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An automated approach to enrich OpenStreetMap data on footways

GEO 511 Master's Thesis

Author
Yannik Pude
15-050-560

Supervised by
Dr. Hoda Allahbakhshi

Faculty representative
Prof. Dr. Robert Weibel

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Department of Geography, University of Zurich

Abstract

Urbanization and the rising global life expectancy are shaping the 21st century, and an increasing number of the older and disabled population is expected, emphasizing the need of developing age-friendly and accessible cities for all. The disabled population encounters barriers in accessing public services that able-bodied people do not, especially on footways. OpenStreetMap (OSM) data is applied in many routing applications for disabled people but does still lack a considerable amount of accessibility information, for example, only less than 2% of OSM footpaths in the city of Zurich contain inclination information. This thesis aims to enrich OSM footpaths in the city of Zurich automatically with inclination information derived from a Digital Elevation Model (DEM) and investigate the influence of inclination-enriched data on spatial accessibility. The spatial accessibility of three population groups (younger adults, older adults, and manual wheelchair users) to six main service providers (Healthcare Services, Daily Shopping, Public Services, Education, Leisure and Sports, Food and Drinks) was analysed using three different Floating Catchment Area (FCA) methods including 2SFCA, E2SFCA, and KD2SFCA. OSM footpaths were successfully enriched with inclination information using a high-resolution DEM. Results of the spatial accessibility analysis showed differences in the influence of accessibility enriched footpath data per population group, where manual wheelchair users were most affected in their spatial accessibility. Results from the 2SFCA method showed smallest areas that changed but a higher magnitude in change than the other two FCA methods, which yielded similar results. Furthermore, deprived areas concerning accessibility in the city of Zurich were found for all population groups and service providers in different areas of the city. The accessibility enriched footpath data can be used in spatial accessibility analysis, however, the data was not uploaded to OSM, as in other studies that applied an automated enrichment of OSM data. It can be concluded that mobility-impaired people such as manual wheelchair users are most affected by accessibility inhibiting barriers such as inclination. Furthermore, deprived areas concerning spatial accessibility are mainly found in areas where low accessibility and high demand and supply concur or when accessibility and supply are low. The results of this thesis confirmed the vulnerability of the mobility-impaired population in accessing public facilities, which strengthens the need for further research and development of an accessible city for all. Moreover, first insights in areas with lower spatial accessibility in the city of Zurich were made, which gives a basis for more in-depth research in this matter. The applied methods can be replicated if the necessary data is available.

Keywords: OpenStreetMap, Footways, Spatial Accessibility, Inclination, Mobility-impairment, Aging population

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1 Introduction

1.1 Motivation and Background

Human life now is longer than at any time in history. Global life expectancy has doubled since 1900 and continues to rise (World Health Organization, 2020) leading to a predicted total number of 2 billion older adults by 2050 (United Nations. Department of Economic and Social Affairs, 2011). Population ageing and urbanization are major global forces shaping the 21st century. As the cities are growing, the proportion of residents aged 60 and above is also rising (World Health Organization, 2007). Currently, more than one billion people in the world live with some form of disability, of which up to one-fifth experience considerable difficulties in functioning (World Health Organization, 2011). In Switzerland, as of 2019, approximately 1.5 million people live with some kind of disability from which around 27% can be considered severely disabled (Federal Statistic Office, 2019). Due to the increase in the ageing population and the accompanying higher risk of disability in older people, as well as the global rise in chronic health conditions, disability will be an even more significant concern in the future (World Health Organization, 2011). In the city of Zurich, the proportion of residents aged 60 or above has decreased in the last 20 years, from approximately 23% in 2000 to 18.5% in 2020. However, the total number has remained roughly the same at about 80,000 people over 60 (City of Zurich, 2021a). Estimations from various sources suggest a proportion of 0.8% of the population of Zurich is using a wheelchair (Zürcher Verkehrsverbund, 2002).

In many cities, in both developed and developing countries, residents think that their city has not been designed for older people where reference to barriers to physical access is made (World Health Organization, 2007). An accessible environment is a prerequisite for a society where everybody can pursue an active social and economic life regardless of their age or disability (CCPT, 1996; Aragall, 2003; Walder et al., 2010; Park and Chowdhury, 2018)

The disabled population encounter barriers in accessing public services that many of us have long taken for granted (CCPT, 1996; World Health Organization, 2011), such as healthcare, education, employment, transport, and information (World Health Organization, 2011). Examples of insurmountable physical barriers for wheelchair users are lack of ramps or ramps that are too steep, inaccessible bathrooms, high curbs, street crossings, long inclines, steps, and many more (Meyers et al., 2002; Matthews et al., 2003; Beale et al., 2006; Mitchell, 2006; Gharebaghi et al., 2021).

The World Health Organisation (WHO) is encouraging cities worldwide to become more age-friendly, which means adapting their structure and services to be accessible to people with varying needs and capacities. This requires services to be clustered and located in close proximity to where older people live and in places where they can be easily reached (World Health Organization, 2007).

According to Rispens et al. (2021) walking is considered the most basic means of travelling, second only to cars (Mitchell, 2006), and is related to health, social interaction, and a liveable urban environment (Mitchell, 2006; Abellan Van Kan et al., 2009; Rispens et al., 2021).

Especially children and older people predominantly travel by foot (Mitchell, 2006; Bundesamt für Strassen (ASTRA) and Fussverkehr Schweiz, 2015), where typically 25% to 30% of all journeys of older people in Europe are made as pedestrians (Mitchell, 2006). In Switzerland, almost 50% of all trips and more than one third of the time travelling are done on foot (Bundesamt für Strassen (ASTRA) and Fussverkehr Schweiz, 2015).

Common routing and navigation systems such as Google Maps presently do not take information about elevation or incline as well as other access inhibiting features into account once computing a route. Route generation considering accessibility information such as the incline of footways will be of great benefit in an exceeding range of use cases (John et al., 2017). While particularly relevant for people with disabilities, an accessible environment is beneficial for a broader range of people (World Health Organization, 2011). For example, steep street segments must be avoided for energy-efficient routes suited for mobility-restricted persons such as wheelchair users, older people, parents with pushchairs, or passengers with heavy luggage (Müller et al., 2010; World Health Organization, 2011; John et al., 2017). For instance, evidence indicates that the maximum incline a manual wheelchair user can climb is between 3% and 8% (Menkens et al., 2011).

Recent years have seen new ways of collecting geographic information via crowds instead of organisations. The term "Volunteered Geographic Information" (VGI), created by Goodchild (2007), describes a collection of spatial data captured by citizens, where the data is edited and managed as part of a collaborative web platform. The strong demand for freely available spatial data has increased the number of VGI available online (Zipf and Zielstra, 2014).

OpenStreetMap (OSM) is a prime example of this procedure (Forghani and Delavar, 2014; Mooney and Corcoran, 2014; Zipf and Zielstra, 2014; Asanjani et al., 2015) and has brought free access to a wealth of geographic information for many places around the globe for the first time (Goodchild and Li, 2012; Forghani and Delavar, 2014; Asanjani et al., 2015). However, some general concerns still exist about OSM and VGI data, where data quality is one of the main problems (Cooper et al., 2011a; Goodchild and Li, 2012). OSM still lacks a considerable amount of information about accessibility features. For instance, only less than 2% of OSM footpath data in Zurich contains information about inclination (Stoll, 2020).

1.2 Research Gap

Applications for routing and navigation are widely available on the Internet, in cars, and on personal smartphones (Neis and Zielstra, 2014). These routing and navigation systems offer pedestrian navigation, however, the datasets used to generate the routes are based on road networks and lack sidewalk information (Gaisbauer and Frank, 2008; Mobasheri et al., 2018a). While many navigation services are available today to help drivers, interest in creating a new type of navigation service to help pedestrians has recently grown. These systems and services must include pertinent and helpful accessibility information, use accessibility information in meaningful ways (such as for trip planning and real-time navigation) to address specific mobility challenges, and present accessibility information or the outcome of computation on accessibility data/information through intuitive user interfaces for people with mobility challenges to find value in them (Karimi et al., 2014). The quality of said routing and navigation services is determined by the quality and availability of input datasets (Mobasheri et al., 2017b; 2018a). There are various data solutions for routing and navigation systems available today, with OpenStreetMap data being one of the most up to date (in densely inhabited areas) and free to use. However, specific routing and navigation systems, such as those for people with limited mobility, require additional consideration in terms of data suitability for their needs (Neis and Zielstra, 2014; Mobasheri et al., 2017b). The quality of its data has always been a concern for both research and industrial communities, since the launch of OSM in 2004 (Goodchild and Li, 2012). This concern may be caused by the fact that data are gathered by volunteers who may not be familiar with data collection processes and that volunteers have varying degrees of expertise (Mobasheri et al., 2017b). The most essential data for such services is sidewalk geometries and their specific details, such as sidewalk width, inclination, surface roughness, and so on (Mobasheri et al., 2018a). However, OSM still lacks a considerable amount of information about accessibility features (Stoll, 2020). OSM provides inclination information in only 0.2% of the street network (John, 2015; John et al., 2017). Furthermore, in 82.6% of all inclination data on OSM, only a temporary value such as “up” or “down” is provided (taginfo, 2022). In the city of Zurich, only less than 2% of OSM footpath data includes information about the inclination (Stoll, 2020).

Often spatial accessibility has been investigated by only considering different modes of transport, for example, car (Luo and Wang, 2003; Luo and Qi, 2009), or car and public transport (Mao and Nekorchuk, 2013; Langford et al., 2016; Tao et al., 2018). However, it has not been examined for population groups with different movement capacities. Assuming that many daily activities are done by foot, analysing the spatial accessibility on footways for various population groups is needed.

In a recent study of routing algorithms, researchers discovered that wheelchair users would have to travel substantially longer to reach the same location as able-bodied pedestrians, regardless of age (Tannert and Schöning, 2018). Similarly, preliminary data from an exploratory study revealed that manual wheelchair users travel much further than power wheelchair or scooter users to reach the same locations, and that they go 35% further than the shortest available path across mobility modes (Prescott et al., 2021). These findings indicate that mobility-impaired people experience barriers on their routes as well as having potentially slower travel speeds. Furthermore, one of the major current issues is the difficulty in determining what and where cities' accessibility deficits are (Mora et al., 2017).

1.3 Research Objective

This master’s project is part of an interdisciplinary DIZH-funded postdoc fellowship project “SISAL: Situation-Aware Individualized Spatial Accessibility Analytics”, awarded to Dr. Hoda Allahbakhshi (Postdoctoral Fellow at Digital Society Initiative, UZH). One of the objectives of the SISAL project is to apply enriched OSM data to assess the spatial accessibility of different population groups with mobility restrictions, including the older population in the city of Zurich.

The overall aim of this master’s thesis is to enrich OSM accessibility data on footpaths and examine the effect of the enriched OSM/footpath network data on spatial accessibility of different population groups in the city of Zurich. Different population groups can be people without mobility impairment and people with mobility impairment or they could be differentiated more into age groups for example, children, younger adults, older adults. Furthermore, groups of mobility impaired people could be manual wheelchair users or powered wheelchair users. In this thesis the focus lies on 3 different population groups, namely younger adults, older adults, and manual wheelchair users.

Enriching OSM accessibility data has great benefits. In recent years, many OSM-based routing services that offer support for mobility-impaired people such as wheelchair users, were developed. Examples of currently available routing engines, services, and/or applications include GraphHopper (GraphHopper GmbH, n.d.), OpenRouteServices (ORS) (HeiGIT GmbH, n.d.), or Routino (Bishop A M, n.d.). The fundamental problem with these tools is that they rely on the availability of specific accessibility data, which is typically not readily available for most geographical locations (for example, knowledge about the surface material of a sidewalk or the inclination) (Stoll, 2020). Enriching OSM data on footpaths can fill part of this gap in the city of Zurich. Automating this process can make it possible for other people to easily enrich OSM in other locations with accessibility data as long as necessary data exist.

Furthermore, the enriched accessibility data can also be used for spatial accessibility analysis as it will be done in this thesis. Examining the spatial accessibility of different areas in the city can give knowledge about where in a city public services and other demands are not spatially accessible for parts of the population. This can help city planners and engineers develop a city accessible for as many people as possible.

1.4 Research Questions

The following research questions were formulated based on the research gaps and the research objective set for this thesis.

Research Question 1:

How can OSM accessibility data on footpaths automatically be enriched using additional data sources?

OSM accessibility data can be enriched in two ways. Through a crowdsourcing approach and through an automated approach using additional data sources. Sources of additional data can be for example official publicly available datasets. With crowdsourced data often seen as being of low quality, additional data from official sources can provide high quality data for areas where it's available. Additionally, these data sources can cover larger areas e.g., a city, a region or even a whole country, where crowdsourced data is often added only on a small spatial scale e.g., the contributors home street or neighbourhood.

Research Question 2:

What is the influence of accessibility-enriched footpath data on spatial accessibility for people in different population groups?

Hypothesis: I expect the spatial accessibility to be lower when including inclination information than without including inclination information in areas where the footpaths are inclined. This is due to walking speeds decreasing on greater inclinations. With that increased travel times to reach a destination are to be expected. Walking speeds presumably decline with higher ages and even lower travel speeds for wheelchair users are estimated. Therefore, differences in spatial accessibility between the population groups are likely to be found, where older adults and mobility impaired people are likely to have lower spatial accessibility than younger adults. Moreover, older adults and wheelchair users are expected to be more affected by adding inclination information to footpath data, as these groups are more sensitive to inclined footpaths.

<u>Research Question 3:</u>

Are there any patterns of deprived areas concerning spatial accessibility to public services in the city of Zurich for certain population groups?

<u>Hypothesis:</u> Assuming that different types of public services are not equally distributed throughout the city, there will be areas with lower supply. Additionally, the actual number of supplies differs between the services. This can lead to lower spatial accessibility in areas of the city to certain public services. Furthermore, due to different travel times and sensitivity to inclined footpaths, the spatial accessibility of certain population groups maybe influenced dissimilar to some public services. There could be deprived areas of spatial accessibility to individual services only for certain population groups.

1.5 Structure of the Thesis

This thesis is structured as follows. In Chapter 1 the topic was introduced, and the research objectives were established. Chapter 2 presents related work and gives further background information on the topics of this thesis, whereas in Chapter 3, the utilised datasets and the applied tools are described. The methodology of all conducted data processing and analyses are outlined in Chapter 4 and the results of the performed analyses are presented in Chapter 5. In Chapter 6, the obtained results are discussed, limitations of the applied methods are pointed out, and recommendations for future research are made. Finally, Chapter 7 concludes this thesis.

2 Literature Review

2.1 OpenStreetMap

Recent years have seen new ways of collecting geographic information via crowds instead of organisations. Crowdsourcing is one of the most significant and potentially contentious phenomena in Web 2.0 (Web 2.0: “The successful collection of information by masses of volunteering individuals enabled by Web technology” (Schmitz et al., 2008)). The word arose from the concept of outsourcing, in which commercial functions are relocated to less expensive areas (Friedman, 2007). Crowdsourcing was made possible by technological advancements, as well as increased bandwidth and improved collaboration tools, and enables huge user groups to complete tasks that are either difficult to automate or expensive to accomplish (Howe, 2006). This does not stop before the area of geographic information. Several projects focusing only on the collection of geographic information have emerged (Schmitz et al., 2008). This special case of user-generated content was named “Volunteered Geographic Information” (VGI) by Goodchild (2007). The term VGI describes a collection of spatial data captured by citizens, where the data is edited and managed as part of a collaborative web platform. The strong demand for freely available spatial data has increased the number of VGI available online. This spatial data, which is primarily collected by volunteers, is freely available to Internet users and can be deployed to a variety of GIS projects and applications (under specific licensing requirements). Some of these free data suppliers are able to offer a vast amount of information thanks to advanced data donations as well as a variety of other non-proprietary data sources (Zipf and Zielstra, 2014). OpenStreetMap (OSM) is one of the most prominent and sophisticated VGI projects on the Internet (Goodchild and Li, 2012; Forghani and Delavar, 2014; Mooney and Corcoran, 2014; Zipf and Zielstra, 2014; Asanjani et al., 2015).

2.1.1 History and Purpose

The OSM project was founded by Steve Coast in 2004, first with the aim to map the United Kingdom (OpenStreetMap Wiki, 2022f). Later, Coast declared the goal of OSM to replace every other map in the world (Freyfogle, 2014). With the support of the OpenStreetMap Foundation, an international non-profit organisation (OpenStreetMap Foundation, 2021), OSM aims at creating and collecting free geodata covering the whole planet (Haklay and Weber, 2008; Schmitz et al., 2008; OpenStreetMap Wiki, 2021). The OSM community organizes a series of local workshops (referred to as "mapping parties") with the goal of creating and annotating data for local geographical areas, in contrast to Wikipedia, where individuals contribute the majority of the content at various locations. These activities are intended to give novice users and community contributors practical experience in gathering, processing, and uploading data to the OSM project (Haklay and Weber, 2008). The number of these contributors has been greatly increasing since the start of the project. In early 2013 the OSM project gained its one-millionth member; two years later, in early 2015, the number of registered contributors exceeded two million (OpenStreetMap Wiki, 2022f). As of writing this thesis, the OSM project has almost 8.8 million registered users (OpenStreetMap, 2022d). While the number of these contributors who actually make more than a few cursory or exploratory adjustments is in the tens of thousands, studies (Neis and Zipf, 2012; Mooney and Corcoran, 2014) have demonstrated that the project still shows extraordinary growth rates in terms of contributors and the volume of spatial data in the global database. All OSM data can be downloaded for free and in vector format, which has led to their widespread use (Forghani and Delavar, 2014). Many researchers utilize OSM as their spatial data source, and academic research interest has expanded on the project ecosystem as a whole (including the community and volunteer motivation for OSM) (Asanjani et al., 2015).

2.1.2 Structure

The core database, which holds live data and is implemented in PostgreSQL, is at the heart of OSM technical infrastructure (OpenStreetMap Wiki, 2022c). The database schema is designed to accommodate wiki activities such as versioning and rollbacks, and it retains infinite copies of modified or deleted features. Access to the core OSM database is provided by a dedicated RESTful API, which accepts and outputs data in OSM Extensible Markup Language (XML), a dedicated data transport format developed for the project. This API is used by all editing tools to access and modify the main database enabling users to add, update, and delete geographical features (OpenStreetMap Wiki, 2022d).

OSM data model is based on three basic components: nodes, ways, and relations. All geographical entities are stored as points (nodes), which include the latitude and longitude coordinates, as well as the username and timestamp. Linear and area features refer to a collection of ordered nodes known as ways. Area characteristics are not directly specified in the database schema; instead, they are defined implicitly by the condition of a closed way (the initial node of a way is the same as the last one) and explicit tagging practices (using the tag *area=yes*). Relations contain information on the relationship of two or more objects (e.g., a bus or tram line of the public transportation network) (OpenStreetMap Wiki, 2022e).

A changeset is a collection of database edits made by a single person over a short period of time (OpenStreetMap Wiki, 2022a). Tags consist of a *key=value* pair and are used to add attribute information to the map elements or changesets. Each tag consists of a key and a value with free format text fields, but often represents numeric or other structured items (OpenStreetMap Wiki, 2022e). An example of an accessibility tag is *footway=crossing*, where footway is the key and crossing is the value indicating a crossing on a footway. A thorough list of OSM *key=value* pairings for a wide range of map features may be found on one of the OSM-related wiki sites. This tagging system, which is evolving into a complex taxonomy of real-world feature classes and objects, is a key component of the OSM project and is driven by the community. Any community member can contribute to and change the schema by providing new *key=value* pairs (Haklay and Weber, 2008).

2.1.2.1 Accessibility Tags

The physical barriers that disabled people encounter in their everyday life can be easily tagged in OSM. The most relevant accessibility tags are presented below. Table 2.1 summarises the accessibility attributes and their corresponding tags in OSM.

Highway

The *highway* tag is used to identify route elements that reflect any type of road, street, or path. The value of this tag indicates the relevance of the route in the road network. This tag can also be used to designate a stair on a pathway that needs to be considered for accessibility (OpenStreetMap Wiki, 2022i).

Sidewalks

There are currently two methods used in the OSM community for mapping sidewalks. A sidewalk can be mapped as a refinement of a street using the *sidewalk* tag (*sidewalk=no/left/right/both*), or it can be mapped as a separate way, that is parallel to the street and intersect it and other streets in the crossings, using the *sidewalk* tag. In the latter scenario, the sidewalk is described by the tags *highway=footway* and *footway=sidewalk* (OpenStreetMap Wiki, 2022r).

Width

The actual width of a way or other feature can be described with the tag width. Typically, its values are interpreted in meters; however, to reduce the risk of misunderstandings, it is always advised to specify the unit (OpenStreetMap Wiki, 2022p).

Crossings

In OSM, pedestrian crossings are mapped by attaching the tag *highway=crossing* to a node that belongs to a street. If the footpath is present as an independent way (such as a separately mapped sidewalk), the tag combinations *highway=footway* and *footway=crossing* should be used. The crossing tag itself might indicate whether the crossing has traffic lights, and road markers, or is uncontrolled. Furthermore, similar tags such as *crossing:island* can be used to map the presence of a pedestrian island on a crossing (OpenStreetMap Wiki, 2022b).

Kerbs

The *kerb* tag describes the point where a road meets a sidewalk. It is usually mapped on the nodes of a pedestrian crossing when there is a kerb. The possible values are *raised*, *lowered*, *flush*, and *rolled*. "*Yes"* is also an option if the mapper is unsure of the particular kerb type. Although these values indicate certain height ranges, the *kerb:height* tag can be used to provide a precise number. It is worth noting that in OSM standards, kerbs greater than 3 cm are considered inaccessible to wheelchairs and bicycles (OpenStreetMap Wiki, 2022k).

Surface

The *surface* tag identifies the physical surface material, mostly of roads and footpaths. Aside from various specified values such as asphalt (*surface=asphalt*) or paving stones (*surface=paving_stones*), mappers can also utilize non-specific values such as *paved* or *unpaved* if they are unsure about the actual surface material (OpenStreetMap Wiki, 2022n).

Smoothness

Smoothness accurately characterizes the accessibility of sidewalks because it quantifies the condition of the path. Smoothness is a classification scheme for the physical usefulness of a path for wheeled vehicles, specifically surface regularity/flatness. The *smoothness* tag can be used to classify which kind of wheeled vehicles can utilize a path (meaning that the vehicle can traverse it without significant risk or damage). The range of potential values is hierarchical and includes excellent and impassable (not useable by any wheeled vehicle). The classification should be based only on the surface's regularity and flatness. The goal of this tag should be to enable navigation software providers to use its information to recommend the best route based on the vehicle the user is driving (OpenStreetMap Wiki, 2022m).

Incline

The *incline* tag is used to indicate the maximum slope or incline of a path. Depending on the direction in which a way has been mapped, there can be either an upward or a downward inclination. The latter requires the usage of negative inclination values. The values can either be expressed as a percentage (value postfixed with the percentage sign %) or in degrees (value postfixed with the degree sign °). If the precise value is uncertain, the values up and down can be used. This is commonly applied to stairs (OpenStreetMap Wiki, 2022j).

Barrier

The *barrier* tag is applied to a range of physical features that restrict or obstruct mobility. This covers objects like fences, gates, kerbs, debris, or bollards. It is applied to a node or a path depending on the barrier. The *barrier* tag only applies to barriers on the ground. It is advised to add more tags to the barrier in order to explain it in greater detail (OpenStreetMap Wiki, 2022g). One of these is the tag *wheelchair*.

Wheelchair

The tag *wheelchair* can be used to indicate the accessibility of locations or pathways to people using wheelchairs and other mobility aids such as walkers (OpenStreetMap Wiki, 2022o).

Construction

The tag *highway=construction* should be used to indicate that a road is currently under construction, replacing the actual tag for the road (e.g., from *highway=tertiary* to *highway=construction*). The construction tag is then used to define the type of highway that is currently being developed (i.e., *construction=tertiary*). If the end date of the construction is known, the tag *opening_date* can be added. Construction sites should only be tagged if they are planned to be closed for at least 6 to 9 months (OpenStreetMap Wiki, 2022s).

Parking

A car parking location is mapped as an area with the tag *amenity=parking* (OpenStreetMap Wiki, 2022l). Whether or not dedicated spaces for disabled people are available can be specified with the key *capacity* and more precise with the subkey *capacity:disabled* (OpenStreetMap Wiki, 2022h).

Table 2.1: OSM accessibility attributes. Based on Mobasheri et al. (2017b)

Parameter	OSM tag	Scale
Type of street	highway=*	
Sidewalk	sidewalk=left | right | yes | no | both footway=sidewalk	
Width	width=*	[m]
Surface	surface=*	
Smoothness	smoothness=*	
Incline	incline=*	[%]
Kerb	kerb=*	[m]
Steps	highway=steps step_count=* step:height=*	
Crossing	footway=crossing	
Barrier	barrier=*	
Construction	highway=construction	
Parking	amenity=parking capacity:disabled=*	
Wheelchair	wheelchair= yes | no | limited	

2.2 Enriching OSM Accessibility Data

2.2.1 Crowdsourcing Approach

Data can be added to OSM in various ways by the crowd. Two main techniques mainly used for the field data collection by the OSM community were described by Biagi et al. (2020). The first is a two-step method where data and notes are written and mapped on paper maps in the field and later inserted in OSM by desktop applications. A printed “atlas” based on FieldPapers (FieldPapers, 2012), a web-based tool allowing to create printable maps by OSM, is used in the field to take notes and map elements of interest. Furthermore, the collected data can be improved by collecting street view images during the collection. After collecting data in the field, the mapped elements are uploaded to the OSM database using appropriate web editors such as iDeditor or JOSM.

