasium
		pitch		golf course
		playground		

Appendix C: The quality of environmental characteristics in Helsinki

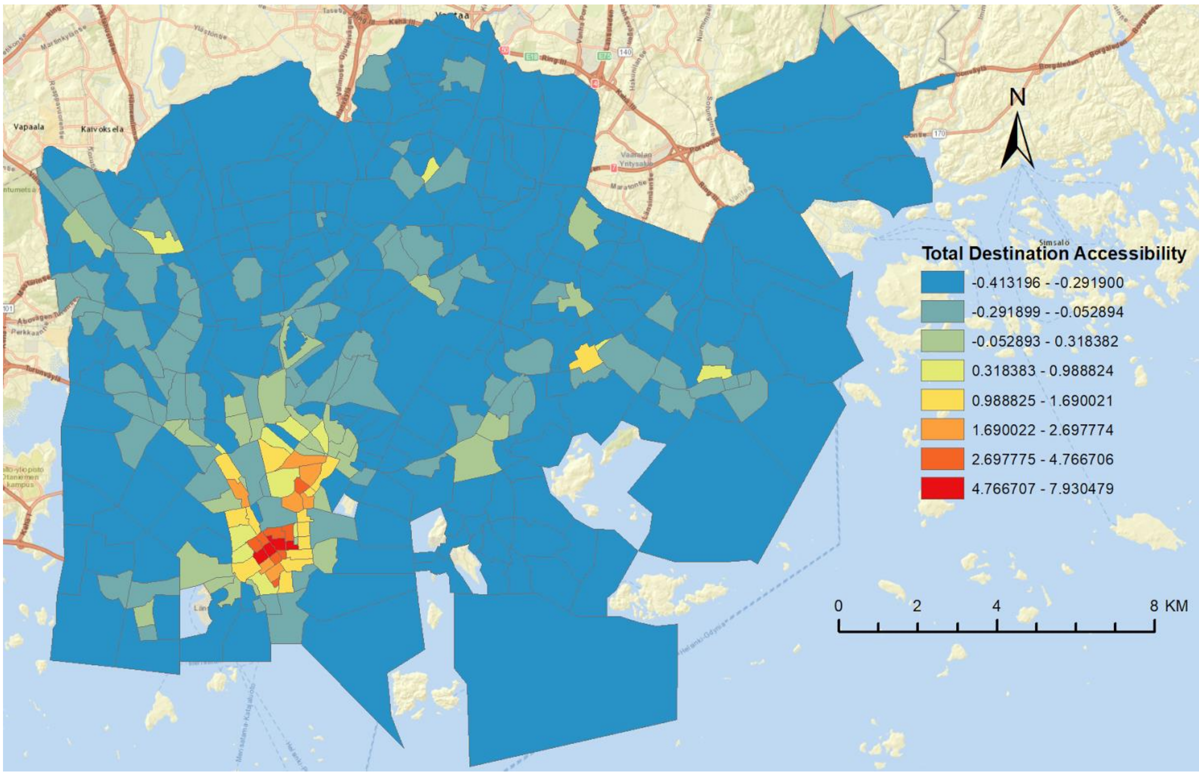

Figure C-1. Normalized (z-score) total destination accessibility based on administrative units

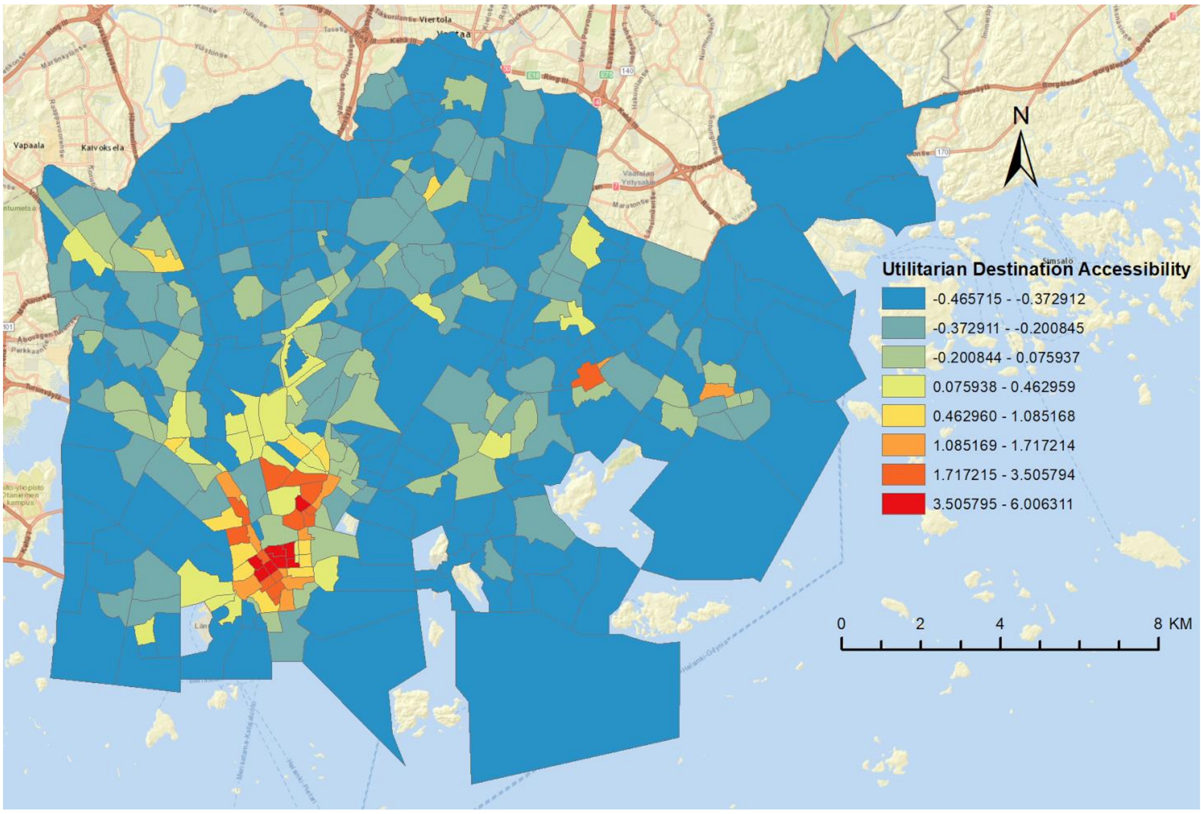

Figure C-2. Normalized (z-score) utilitarian destination accessibility based on administrative units