The second method uses mobile applications to insert data collected in the field directly. Different applications exist for iOS and Android. The two most popular Android applications are Geopaparazzi, and Vespucci. For iOS, only two working applications are still available: GoMap!! and MAPS.ME. The pros and cons of each of these applications can be found on OSM wiki pages (OpenStreetMap Wiki, 2022q). Of all these applications, only Vespucci and GoMap!! allow the user to add new elements, edit existing ones, edit tags with custom values, edit geometries, and upload the data into OSM (Biagi et al., 2020). Thus, both Vespucci and GoMap!! are very feature-rich but require some familiarity with OSM, making them not a good entry for people who never used OSM (Stoll, 2020). In order to address this problem AccessComplete, an android-based crowdsourcing app for collecting wheelchair-related accessibility data on OSM was developed by Sven Stoll in 2020. The goal for AccessComplete was to involve laypersons who do not have previous knowledge about OSM in collecting accessibility data (Stoll, 2020). AccessComplete is, however, not yet released but its predecessor IOS-based app Capture and Go is going to be released on app store.

The subject of mapping accessibility became popular in the OSM community in 2010, when the application Wheelmap was released (Biagi et al., 2020). On Wheelmap, anyone from anywhere in the world may search, add, and rate locations. The software presents a basic tagging schema that uses a green, orange, and red scale to indicate the level of accessibility of specific Points of Interest (POIs), such as hotels, restaurants, or public transportation stops. These data are entered into the OSM database using the key "wheelchair": the three colours are associated with the relevant values "yes," "limited," and "no" based on the accessibility level (Mobasheri et al., 2017a). A more recent addition to the tagging schema is the key "barrier," which allows for the addition of information for obstacles (Biagi et al., 2020).

Menkens et al. (2011) conceptualized, designed, and implemented a mobile wheelchair navigation and support system called EasyWheel, specifically for wheelchair users' special needs, requirements, and characteristics. EasyWheel was designed around three primary features: Geo-tagging of points of interest, personalized barrier-free routing, and social community. Users can add or label specific POIs, entire streets, walkways, or other locations on their mobile application by using geotagging, which allows them to include detailed accessibility information and images of barriers. Personalized barrier-free routing enables wheelchair users to travel a city on a path based on personalized mobility parameters that avoids barriers that they cannot surmount. The integration of the OSM service is the key component of EasyWheel. The application can directly communicate with the OSM Server and upload newly geo-tagged POIs. Users of EasyWheel contribute to the system by geotagging POIs or providing accessibility information about POIs (e.g., places, stores...), streets, walkways, and routes, therefore expanding the OSM database (Menkens et al., 2011).

Two European projects, i-SCOPE (Prandi et al., 2014) and Cap4Access (Voigt et al., 2016; Mobasheri et al., 2018b), had the scope of collecting data relevant to the presence and the geometry of sidewalks. The goal of the i-SCOPE project was to deploy a collection of services to promote the development of living quality in urban areas based on a new generation urban city concept. One of these services was a tailored routing service for people with disabilities, specifically for people with visual impairments, wheelchair users, but also regular pedestrians. The purpose behind the i-SCOPE routing data is to supplement the data model provided by OSM with additional information derived from specific volunteer surveys conducted in the field using the mobile application (Prandi et al., 2014).

The collective awareness platforms for improving accessibility (CAP4Access) across European cities and regions was a European project that aimed to use the power of online maps and mobile devices to raise awareness of barriers for people with limited mobility and, as a result, aid in the elimination of such barriers (Zipf et al., 2016; Mobasheri et al., 2018b). Different approaches were applied and tested in London (UK), Vienna (AU), Elche (SPA), and Heidelberg (GER), trying to find the ideal way for data collection, considering both quantity and accuracy (Voigt et al., 2016; Mobasheri et al., 2018b). CAP4Access proved that public awareness and involvement have a direct impact on data enrichment, particularly for information that targets special needs (e.g., sidewalk information). This implies that the volunteers are unaware of the relevance of sidewalk information and, as a result, are unwilling to map them in the first place. By providing them with accurate information, volunteers are more likely to pay attention and include sidewalk information in their daily/monthly mapping efforts (Mobasheri et al., 2018b). It is possible to collect a large amount of information in a short period of time by encouraging groups of individuals and providing them with appropriate tools. The biggest problem is mobilizing these individuals for data collection; this is a highly challenging topic, and there is not a unique solution (Prandi et al., 2014).

2.2.2 Automated Approach

In an automated approach, OSM data is enriched by using existing datasets such as GPS traces, drone images, or satellite data (for example Digital Elevation Models (DEMs). There is literature applying an automated approach to enrich accessibility data on OSM. One thing that all the below mentioned studies have in common is that their enriched data was not uploaded to the OSM database as OSM discourages automatic and bulk uploads (OpenStreetMap, 2022a).

For instance, John (2015) enriched street networks with incline information by using voluntarily collected GPS traces for the study area of Heidelberg, Germany. The purpose of his thesis was to establish methods and tools for calculating the inclination of a street network, including pedestrian and bicycle paths. The incline was estimated using GPS traces supplied by OpenStreetMap volunteers, as this may represent a low-cost alternative to expensive high-accuracy DEMs. Due to the high relative accuracy of the GPS traces John derived, for many use-cases, reasonably accurate incline values if the streets were covered with multiple GPS traces. When compared to the SRTM DEM, the inclines estimated with GPS performed slightly better, with a standard deviation of GPS=1.6% (SRTM=3.1%), when considering streets with at least 5 GPS traces. In contrast to SRTM with full coverage, it was only possible to determine the incline for 18% of the street network (streets with > 5 GPS traces). The results suggest that it is now possible to produce comparable or even slightly better outcomes with user-generated data than with data gathered by a research satellite. However, user-generated GPS traces require satellites as well, although the data was not principally collected for the purpose of calculating inclination. As average incline was calculated in this study, the data was not suitable for OSM as on OSM the maximum incline on a way shall be mapped (see Section 2.1.2.1) (John, 2015).

Sachdeva (2015) successfully demonstrated a technique to automatically enrich OSM by pre-processing crowdsourced sensor data taken from a driving vehicle's navigation system and driver assistance systems. The algorithmically obtained data comprised the curvature of the underlying road, the correction of speed limit values for specific road segments, and the identification of changes in the geometry of existing roads due to the closure of old ones or the addition of new ones in the Nuremberg region of Bavaria, Germany. The generated data was uploaded to a private instance of the OSM database.

Within the CAP4Access project Mobasheri et al. (2018a) aimed to utilise OpenStreetMap data to provide routing and navigation services for people with limited mobility. In this regard, their paper proposed a modified methodology for building sidewalk geometries, utilizing multiple

GPS traces acquired by wheelchair users during an urban travel experiment in Heidelberg (GER), based on data mining techniques. To derive sidewalk geometries, they used GPS traces from wheelchair volunteers, as well as a road network dataset and building footprints from the OSM database. The evaluation concluded that the algorithm can automatically construct sidewalk networks using multiple GPS traces. The number of GPS traces used is highly predicted to positively correlate with the positional accuracy of the generated pedestrian network. Hence, with more GPS data available, the generated segments will likely be more accurate positioned. Their method can be used to enrich OSM data with sidewalk geometries, and it can also be used to route and navigate pedestrians and persons who rely heavily on sidewalk availability for their travels (e.g., wheelchair users). The authors noted that the enrichment of the sidewalks is done on a local database and not on the original OSM database, as OSM does not allow bulk editing.

2.3 Spatial Accessibility Concepts

In reference to the healthcare system, Penchansky & Thomas (1981) defined “access” as a “concept representing the degree of "fit" between the clients and the system.” They view access as a general concept summarizing more specific areas of fit between the patient and the healthcare system. The specific dimensions of areas defined by the authors are availability, accessibility, accommodation, affordability, and acceptability. The first two dimensions describe the spatial aspects of access (Jörg et al., 2019). This concept can of course be translated to other fields than healthcare. The concept of access can further be divided into two broad stages: potential and realized (Guagliardo, 2004). Latter describes the actual utilisation of a service, whereas potential access describes the status quo and, therefore, makes no reference to the effective claim of a service (Jörg et al., 2019).

Both the aspatial dimensions of access and the realized access to services are not in the scope of this thesis. The spatial dimensions in a potential stage of access are described in the following section.

2.3.1 Availability

Availability is defined by Penchansky & Thomas (1981) as “the relationship of the volume and type of existing services (and resources) to the clients' volume and types of needs”. It relates to the sufficiency of the supply of services and facilities such as clinics and hospitals. Therefore, the existence, quantity, and quality of a spatial resource in a study region are of interest in availability research, providing a simple way for evaluating various administrative units based on their available spatial resources (Luo and Wang, 2003). Similarly, Guagliardo (2004) defined availability as “the number of local service points from which a client can choose”, and Bryant & Delamater (2019) as “the amount or volume of services available, often in relation to the number of people that must be served”. Thus, availability refers to the number of services (supply) concerning the demand for these services, for example, the number of services per 1000 residents (Jörg et al., 2019).

2.3.2 Accessibility

The second spatial dimension of access “accessibility” defined by Penchansky and Thomas (1981), is “the relationship between the location of supply and the location of clients, taking account of client transportation resources and travel time, distance and cost.” Therefore, accessibility is the travel impedance (distance or time) between a person’s location and service locations (Guagliardo, 2004). Measures of accessibility capture the distance that people must travel to reach a resource (Bryant and Delamater, 2019; Jörg et al., 2019). The accessibility of a person is determined by the interactions between the person and the environment. A path, for instance, may be accessible to certain people but not others. Therefore, not only environmental factors but also the persons’ capabilities play a significant role in their accessibility and should be assessed accordingly (Gharebaghi et al., 2017). This concept of interaction between individual and environment has been defined as mobility: “the ease of movement from place to place” (Tyler, 2002; 2004; Holloway, 2011). Mora et al. (2017) see accessibility as an element of life quality and a determining factor of the liveability of a city, which provides comfort and autonomy using all kinds of travel modes.

2.3.3 Spatial Accessibility

Measures of supply level are only applicable to sufficiently vast geographies and cannot identify variations in supply within big bordering areas. Distance or travel time to the nearest provider ignores the potential service of providers who may be located only a short distance away. Although the differentiation between availability and accessibility might be helpful, in urban regions with various service locations and where the majority of the population lives, the two dimensions should be examined simultaneously (Guagliardo, 2004). The integration of both availability and accessibility into one measure was coined “spatial accessibility” by Guagliardo (2004), who recognized this term as common in the geography and social science literature. For example, Fryer et al. (1999) saw the necessity to combine measures of travel impedance (accessibility) and supply (availability) in order to properly understand spatial accessibility. Thus, spatial accessibility provides a richer evaluation of access, instead of measuring the two components individually (Bryant and Delamater, 2019). Both low availability and poor accessibility reduce the spatial accessibility of services (Jörg et al., 2019). Moreover, spatial accessibility can be seen as a result of interaction between the individual and the surrounding environment (Gharebaghi et al., 2017).

2.4 Spatial Accessibility Measures

Given the widespread interest in accessibility measurements, multiple approaches have been developed for various applications (Luo and Wang, 2003). Some of these approaches are presented in the following Section.

2.4.1 Early Methods

2.4.1.1 Gravity-based Method

One of the first models to measure accessibility was the gravity model proposed by Hansen (1959). He proposed the model for accessibility (A_i^H) at location i:

$$A_i^H = \sum_{j=1}^{n} S_j d_{ij}^{-\beta} \,, \tag{1}$$

where S_j is the number of services at location j, d_{ij} is the travel time between population location i and provider location j, β is the travel-friction coefficient, and n is the total number of service locations. In the model, a nearby provider is regarded as more accessible than a distant one and hence is weighted higher. One shortcoming of Equation (*1*) is that it only examines the “supply side” (providers) and not the “demand side” (competition among residents for available services) (Luo and Wang, 2003). Weibull (1976) improved the measurement by accounting for service competition among residents. The gravity-based accessibility proposed by Weibull (1976) can be written as:

$$\boldsymbol{A_j^G} = \sum_{j=1}^{n} \frac{S_j\, d_{ij}^{-\beta}}{V_j}, \qquad (2)$$

where

$$\boldsymbol{V_j} = \sum_{k=1}^{m} \boldsymbol{P_k d_{k_j}^{-\beta}}, \qquad (3)$$

A_j^G is the gravity-based index of accessibility, where n and m are the total numbers of provider and population locations, respectively, V_j is the service competition intensity at location j, P_k is the population of location k, and d_{kj} is the travel time between population location k and provider location j. The other variables are the same as in Equation (1).

2.4.1.2 Early Floating Catchment Area Methods

Earlier versions of the floating catchment area (FCA) method were used to measure employment accessibility. FCA methods in some degree resemble kernel estimation, where a window (kernel) is moved across a study area, and the density of events within the window is used to indicate the density at the window's centre. In order to estimate the density, one may use a gravity model to weigh events by the inverse of their distances from the centre (Luo and Wang, 2003).

Figure 2.1 illustrates an example of the method. For simplicity, it is assumed that each census tract has only one inhabitant and each provider location has only one service available. The catchment areas of census tracts 2 and 3 are defined by a 15-mile radius around their centroids. The provider-to-population ratio within its catchment area represents the accessibility in a census tract. For example, there are eight residents and only one physician (that is, a) in the catchment area of tract 2. Thus, the accessibility for this tract is their ratio 1/8. The circle "floats" from one centroid to another, while keeping the same radius. Similarly, two physicians and five residents lie within the catchment of census tract 3; therefore, the accessibility of tract 3 is 2/5. The underlying assumption is that services within the catchment area will be completely accessible to residents in that area, which is obviously faulty. For instance, the distance between a resident and physician may exceed the threshold travel time within a catchment (e.g., the distance between 1 and b). Furthermore, while the physician at b is within tract 3, they may not be fully accessible to serve residents within the catchment since they will also serve neighbouring (but outside-the-catchment) individuals at 5, 8, or 11 (Luo and Wang, 2003).

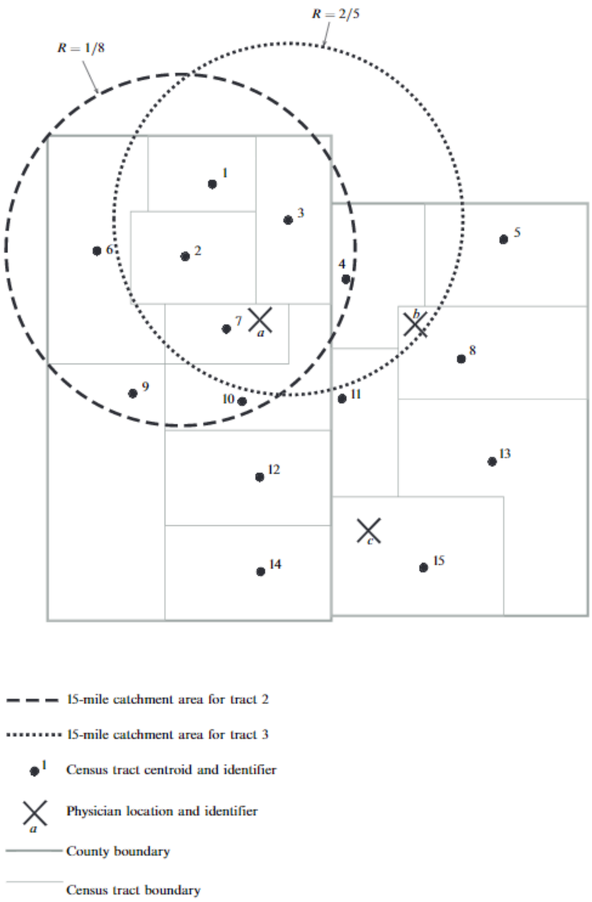

Figure 2.1: An early version of the floating catchment area (FCA) method (Luo and Wang, 2003).

Radke & Mu (2000) developed the spatial decomposition method in order to address these issues. Their approach computes the ratio of suppliers to residents within a service area centred on a supplier's location and aggregates the ratios for residents residing in places where the services of different providers overlap. They used straight-line distances, as in previous versions of the FCA method. In their study, analysis areas are separated by an overlaying circle, while service areas are a collection of decomposed areas (Luo and Wang, 2003).

2.4.2 Floating Catchment Area Methods

2.4.2.1 Two-Step Floating Catchment Area Method

To reflect its connection to the tradition of FCA methods, Luo & Wang (2003) called their method to measure spatial accessibility, the two-step floating catchment area (2SFCA) method. They used centroids to represent whole census tracts or zip-code areas for simplicity; therefore, their method does not involve any spatial decomposition of polygons as described by Radke & Mu (2000). As it says in the name the method is implemented in two steps. Instead of Euclidian distances, travel times are used. The two steps are as follows, according to Luo & Wang (2003):

Step 1: For each provider location j, search all population locations (k) that are within a threshold travel time (d_0) from location j (that is, catchment area j), and compute the provider-to-population ratio, R_j, within the catchment area:

$$\boldsymbol{R_j} = \frac{\boldsymbol{S_j}}{\sum_{k\in\left(d_{kj}\le d_0\right)} \boldsymbol{P_k}}\ , \tag{4}$$

where P_k is the population of tract k that falls within the catchment (that is, $d_{kj} \le d_0$), S_j is the number of providers at location j, and d_{kj} is the travel time between k and j.

Step 2: For each population location i, search all provider locations (j) that are within the threshold travel time (d_0) from location i (that is, catchment area i), and sum up the provider-to-population ratios, R_j, at these locations:

$$\boldsymbol{A_i^F} = \sum_{j\epsilon\{d_{ij}\le d_0\}} \boldsymbol{R_j}\ , \tag{5}$$

where A_i^F represents the spatial accessibility at population location i based on the 2SFCA method, R_j is the provider-to-population ratio at provider location j whose centroid falls within the catchment centred at i (that is, $d_{ij} \leq d_0$), and d_j is the travel time between i and j.

Better spatial accessibility at a location is indicated through a larger value of A_i^F. In the first step, an initial ratio is assigned to each service area centred at the provider locations. In the second step, these initial ratios are summed up in the overlapped service areas, where residents can access multiple providers. When implementing this method, a matrix of travel times between the provider and population locations is computed once and accessed in both steps.

Figure 2.2 illustrates the 2SFCA method with a threshold travel time of 30 minutes. The same provider and population distribution as in Figure 2.1 are assumed. The shaded areas correspond to different provider-to-population ratios. One provider and eight residents fall within catchment the area of physician a, giving it a provider-to-population ratio of 1/8. Similarly, in catchment area b, the provider-to-population ratio is 1/4. Residents that are located in only one of these catchment areas keep the calculated provider-to-population ratio; for example, resident 6 has a ratio of 1/8. However, residents that are located in an overlapping area of catchment areas have access to multiple providers. For example, resident 4 has access to both providers a and b and therefore, has a summed-up ratio of 3/8. The overlapping catchment areas are defined in step 2 of the 2SFCA.

Note that the catchment areas shown in Figure 2.2 are drawn in the first step with the provider locations at the centre. The catchment areas that are calculated in the second step are centred at the population locations (not shown in Figure 2.2). Only the providers within the catchment calculated in step two can be accessed by the residents, contributing to the provider-to-population ratios for these residents (Luo and Wang, 2003).

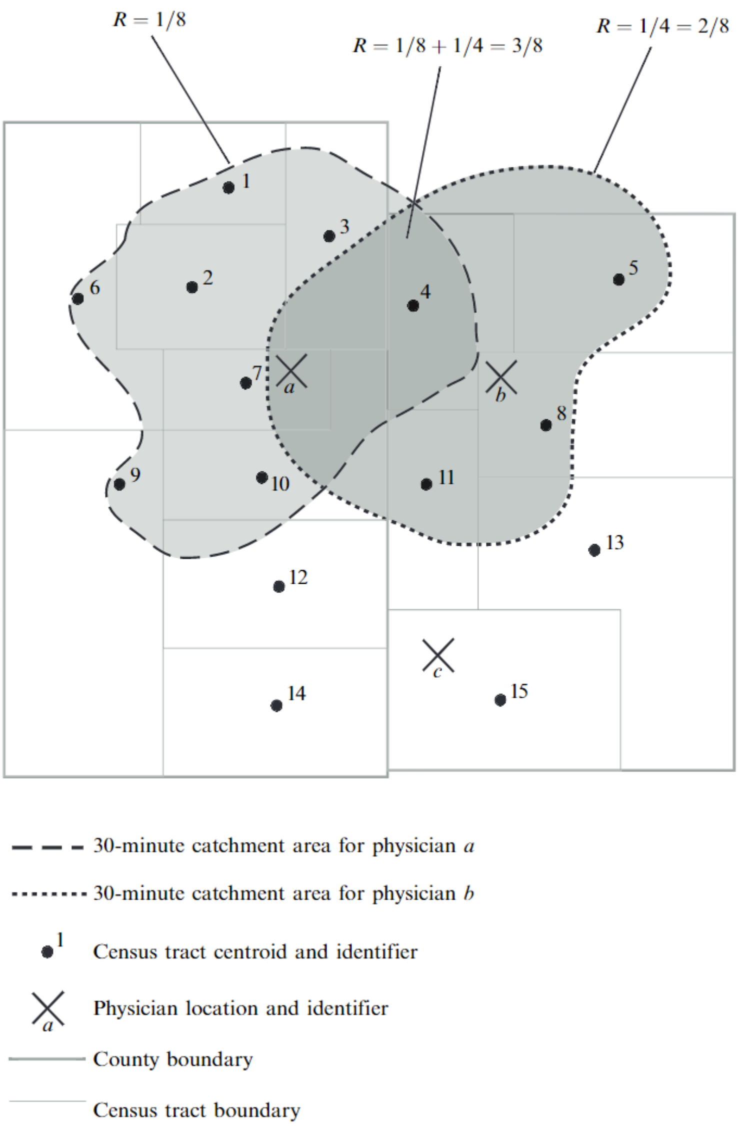

Figure 2.2: The two-step floating catchment area (2SFCA) method (Luo and Wang, 2003).

Equation (5) can be basically seen as a ratio of supply to demand, where only selected providers and residents enter the equation dependent on travel times. In the original 2SFCA method, providers are either accessible or inaccessible. All accessible providers are counted equally regardless of their actual travel time if they are within the threshold travel time (for instance, a provider 5 minutes away from a resident is counted equally as a provider 25 minutes away). All providers beyond the threshold travel time are defined as inaccessible (Luo and Wang, 2003).

The 2SFCA method stands as a starting point for a multitude of further developments of the original method, which try to tackle the problems of the 2SFCA method (Jörg et al., 2019).

2.4.2.2 Enhanced 2SFCA Method

The enhanced two-step floating catchment area (E2SFCA) method proposed by Luo & Qi (2009) was built on the previous 2SFCA method and enhanced it by applying weights to differentiate travel time zones in both steps, and thus accounting for distance decay. Hence, this method solves the problem of not differentiating accessibility within a catchment that was imminent in the original 2SFCA method. The E2SFCA method is again implemented in two steps. The two steps are as follows based on Luo & Qi (2009):

Step 1: The threshold travel time is defined as 30 min. Three travel time zones with minute breaks of 0-10, 10-20, and 20-30 min (zones 1-3, respectively) are computed within each catchment of provider location j. Search all population locations (k) that are within a threshold travel time zone (D_r) from location j (this is catchment area j), and compute the weighted provider-to-population ratio R_j, within the catchment area as follows:

$$\boldsymbol{R_j = \frac{S_j}{\sum_{k\in\{d_{kj}\in D_r\}} P_k W_r}}$$

$$\boldsymbol{= \frac{S_j}{\sum_{k\in\{d_{kj}\in D_1\}} P_k W_1 + \sum_{k\in\{d_{kj}\in D_2\}} P_k W_2 + \sum_{k\in\{d_{kj}\in D_3\}} P_k W_3}}\ , \qquad (6)$$

where D_r is the rth travel time zone and W_r is the distance weight for the rth travel time zone (r = 1 - 3) calculated from the Gaussian function. All other variables are the same as in Equation (4).

Step 2: In the second step, the provider-to-population ratios are summed up equally to the second step in the 2SFCA method:

$$\boldsymbol{A_i^F = \sum_{j\in\{d_{ij}\in D_r\}} R_j W_r}$$

$$\boldsymbol{= \sum_{j\in\{d_{ij}\in D_1\}} R_j W_1 + \sum_{j\in\{d_{ij}\in D_2\}} R_j W_2 + \sum_{j\in\{d_{ij}\in D_3\}} R_j W_3}\ . \qquad (7)$$

The same distance weights as in step 1 are applied to different travel time zones to account for distance decay.

The E2SFCA addresses the issue of not distinguishing accessibility throughout the catchment and is thus conceptually more equivalent to the gravity model. One issue raised at 2SFCA is that accessibility is overestimated in overlapping provider catchment areas, where residents are presumed to get services from all providers whose service areas overlap. This may not always be the case because residents on the outskirts of a catchment may not be adequately addressed by providers in the catchment's core. This challenge is overcome in E2SFCA because distance decay within the catchment is taken into account by distance decay weights (Luo and Qi, 2009).

2.4.2.3 Kernel Density 2SFCA Method

Some methods require the operationalisation of distances on a continuous scale. This means that all distances are measured separately for all offers and population points, as long as the distance is smaller than the maximum radius (Jörg et al., 2019). The kernel density two-step floating catchment area (KD2SFCA) method proposed by Dai & Wang (2011) is one of these methods. The method incorporates a kernel function (KD) into the 2SFCA to capture variation within each catchment area. The KD2SFCA incorporates a kernel function in each of the steps of the 2SFCA to account for distance decay between providers and residents. The bandwidth (h) in the KD function is the same as the catchment range (also known as the threshold travel distance or travel time, i.e., d_0) in the 2SFCA. In the KD function, spatial accessibility is decreased by travel distance or time to the kernel's edge and hits 0 beyond the kernel. In particular, the KD function (f) is utilized in the first phase to rescale the population at each location (k) based on its travel distance or trip time from a provider location (j), while everything else remains unchanged. In the second stage, the KD function is used to rescale R_j based on the travel distance or time between a provider location and a population location (Dai and Wang, 2011). The KD2SFCA is written as follows, according to Dai & Wang (2011):

$$\boldsymbol{A_i^F} = \sum\nolimits_{j\epsilon\{d_{ij}\leq d_0\}} \boldsymbol{R_j f(d_{ij}, h)} = \sum\nolimits_{j\epsilon\{d_{ij}\leq d_0\}} \frac{\boldsymbol{S_j f(d_{ij},h)}}{\sum_{k\in(d_{kj}\leq d_0)} \boldsymbol{P_k f(d_{ij},h)}}\ , \qquad (8)$$

where f is the kernel density function (Equation (9)), and all other variables are the same as in Equations (4) and (5).

Prior to performing the analysis, the kernel function (or kernel shape) and bandwidth h (or the threshold that sets the catchment area) must be determined. (Dai and Wang, 2011) found various kernel functions proposed in the literature. The kernel function and bandwidth should ideally be decided by how residents perceive trip impedance (e.g., time, monetary cost, and convenience). Such a perspective differs across ages, races, and socioeconomic conditions, therefore determining it would necessitate comprehensive surveys (Dai and Wang, 2011). For convenience, they used the Epanechnikov function (Epanechnikov, 1969) written as follows:

$$\begin{aligned} f(d_{ij}, h) &= \frac{3}{4}\left[1 - \left(\frac{d_{ij}}{h}\right)^2\right], \qquad if\ d_{ij} \leq h; \\ f(d_{ij}, h) &= 0, \qquad\qquad\qquad\qquad if\ d_{ij} > h, \end{aligned} \tag{9}$$

where i and j are the same as in Equations (*4*) and (*5*).

2.4.2.4 Other FCA Methods

A variety of further developments of the original 2SFCA method have been developed.

Wan et al. (2012) suggested a three-step floating catchment area (3SFCA) method to address demand overestimation in gravity-based spatial access models. The method assumes that the availability of other nearby services influences a population's demand for a service. In practice, it adds a travel-time-based competition weight to each population-provider pair in addition to the E2SFCA method. The 3SFCA selection weight does not account for the supply side effect on people's selection. As a result, the selection weight of 3SFCA was enhanced (E3SFCA) to account for capacity disparities among potential service sites by J. Luo (2014, 2016). For that they integrated the Huff Model, a widely used method for calculating the likelihood of customers choosing one service site over another, into the 3SFCA. According to Delamater (2013), all FCA measures include the underlying premise that supply locations are ideally organized to fulfil the population’s needs inside the system. Because completely optimal configurations in real-world health care systems are exceedingly implausible, Delamater (2013) proposed a modified two-step floating catchment area (M2SFCA) metric to solve this issue. The M2SFCA is based on the E2SFCA and includes an additional distance weight in the calculation. The additional weighting ensures that the distances between services and population locations will be considered both in a relative and absolute sense. In the Modified-Huff-Model-Three-Step-Floating-Catchment-Area (MH3SFCA) method, Jörg et al. (2019) combined different aspects of earlier FCA methods. They used the Huff-model in order to consider supply competition analogue to the E3SFCA method. Furthermore, the influence of the distances is considered not only relatively, but also absolutely (analogous to M2SFCA). In contrast to the M2SFCA, the MH3SFCA represents changes in absolute distance weights proportionally. In addition, the MH3SFCA, in contrast to the earlier FCA methods, assumes a constant total demand for each population. This means that the total demand for a population is independent of the number of accessible offers and the distance to these offers.

As mentioned before, some approaches require distances to be operationalized on a continuous scale. One of these methods is the KD2SFCA introduced in the section above (Jörg et al., 2019). W. Luo & Whippo (2012) proposed the variable 2SFCA method (V2SFCA), a method for dynamically determining provider and population catchment sizes by incrementally extending the catchment until a basic population and provider-to-population ratio are met. They showed that in comparison to results utilizing pre-set catchment sizes, their method is effective in determining the proper catchment sizes across the transition of urban to suburban/rural areas. To reduce mistakes caused by mismatched supply and demand catchments, Ni et al. (2015) enhanced the V2SFCA method by recommending that the facility and population catchment areas must both include the other location when determining accessibility (EV2SFCA). This means that either location must be within the catchment area of the other location in both steps of the method. Polzin et al. (2014) adapted the KD2SFCA method for health care access analysis and extended it to capture other access dimensions. They included a health needs index based on demographic and socioeconomic data, as well as a commuting index with factors referring to the populations' daily movements between their homes and employment or places of study (EKD2SFCA). The integrated-FCA (iFCA) method by Bauer & Groneberg (2016) combines several advancements into a single methodology. These include considering supply competition using the Huff model and variable catchment areas. For the latter, a distinct distance weighting function is calculated for each population point, and the parameters are empirically estimated using the median and standard deviation (SD) of the population-specific distances to the supply sites. For this purpose, they used the logistic distribution function. As a result, there is no longer a requirement to define the distance friction parameter a priori; instead, it can be calculated from the data distribution.

Other methods are extensions that can be integrated independently of the underlying basic model (Jörg et al., 2019). In the optimised 2SFCA (O2SFCA) method by Ngui & Apparicio (2011) the demand is modelled with regard to the age distribution of a certain population instead of the total population volume. For this purpose, each age group is multiplied by its share of "medical users". Mao & Nekorchuk (2013) proposed the multi-mode-2SFCA (mm2SFCA), a method for including transportation options in the estimate of accessibility. By accounting for population heterogeneity (meaning variable travel mode availability for the population), they claimed to provide a more accurate accessibility estimation. By taking daily commuting behaviour into account, in both the first and second steps of the 2SFCA procedure, Fransen et al. (2015) proposed the commuter-based two-step floating catchment area (CB2SFCA) method. In this method, the demand is not simply equated to the number of stationary people inside a zone but is made reliant on the commuting behaviour of the inhabitants whose position is deemed to shift within the study region. Table 2.2 gives an overview of the characteristics of all the mentioned FCA methods.

Table 2.2: Overview of the properties of the mentioned FCA methods. Based on Jörg et al. (2019).

properties	**2SFCA**	**E2SFCA**	**KD2SFCA**	**3SFCA**	**E3SFCA**	**M2SFCA**	**MH3SFCA**	**V2SFCA**	**EV2SFCA**	**EKD2SFCA**	**iFCA**	**O2SFCA**	**mm2SFCA**	**CB2SFCA**
Consideration of relative distance differences (within the max. radius)	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Supply competition is considered	x	x	x	✓	✓	x	✓	x	x	x	✓	x	x	x
Consideration of relative and absolute distances	x	x	x	x	x	✓	✓	x	x	x	x	x	x	x
Constant total demand per population	x	x	x	x	x	x	✓	x	x	x	x	x	x	x
Consideration of variable catchments	x	x	x	x	x	x	x	✓	✓	x	✓	x	x	x

2.5 Travel Time and Walking Speed

As mentioned before, travel time takes an important role in calculating spatial accessibility since only locations within a threshold travel time are considered accessible. Therefore, it is important to know the walking speed, which affects the time one must travel to reach a certain point. Especially, when walking speeds vary due to changes in inclinations. Furthermore, the maximum time people are willing to travel to a certain location defines the travel time threshold used in spatial accessibility analysis. Besides, barriers that need to be overcome or evaded, especially by mobility-impaired people, play another role in travel time.

2.5.1 Walking Speed

Walking is one of the most important modes of transportation since every trip begins and ends with walking (Sangeeth and Lokre, 2019). Studies investigating the walking speed of pedestrians by age, gender, trip purpose, time of day, level of mobility, incline, and various more factors can be found in the literature. Results of some of the below-mentioned literature by age/population group can be found in Tables 2.3 and 2.4.

Sun et al. (1996) studied uphill and downhill walking of urban pedestrians on inclines up to 9°. During a 3-month period, they recorded gait characteristics of 2400 pedestrians traversing a ramp of naturally varying inclinations in Sidney, Australia. For each subject, walking speed, cadence and step length were determined, and for each ramp angle average population gait parameters were calculated.

In a video-based observational study, Willis et al. (2004) explored individual movement preferences within uncluttered environments in Edinburgh, covering particularly desired walking speeds, microscopic position preferences, and interpersonal distances between accompanying persons while walking. Furthermore, they investigated how said variables might be affected by the many personal, situational, and environmental factors that describe the surroundings in which pedestrians move. It was discovered that movement preferences varied significantly across the different locations surveyed, depending on age, gender, mobility level, group size, time of day, and location.

In a meta-analysis, Bohannon & Williams Andrews (2011) described normal gait speed for healthy individuals by age and gender. The requirement for articles to be included in the analysis was that the gait speed of seemingly healthy adults was measured as they walked at a typical pace across a distance of 3 to 30 m. The authors analysed 41 articles providing data from 23’111 subjects.

Finnis and Walton (2007) evaluated pedestrian walking speeds in New Zealand in order to estimate the effects of mean walking speeds on urban planning and pedestrian facility design. They used field observations of walking speeds under different conditions: inclination and urban/rural townships. Their findings demonstrate complicated interrelationships between the environment, pedestrian personal qualities, and physical factors. These findings contradict the notion that walking speeds are indicative of life pace. Rather, walking speeds are advocated as an indicator of the environment's "walkability," as walking rates that closely mirror those of the average population are critical to the successful design of pedestrian infrastructure.

Silva et al. (2014) focused on identifying and evaluating the effects of several factors on pedestrian walking speed. Moreover, they developed a mathematical model estimating pedestrian walking speed according to the relevant variables. The study resulted in average walking speeds (see Table 2.3), confirming the results they found in the specialised literature.

Trpković et al. (2017) conducted a study determining the crossing speed of elderly pedestrians (65+) at ten intersections in Belgrade, Serbia. Data was collected using direct observation and a questionnaire. Their results showed lower walking speeds for the older population and a significant influence of the crossing type on walking speed.

The mean individual pedestrian speed and its connection with age and mean walking speed were studied by Pinna & Murrau (2018). Additionally, statistical models able to interpret pedestrian behaviour were found. The research was conducted in an urban setting in Oristano (Sardinia, Italy), where pedestrian speed was determined using video processing. The authors described their choice of the mean individual pedestrian speed as a dependent variable as a novelty, as they analysed a real condition where pedestrians walk within a flow, and not alone. They found a decrease in individual pedestrian’s speed with increasing age.

The pedestrian’s speed, along with the factors influencing it, such as gender, age, group size, and trip purpose, was evaluated by Sangeeth & Lokre (2019). Their hypothesis that the pedestrian’s speed alters based on each factor was proven.

In a study by Thomson et al. (2019), healthy adults between 20 and 80 years of age completed the 10m walk test on flat, downhill, and uphill surfaces at the fastest and preferred walking speed. For each speed and inclination an analysis of variance was implemented to discriminate age-related changes in gait speed by decade.

Rispens et al. (2021) collected walking speed data from different population groups (healthy adults, elderly, and elderly patients) in several environments (overground, treadmill, and using walking aids) to evaluate the performance of wearable accelerometers.

2.5.1.1 Wheelchair Propulsion Speed

Boyce et al. (1999) determined the capabilities of disabled people to move on flat and inclined surfaces separated by the use of a mobility aid, the degree of assistance needed, and the presence or absence of a handicap limiting locomotion. Participants had to traverse a 50 m long horizontal route and a ramp of 3° to 4°. Movement speeds were captured using a handheld stopwatch. They found only one of the participants using a manual wheelchair could traverse the ramps (~4°) without assistance.

A kinetic investigation of manual wheelchair propulsion on selected indoor and outdoor surfaces during start-up was conducted by Koontz et al. (2005). The participants were asked to push on a course consisting of various surface types, including high- and low-pile carpet, grass, and a sidewalk with a 5° incline. Data was obtained using a force and torque-sensing push rim. Variables analysed included peak resultant force, peak velocity, and distance travelled during the first 5 seconds of the trial. They found no difference in peak velocity during start-up. However, average speeds were lower on the ramp and grass.

Tolerico et al. (2007) investigated mobility characteristics and activity levels of manual wheelchair users in a home environment and at the National Veterans Wheelchair Games (NVWG) from 2004 to 2006. The activity was monitored using a custom data logger for 13 to 20 days and through a brief survey. Results included overall travel time per day and average speed. Both variables were lower in the home environment compared to an average day at the NVWG.

Correlations between wheelchair activity and community participation was investigated by R. A. Cooper et al. (2011). Data was collected using a data logging device during weeks. The authors found significant positive correlations between average speed and community participation in areas of transportation and socialisation, as well as a trend to significant correlation between average speed and total community participation for manual wheelchair users.

Karmarkar et al. (2011) determined and compared wheelchair mobility patterns for older adults during the NVWG 2007 and their home environment. Data was collected using data logging devices attached to the wheelchairs. Results showed that participants were significantly more active during the games than at home in terms of distance travelled and average propulsion speed.

Chénier et al. (2018) assessed the perception of speed when propelling on a treadmill versus overground for manual wheelchair users and related this perception to measured spatiotemporal variables, kinetics, and work. Participants propelled their wheelchairs in a 20 m level tilted hallway, keeping a preferred constant speed (OG) and on a treadmill once with a speed they perceived as the same as in the hallway ($TM_{perceived}$) and once with the real speed matched ($TM_{matched}$). Results showed that all participants chose a lower speed for $TM_{perceived}$ than for OG.

Table 2.3: Mean walking/travel speeds on flat surfaces by age/population group.

age	speed [m/s]	source
20 to 60	1.380	(Bohannon and Williams Andrews, 2011)
60 to 80	1.245	
80+	0.955	
15 to 30	1.462	(Finnis and Walton, 2007)
30 to 55	1.487	
55+	1.374	
65+	1.200	
16 to 25	1.550	(Willis et al., 2004)
26 to 50	1.470	
51 to 64	1.380	
64+	1.160	
19 to 40	1.000	(Pinna and Murrau, 2018)
41 to 65	0.990	
65+	0.840	
20 to 59	1.465	(Thomson et al., 2019)
60 to 79	1.380	
18-64	1.222	(Silva et al., 2014)
65+	0.950	
manual wheelchair	0.690	(Boyce et al., 1999)
	1.310	(Chénier et al., 2018)
	0.810	(Cooper et al., 2011b)
	0.790	(Tolerico et al., 2007)

Table 2.4: Mean walking/travel speed [m/s] on inclinations by age/population group.

age	inclination [°]																source
	-9	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**+2**	**+3**	**+4**	**+5**	**+6**	**+7**	**+8**	**+9**	
10 to 35	1.450	1.200	1.250	1.300	1.275	1.275	1.175	1.350	1.325	1.325	1.275	1.250	1.275	1.250	1.225	1.200	(Sun et al., 1996)
35 to 55	1.200	1.150	1.150	1.150	1.175	1.225	1.150	1.200	1.230	1.200	1.225	1.270	1.225	1.150	1.180	1.125	
55 to 75	0.910	0.900	0.925	0.920	0.925	1.000	0.970	1.020	1.080	1.080	1.000	0.980	1.000	0.975	0.980	0.880	
no											1.377	1.530	1.530	1.393			(Finnis and Walton, 2007)
20 to 59		1.553													1.510		(Thomson et al., 2019)
60 to 79		1.395													1.345		
manual wheelchair												1.100					(Koontz et al., 2005)
						1.050					0.700						(Boyce et al., 1999)

2.5.2 Maximum Travel Times/Trip Distances

The basic unit of travel, a trip, is defined by the Department for Transport UK (2006) as a "one-way course of travel having a single main purpose. Outward and return halves of a return trip are treated as two separate trips."

A national travel survey was conducted by the Department for Transport UK (2006). Average walking trip durations were reported as 16 minutes in 2006. 37% of the participants replied that they walked for 20 minutes or more at least three times per week, with another 22% doing so at least once or twice weekly.

Yang & Diez-Roux (2012) examined the frequency of walking, as well as the length and purpose of walking trips among U.S. residents. Using nationally representative data from the 2009 National Household Travel Survey (NHTS), the length and purpose of walking trips were examined across population groups. The mean walking duration found was 14.9 minutes. Roughly 65% of walking trips exceeded 0.25 miles (400m) in distance, and 18% were more than 1 mile (1600m). Furthermore, about 69% of walking trips lasted more than 5 minutes and around 23% lasted more than 20 minutes. Large variations for both distance and duration were found among different trip purposes. The distance and duration of trips were considerably longer for recreational trips than other purposes.

Barnett et al. (2015) used a 7-day diary and accelerometery to investigate the purposes and destinations of older adults in Hong Kong. The average return trip duration was 41.7 minutes within the neighbourhood and 38.7 minutes outside of the neighbourhood. Trip walking time averaged 735 minutes per week and an average of 17.1 walking trips per week were reported. The authors stated that these findings are much higher compared to older adults in non-Asian settings.

The characteristics of active transportation utilisation among older adults (those over the age of 65) in Melbourne, Australia, were explored by O'Hern & Oxley (2015). The authors used data from the Victorian Integrated Survey of Travel Activity (VISTA). Overall, the mean lengths of walking intervals were roughly 10 minutes. The average walking time was found to be longer for adults between the ages of 65 and 85 than for younger adults but shorter for those 85 and older.

Macioszek et al. (2022) identified and compared the effects of various socioeconomic, transportation-related, and built-environment variables on the likelihood of walking and respondents' sensitivity to the walking distance, both for optional and required trips. Data was collected through an intensive travel survey in Qazvin, Iran. The data showed that mandatory trips had a higher likelihood of walking than optional trips at practically all distances. The authors indicated that in comparison to other age groups, the elderly are more likely to prefer walking for trips between 1200 and 1600 meters.

2.5.3 Barriers

Mobility-impaired persons such as wheelchair users experience barriers in accessing public services in their everyday life. Meyers et al. (2002) commenced an intensive study of adult wheelchair users in order to determine the ability of reaching or failing to reach specific locations, determine encounters with environmental barriers and facilitators and the frequency of encountering them. Most frequent barriers that were reported as overcome by the subjects included personal barriers, such as personal illness, lack of motivation, or limited fitness and environmental barriers, such as inaccessible bathrooms, no ramps or ramps too steep, narrow aisles, wheelchair problems, travel surfaces, and bad weather. Barriers not overcome by the subjects included personal illness, limited fitness, or unsafe neighbourhoods.

For developing a wheelchair routing system, Matthews et al. (2003) gathered the experiences of wheelchair users through a questionnaire. The most common barriers cited included steps, high kerbs and no dropped kerbs, bad surfaces, steep gradients, and narrow pavements. The length and gradient of inclines was detected as especially problematic for wheelchair users by Beale et al. (2006) using the same questionnaire results as Matthews et al. (2003). Furthermore, the type of wheelchair (i.e., manual or powered) influenced which barriers hindered access, where some surfaces and inclinations are easier to navigate for powered wheelchair users.

In order to specify requirements for ramp design, including maximum running and cross slope, Vredenburgh et al. (2009) studied the perceived effort of wheelchair users to negotiate these ramps. They suggested a reasonable ramp design with a maximum cross slope of 5% when the running slope is less than 2% and a maximum running slope of 7% when the cross slope is 2% or less.

Holloway & Suzuki (2010) found the only capability to travel on a flat footway to be the ability to produce enough force to move the wheelchair. However, travelling on a way with a cross slope requires a second capability, namely the ability to provide different forces to both wheels of the wheelchair.

Menkens et al. (2011) interviewed several wheelchair users about their needs in a wheelchair navigation application. Unannounced road or sidewalk construction sites, variations in street surfaces, steep road inclines, high kerbs, narrow streets/sidewalks, and uneven surfaces were found to be the main problems of wheelchair users. Furthermore, they found a difference in wheelchair user type; where a fit wheelchair user could easily traverse a kerb, a help-dependent user in a powered wheelchair may have difficulties overcoming the barrier. They found that the maximum incline a manual wheelchair user can climb is between 3% and 8% and 10% for a powered wheelchair user. In the pedestrian traffic planning in Switzerland ramps with a maximum gradient of 6% (12% for natural ramps) are allowed to ensure accessibility not only for wheelchair users but also for older people, parents with pushchairs, or persons with luggage (Bundesamt für Strassen (ASTRA) and Fussverkehr Schweiz, 2015).

Gharebaghi & Mostafavi (2018) identified the characteristics of footpaths (e.g., surface quality and incline) and the users’ capabilities as factors affecting the speed of manual wheelchair users.

Henje et al. (2021) identified barriers and risks of powered wheelchair users by surveying their behaviour and experiences in traffic environments based on the human, vehicle (wheelchair), and environmental factors. Barriers found included uneven surfaces, differences in ground level (kerbs), steep gradients, interactions with other road users, and the influence of weather conditions.

3 Data And Tools

The main data sources for this project are OSM (OpenStreetMap, 2021), the Open Data Catalogue of the city of Zurich (ODCZ) (City of Zurich, 2022a), and the Federal Office of Topography Switzerland (swisstopo) (swisstopo, 2021). Section 3.1 provides an overview of the tools used in this thesis. The exact sources and use cases, regarding the components of spatial accessibility, of the data are explained in Sections 3.2 to 3.4.

3.1 Tools

A variety of tools were employed to work on this topic and implement the steps of the workflow. The R programming language (version 4.1.2) in the integrated development environment (IDE) RStudio (version 2022.02.3+492) was used to implement most of the data processing and data analysis, as well as the visualisation of intermediate results. The open-source GIS-tool QGIS (version 3.16.14) has been used to visualise final results and to download data from OSM using the Add-In “Quick OSM” and to pre-process the OSM data. “Quick OSM” allows users to easily download data from OSM by tag/key and area.

3.2 Supply

Public and commercial facilities were used as the supply in spatial accessibility analysis. All data was downloaded from OSM in ESRI Shapefile format (OpenStreetMap, 2022c). A list of all public facilities/points of interest (POIs) downloaded from OSM can be found in Table 3.1. Tags that were downloaded on different dates than the main part of the data are marked accordingly.

Table 3.1: All POIs downloaded from OSM.

OSM tag	**# of POIs**	**description**
amenity=clinic	33	medical centre with more staff than a doctor's office
*amenity=doctors**	80	place to get medical attention
amenity=dentist	39	place where a professional dental surgeon is stationed
amenity=pharmacy	112	shop where a pharmacist sells medication
amenity=hospital	6	hospital providing in-patient medical treatment
*shop=supermarket***	161	large shop for groceries and other goods
amenity=marketplace	7	public marketplace where goods are traded daily or weekly
amenity=bank	84	financial establishment where customers can, among other services, deposit money and take loans
amenity=post_office	37	place where letters and parcels may be sent or collected
amenity=townhall	1	seat of the mayor, a community meeting place, or building with offices of a city administration
amenity=college	52	place for further education (no university)
amenity=university	24	institution of higher education
amenity=music_school	8	educational institution for music
amenity=language_school	5	educational institution for (foreign) languages
amenity=library	58	place to read and/or lend books
leisure=sports_centre	96	distinct facility where sports take place within an enclosed area
leisure=stadium	4	major sports facility with substantial tiered seating
amenity=public_bath	27	location where the public may bathe in common (visible signed and some kind of man-made facilities)
amenity=theatre	39	place where live theatrical performances are held
tourism=zoo	4	zoological garden, where animals are confined for viewing by the public
leisure=park	166	area of open space for recreational use
amenity=cinema	21	place showing movies
amenity=community_centre	50	place mostly used for local events, festivities, and group activities
*amenity=place_of_worship****	128	place where religious services are conducted
amenity=bar	204	establishment that sells alcoholic drinks to be consumed on the premises

amenity=pub	79	same as amenity=bar but also sells food
amenity=biergarten	3	open-air area with benches where beer is served
amenity=cafe	337	generally informal place with sit-down facilities selling beverages and light meals and/or snacks
amenity=fast_food	316	place concentrating on very fast counter-only service and take-away food
amenity=bbq	78	permanently built place for having a BBQ
amenity=restaurant	1087	generally formal eating places with sit-down facilities selling full meals served by waiters

*downloaded on 28.11.2021.

**downloaded on 29.11.2021.

***downloaded on 14.07.2022.

3.3 Demand

The demand in spatial accessibility analysis was covered using the population dataset "Räumliche Bevölkerungsstatistik (OGD)" (City of Zurich, 2022b) retrieved from the Open Data Catalogue of the city of Zurich in Esri Shapefile format. The population dataset consists of a polygon grid layer with a 100mx100m cell size and a point layer containing the centroids of the grid cells. The data in each cell consists of the total population in that cell (Figure 3.1) as well as the population of different age groups in percent of the total population in the cell. Status of the population data is the 30.06.2020 (Statistisches Amt Kanton Zürich, 2020).

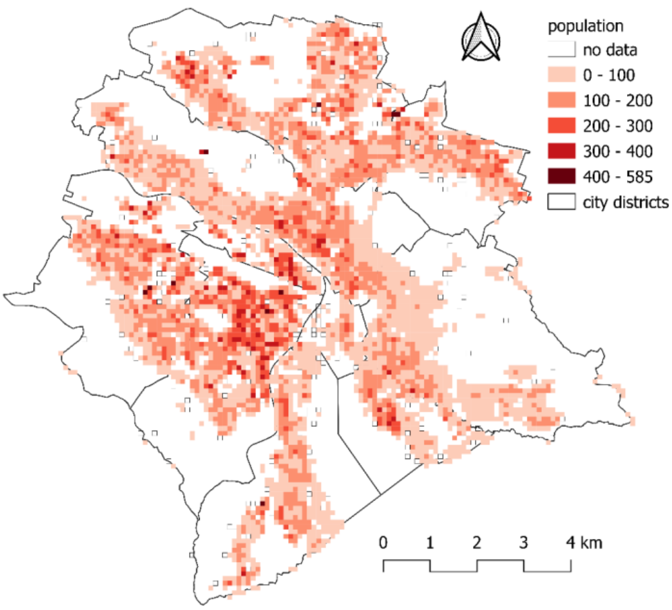

Figure 3.1: Distribution of the total population in the city of Zurich.

3.4 Travel Times

In order to compute the travel times, used in spatial accessibility analysis, footway data from OSM and the Open Data Catalogue of the city of Zurich (Figure 3.2) was used to create footway networks (see Section 4.1.1). The OSM footpath network was used for the spatial accessibility analysis, the footpath network from ODCZ was used for assessing the completeness of the OSM network.

All final footway data from OSM was downloaded in Esri Shapefile format (OpenStreetMap, 2022b). The exact tags and the number of footways on OSM can be found in Table 3.2. The official footway dataset of the city of Zurich "Fuss- und Velowegnetz" (City of Zurich, 2021b) was downloaded through the Open Data Catalogue of the city of Zurich in Esri Shapefile format.

Table 3.2: All footways downloaded from OSM for the city of Zurich. Earlier versions (in brackets) were used for intermediate results.