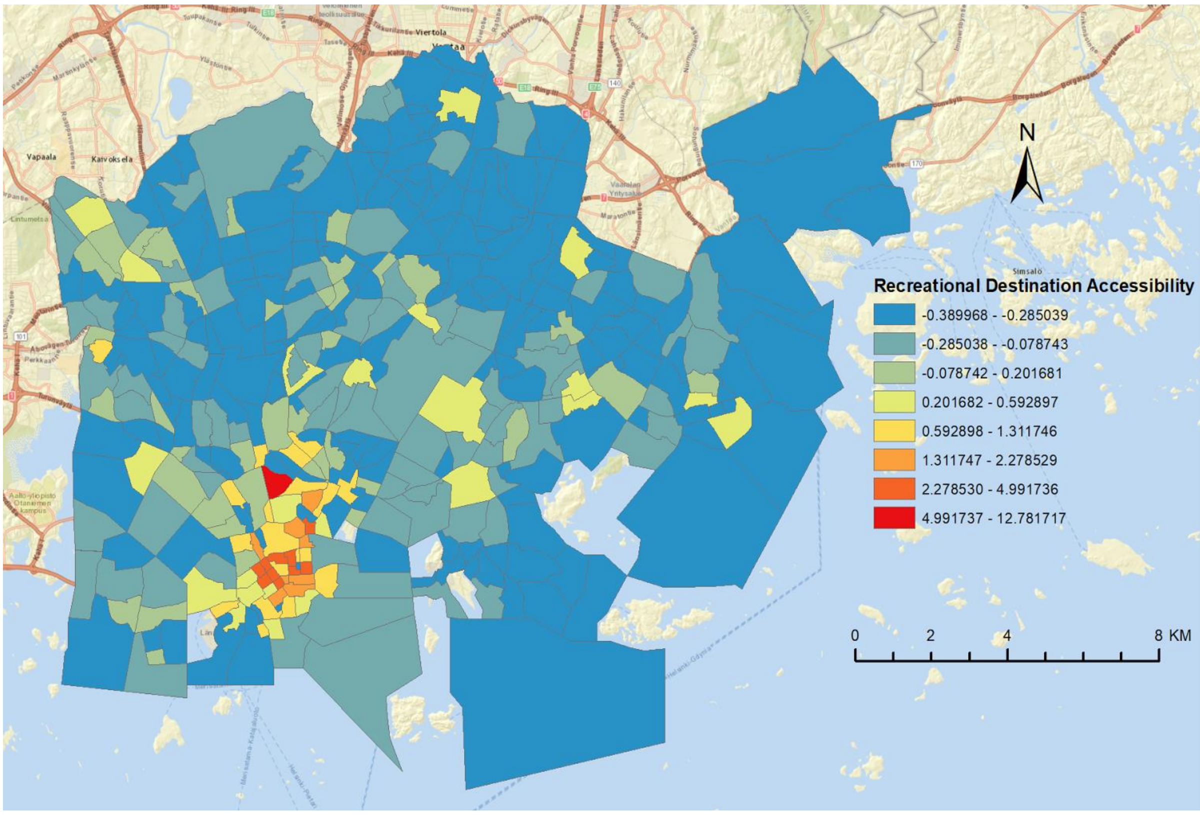

Figure C-3. Normalized (z-score) recreational destination accessibility based on administrative units

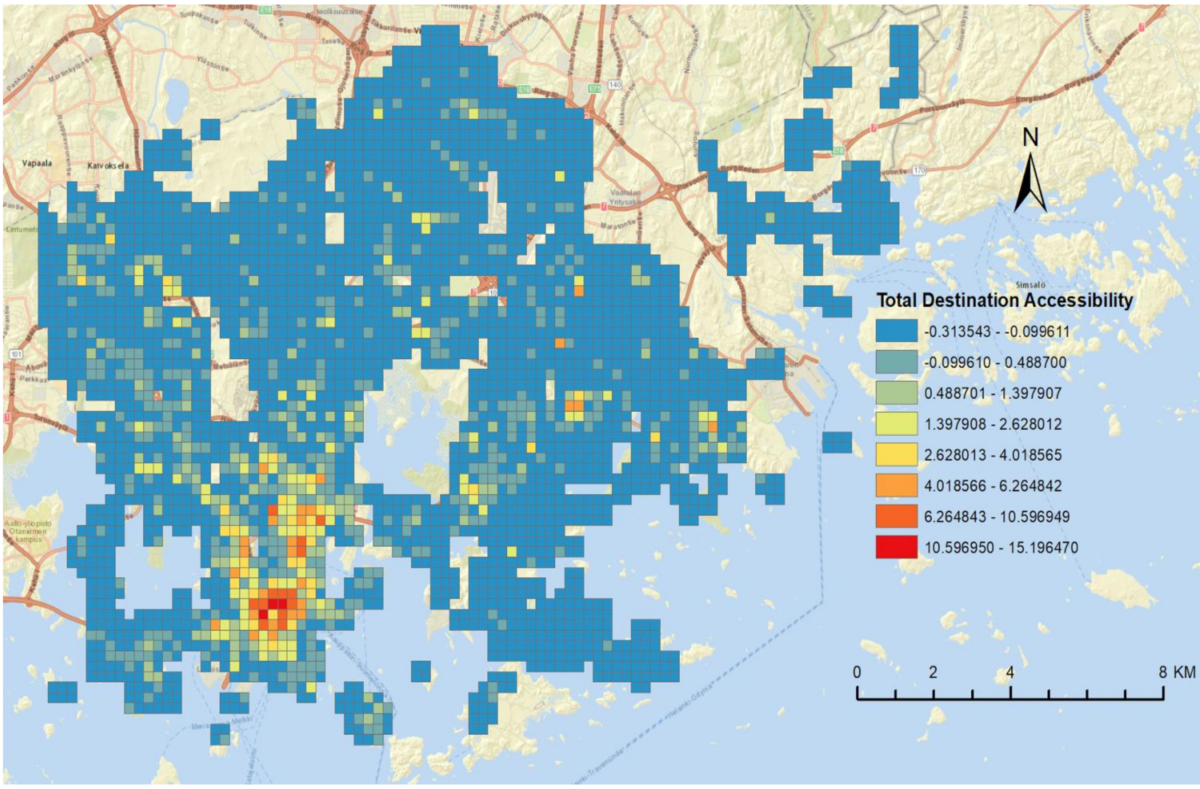

Figure C-4. Normalized (z-score) total destination accessibility based on 250m*250m grids

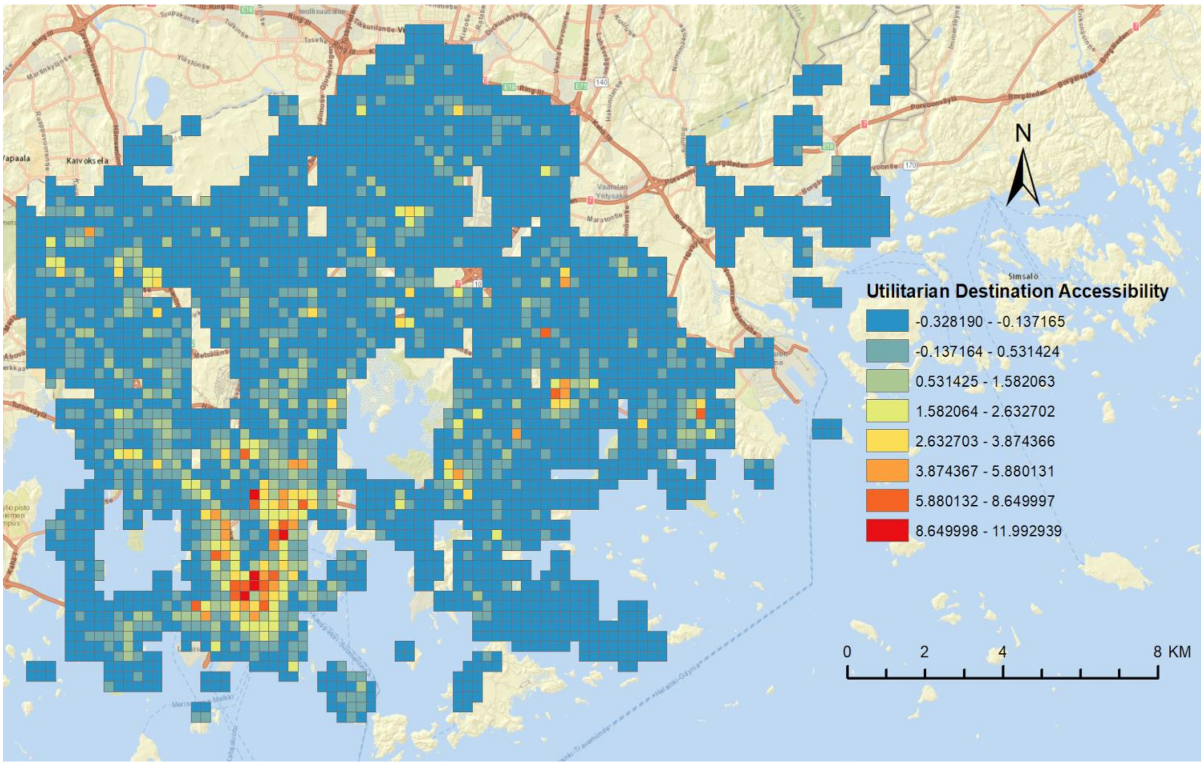

Figure C-5. Normalized (z-score) utilitarian destination accessibility based on 250m*250m grids

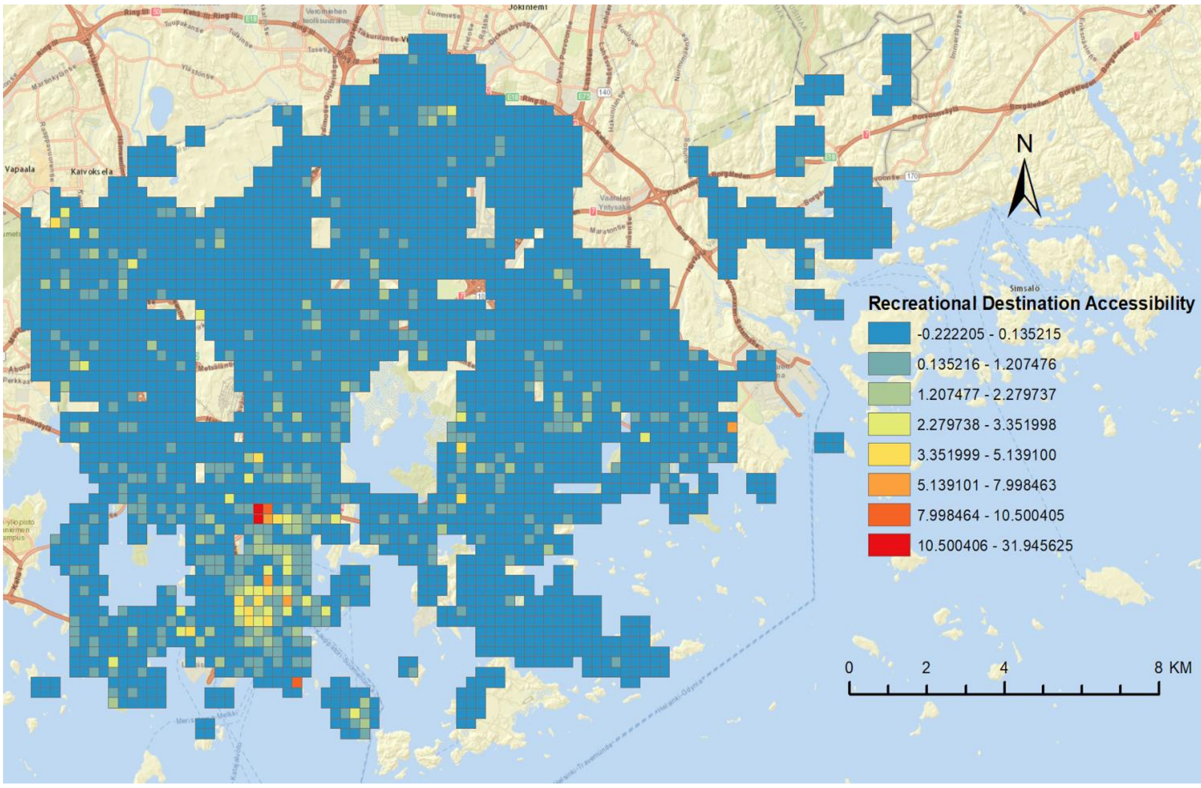

Figure C-6. Normalized (z-score) recreational destination accessibility based on 250m*250m grids