OSM tag	**# of ways**	**description (OpenStreetMap Wiki, 2022q)**
highway=footway	20233 (17709*)	designated footpaths, i.e., mainly/exclusively for pedestrians
highway=living_street	319 (297**)	road with very low speed limits and other pedestrian friendly traffic rules
highway=path	2515 (2461*)	generic or multi-use path open to non-motorized traffic
highway=pedestrian	288 (253**)	roads mainly/exclusively for pedestrians
highway=track	1524 (1520**)	minor land-access road like a farm or forest track

*downloaded on 24.11.2021.

**downloaded on 20.12.2021.

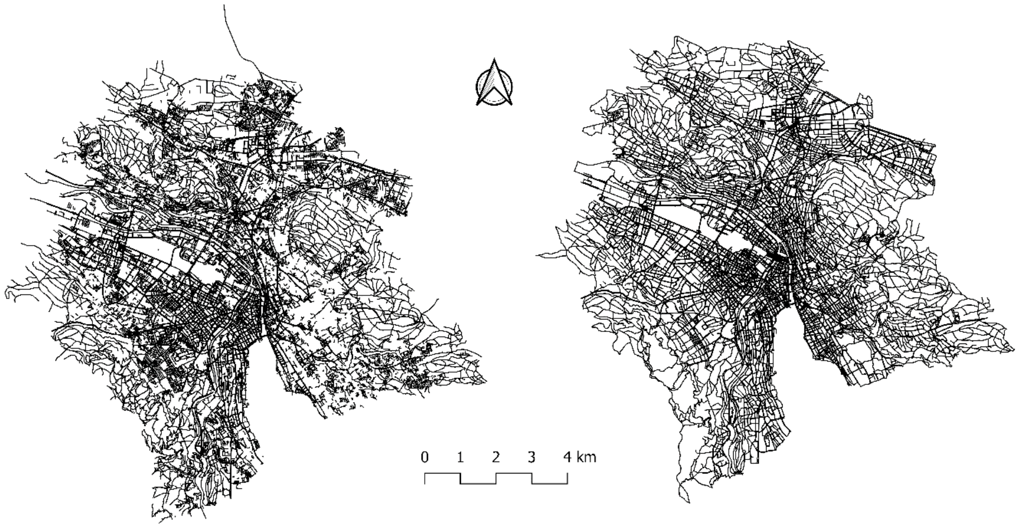

Figure 3.2: Footway data from OSM (left) and the ODCZ (right) for the city of Zurich.

Furthermore, in order to calculate the inclination of footways “swissALTI3D”, a Digital Elevation Model (DEM) in 0.5 m resolution was retrieved from swisstopo in TIFF file format (swisstopo, 2021). A DEM is a bare-earth elevation raster grid filtering out all natural and built features on earth (GISGeography, 2021). SwissALTI3D is a digital elevation model that is exceptionally accurate and portrays the topography of Switzerland without vegetation or development. Updates are made every six years (swisstopo, 2021). Figure 3.3 shows 10m contour lines of the said DEM for the city of Zurich.

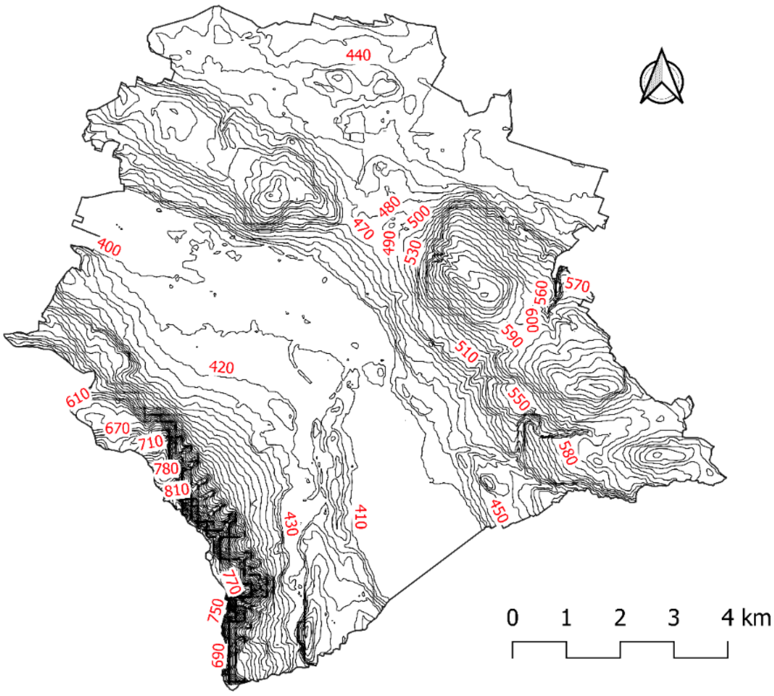

Figure 3.3: 10m contour lines of the used DEM for the city of Zurich.

4 Methodology

4.1 Accessibility Data Enrichment

The available OSM footpath dataset was enriched with inclination information. The following Sections describe the necessary steps that had to be done to execute the enrichment.

4.1.1 Pre-processing Footpath Data

In the first step, the downloaded OSM footpath data (Figure 3.2, Section 3.4) was read into R, and the Coordinate Reference System (CRS) was set to CH1903+ / LV95, which is the standard CRS used in Switzerland.

Only ways that are mainly/exclusively designated for pedestrians were included in this study. Figure 4.1 illustrates an example of why sidewalks that are mapped as a refinement of a street are missing in this study. Here, the same sidewalks are mapped once as an individual way (as *highway=footway*), but also as a refinement of the street (as *highway=tertiary*). In other cases, sidewalks are mapped as an individual way but are missing in the attributes of the intervening street or sidewalks are not mapped as individual ways but only as attributes of a street. These cases would either lead to duplicated data or topologically incorrect data.

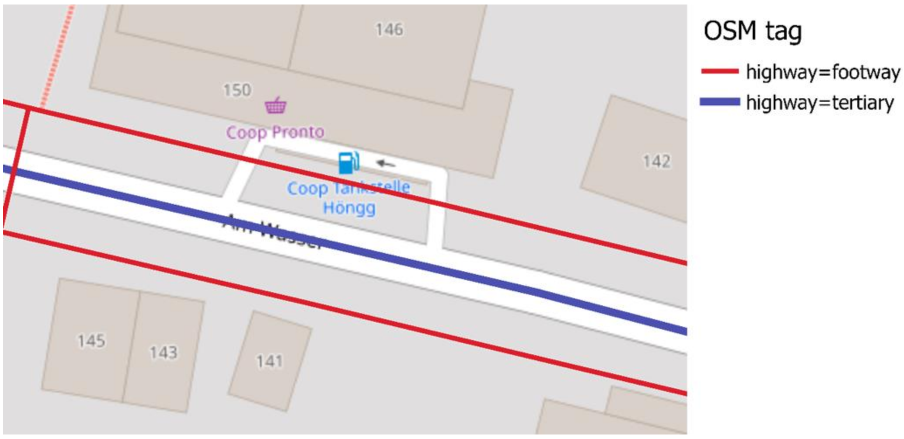

Figure 4.1: Example of identical sidewalks mapped in different ways on OSM (OpenStreetMap, 2021).

In the next step, all OSM footpaths were merged into one spatial lines object. The footway data from ODCZ, which was used as a comparison to the OSM footway dataset, originally consists of two different ways, namely footways and cycleways. All ways that are solely cycleways were therefore removed from the dataset.

4.1.1.1 Quality Analysis

To inspect the two datasets further mentioned above, a small quality analysis was conducted. According to Goodchild (2008) one of the most significant aspects of VGI data is the completeness of the data. Haklay (2010) defined completeness as a measure of the lack of data, meaning data that is expected to be in a database but is missing, as well as an assessment of data that should not be included. Road length is commonly used to examine the completeness of OpenStreetMap data in contrast to a reference dataset (Forghani and Delavar, 2014). Calculating the total length of the roads from one dataset supplier within a given area and comparing it to the total length of the roads from the other provider within the same area can be used to assess how complete a road network is. One of the datasets is likely to be more complete than the other if there is a difference in the overall lengths (Forghani and Delavar, 2014; Zipf and Zielstra, 2014). Since there is no hint of the exact length of the full street network in the real world, this is obviously merely a relative measurement (Zipf and Zielstra, 2014). To conduct he quality analysis, a 100m*100m grid was laid over the study area and the length of the two networks in each grid cell was calculated.

As seen in Figure 3.2, the OSM footpath dataset does not cover the whole city, whereas the official footpath dataset does. In contrast, in parts of the city the OSM data has more footpath data available. Figure 4.2 shows the distribution of which dataset has a greater overall length of footpaths available. In the red areas the reference dataset has an overall greater footpath length and in the blue area the OSM dataset. At first glance, the OSM dataset seems to be more complete than the reference dataset as more blue than red areas can be seen. However, as mentioned before, in some areas of the city the OSM dataset has no data at all, for example, the large area in the south-east of the city, which can be also seen in Figure 3.2. This reduces the quality of the OSM dataset drastically. The main difference between the two datasets is that the official dataset consists of mainly sidewalks and the OSM one also includes other footpaths (for instance, paths between buildings), which explains why the OSM dataset seems to be more complete in many areas of the city.

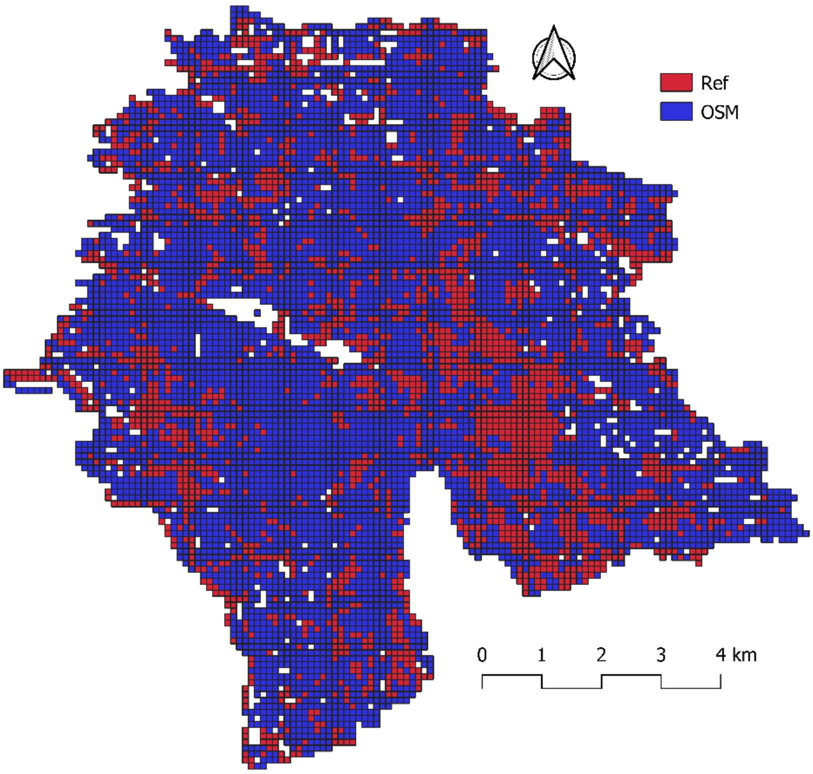

Figure 4.2: Binary view of the length difference of OSM and Reference footpath data in the city of Zurich.

4.1.1.2 Segmenting

Routing networks for routing applications need to be built from a topologically correct dataset: Nodes represent junctions, and streets represent the edges that connect them. Junctions are only recognized if the crossing streets share a common node at their intersection (Schmitz et al., 2008). Figure 4.3 shows examples of unrecognized junctions.

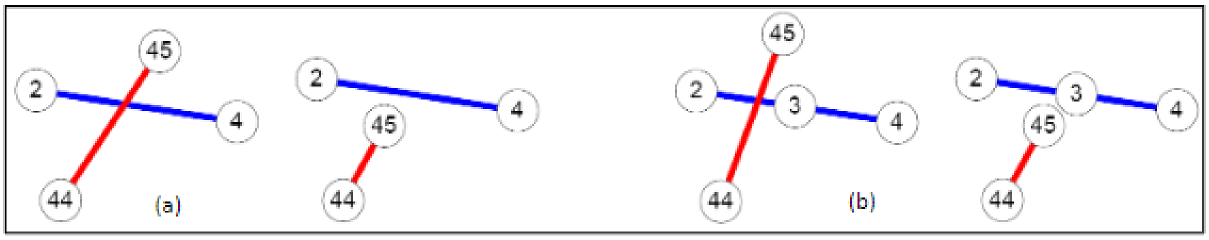

Figure 4.3: Examples of unrecognized junctions (Schmitz et al., 2008).

Topology is already regarded by the volunteer mappers as being a crucial component during the collecting and upkeep of OSM data. The above examples are not frequently seen in the OSM dataset, according to tests by Schmitz et al. (2008). Consequently, they were disregarded in further steps. Schmitz et al. (2008) investigated the existing topology of OSM data in terms of the occurrence of street intersections with shared nodes, i.e., junctions. Streets are separated into distinct edges (ways) at these common nodes (see Figure 4.4).

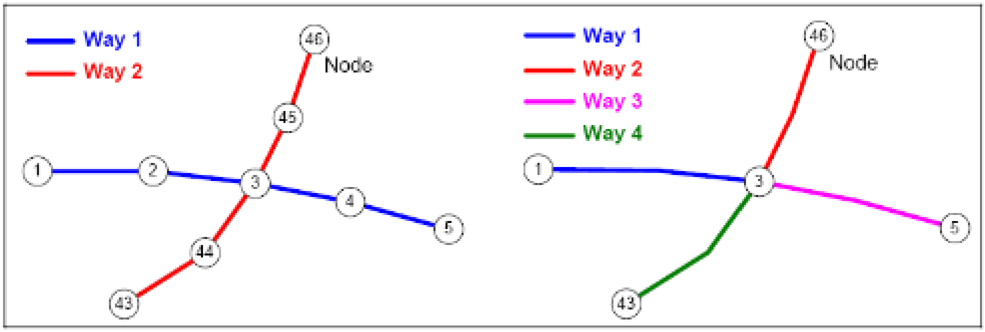

Figure 4.4: Building a routing graph from OSM data. left: original OSM data. right: modified OSM data (Schmitz et al., 2008).

In this study, however, the focus lies not on building a routing graph but enriching the footway data with inclination. Therefore, the original OSM/footway data had to be modified in a different way. Since the inclination is typically calculated using only the start and end nodes of each edge in the final footpath network (see Section 4.1.2), data loss in calculating the footway incline might happen. For instance, Figure 4.5 displays two situations in the real world where the calculated inclination would not reflect the reality. In Figure 4.5a, the street contains three segments, two of them being flat and one in the middle of these two segments being inclined. The average incline computed for this street segment yields a value that is lower than the actual incline. This causes a problem if a person expects, say, a 5% inclination along a 100m distance and instead encounters a 10% incline within 50m (John, 2015). Figure 4.5b depicts a situation where the average inclination is 0% because the street segments contain two inclined regions of equal magnitude but opposite directions.

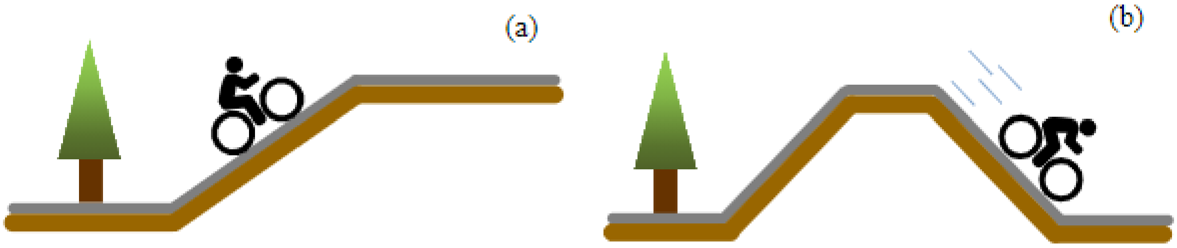

Figure 4.5: Situations where the calculated incline does not reflect the reality (John, 2015).

Therefore, to minimize the miscalculation of the inclination, the original footway data should be segmented even further. In this thesis, the original footway data was divided into smaller segments in two ways. Once so that the maximum segment length is 20 m. To do that, points (later called split points) were generated on all edges so that the maximum distance between the points is 20 m. This maximum length was assumed to adequately capture all inclination changes so that the average inclinations of the segments reflect the reality. Additionally, Haklay (2010) stated that the OSM dataset could be expected to be accurate within a region approximately 20 m from the actual location.

In a second approach, the maximum incline of each original OSM footway segment was searched. This is due to the convention on OSM, that the key “incline” shall be the maximum incline one will encounter traversing the way (OpenStreetMap Wiki, 2022j). The original data was segmented at every change of incline maximum. For this, each segment of the original footway data was further divided into subsegments with a maximum length of 0.5 m. Then, the elevation derived from the available DEM was added to the start and end points of each subsegment (the nodes), and the subsegment inclination was calculated using Equation (10) (see Section 4.1.2). Figure 4.6 gives an example of this method. For each original way, starting at the first node in direction of digitalization, the incline was calculated first between node 1 (the original node) and 2, then between nodes 1 and 3. If the incline between nodes 1 and 3 is greater than between nodes 1 and 2, the incline from the original node (1) to the next node (4) will be checked likewise. If the incline gets smaller at one of these checks, for example the incline from nodes 1 and 4 is smaller than from nodes 1 and 3, a point is generated at the location where the maximum incline was calculated (here node 3). These points are later used to split the edges of the original data. The incline between nodes 3 and 4 is then newly defined as the original incline. These checks are made in both positive and negative directions of incline. OSM ways where no elevation could be added due to lack of data values in the DEM were removed from this check.

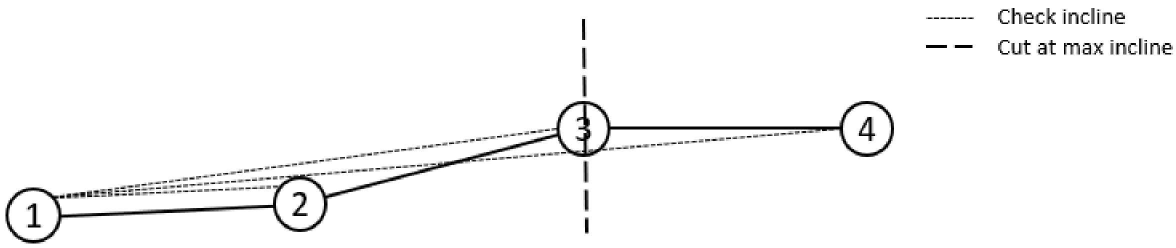

Figure 4.6: Illustration of the workflow of the second segmenting method yielding maximum incline.

Only results of the first approach were used for the conducted spatial accessibility analysis as the second approach was conducted after most of the spatial accessibility analyses were carried out and thus time constraints did not allow for using the results of the second approach.

4.1.2 Adding Inclination Information

The inclination of the footpaths was calculated in a simple geometric way using the elevation retrieved from the available DEM and the length of the individual edges of the network.

First, the footpaths were converted into a directed network (meaning a network where edges can only be traversed in one direction). Then, the before generated split points were used to cut the edges of the network and therefore, generating new edges and nodes.

The elevation at all nodes of the footpath network was then added to the nodes. Next, the incline of the edges was calculated as follows:

$$\boldsymbol{\theta} = \tan^{-1} \frac{y_{to} - y_{from}}{d_{from-to}}, \quad \textbf{(10)}$$

where θ is the angle of incline of the edge in radians, y_{to} is the elevation at the end node of the edge, y_{from} is the elevation at the start node of the edge, and $d_{from-to}$ is the network distance between both nodes. $d_{from-to}$ was calculated from the geometry of the edge. θ was then converted from radians to degree.

Furthermore, as walking speeds differ on positive and negative inclines, all edges of the network were duplicated and the direction of these duplicated edges and the sign of the incline (meaning positive inclines were changed to negative inclines of the same value and vice versa) were reversed.

Normally, outlier and unreasonably large values are removed from datasets. However, for the use case in this thesis these outliers were negligible as most of the outliers are located in the western mountainous region of the city (Uetliberg) where large inclinations can be reasonable. Only a small number of outliers, and these only on very small network edges, were detected in the city itself. Furthermore, for manual wheelchair users inclinations greater than 5° were seen as inaccessible and thus were already excluded; for the other population groups the effect of the outliers were assumed to be insignificant.

4.2 Spatial Accessibility Analysis

The necessary data and information to execute the spatial accessibility analysis are outlined in Sections 4.2.1 to 4.2.3. Section 4.2.4 describes how the utilized spatial accessibility measures were chosen and how they were implemented.

4.2.1 Population Groups

The population groups were chosen based on the used population dataset introduced in Section 3.3 and the available information on walking speeds, including younger adults (age 20 - 64), older adults (age 65 - 79), and healthy manual wheelchair users (all ages). The population dataset also contains information on adults aged 80 and above; however, there was no reliable walking speed information found for these people (see Section 4.2.3.1). As I wanted to include a population group of mobility impaired people (in addition to older adults, which could also be seen as mobility impaired compared to younger adults), wheelchair users were the logical conclusion, based on the high scientific awareness on this population group (Tolerico et al., 2007; Cooper et al., 2011b; Karmarkar et al., 2011; Menkens et al., 2011; Zipf et al., 2016; Mobasheri et al., 2017a). The population group was restricted to manual wheelchair users; as for these, reliable propulsion speeds were found (see Section 4.2.3.1). Furthermore, no age restriction was used for this population group due to no available information on this matter.

For the spatial accessibility analysis, the total number of residents in each grid cell (see Figure 3.1 in Section 3.3) were used, regardless of the population group that was analysed. The utilized population dataset would have had population numbers for each age group, but these were not used to make the results comparable among the groups. Additionally, no reliable information on the number of manual wheelchair users in the city of Zurich was found. The public transport operator in Zurich (ZVV) estimated that 0.8% of the transport net are wheelchair users (Zürcher Verkehrsverbund, 2002). However, this number was said to be an underestimation as mobility impaired persons are using public transport less than the average person. Conclusively, for the later spatial accessibility analysis it is assumed that all of the population in Zurich is part of the analysed population group.

4.2.2 Relevant Points of Interest

The POIs utilized as provider locations in spatial accessibility analysis were chosen based on the available data on OSM and the literature (Meyers et al., 2002; Yang and Diez-Roux, 2012; Hatamzadeh et al., 2014; Barnett et al., 2015). The included POIs were also aggregated to lower the number of analyses. The list of final POI groups and the included OSM tags can be found in Table 4.1.

Primary healthcare services are the subject of many spatial accessibility analyses and were the foundation of many FCA methods (e.g., (Penchansky and Thomas, 1981; Luo and Qi, 2009; Luo and Whippo, 2012; Delamater, 2013; Luo, 2014; 2016; Bryant and Delamater, 2019; Jörg et al., 2019)). Therefore, these services had to be included in this study. Pharmacies were included in this group since they play an important role in the primary healthcare of Switzerland (Bundesamt für Gesundheit BAG, 2020).

Daily Shopping destinations, such as supermarkets, and Public Services, such as banks and post offices, have been found to be destinations often made on foot and thus, were also included. They were separated into two groups according to the literature.

The groups “Education”, “Leisure and Sports”, and “Food and Drinks” were included based on the literature. The two latter groups are aggregates of smaller sets of destinations more or less frequently travelled to on foot.

Table 4.1: Relevant Point of Interest groups.

POI group	# of POIs	OSM tags included
Healthcare Services	270	amenity=clinic, amenity= dentist, amenity=doctors, amenity=pharmacy, amenity=hospital
Daily Shopping	168	shop=supermarket, amenity=marketplace
Public Services	122	amenity=bank, amenity=post_office, amenity=townhall
Education	421	amenity=college, amenity=university, amenity=music_school, amenity=language_school, amenity=library
Leisure and Sports	613	leisure=sports_centre, leisure=stadium, amenity=public_bath, amenity=theatre, tourism=zoo, leisure=park, amenity=cinema, amenity=community_centre, amenity=place_of_worship, amenity=bbq
Food and Drinks	2026	amenity=bar, amenity=pub, amenity=biergarten, amenity=cafe, amenity=fast_food, amenity=restaurant

Figures 4.7 and 4.8 illustrate the spatial distribution of all POI groups listed in Table 4.1.

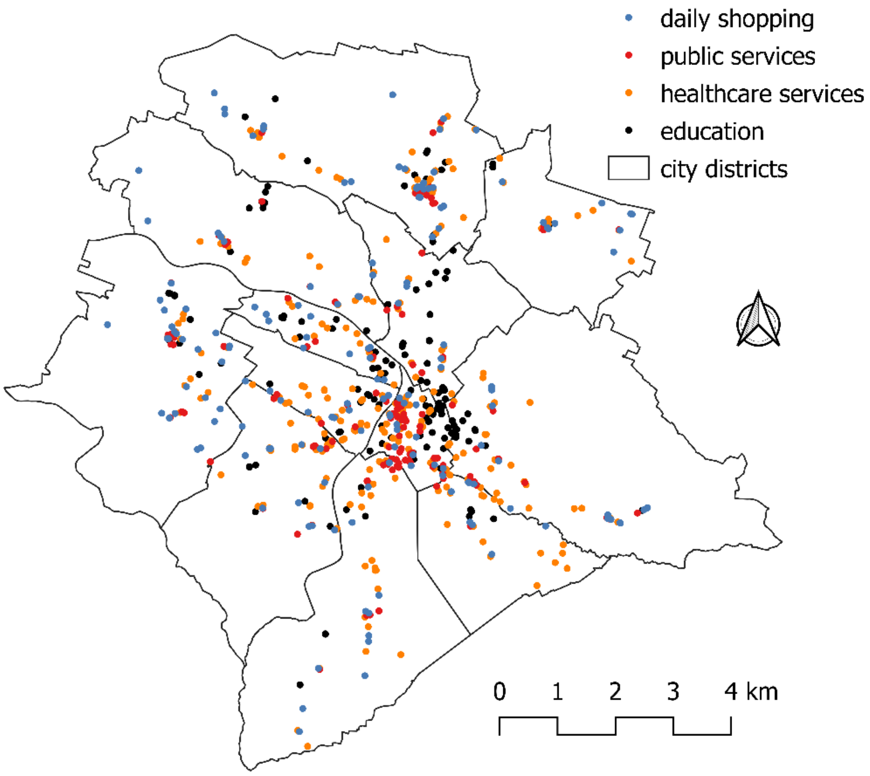

Figure 4.7: Distribution of POI groups 1-4 (Table 4.1) in the city of Zurich.