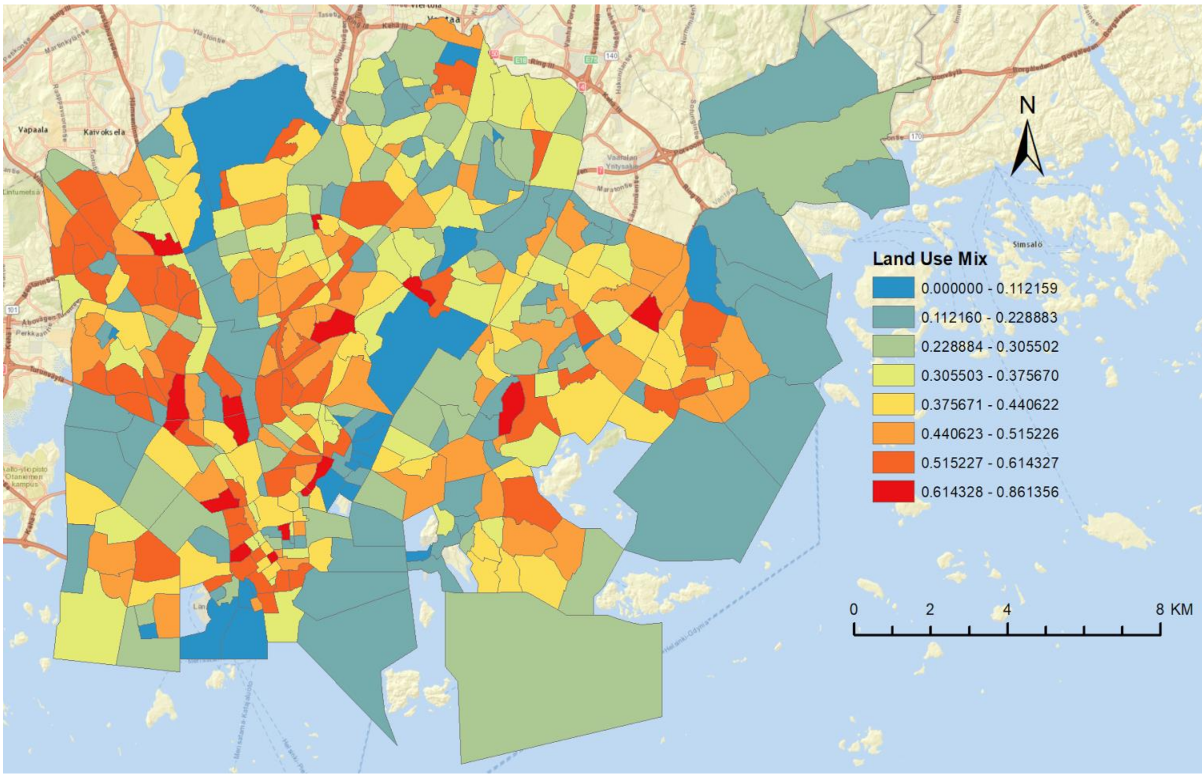

Figure C-7. Entropy index for land use mix based on administrative units

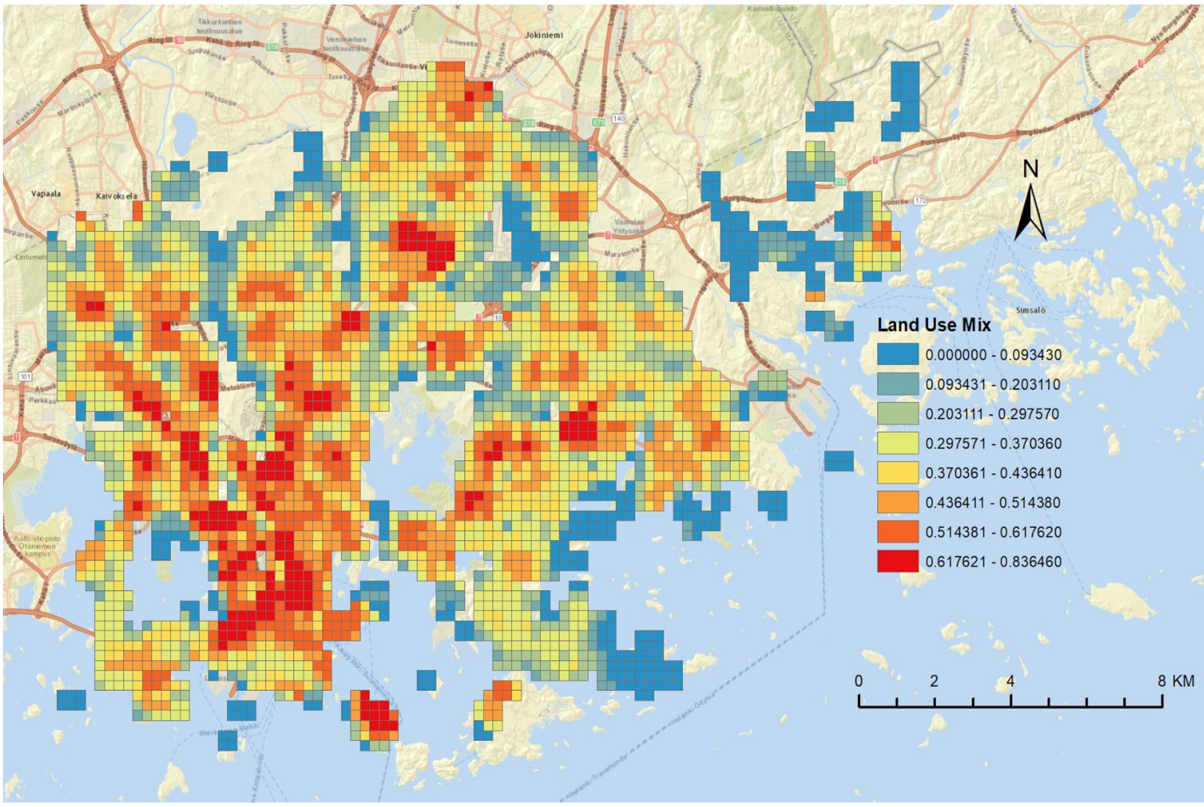

Figure C-8. Entropy index for land use mix based on 250m*250m grids

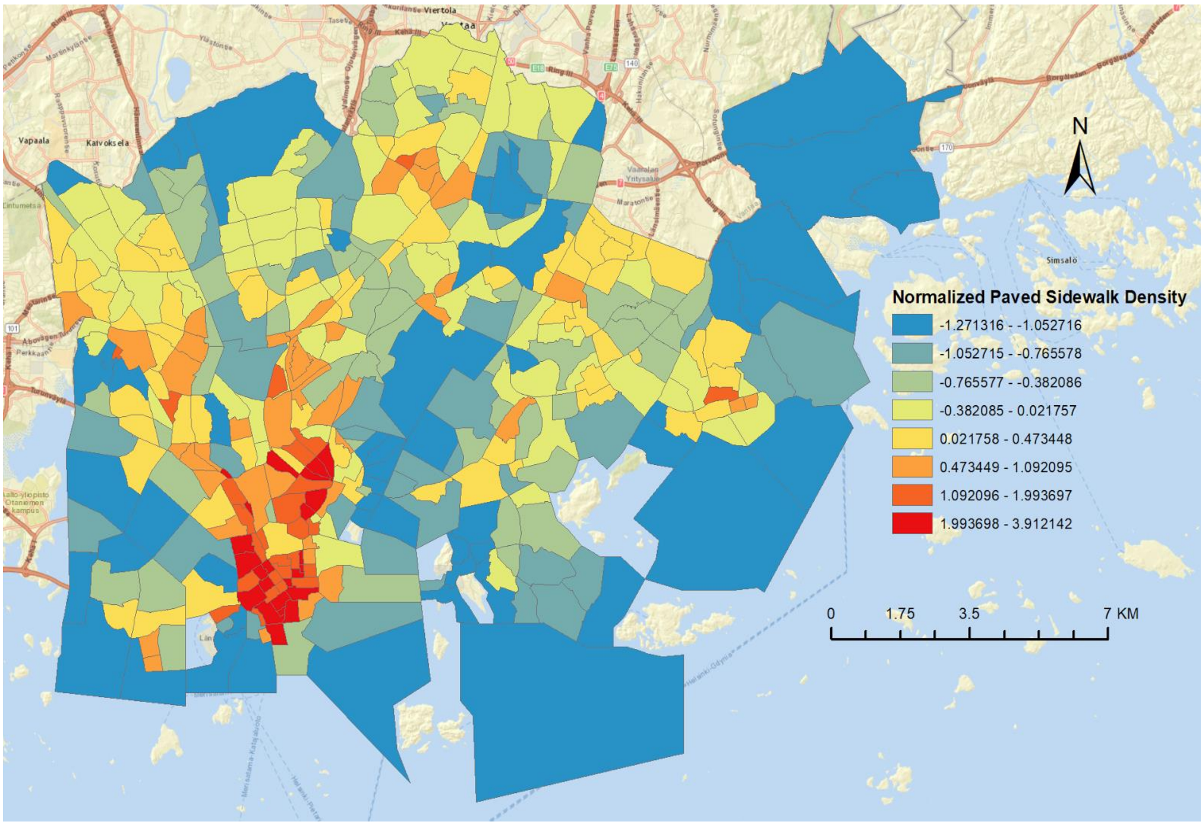

Figure C-9. Normalized (z-score) paved sidewalk density based on administrative units

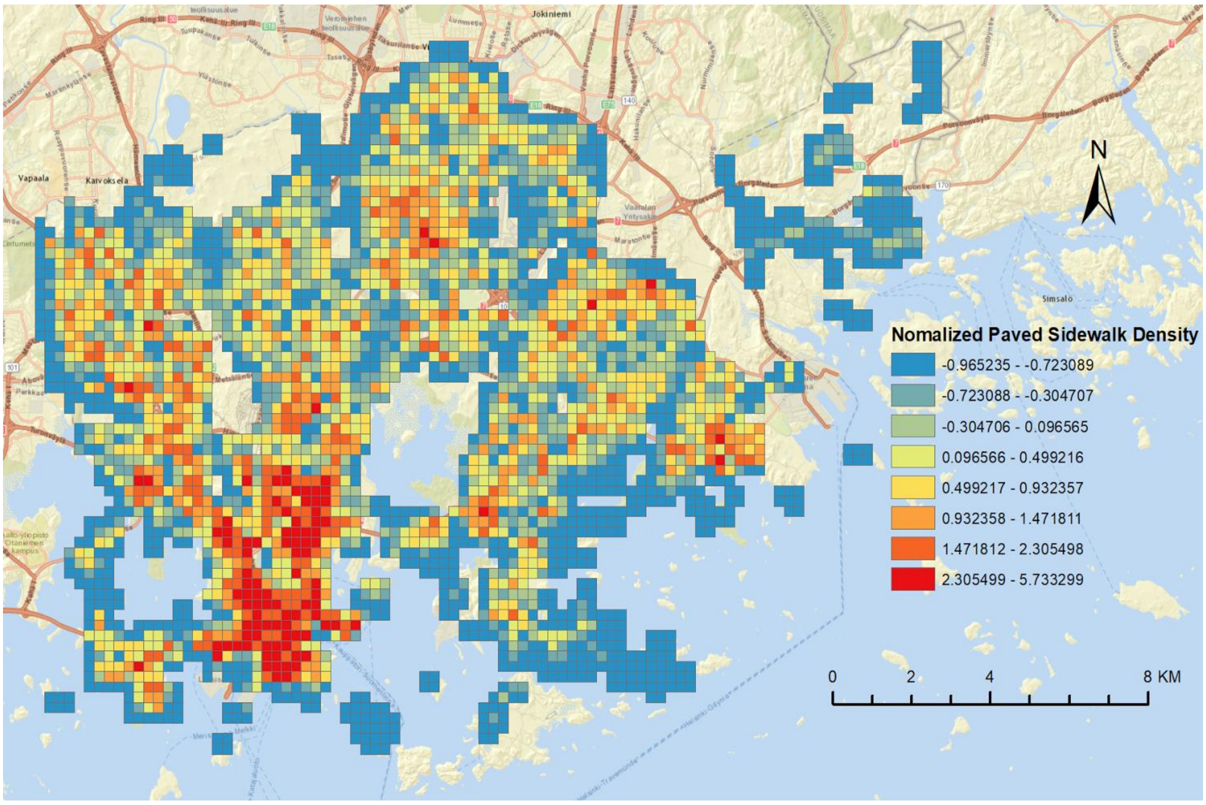

Figure C-10. Normalized (z-score) paved sidewalk density based on 250*250m

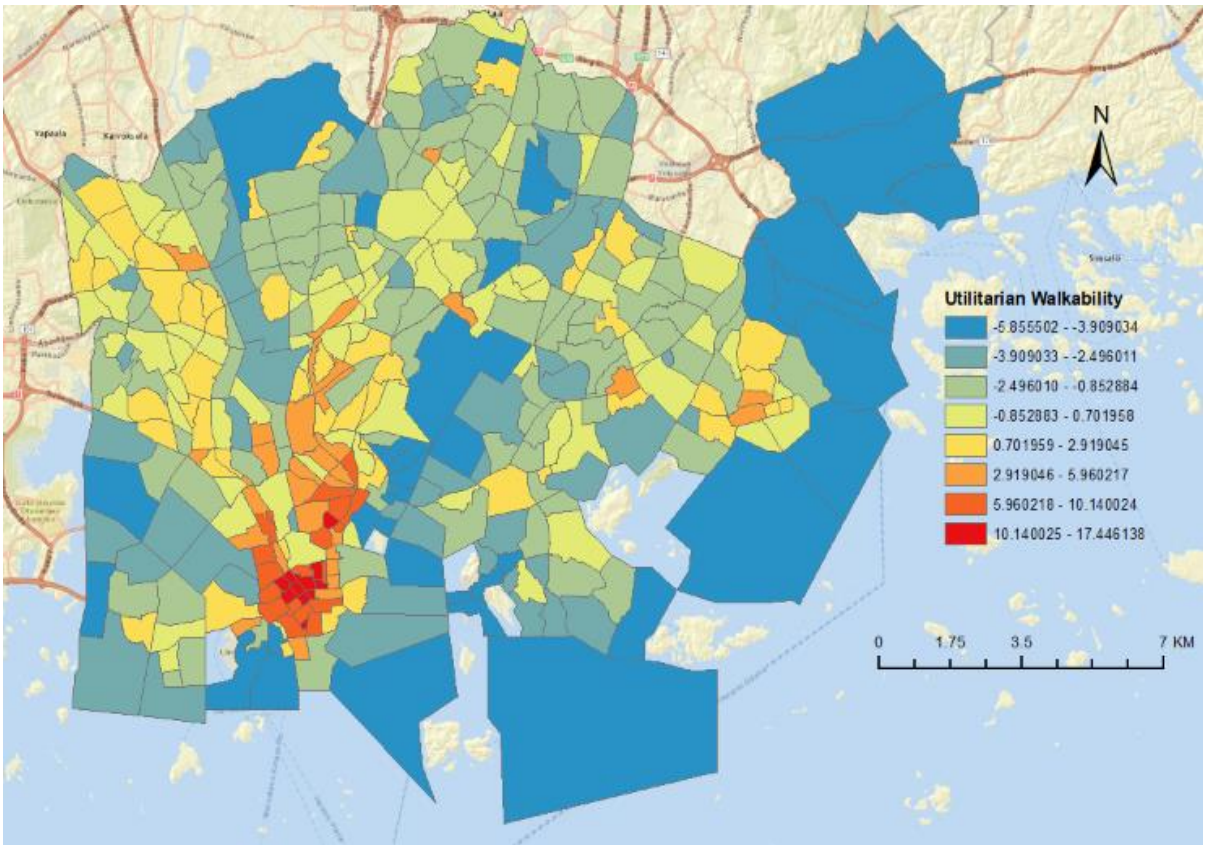

Figure C-11. Utilitarian walkability for City of Helsinki based on district unit