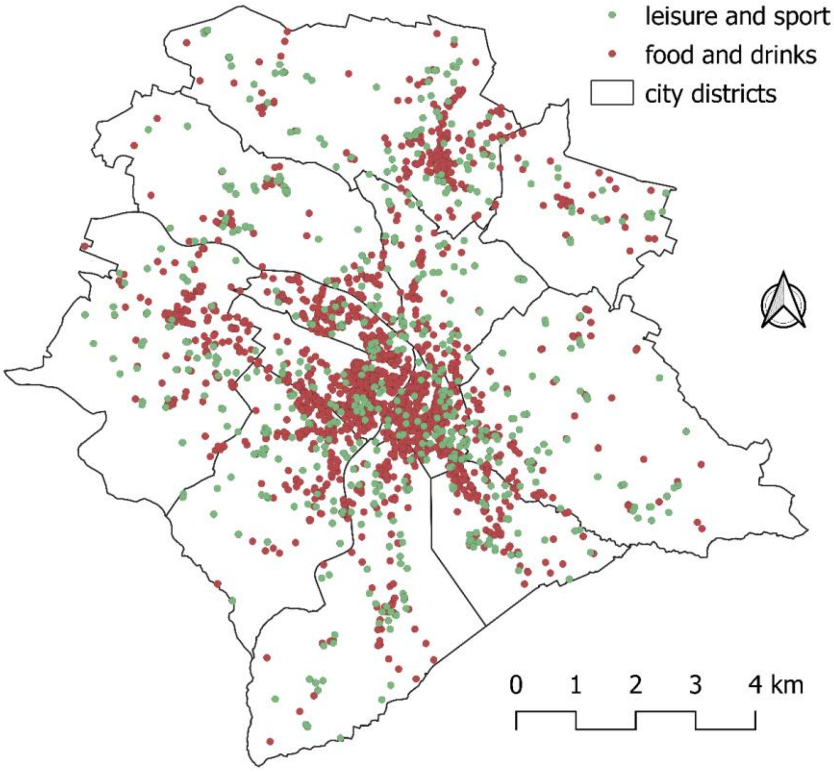

Figure 4.8: Distribution of POI groups 5 and 6 (Table 4.1) in the city of Zurich.

4.2.2.1 Capacity

The capacity of all provider locations (POIs) is assumed as 1, meaning the spatial accessibility is calculated to only the provider locations and not to the actual supply that these providers could give. The actual capacity, for example, doctors in a doctor's office or the area of a park, could have been assumed from various sources. This would have needed an extensive search as so many provider locations were used. Therefore, it was decided to assume the capacity for all providers as 1 in this thesis.

4.2.3 Computing Travel Times

In order to compute travel times, which will later be used as weights of the footpath segments in spatial accessibility analysis, two variables had to be determined. One being the walking/travel speed on different inclinations for each population group and the other being maximum travel time.

4.2.3.1 Walking Speeds

The final walking speeds used in spatial accessibility analysis (Table 4.2) were derived based on the values presented in Tables 2.3 and 2.4 (Section 2.5.1.1).

Table 4.2: Final walking/travel speeds [m/s] by population group and inclination used in spatial accessibility analysis.

inclination [°]	younger adults	older adults	manual wheelchair users
< - 9	1.325	0.910	0.8 (inaccessible)
- 8 to - 7	1.188	0.913	0.8 (inaccessible)
- 6 to - 5	1.225	0.923	0.8 (inaccessible)
- 4 to - 2	1.229	0.997	0.8
- 1 to + 1 (flat)	1.447	1.290	0.8
+ 2 to + 4	1.263	1.080	0.8
+ 5 to + 6	1.255	0.990	inaccessible
+ 7 to + 8	1.201	0.978	inaccessible
> + 9	1.163	0.880	inaccessible

<u>Flat Surfaces</u>

For the population group of younger adults (age 20-64) the mean of walking speed from the four sources below was taken:

- Willis et al. (2004): 1.467 m/s (mean of ages 16-25, 26-50, and 51-64)
- Bohannon & Williams Andrews (2011): 1.380 m/s (age 20-60)
- Finnis and Walton (2007): 1.475 m/s (mean of ages 15-30 and 30-55)
- Thomson et al. (2019): 1.465 m/s (age 20-59).

The values were picked so that the age groups from the literature are as close to the age groups defined in this thesis. The results from Silva et al. (2014) and Pinna & Murrau (2018) were not used for the final walking speeds. In the case of Silva et al. (2014) it was not clear if the authors included walking speeds on all gradients for their age-divided results, which could explain the significantly lower walking speeds (1.222 m/s) compared to above-mentioned values. Even lower walking speeds (0.995 m/s) were obtained by Pinna & Murrau (2018) with their results being approximately 31% lower than the final walking speed used. These low walking speeds could be explained by their real-life study setting. However, Finnis and Walton (2007) used a similar approach which did not result in such low walking speeds. A reason behind these differences could be the difference in individuals' movement behaviour. Maybe Italian people just walk significantly slower than others. As this could not be assessed, the speeds by Pinna & Murrau (2018) were not considered.

For the population group of older adults (age 65-79) the mean walking speed of the following four sources was taken:

- Willis et al. (2004): 1.27 m/s (mean of ages 51-64 and 64+)
- Bohannon & Williams Andrews (2011): 1.245 m/s (age 60-80)
- Finnis and Walton (2007): 1.287 m/s (mean of ages 55+ and 65+)
- Thomson et al. (2019): 1.38 m/s (age 60-79).

In order to compensate for adults aged 80+ that may have been included in the studies of Willis et al. (2004) and Finnis and Walton (2007) walking speeds of some younger adults (55+) were included. Walking speeds from Silva et al. (2014) and Pinna & Murrau (2018) were excluded for the same reasons mentioned above.

For the population group of manual wheelchair users (all ages) the mean propulsion speed of the two sources below was taken:

- Tolerico et al. (2007): 0.79 m/s
- R. A. Cooper et al. (2011): 0.81 m/s.

In both these studies participants had a large range of age (19-73 years with a mean of 46.8 and a mean of 49.13, respectively). Additionally, they extracted their results from long-running data sampling (two weeks and more) in a home environment which was assumed to give results that mirror the real-life setting the best, including possible movement on inclinations (see further below). In contrast, both Boyce et al. (1999) and Chénier et al. (2018) conducted their studies in a controlled environment on flat surfaces.

Inclined Surfaces

There was little precise information found in the literature concerning pedestrian movement on inclines. The only study that included walking speed information for different age groups as well as on different gradients was that of Sun et al. (1996). Finnis and Walton (2007) only provided walking speeds on inclinations of 4° to 7° without any reference to age groups. Thomson et al. (2019) obtained walking speed information only for uphill and downhill movement on 8° gradients. With the study of Sun et al. (1996) having a large group of subjects (n=2400) and an extensive testing period (8 weeks) their data was assumed to be highly accurate and, therefore, used in this thesis. These walking speeds were aggregated where little to no change in speed was observed, resulting in the inclination groups in Table 4.2. As there is no information on walking speeds above 9° and below -9° walking speeds were assumed to be constant on larger gradients. Meaning, for inclinations above 9° the walking speed at 9° was used and for inclinations below -9° the walking speed at -9° was used.

Even less information for movement speed on inclines was found regarding manual wheelchair users. Boyce et al. (1999) obtained data on inclines of -4° and +4°; however, only with one subject. Koontz et al. (2005) acquired speeds on a 5° ascent, but only peak velocity, not average velocity. As there was no reliable data on movement speed of manual wheelchair users on inclines, a constant speed over all accessible inclinations had to be assumed.

As mentioned in Section 2.5.3, inclined surfaces are considered environmental barriers to manual wheelchair users' accessibility. Therefore, not all footways are accessible by manual wheelchair users. Based on the literature (Section 2.5.3), and recommendations of official sources (CCPT, 1996; Aragall, 2003), the threshold for inaccessible inclinations for manual wheelchair users were set to 5° (8% = ~4.57°). As the available information often only considers positive inclines, at first only positive inclines above the threshold were seen as inaccessible. However, considering the force that must be applied to stabilize the wheelchair on downhill passages, negative inclinations below the same threshold (here -5°) were also assumed to be inaccessible.

4.2.3.2 Maximum Travel Time

The maximum travel time or threshold travel time was set to 20 minutes (1200 seconds).

The literature, discussed in Section 2.5.2, suggests slightly lower average travel times of 10 to 16 minutes however, there were also a significant number of cases reported where pedestrians travelled 20 minutes or more (Department for Transport UK, 2006; Yang and Diez-Roux, 2012; Barnett et al., 2015; Macioszek et al., 2022). With distance decay implemented in the spatial accessibility analysis, these differences can be compensated; the likelihood of a trip is lower the longer the trip time, which is addressed by distance decay where locations that are further away are counted less than locations nearby. This threshold is supported by Bryant & Delamater (2019), who used a distance threshold of 1 mile in their spatial accessibility analysis on pedestrians, which is a similar travel time (1 mile equals 1.61 kilometres, which translates to a travel time of about 20 minutes dependent on the population group and inclination).

4.2.3.3 Travel Time Weights

Based on the walking speeds of the population groups and on different inclinations, a weight was added to each edge of the footpath network. This weight, which was later used in calculating the shortest paths between population and provider locations, was calculated as follows:

$$t_e = \frac{s_e}{v_{ps}}, \qquad (11)$$

where t_e is the time to traverse the edge (the weight of the edge) in seconds, s_e is the length of the edge in metres, and v_{ps} is the walking speed of the specific population group on the incline of the edge in metres per second. It has to be assumed that walking speeds are constant on each edge.

In a first attempt, edges that are inaccessible due to their inclination, were removed from the network prior to the shortest path calculation (see Section 4.2.4.1). However, this led to error results in the spatial accessibility analysis. The exact reason for these results was not found, but it is assumed that the removed edges break the R-function, which calculates the shortest paths, at some point. Therefore, a workaround had to be done. The inaccessible edges were no longer removed but received a very large weight (a walking speed v_{ps} of 1/1200 m/s was used in the calculation) so that the travel time on these edges would surely exceed the threshold travel time.

4.2.4 Spatial Accessibility Measure

Of the FCA methods for measuring spatial accessibility introduced in Section 2.4.2, only a few are appropriate for use in this thesis. For example, methods that account for supply and demand competition (3SFCA, E3SFCA, M2SFCA, MH3SFCA, O2SFCA, iFCA) are not appropriate as the supply utilized here is only the supply location and not the actual supply capacity (see Section 4.2.2.1) and the demand is assumed as the same for all population groups. Furthermore, the V2SFCA and EV2SFCA were introduced to capture the spatial accessibility at the transition of urban to suburban/rural areas, which is not the case in the study area. Methods that are implemented for particular use cases (EKD2SFCA, CB2SFCA) or for multiple transport modes (multi-mode-2SFCA) are not suitable as well. This left three possible methods: 2SFCA, E2SFCA, and KD2SFCA. All these three methods were implemented in the spatial accessibility analysis in this thesis, with one slight modification. As the travel times are calculated on a continuous scale and not in subzones, the E2SFCA was modified so that the distance decay weights were continuous, similar to the KD2SFCA but with the Gaussian function as the distance decay function (Figure 4.9).

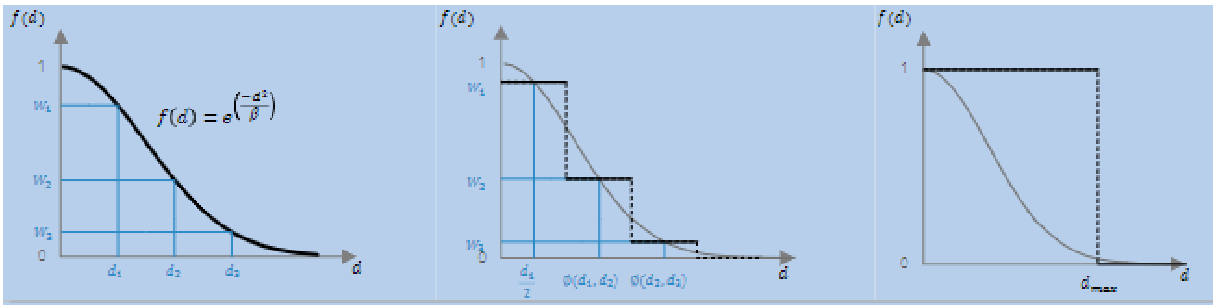

Figure 4.9: Distance decay functions to operationalise the relationship between distance and accessibility. Left: Gaussian function (E2SFCA with continuous decay); Middle: Staircase function based on a Gaussian function, where the mean values of the subzones are used to derive the distance weights (E2SFCA); Right: Binary-discrete staircase function (2SFCA) (Jörg et al., 2019).

4.2.4.1 Implementation

Three types of FCA methods were implemented in this thesis: 2SFCA, E2SFCA (with continuous distance decay), and KD2SFCA.

In the first attempt, a matrix of travel times, as described by Luo and Wang (2003), was calculated. However, the function “distances” (from the igraph package) in R for calculating such matrices was not working with the population and provider locations used. These locations are snapped to the nearest node in the network. If two locations are snapped to the same node, the distance matrix function deletes one of these locations as it is seen as a duplicate. Thus, the shortest paths were individually calculated in each step of the 2SFCA methods. The population locations and provider locations were automatically blended into the footpath network by the function st_network_paths (which is part of the sfnetworks package available in R). This function snaps the start and end points, of which the shortest path should be calculated, to the nearest node in the network, respectively. The shortest paths were calculated based on the weights calculated for each edge of the network (Section 4.2.3.3).

All three FCA methods were implemented as described in Section 2.4.2. For the calculation of the spatial accessibility indices (A_i^F, also called SPAI) the following assumptions were made, as discussed in the previous sections:

- The inclination is constant on each edge
- Walking speeds are constant on each edge
- The capacity of each provider location (S_j) is 1
- Locations outside the threshold travel time (d_0) are spatially inaccessible.

As mentioned before, the E2SFCA method was altered to account for the continuous travel times. This means that it was basically implemented similar to the KD2SFCA (Equation (8)) but with a different distance decay function. Instead of a kernel function $f(d_{ij}, h)$ a Gaussian function was used to describe the distance decay (as in the original E2SFCA). The Gaussian function $f(d_{ij})$ is written as follows,

$$\boldsymbol{f(d_{ij}) = \mathrm{e}^{\frac{-d_{ij}^2}{\beta}}}, \qquad \textit{(12)}$$

where β is the distance-friction-coefficient, and the other variable are the same as in Equation (7). β must be defined prior to the calculation. Therefore, the maximum threshold time d_0 is set as d_{ij} in Equation (12) and the coefficient of distance friction was calculated for the condition $f(d_0) \cong 0.01$, resulting in a β of 312’692.027. This limit was given in various studies as the critical value when the Gaussian function tends to zero (Jörg et al., 2019).

Furthermore, in order to answer Research Question 2 (see Section 1.1) all steps described above were implemented in two ways: once with the inclination enriched footway network and once with a network without any inclination information. In the latter case, the walking/propulsion speed on flat surfaces (see Table 4.2, Section 4.2.3.1) were used for calculating travel times on all edges of the network.

5 Results

This Section presents the results from the analyses conducted in this thesis. Section 5.1 focuses on the OSM footway data enriched with inclination information. Sections 5.2 and 5.3 focus on the conducted spatial accessibility analysis. The former presents the change in spatial accessibility when using enriched footway data compared to not using enriched footway data and the latter focuses on the spatial accessibility to different providers in the city of Zurich.

5.1 OSM Accessibility Enrichment

As described in Section 4.1.2, the OSM footpath data was enriched with inclination information in two ways. Table 5.1 shows the proportions of the network that are inclined versus flat and accessible versus inaccessible for manual wheelchair users. The definition of these differentiations was made in Section 4.2.3.1. Overall, method 1 (average incline on max 20m subsegments) yielded less inclined and inaccessible footpaths than method 2 (maximum incline starting with 0.5m subsegments) (Section 4.1.1.2).

Table 5.1: Proportions of the OSM footpath network [%].

	Method 1 (Average incline)	Method 2 (Maximum incline)
Flat	59	46.6
Inclined	41	53.4
Accessible	85.5	82.2
Inaccessible	14.5	17.8

Figure 5.1 displays the distribution of inclined and flat footpaths (a) and inaccessible and accessible footpaths for manual wheelchair users (b) in the city of Zurich using method 1, where the average incline for subsegments of maximum 20 meters was calculated. Only districts 4 and 5 have large proportions of flat footpaths, whereas in the other districts, many footpaths have at least some degree of inclination. Looking at inaccessible footpaths for manual wheelchair users, districts 2, 7, and 10 are greatly interspersed with footpaths inaccessible for manual wheelchair users. More areas with inaccessible footpaths can be seen in the western outskirts of the city and some smaller areas spread all over the city. Looking back at Figure 3.3 (Section

3.4) the inclined and inaccessible parts are in unison with the topography of the city, where the inaccessible (for manual wheelchair users) footpaths are located in regions with great elevation differences.

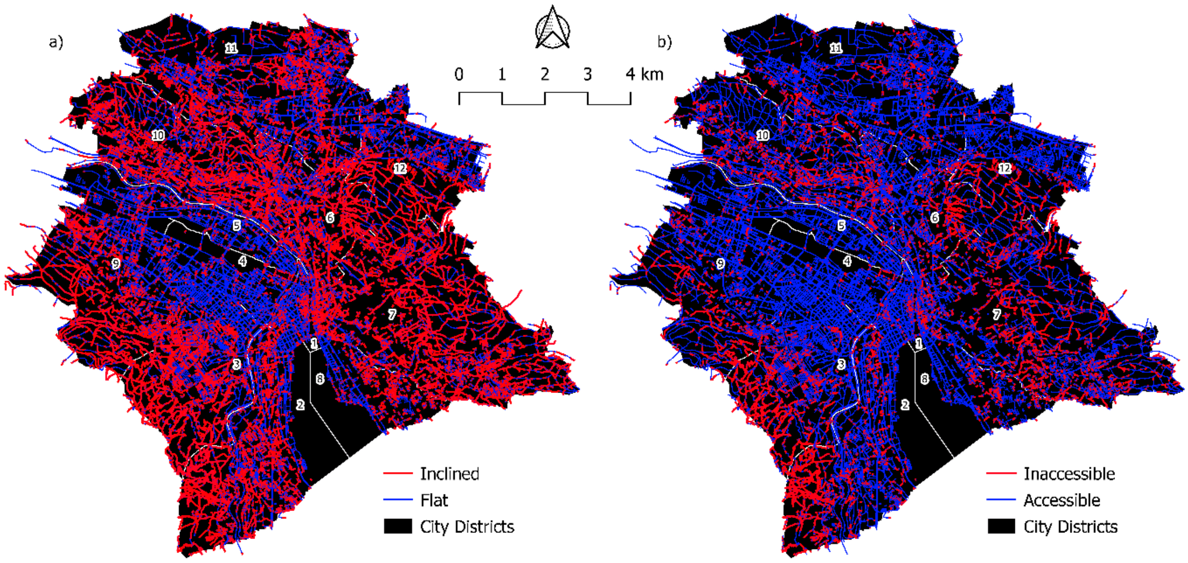

Figure 5.1: Inclination of the OSM footpath network. Average incline (20m segments). a) Incline vs. flat; b) Inaccessible vs accessible for manual wheelchair users.

Figure 5.2 shows the distribution of inclined and flat footpaths (a) and inaccessible and accessible footpaths for manual wheelchair users (b) in the city of Zurich using method 2, where the maximum incline was calculated using 0.5 m subsegments and step by step checking for larger inclines. In contrast to method 1, method 2 resulted in inclined footpaths all over the city. Inaccessible footpaths for manual wheelchair users have similar patterns as with method 1.

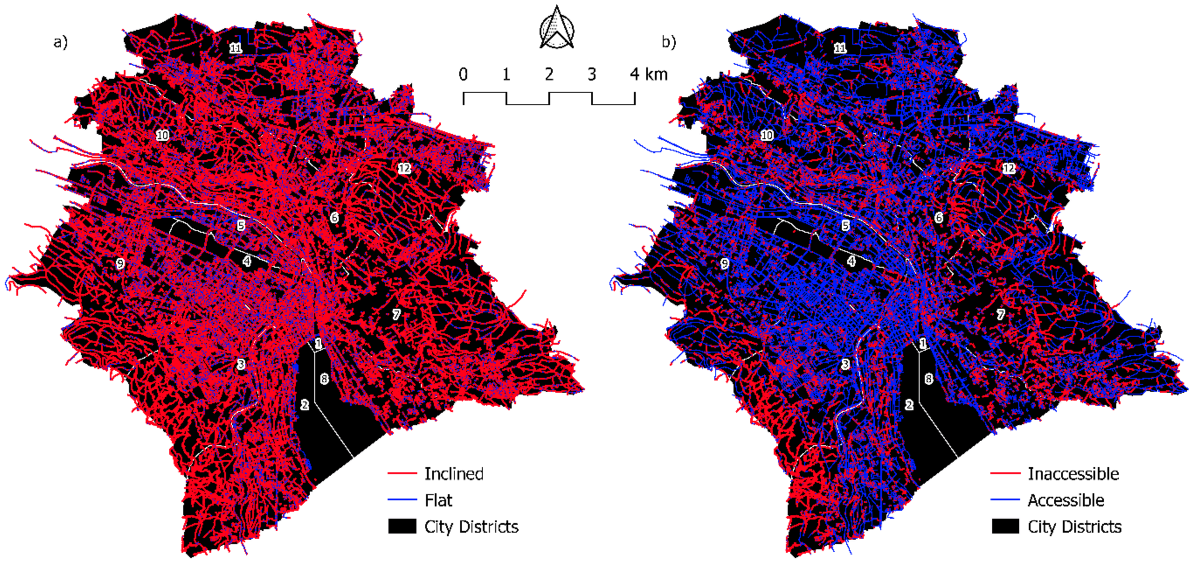

Figure 5.2: Inclination of the OSM footpath network. Maximum incline (0.5 m segments at start). a) Incline vs. flat; b) Inaccessible vs accessible for manual wheelchair users.

5.2 Effect of Enriched OSM Data on Spatial Accessibility by Population Group

As mentioned in Section 4.2.4.1, the spatial accessibility analysis was conducted twice, once with inclination enriched footway data and once without. The change in the SPAI values when using inclination enriched footway data compared to not using enriched data is presented in this Section, focusing on the different population groups.

5.2.1 Younger Adults

Table 5.2 gives an overview of the change in spatial accessibility for younger adults when using inclination enriched footway data compared to not using enriched footway data. The row “Changed” in Table 5.2 (and Tables 5.3 and 5.4) refers to the percentage of locations where any change in spatial accessibility was detected. Mean, max, and standard deviation (SD) were computed only for the areas that see any change in spatial accessibility. Negative mean and max values indicate a lower spatial accessibility when using enriched footway data.

The 2SFCA method resulted in the smallest areas that see a change in spatial accessibility with only 0.6% (Public Services) to 1.5% (Healthcare Services) of the area. The overall mean change is very low with values from -0.11% (Food and Drinks) to -0.86% (Public Services). Maximum changes range from -0.66% (Leisure and Sports) to -1.68% (Public Services).

The E2SFCA method as well as the KD2SFCA method, resulted in larger areas that see a change in spatial accessibility ranging from 7.2% to 12.6% and 6.5% to 11.9%, respectively. In both methods the smallest changes can be seen in Public Services and the largest in Leisure and Sports. Mean changes are even lower in E2SFCA and KD2SFCA methods with -0.01% (Leisure and Sports) to -0.04% (Public Services) and -0.02% (Leisure and Sports) to -0.07% (Public Services), respectively. Maximum changes range from -0.13% (Leisure and Sports) to -0.38% (Food and Drinks) in E2SFCA and -0.26% (Leisure and Sports) to -0.64% (Food and Drinks).

Standard deviations (SD) are very low in all FCA methods to all POIs, indicating very low dispersion among the values.

Table 5.2: Statistics [%] of locations where SPAI values changed due to the enriched accessibility data for younger adults.

POI	2SFCA				E2SFCA				KD2SFCA			
	Changed	**Mean**	**Max**	**SD**	**Changed**	**Mean**	**Max**	**SD**	**Changed**	**Mean**	**Max**	**SD**
Healthcare Services	1.5	-0.44	-1.14	0.18	10.8	-0.03	-0.18	0.03	8.9	-0.05	-0.39	0.06
Daily Shopping	0.7	-0.71	-1.26	0.24	9.7	-0.02	-0.14	0.02	8.5	-0.04	-0.29	0.05
Public Services	0.6	-0.86	-1.68	0.16	7.2	-0.04	-0.24	0.05	6.5	-0.07	-0.42	0.08
Education	1.1	-0.35	-1.19	0.25	8.9	-0.03	-0.29	0.06	7.5	-0.05	-0.49	0.09
Leisure and Sports	1.2	-0.19	-0.66	0.09	12.6	-0.01	-0.13	0.02	11.5	-0.02	-0.26	0.03
Food and Drinks	4.2	-0.11	-1.39	0.17	11.9	-0.02	-0.38	0.06	11.9	-0.03	-0.64	0.07

In the following figures, only the results of the E2SFCA method will be shown as the distribution of changed areas is similar for all implemented 2SFCA methods and the main distinction between the methods is the magnitude in change displayed in Table 5.2 (and Tables 5.3 and 5.4). Results of the other implemented 2SFCA methods can be found in the Appendix.

Figure 5.3 shows the change in spatial accessibility to Healthcare Services (a) and Daily Shopping POIs (b) for younger adults. Spatial accessibility to healthcare services changed mostly in districts 1, 6, 7, and 10. Spatial accessibility to daily shopping POIs is most affected in districts 6, and 10, and smaller areas in all other districts

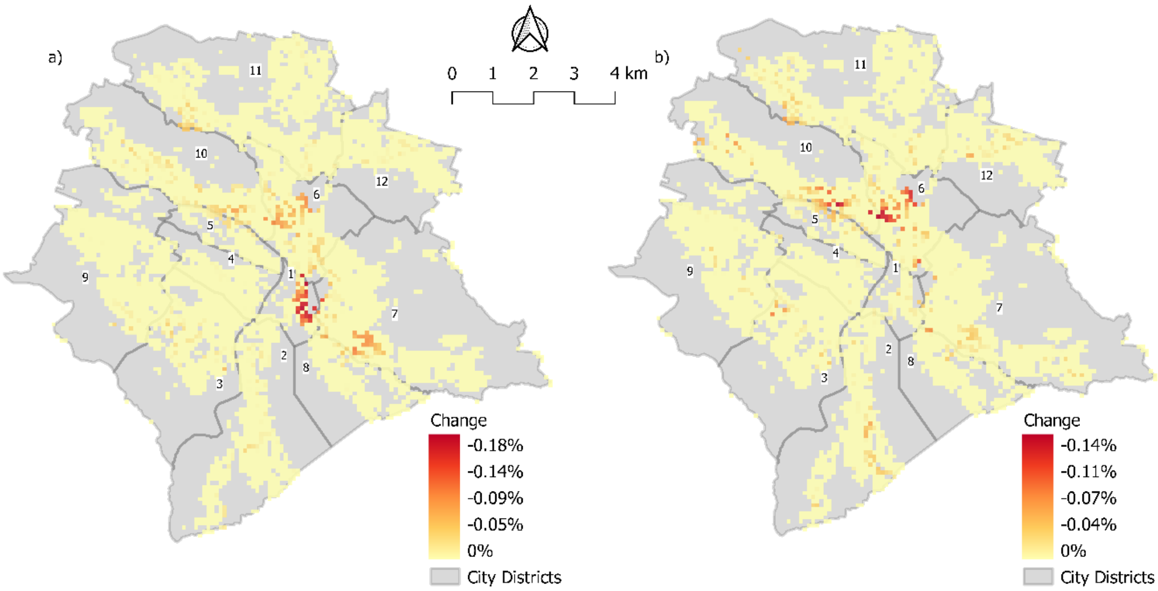

Figure 5.3: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Younger adults. a) Healthcare Services; b) Daily Shopping.

Spatial accessibility to Public Services mostly changed in districts 1, 6, 7, and 10, with district 1 being the most affected (Figure 5.4a).

The same pattern can be observed looking at changes in spatial accessibility to Education (Figure 5.4b), Leisure and Sports (Figure 5.5a), and Food and Drinks (Figure 5.5b) changed almost solely in district 1.

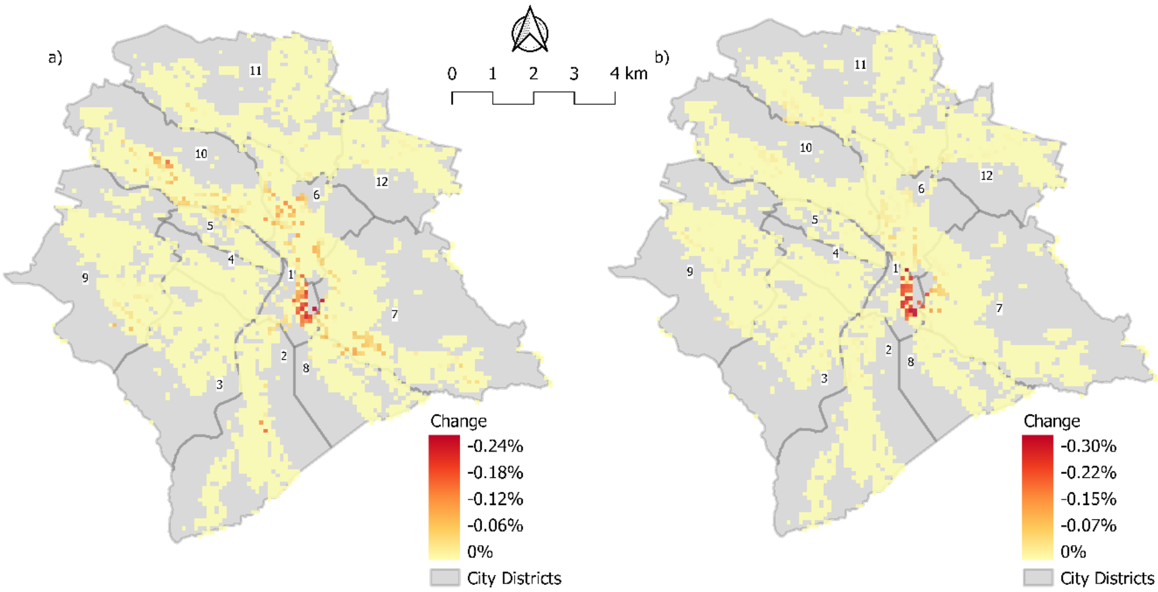

Figure 5.4: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Younger adults. a) Public Services; b) Education.

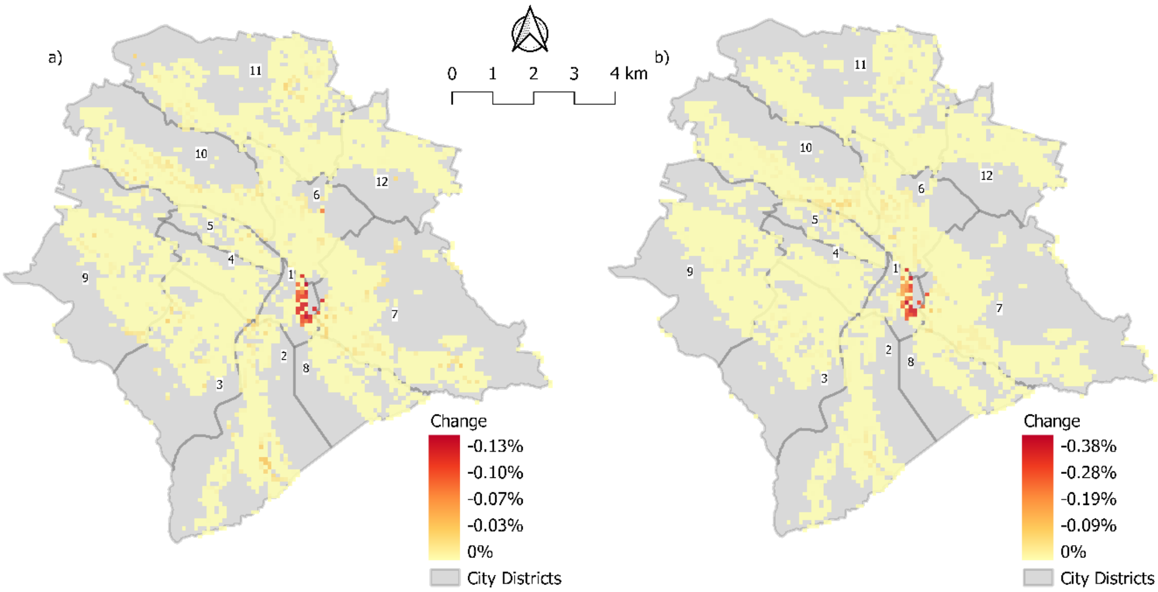

Figure 5.5: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Younger adults. a) Leisure and Sports; b) Food and Drinks.

5.2.2 Older Adults

Table 5.3 gives an overview of the change in spatial accessibility for older adults when using inclination enriched footway data compared to not using enriched footway data.

The 2SFCA method resulted in the smallest areas that see a change in spatial accessibility, with only 0.9% (Public Services) to 1.8% (Healthcare Services) of the area. The overall mean change is higher compared to younger adults, from -0.23% (Leisure and Sports) to -1.51% (Education). Maximum changes range from -0.65% (Leisure and Sports) to -4.82% (Education).

The E2SFCA method as well as the KD2SFCA method, resulted in larger areas that see a change in spatial accessibility ranging from 3.9% to 11.9% and 3.5% to 12.3%, respectively. In both methods the smallest changes can be seen in Education and the largest in Leisure and Sports. Mean changes are lower in E2SFCA and KD2SFCA methods with -0.02% (Leisure and Sports) to -0.17% (Education) and -0.03% (Leisure and Sports) to -0.31% (Education), respectively. Maximum changes range from -0.19% (Leisure and Sports) to -1.06% (Education) in E2SFCA and -0.37% (Leisure and Sports) to -2.1% (Education) in KD2SFCA.

Standard deviations are very low in all FCA methods to all POIs, indicating very low dispersion among the values.

Table 5.3: Statistics [%] of locations where SPAI values changed due to the enriched accessibility data for older adults.

POI	2SFCA				E2SFCA				KD2SFCA			
	Changed	**Mean**	**Max**	**SD**	**Changed**	**Mean**	**Max**	**SD**	**Changed**	**Mean**	**Max**	**SD**
Healthcare Services	1.8	-0.49	-1.48	0.25	10.9	-0.04	-0.28	0.05	9.1	-0.07	-0.67	0.09
Daily Shopping	1.3	-0.80	-1.89	0.36	9.6	-0.03	-0.20	0.03	8.3	-0.07	0.49	0.08
Public Services	1.0	-0.90	-1.67	0.24	7.0	-0.07	-0.34	0.07	6.5	-0.10	-0.67	0.12
Education	0.9	-1.51	-4.82	1.19	3.9	-0.17	-1.06	0.27	3.5	-0.31	-2.10	0.51
Leisure and Sports	1.7	-0.23	-0.65	0.13	11.9	-0.02	-0.19	0.03	10.9	-0.03	-0.37	0.06
Food and Drinks	5.67	-0.12	-1.49	0.19	11.8	-0.03	-0.59	0.09	12.3	-0.04	-0.99	0.12

For older adults, patterns of distribution of changed spatial accessibility are the same as for younger adults throughout the city and for all POI groups (Figures 5.6, 5.7, and 5.8).

Here only the magnitudes in change alternate from younger adults as shown in Table 5.3.

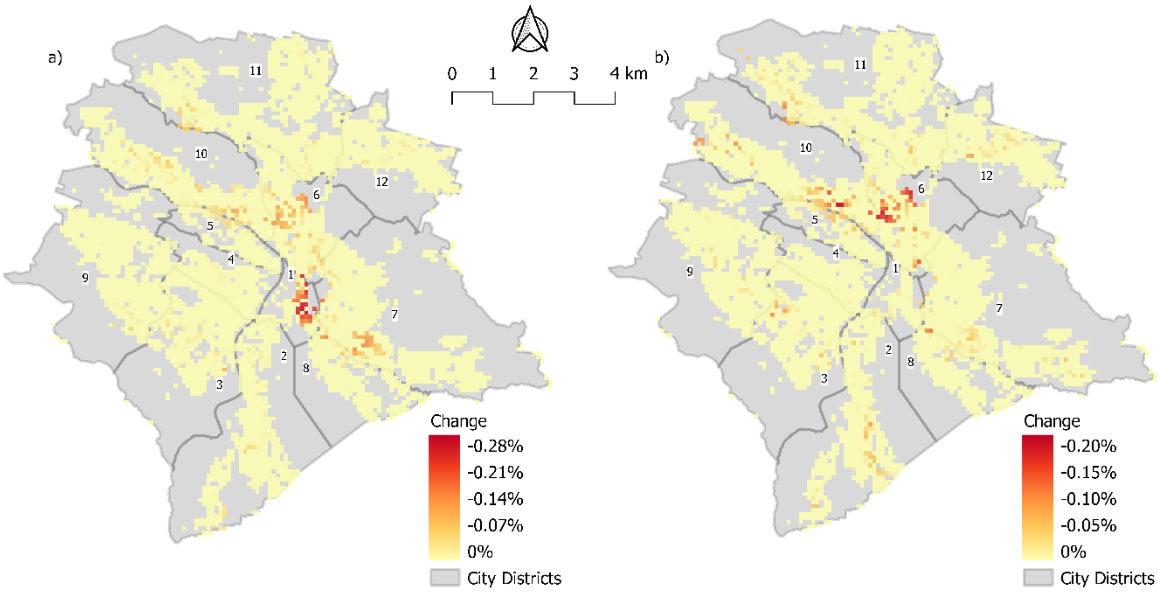

Figure 5.6: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Older adults. a) Healthcare Services; b) Daily Shopping.

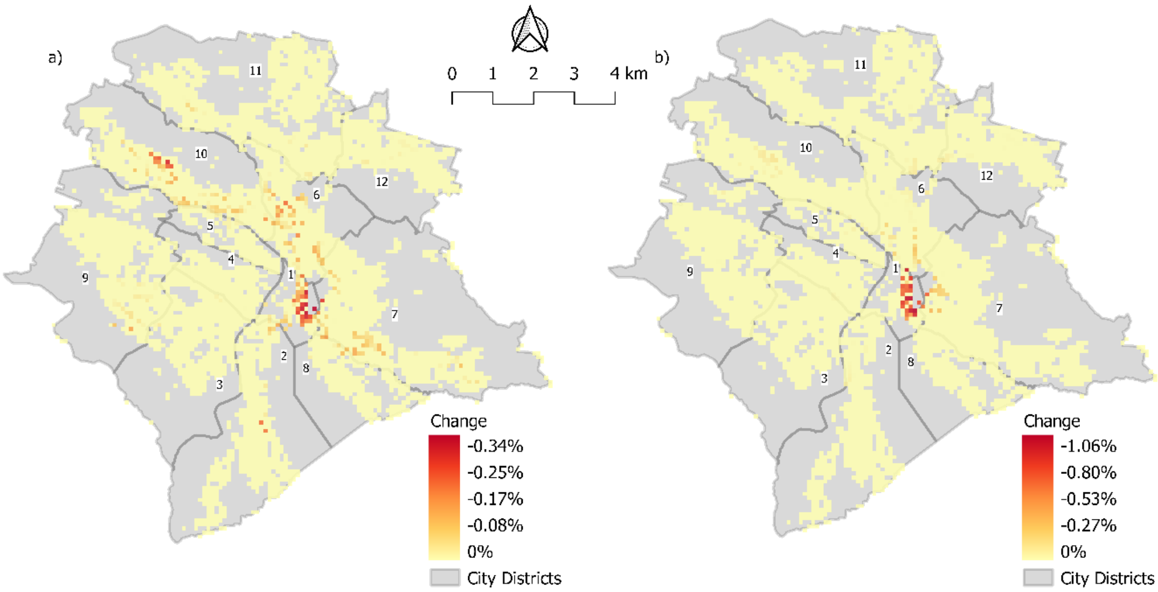

Figure 5.7: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Older adults. a) Public Services; b) Education.

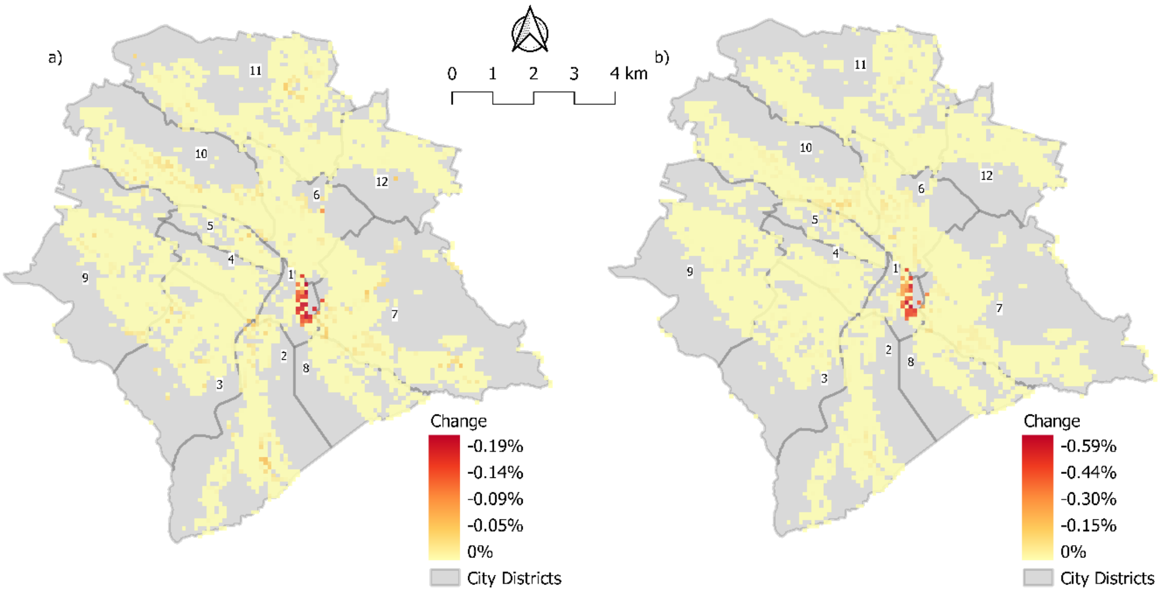

Figure 5.8: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Older adults. a) Leisure and Sports; b) Food and Drinks.

5.2.3 Manual Wheelchair Users

Table 5.4 gives an overview of the change in spatial accessibility for manual wheelchair users when using inclination enriched footway data compared to not using enriched footway data.

For manual wheelchair users, the three FCA methods resulted in similarly large areas that see a change in spatial accessibility. The only exception can be seen in access to healthcare services in the 2SFCA method, where the area that sees a change in spatial accessibility is double the area of the other two methods. In the 2SFCA method, 3.2% to 11.6% of the locations see a change. In E2SFCA and KD2SFCA, 3.4% to 8.8% and 3.5% to 10% of the location changed in spatial accessibility.

The overall mean change is similar to the pattern found for older adults using the 2SFCA method from -0.29% (Leisure and Sports) to -1.34% (Public Services). However, maximum changes are highest compared to the other population groups with a range of -1.96% (Leisure and Sports) to -5.9% (Public Services).

Mean changes are again lower for manual wheelchair users in E2SFCA and KD2SFCA methods compared to the 2SFCA method from -0.09% (Leisure and Sports) to -0.39% (Public Services) and -0.16% (Leisure and Sports) to -0.73% (Public Services) respectively, but still higher than for the other population groups. Maximum changes are highest compared to the other population groups as well and range from -0.69% (Leisure and Sports) to -2.87% (Food and Drinks) in E2SFCA and -1.24% (Leisure and Sports) to -4.43% (Food and Drinks) in KD2SFCA.

Standard deviations are very low in all FCA methods to all POIs indicating very low dispersion among the values.

Table 5.4: Statistics [%] of locations where SPAI values changed due to the enriched accessibility data for manual wheelchair users.

POI	2SFCA				E2SFCA				KD2SFCA			
	Changed	**Mean**	**Max**	**SD**	**Changed**	**Mean**	**Max**	**SD**	**Changed**	**Mean**	**Max**	**SD**
Healthcare Services	10.9	-0.43	-2.94	0.45	5.4	-0.17	-1.03	0.17	5.7	-0.32	-1.94	0.31
Daily Shopping	3.3	-0.77	-2.52	0.38	3.6	-0.22	-1.22	0.24	3.6	-0.39	-1.26	0.29
Public Services	3.2	-1.34	-5.90	1.05	3.4	-0.39	-2.17	0.40	3.5	-0.73	-3.82	0.66
Education	4.9	-0.59	-4.77	0.91	4.6	-0.20	-1.52	0.28	4.9	-0.35	-2.69	0.51
Leisure and Sports	6.7	-0.29	-1.96	0.34	6.7	-0.09	-0.69	0.10	7.2	-0.16	-1.24	0.19
Food and Drinks	11.6	-0.31	-5.45	0.79	8.8	-0.11	-2.87	0.26	10.0	-0.19	-4.43	0.49

For spatial accessibility to Healthcare Services (Figure 5.9a), the district with the most area changed is district 1. More locations that see a change in SPAI are spread over the whole city, where district 10 and the surrounding districts of district 1 changed in larger areas. SPAI to Daily Shopping POIs changed in small areas all over the city, with a minor concentration in districts 6, 7, and 10 (Figure 5.9b).

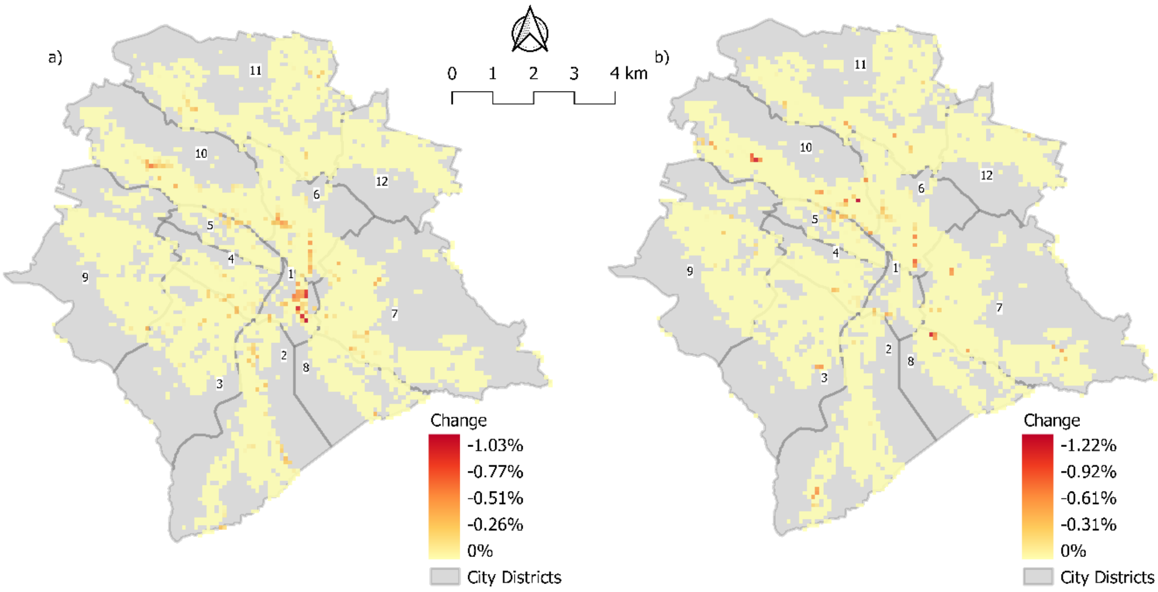

Figure 5.9: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Manual wheelchair users. a) Healthcare Services; b) Daily Shopping.

The distribution of change in SPAI to Public Services (Figure 5.10a) is similar to that of Healthcare Services (Figure 5.9a) but with more compact change areas. Only district 1 and smaller parts in the surrounding districts see a change in SPAI to Education POIs (Figure 5.10b).

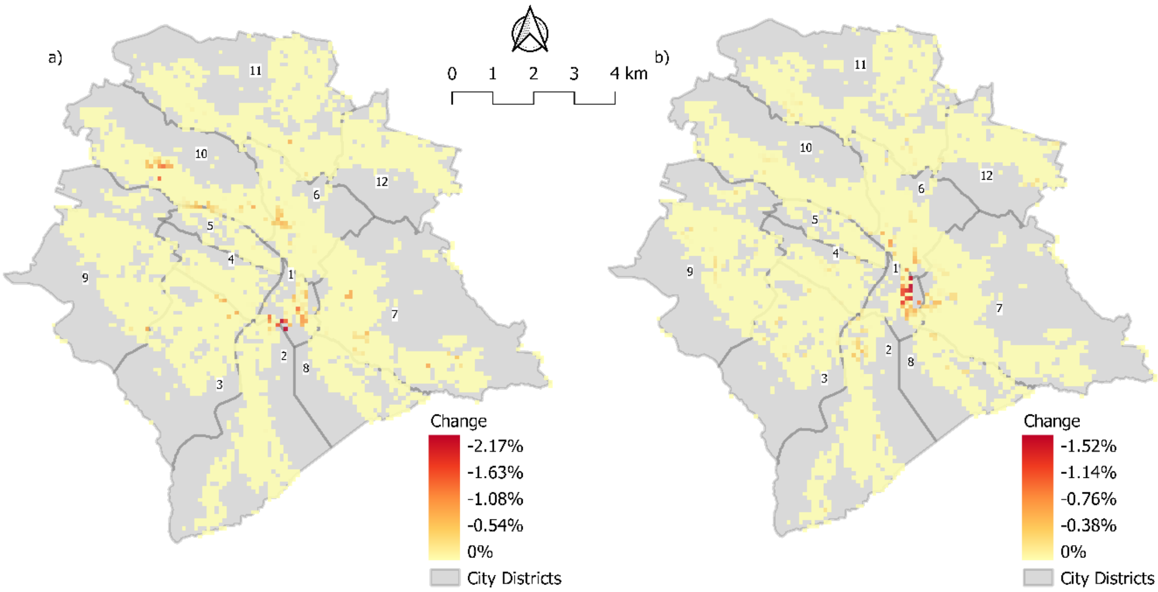

Figure 5.10: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Manual wheelchair users. a) Public Services; b) Education.

The spatial accessibility to Leisure and Sports POIs changed mainly in districts 1 and 8, with smaller areas spread over the city (Figure 5.11a). Spatial accessibility to Food and Drinks POIs changed almost solely in district 1 (Figure 5.11b).

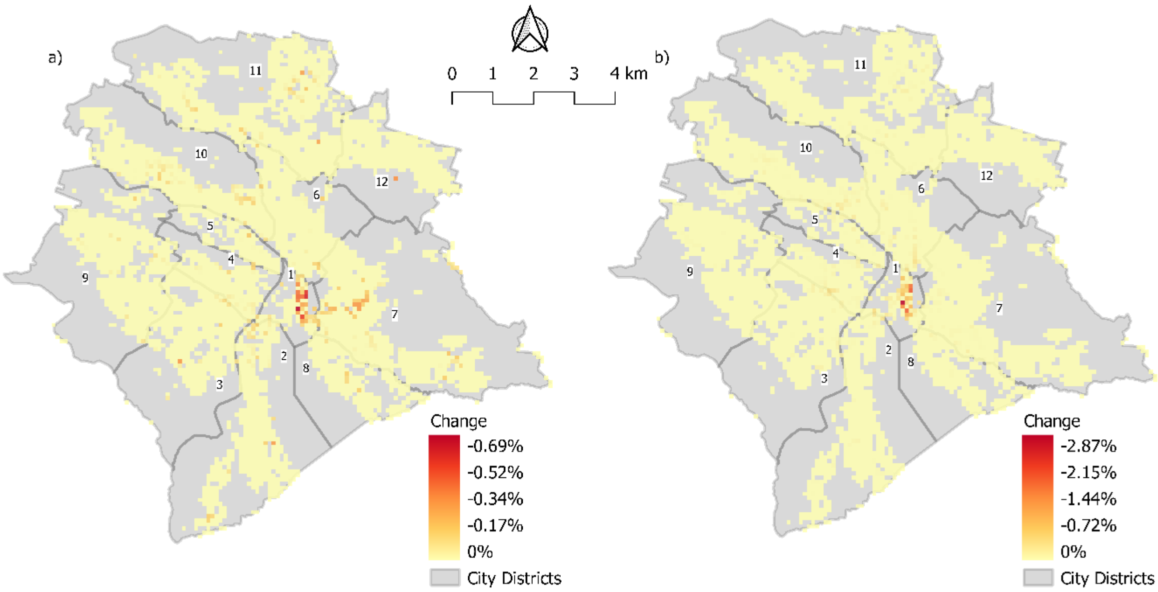

Figure 5.11: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. E2SFCA Method. Manual wheelchair users. a) Leisure and Sports; b) Food and Drinks.