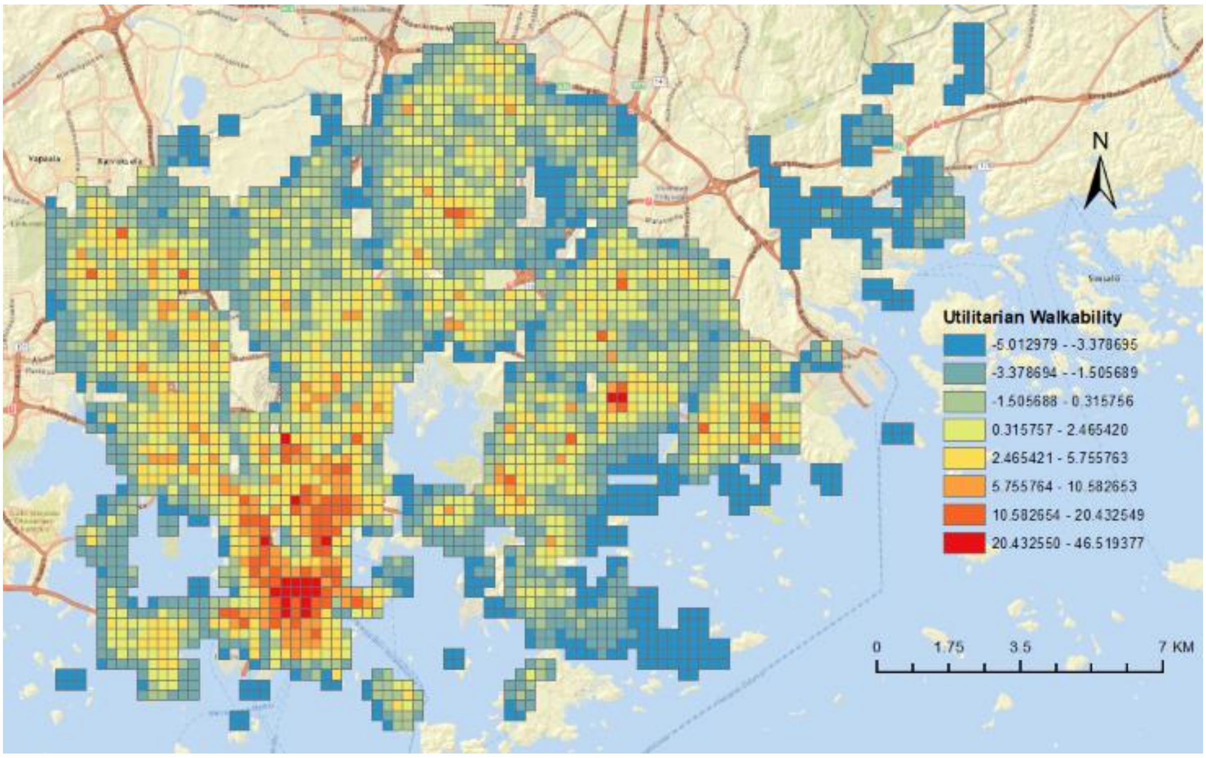

Figure C-12. Utilitarian walkability for City of Helsinki based on 250*250

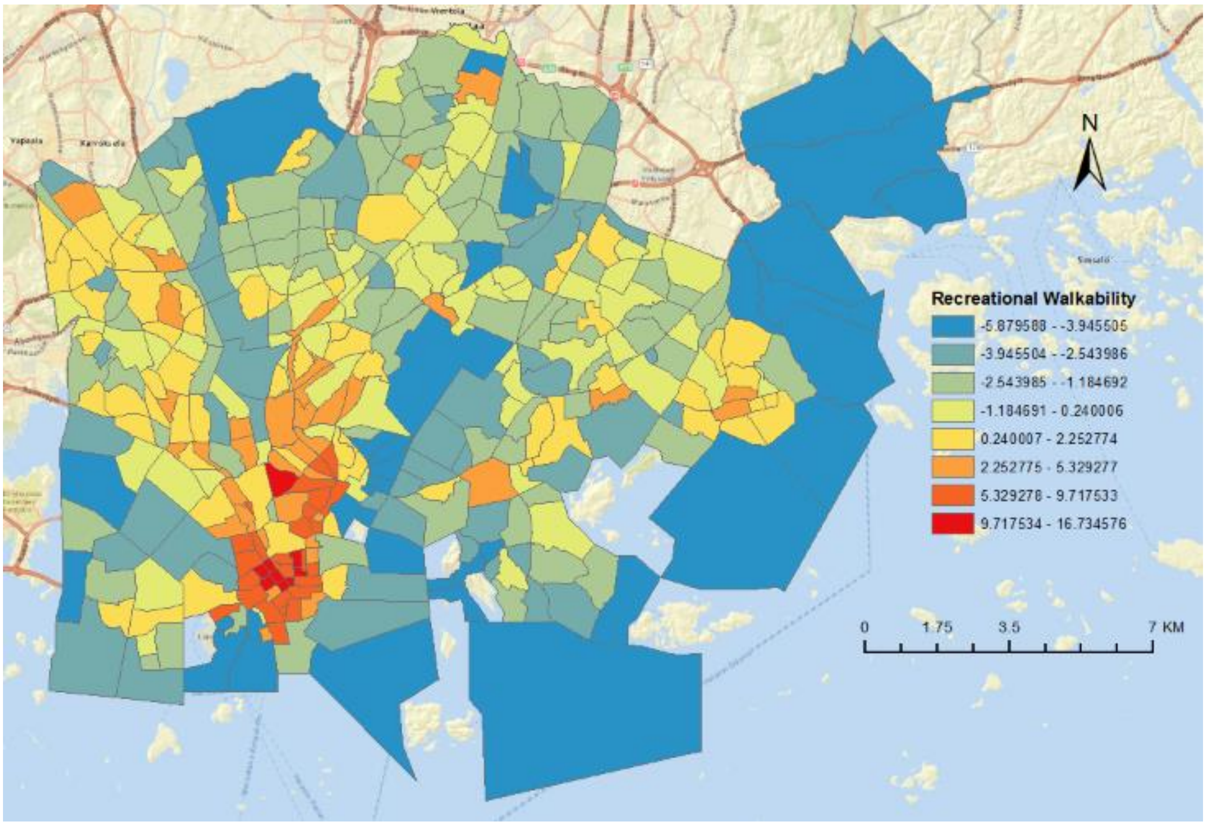

Figure C-13. Recreational walkability for City of Helsinki based on district unit

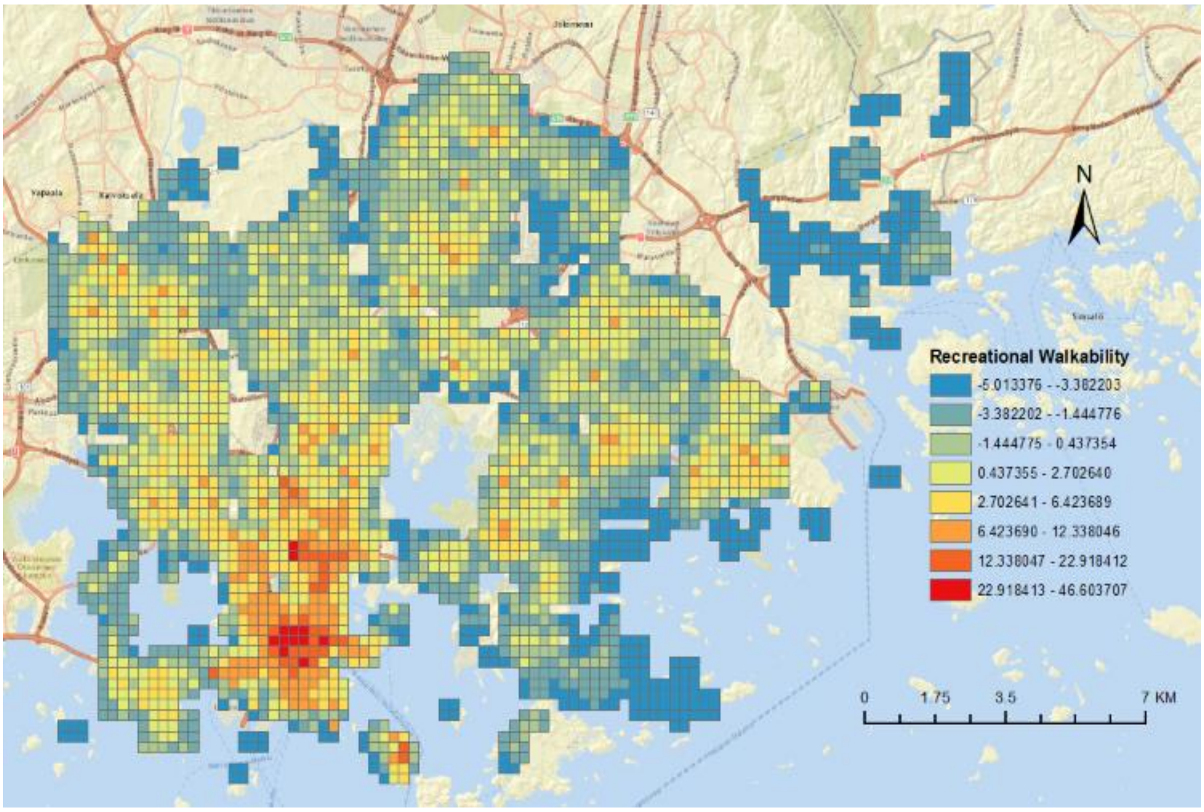

Figure C-14. Recreational walkability for City of Helsinki based on 250*250

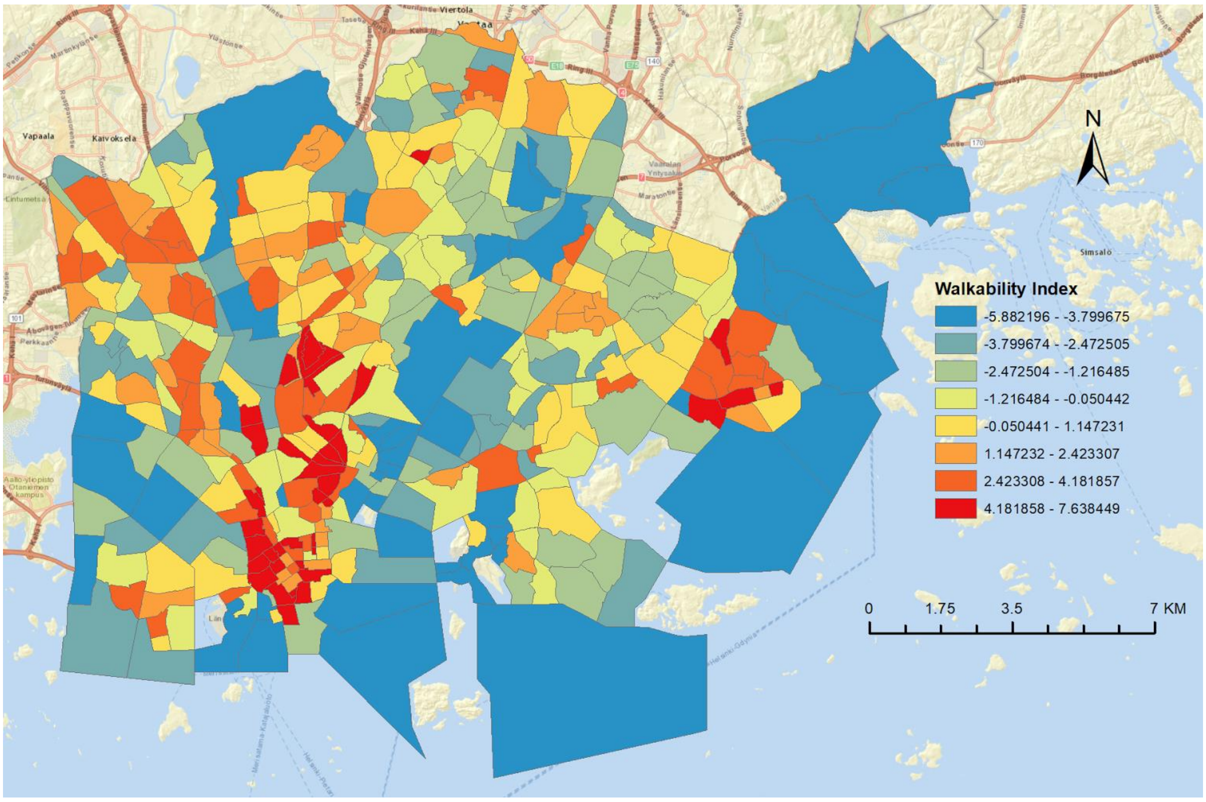