5.3 Spatial Accessibility in Zurich by Provider

This Section presents the spatial accessibility to different service providers in the city of Zurich. The maps show the distribution of SPAI for different population groups to the different providers. Often, in this kind of maps, the spatial accessibility is shown using quantiles or quintiles (see, for instance, Jörg et al. (2019)). However, due to rounding a majority of locations get the same SPAI, which leads to having the same quintiles values as well. Therefore, the SPAI is shown from high to low values for the correspondent population group and POI group compared to the rest of the city. For each POI group, the distribution of SPAI is shown for all three population groups. Furthermore, only the results from the E2SFCA method are shown here for similar reasons mentioned in Section 5.2.1 as the distribution of low spatial accessibility areas is similar on every 2SFCA method. Results of the other methods can be found in the Appendix. All values and figures in this section refer to a calculation of spatial accessibility using the enriched footpath data, as this is assumed to reflect reality the most.

5.3.1 Healthcare Services

Figure 5.12 illustrates the spatial accessibility to Healthcare Services for younger adults (a), older adults (b), and manual wheelchair users (c). For younger and older adults, the accessibility patterns are similar. Areas with moderate spatial accessibility can be seen in districts 1, 5, 7, and 10, and areas, where the spatial accessibility is low, can be observed in districts 1, 2, and 8. Moderate and low spatial accessibility for manual wheelchair users is detected in roughly the same area with more pronounced areas of low spatial accessibility, i.e., more locations in the same area have lower spatial accessibility.

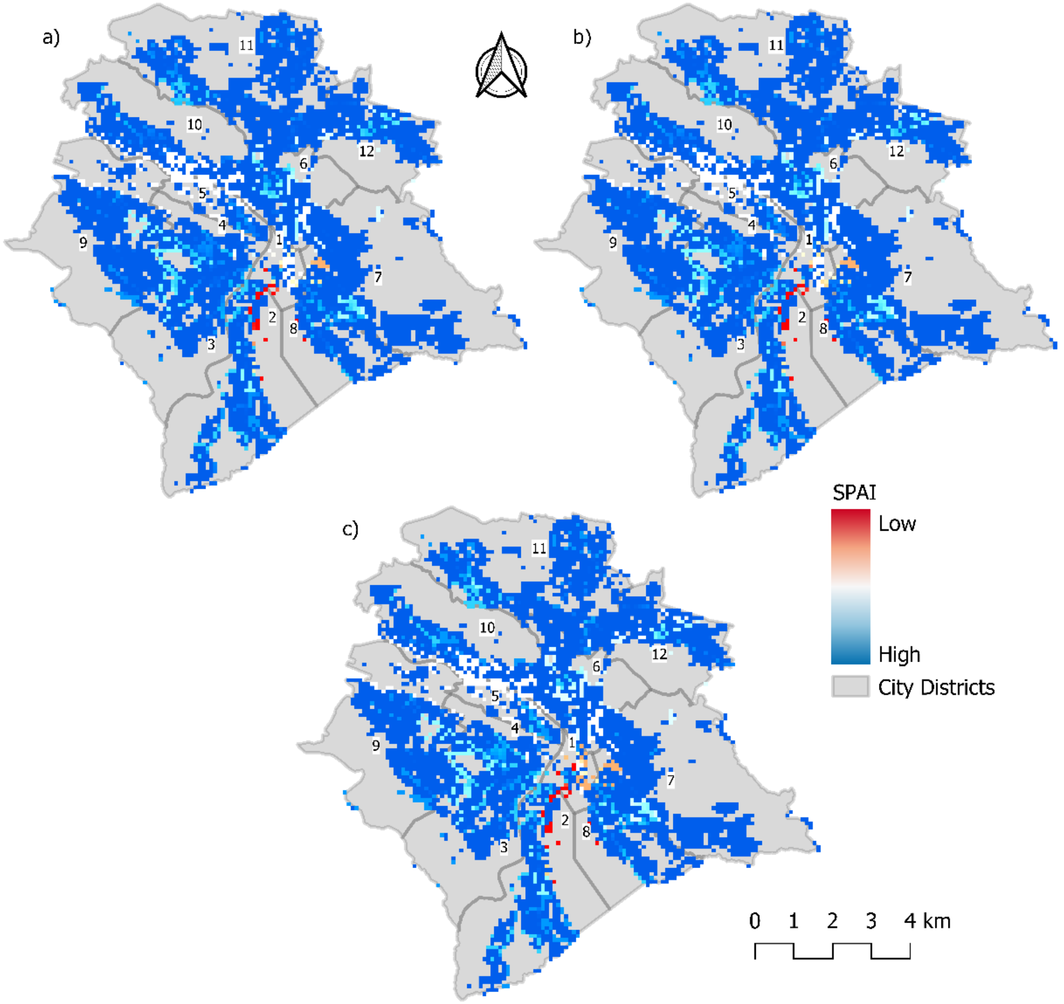

Figure 5.12: Distribution of SPAI in the city of Zurich. Healthcare Services. E2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

5.3.2 Daily Shopping

Figure 5.13 presents the spatial accessibility to Daily Shopping POIs for younger adults (a), older adults (b), and manual wheelchair users (c). For all population groups, the patterns are similar. Areas with low spatial accessibility compared to the rest of the city can be observed in districts 5, 9, and 10.

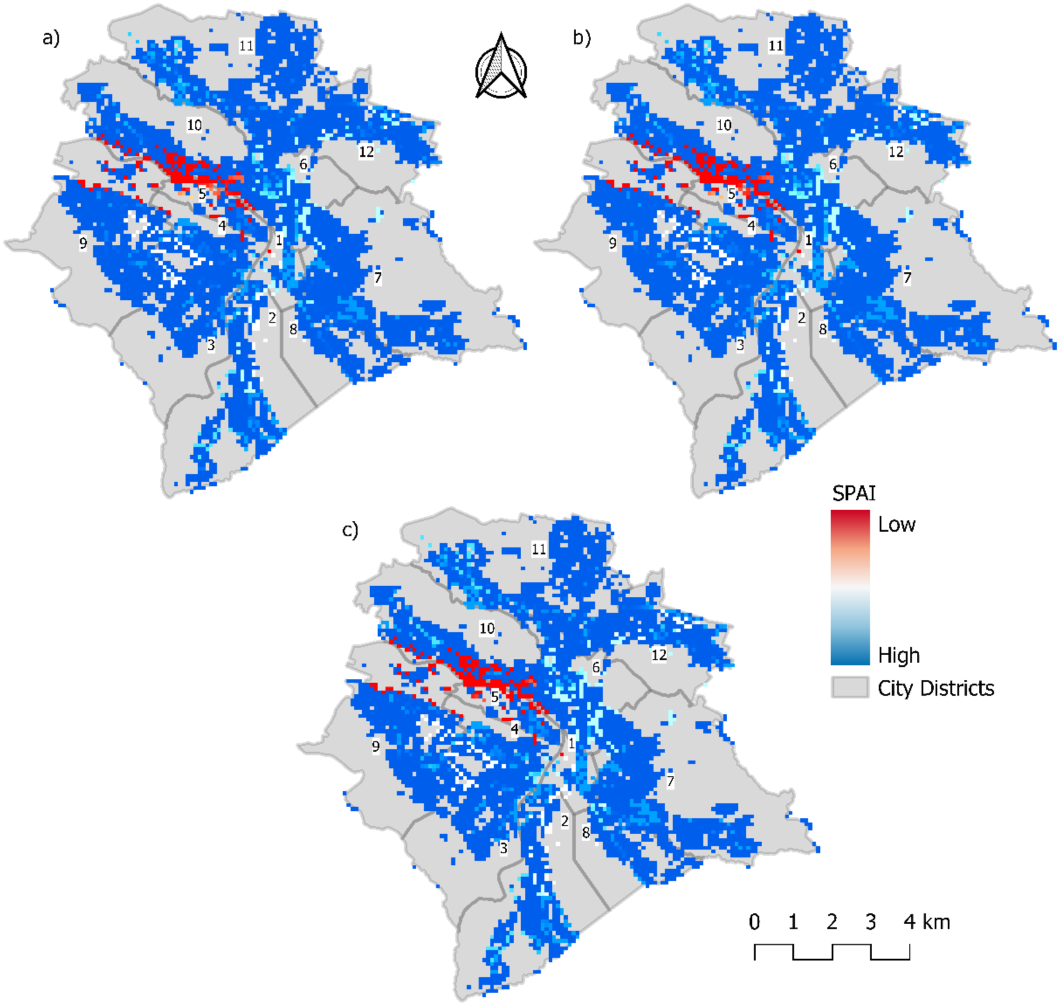

Figure 5.13: Distribution of SPAI in the city of Zurich. Daily Shopping. E2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

5.3.3 Public Services

Figure 5.14 illustrates the spatial accessibility to Public Services for younger adults (a), older adults (b), and manual wheelchair users (c). For all population groups, the patterns are similar. Areas with lower spatial accessibility can be seen in districts 1, 2, and 8. For manual wheelchair users, district 1 shows larger areas of low spatial accessibility than the other population groups.

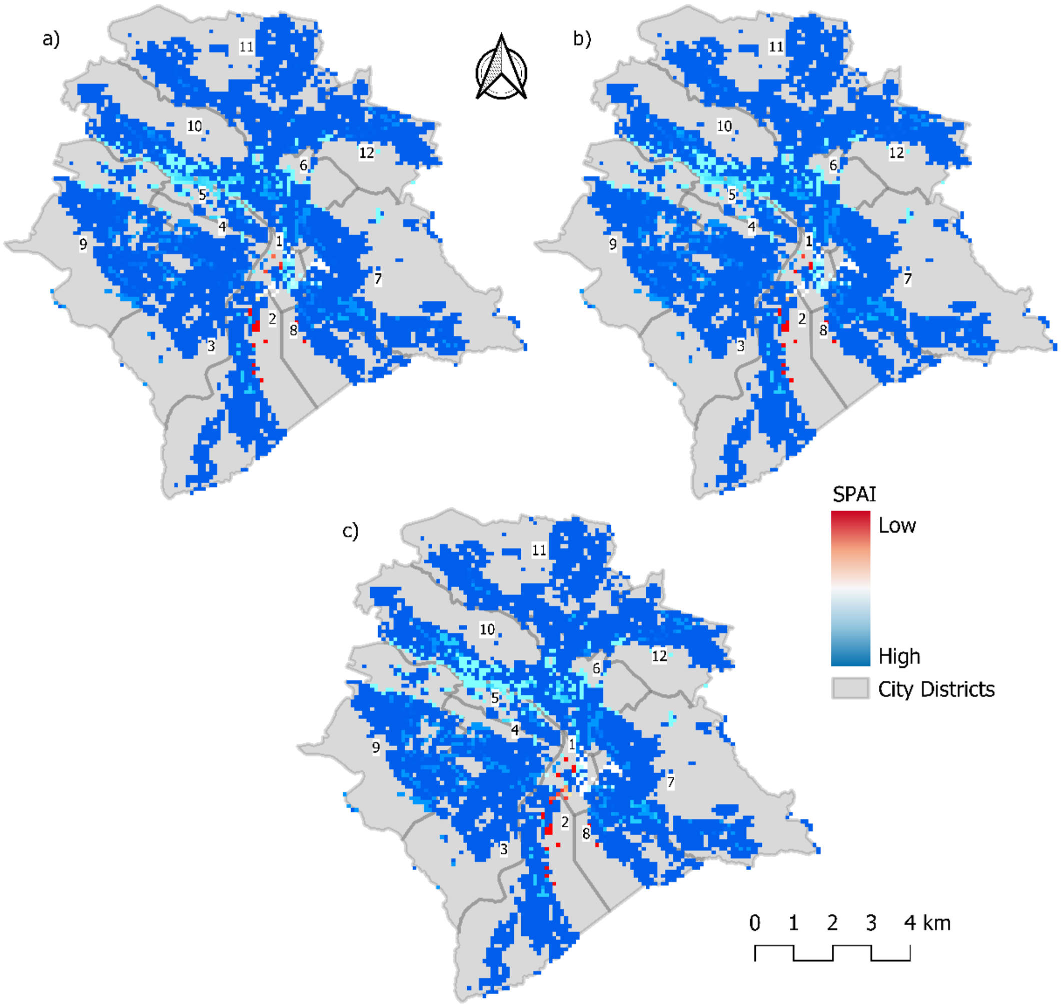

Figure 5.14: Distribution of SPAI in the city of Zurich. Public Services. E2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

5.3.4 Education

Figure 5.15 shows the spatial accessibility to Education POIs for younger adults (a), older adults (b), and manual wheelchair users (c). Here, mainly districts 1 and 7 show low spatial accessibility for all population groups, especially for manual wheelchair users. Furthermore, for younger adults and manual wheelchair users, districts 5 and 10 have moderately low spatial accessibility.

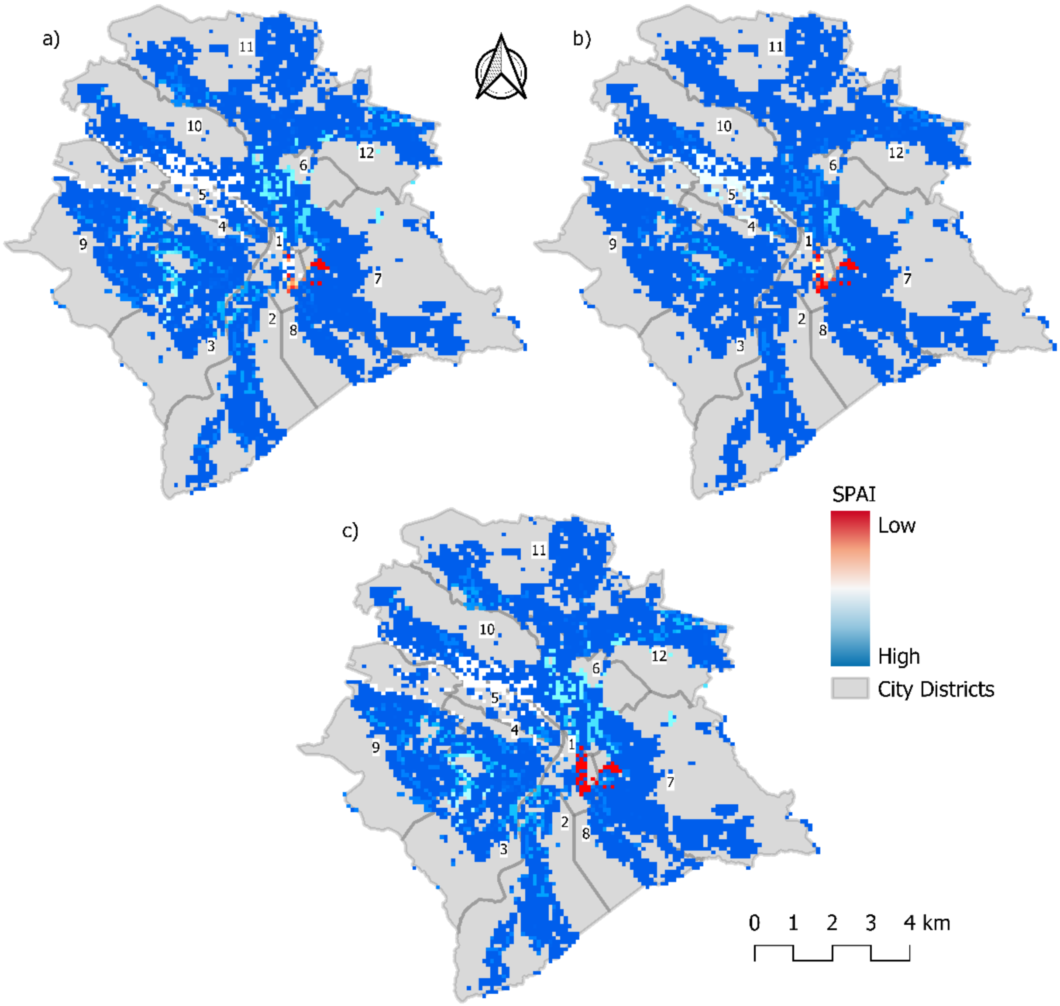

Figure 5.15: Distribution of SPAI in the city of Zurich. Education. E2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

5.3.5 Leisure And Sports

Figure 5.16 displays the spatial accessibility to Leisure and Sports POIs for younger adults (a), older adults (b), and manual wheelchair users (c). Locations with the lowest spatial accessibility can be seen, for all three population groups, in districts 5, 9, and 10. Additionally, moderately low SPAI is observed in small parts of district 7 for all population groups and district 1 for manual wheelchair users.

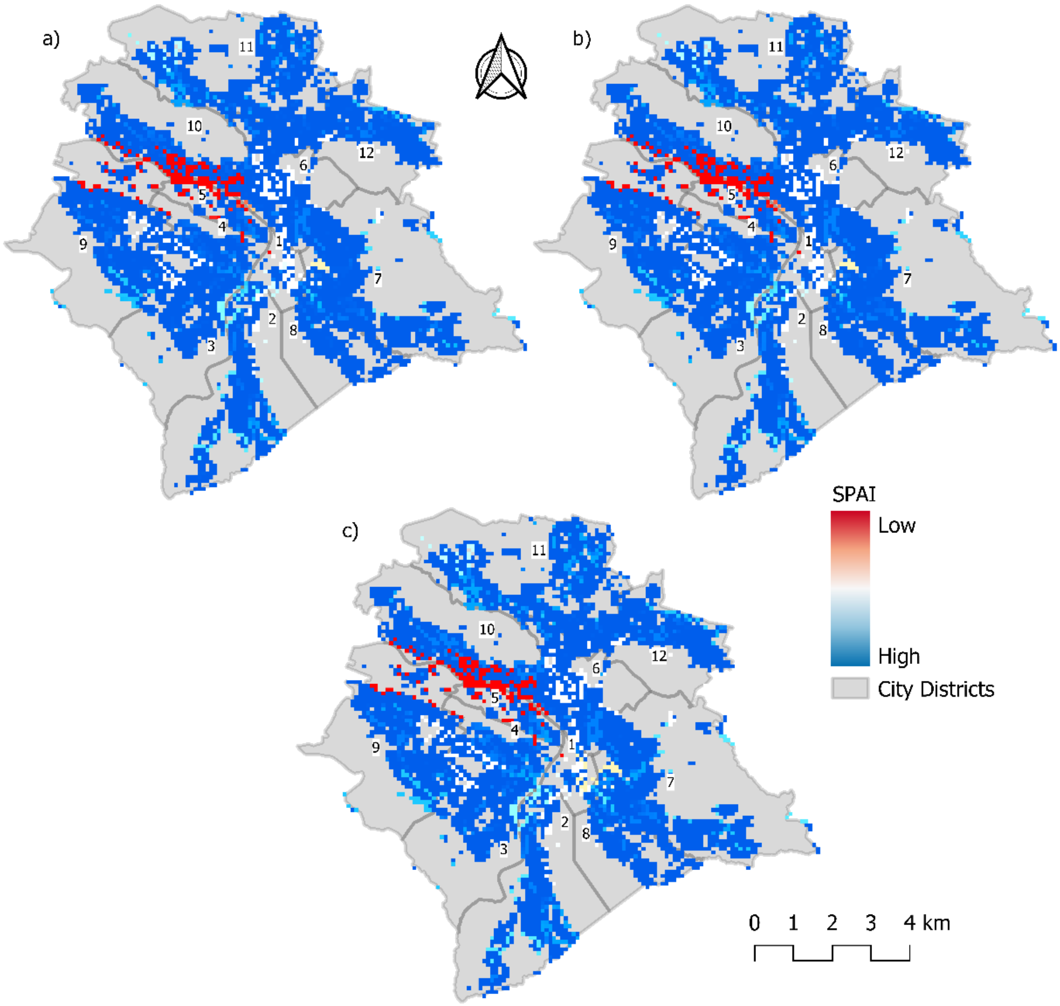

Figure 5.16: Distribution of SPAI in the city of Zurich. Leisure and Sports. E2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

5.3.6 Food And Drinks

Figure 5.17 illustrates the spatial accessibility to Food and Drinks POIs for younger adults (a), older adults (b), and manual wheelchair users (c). For all population groups, the lowest spatial accessibility is observed in small parts of district 7 and in district 1 only for manual wheelchair users. Moderately low spatial accessibility is perceived in districts 5, 9, and 10 for all population groups and in district 1 for younger and older adults.

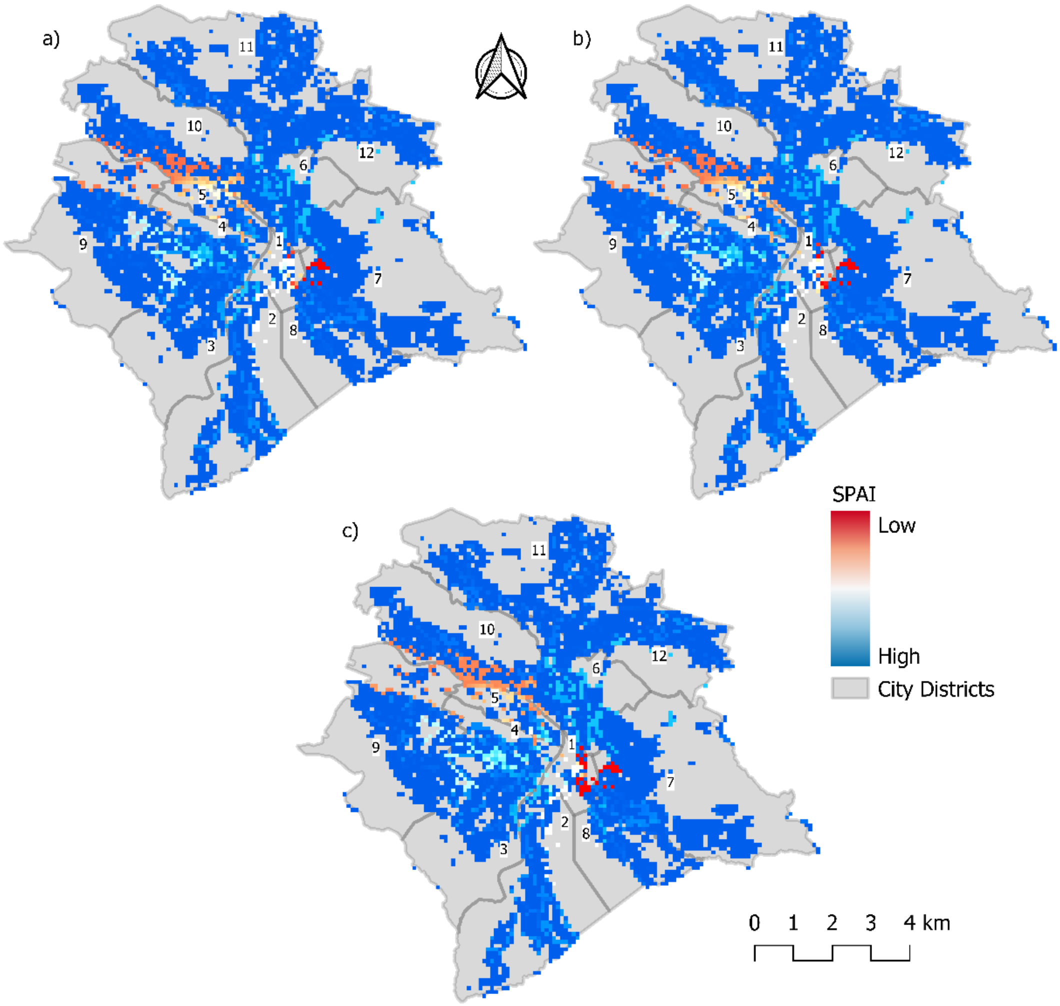

Figure 5.17: Distribution of SPAI in the city of Zurich. Food and Drinks. E2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

6 Discussion

This Chapter of the thesis discusses the results presented in Chapter 5 regarding the research questions formulated in Section 1.1. Furthermore, limitations of the conducted research and recommendations for future research are made.

6.1 Research Question 1

How can OSM accessibility data on footpaths automatically be enriched using additional data sources?

Recapitulating the first research question formulated for this thesis, it was possible to enrich OSM footpaths automatically with accessibility data; in this case with inclination information using a Digital Elevation Model. As stated before, it was possible to enrich the inclination data for the footpaths in the entire city of Zurich in a matter which can be replicated with little effort and in a short time as compared to the field data collection and enrichment. These are the advantages of an automated approach compared to the usual crowdsourcing approach, where typically only small areas are mapped or enriched at a time by a user in the field.

The two methods used to enrich OSM footpaths led to similar results concerning accessibility of manual wheelchair users, which are among the most vulnerable population groups to great inclinations and other physical barriers in their everyday life. The applied methods can be used to enrich footpaths but may also be used to enrich other paths and roads available on OSM or official datasets.

OSM requires maximum inclines in the “incline” tag. Therefore, since the first enrichment method calculates average inclinations, the results could not be used in OSM. The second method would meet this requirement. However, it is still not possible to upload these results to OSM because of a second requirement made by OSM in the tagging schema. It requires users to cut the existing footpaths at the start and end of the inclined footpath (method 2 covers this requirement) and map it as a new way (OpenStreetMap Wiki, 2022j).