Figure C-15. Walkability index calculated for City of Helsinki based on district unit

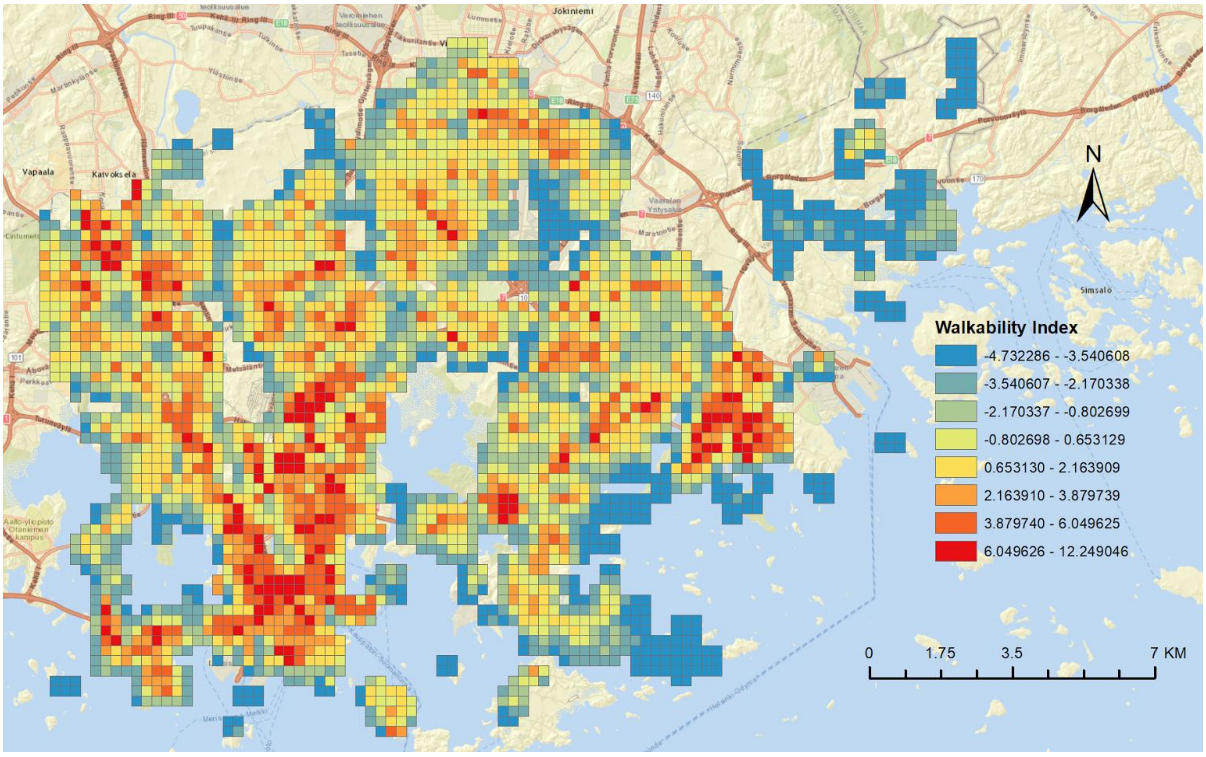

Figure C-16. Walkability index calculated for City of Helsinki based on 250*250m grids