Nevertheless, as mentioned before, OSM discourages bulk updates. In addition to the already large update of the “incline” tag, splitting thousands of existing ways would lead to too large alteration of the existing data. That is why, the calculated inclination data was not uploaded to OSM, as in other studies using an automated approach to enrich OSM data (John, 2015;

Sachdeva, 2015; Mobasheri et al., 2018a). As in the aforementioned studies, the enrichment of OSM accessibility data for the city of Zurich was successful and therefore, another step in researching the accessibility for pedestrians and especially mobility-impaired people was made. In contrast to the studies of Sachdeva (2015) and Mobasheri et al. (2018a) there was an official dataset instead of crowdsourced data used to enrich OSM accessibility data, which made the data acquisition easier and faster. John (2015) successfully utilized crowdsourced data for the enrichment of OSM inclination information in Heidelberg (GER), but also used a DEM as comparison for his findings and therefore, conducted a similar study as in this thesis. Unlike John (2015), I used a high-resolution DEM for enriching OSM footpaths, which was recommended by him as this DEM is available for the city of Zurich.

The quality of the enriched inclination data is still a concern. As DEM's reflect the bare-earth surface of the earth, the built environment, especially bridges and underpasses, cannot be represented appropriately. This can lead to significant inaccuracies in the calculated inclinations at these positions. Still, with the exceptionally high resolution of the utilized DEM (0.5m horizontally and vertically), it can be assumed that the calculated inclinations are accurate for most of the study area. For further studies, different models, such as Digital Surface Models, which include the built environment, could be tested in their ability to calculate inclinations in an urban environment accurately.

As in both applied methods, the original OSM footway segments were used as the base for sub-segmenting, a second limitation is recognisable. When inclinations of a footpath cover several segments of the original data, it is possible that the calculated inclinations do not reflect the real situation, which would especially affect the calculation of maximum inclinations. However, this limitation is assumed to be less significant for the use of the data in the conducted spatial accessibility analysis, as here, average inclinations were used. For additional research, a method that investigates all existing footpaths over the boundaries of the individual original segments, would negate this limitation.

Despite the limitations of both approaches, the resulting inclination data can be used to give a first impression of the topography of footways in a study region. Furthermore, it can be used in spatial accessibility analysis, such as in this study, or other accessibility-related research, and also in routing engines.

The availability of high accuracy elevation data is not given everywhere in the world. However, the utilized DEM is available for the whole of Switzerland; thus, the performed approach could be recreated at least in other regions of the country. Additionally, future studies may enrich OSM footpaths with further accessibility data.

6.2 Research Question 2

What is the influence of accessibility-enriched footpath data on spatial accessibility for people in different population groups?

For research question 2, the assumption was made that spatial accessibility is lower when using inclination enriched footpath data in calculating shortest paths between population and provider location. This hypothesis was found to be correct in regions where the interaction of inclination, supply, and demand was high (the interaction between accessibility and availability). It was found that spatial accessibility was affected differently for different providers. For example, spatial accessibility to Education POIs changed almost solely in district 1, where many POIs are clustered in a region with many inclined footpaths and high demand nearby. In contrast, spatial accessibility to other POIs, for example, Daily Shopping POIs, was not affected in district 1, despite the number of inclined footpaths in this region due to no or few POIs located in the inclined area.

The three investigated population groups were differently affected by the enriched data, as expected. Younger adults were affected the least, older adults only a little more, and manual wheelchair users were affected the most. However, this applies only to the magnitude of change, not the size of the affected areas, which can be explained by considering the utilized walking speeds on inclinations. For younger and older adults, there were walking speeds for all inclinations available, i.e., different walking speeds for different inclination gradients; thus, accessibility was affected on all inclined footpaths (Figure 5.1a, Section 5.1). In contrast, for manual wheelchair users, only differentiation between accessible and inaccessible inclinations was made due to a lack of available speed information on inclinations. Consequently, for this population group, smaller areas (Figure 5.1b, Section 5.1) were affected by the use of the enriched data. Overall, the magnitude of change in spatial accessibility when using inclination enriched footpaths compared to using not enriched data was lower than expected. Especially, manual wheelchair users were affected less than expected. This could be explained by the overall high availability of services in the city of Zurich and the location of these services in areas of the city that are mostly accessible.

The different results of the three FCA methods that were applied can be easily explained. The most significant difference between the FCA methods is the application of distance decay. The 2SFCA method resulted in smaller areas that changed but had a higher magnitude of change than the other two methods. Locations that are situated near the edge of the travel time threshold catchment have a different influence depending on the applied 2SFCA method; in the 2SFCA method they influence spatial accessibility the same as locations in the centre of the catchment; when distance decay is applied, they influence spatial accessibility less than locations at the centre. When a location near the edge of the catchment falls out of the threshold (because it is no longer accessible due to slower walking speeds on inclinations) the effect is larger in 2SFCA compared to the other methods, where due to distance decay the locations at the edge of the threshold already contribute less.

Consequently, when a location that was already close to the edge of the threshold falls out of the threshold, the effect is small. However, for locations that stay within the threshold travel time in 2SFCA, there is no change in spatial accessibility. In contrast, for the other two methods, due to distance decay, the contribution to spatial accessibility of the locations changes even within the threshold travel time. The applied distance decay functions can explain the difference between the E2SFCA and KD2SFCA methods.

As of my knowledge, there was no previous research conducted on the influence of accessibility enriched network data on pedestrian spatial accessibility. Therefore, this thesis can be seen as a starting point for further research on pedestrian and especially mobility-impaired pedestrian spatial accessibility.

Limitations of the spatial accessibility analysis and hence also of these results are discussed in the next section.

6.3 Research Question 3

Are there any patterns of deprived areas concerning spatial accessibility to public services in the city of Zurich for certain population groups?

In the hypothesis to this research question, it was assumed that deprived areas in the city of Zurich concerning spatial accessibility are different depending on the service investigated. Furthermore, an effect of inclined areas, due to their effect on travel times of the investigated population groups, on spatial accessibility was assumed, where inclined areas have potentially low spatial accessibility depending on the population group and the investigated service. Both these assumptions were found to be true.

Spatial accessibility was investigated for every POI group compared to the rest of the city. Statements about the actual SPAI values and a comparison of these values between providers will not be made. Reasons for that will be discussed further below.

Overall spatial accessibility was found to be high in large parts of the city. This could be explained by the overall high number of services and a good distribution of these services throughout the city. Areas that could be seen as deprived concerning spatial accessibility were nevertheless found. Deprived areas were found in districts 1, 2, 5, 7, 9, and 10. What all these areas have in common is the location near the transition from flat to inclined areas. This seems to be a repeating pattern. However, not for all providers, the same areas were deprived of spatial accessibility. The before-mentioned interaction between accessibility and availability in spatial accessibility can be observed here, where deprived areas occur either when accessibility is low, and demand and supply are high or when accessibility and supply are low.

Moreover, for manual wheelchair users, the deprived areas of spatial accessibility have been found to be mainly in the same areas as the other population groups but with higher contrast to the rest of the city, which means that these areas had overall lower spatial accessibility compared to the rest of the city as the other population groups where the differences were found to be less pronounced. This supports the assumption that incline-sensitive population groups may have lower spatial accessibility in inclined areas.

Unexpectedly, to many service providers areas in the city centre (district 1) were found to have low spatial accessibility, where normally you would expect high spatial accessibility. This could be explained by the topography in this area with many inclined footpaths. However. As found in the results, the inclination enriched footpath data did not change the spatial accessibility more than ~5%-6% at most, thus other factors, for instance high demand might play a role in these areas.

Pedestrian spatial accessibility of different population groups in the city of Zurich has not been researched yet. The perceptions of this thesis will be used in the SISAL project where the spatial accessibility of different population groups in the city of Zurich will be further researched and could also stand as a basis for other studies.

One limitation of the conducted spatial accessibility analysis is the available footpath data from OSM that was utilized. OSM still has two ways of mapping sidewalks, once as a refinement of a street and once as an independent way, and in the city of Zurich, OSM still lacks completion of all sidewalks mapped as separate ways. This means that the used footpath network is incomplete; therefore, the analysis results cannot be seen as perfectly accurate. However, the results of the conducted study can still be seen as a first look into this subject for the city of Zurich and further studies can be based on this work. For example, using the official footpath dataset from the city of Zurich or by waiting until the OSM dataset is complete.

A limitation of all FCA methods is that calculated spatial accessibility at the edges of the study area cannot be seen as accurate, as residents and providers outside the study area are likely to interact with those inside the study area.

In this study, it was assumed that all provider locations have a capacity of 1. Thus, only the availability of the service locations and not their actual supply level were considered. This means that the calculated SPAI values can only be seen as a preliminary view of spatial accessibility. Consequently, it makes no sense to compare the actual values. Instead, a relative comparison was conducted, which can still give insights into the distribution of spatial accessibility in Zurich. In further studies, actual supply capacities for the researched providers could be found, and a thorough comparison of spatial accessibility between providers can be made.

7 Conclusion

With the growing older population and the accompanying rise of chronic health diseases, an increase in the number of disabled people is expected. With this in mind, the focus on accessibility research is getting stronger.

In this thesis I applied an automated approach on enriching OSM footpaths with accessibility data. The resulting inclination enriched footpath network was successfully applied in a spatial accessibility analysis in the city of Zurich. Three population groups (younger adults, older adults, and manual wheelchair users) to six service provider groups (Healthcare Services, Daily Shopping, Public Services, Education, Leisure and Sports, Food and Drinks) were analysed. Furthermore, the difference in spatial accessibility when using the enriched footpath network compared to not using enriched data was investigated and potentially deprived areas of spatial accessibility were searched.

The automatic enrichment of OSM footpaths in the city of Zurich has shown again, that in contrast to the common field updates, large areas can be enriched at the same time. Still, the upload of such large alterations of the original OSM dataset is problematic, as the database can easily be damaged and rollbacks might be impossible, thus for the sole purpose of updating the OSM database the common crowdsourcing method is safer. However, the automatically enriched data can still be used in research such as the one in this thesis and a potential application of automated enrichment may be used for routing applications for disabled people.

The results of the comparison between enriched and not enriched footpath data, applied in spatial accessibility analysis in the city of Zurich, have shown that slower walking speeds, due to inclination, lead to lower spatial accessibility as the travel times to reach a destination increase. Furthermore, a change in spatial accessibility was mainly detected in areas with high supply and inclined footpaths. Mobility-impaired people such as manual wheelchair users were most affected of the examined population groups in magnitude of the change but not in the size of the area where changes occurred. The overall effect was smaller than expected, nonetheless, the hypothesis that mobility-impaired persons are more affected than able-bodied persons can still be adopted.

Overall, similar areas in the city of Zurich, which can be seen as deprived concerning spatial accessibility, were found for all population groups. These occur in areas with the combination of low accessibility and high supply and demand, or in areas where accessibility and supply are low. Still for manual wheelchair users these areas were more deprived than for the other population groups as their accessibility is lower than of the other population groups, which is in unison to the hypothesis that mobility-impaired people have lower spatial accessibility than able-bodied people.

The results of this thesis have brought new insights into the accessibility research. It was confirmed that the mobility-impaired population is most vulnerable to physical barriers in their environment, which confirms the need of further research and the development of inclusive cities. The found “deprived” areas of spatial accessibility to certain public service can stand as a starting point to more in-depth research regarding this topic. Furthermore, OSM and the enrichment of its data with accessibility information can greatly help reach these goals in giving a basis for further research.

Inaccuracies of the utilised DEM (mainly at bridges and underpasses) and the incompleteness of the OSM footpath network in certain areas of the city are two of the main limitations of this study. In future research, other data sources such as a Digital Surface Model may be tested for their ability to calculate accurate inclinations in an urban context, and other footpath networks (if available) from official sources could be considered. Additionally, the enrichment of the footpaths with more accessibility data such as other barriers (e.g., sidewalk width, and surface type) could reveal more insights in accessibility of the mobility-impaired population.

In further research, adding the actual capacity of the service providers to the executed spatial accessibility analysis would make a better comparison between the service providers possible, and may reveal other deprived areas concerning spatial accessibility in the city of Zurich.

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A Appendix

A.1 Spatial Accessibility Change – Other FCA Methods

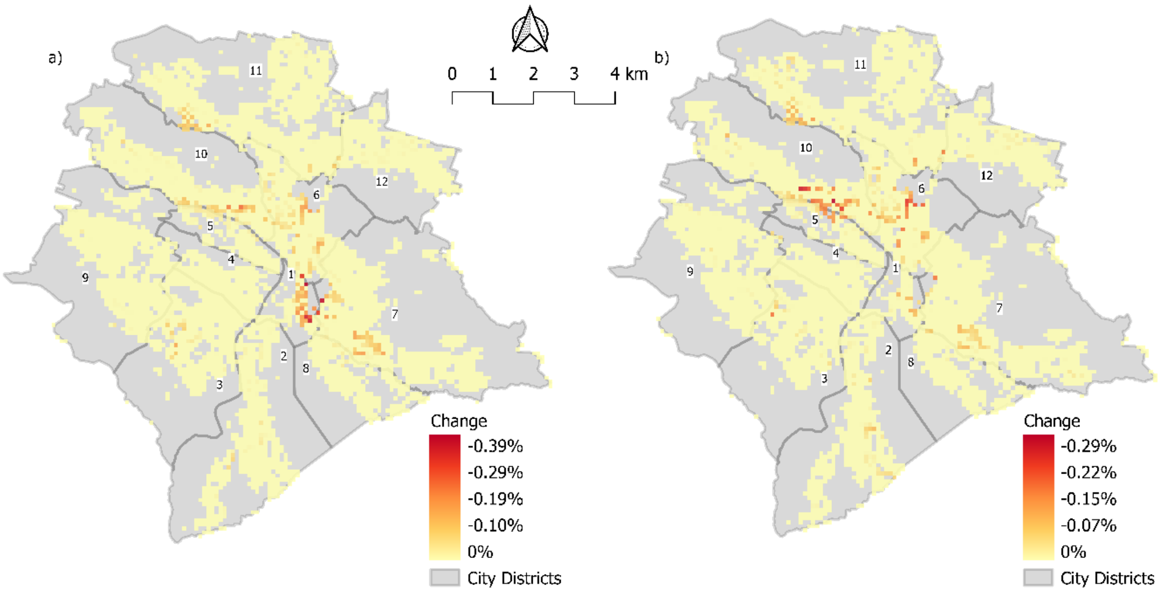

Figure A.1: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Younger adults. a) Healthcare Services; b) Daily Shopping.

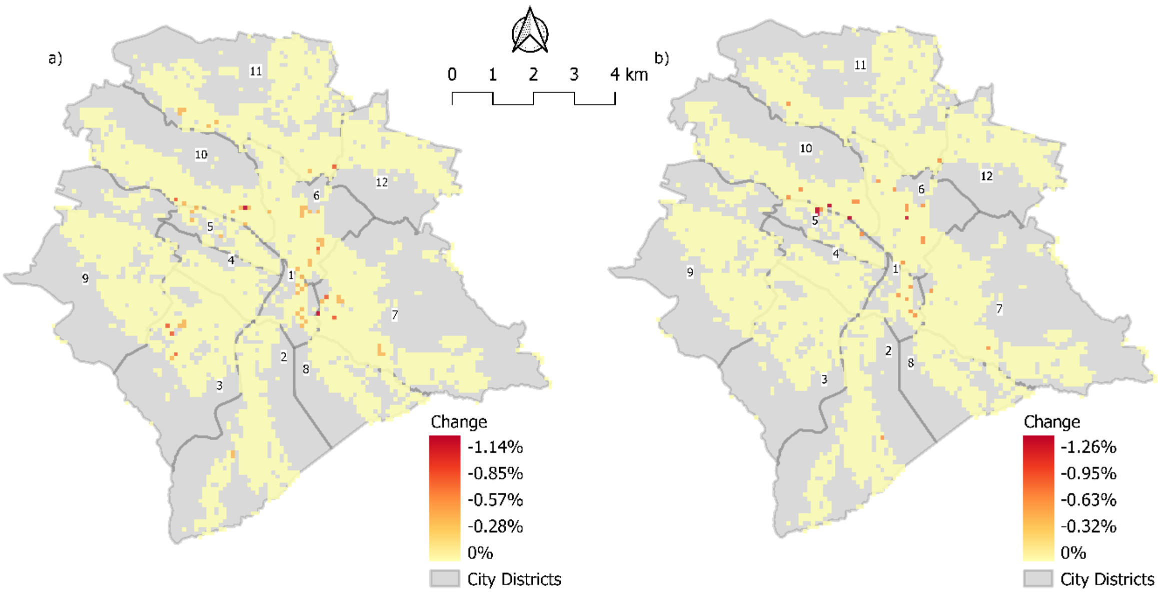

Figure A.2: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Younger adults. a) Healthcare Services; b) Daily Shopping.

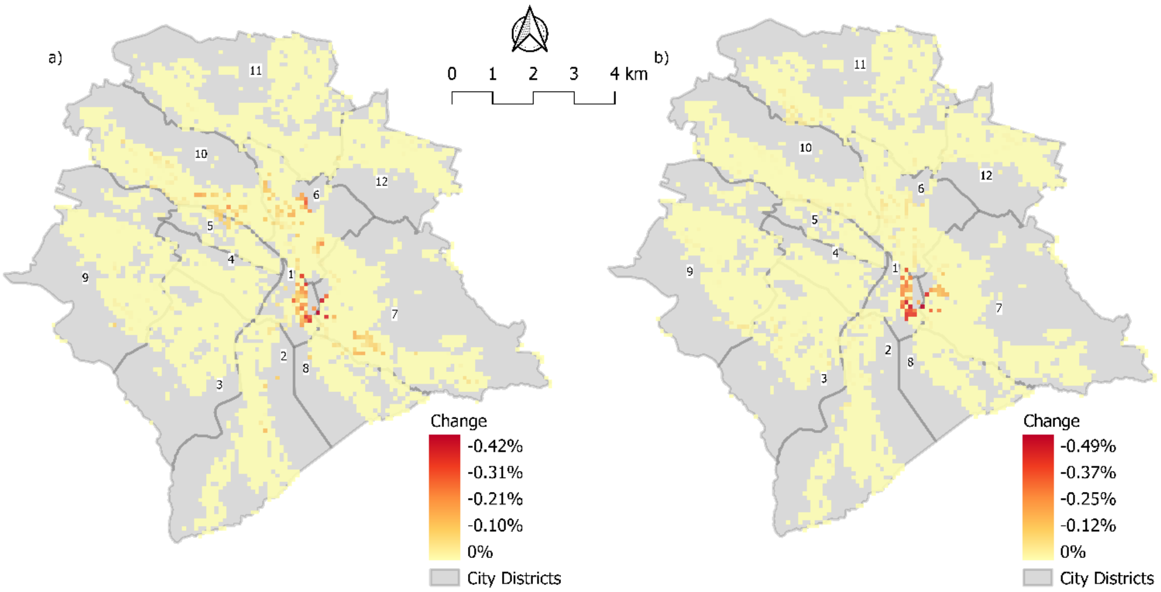

Figure A.3: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Younger adults. a) Public Services; b) Education.

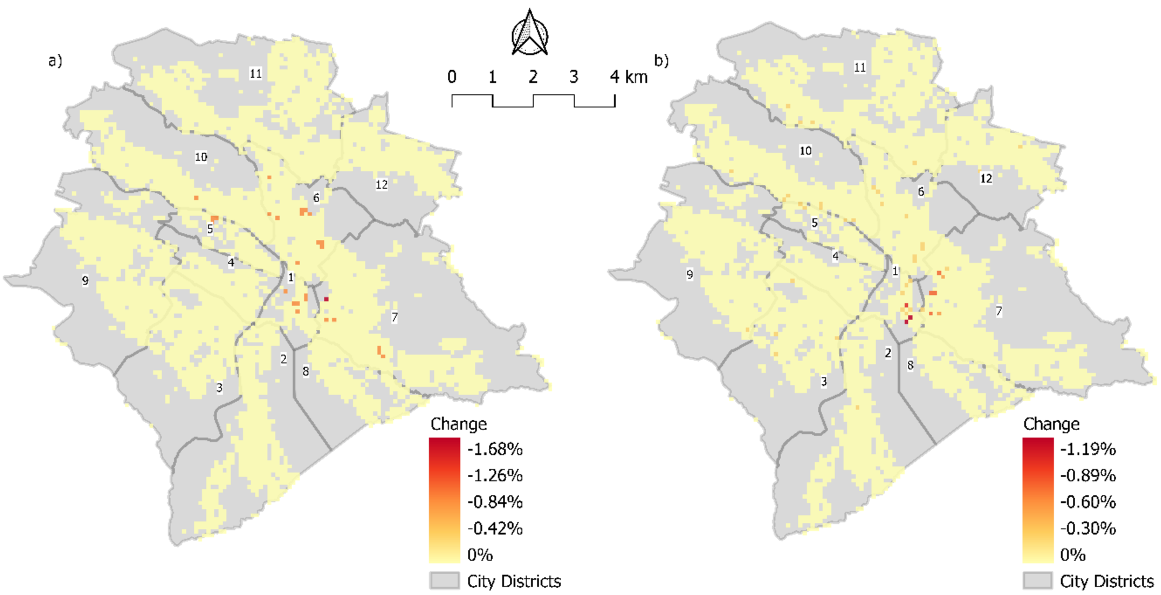

Figure A.4: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Younger adults. a) Public Services; b) Education.

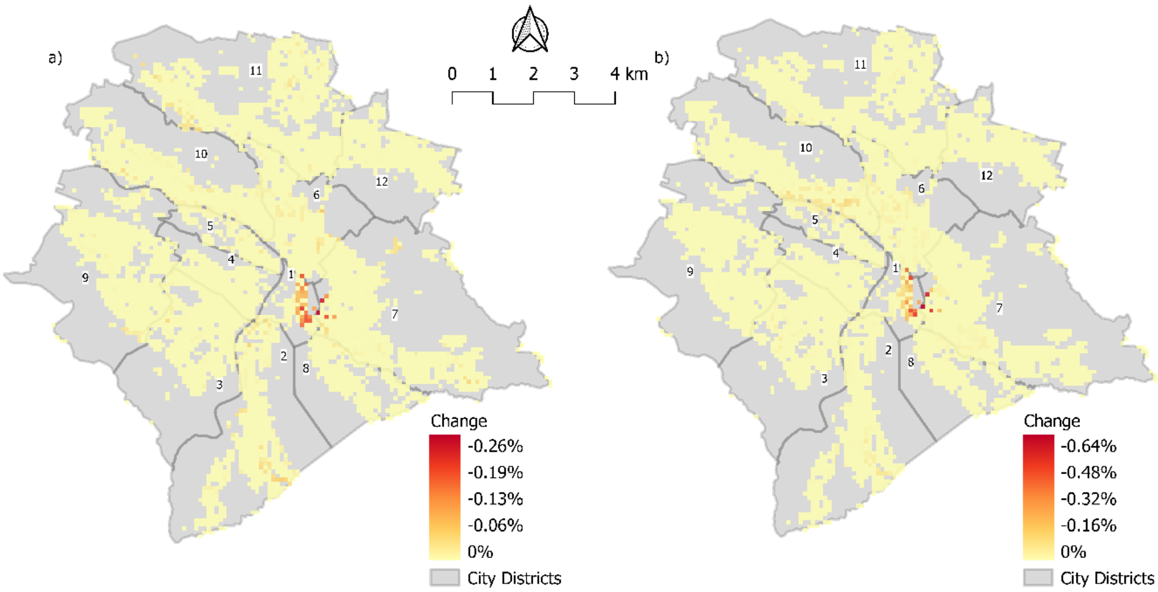

Figure A.5: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Younger adults. a) Leisure and Sports; b) Food and Drinks.

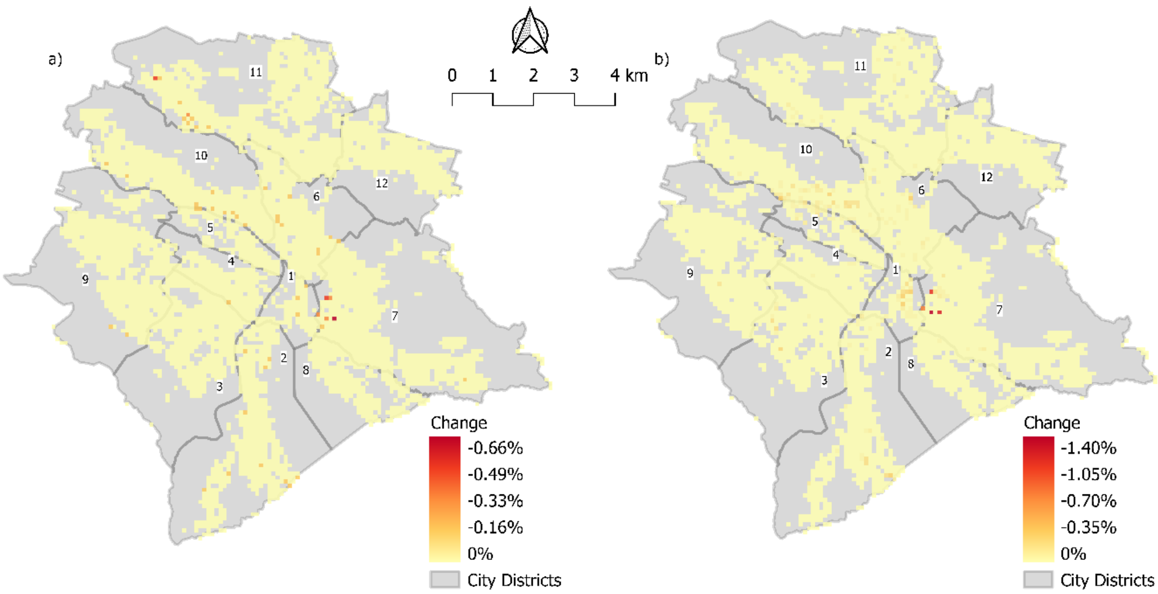

Figure A.6: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Younger adults. a) Leisure and Sports; b) Food and Drinks.

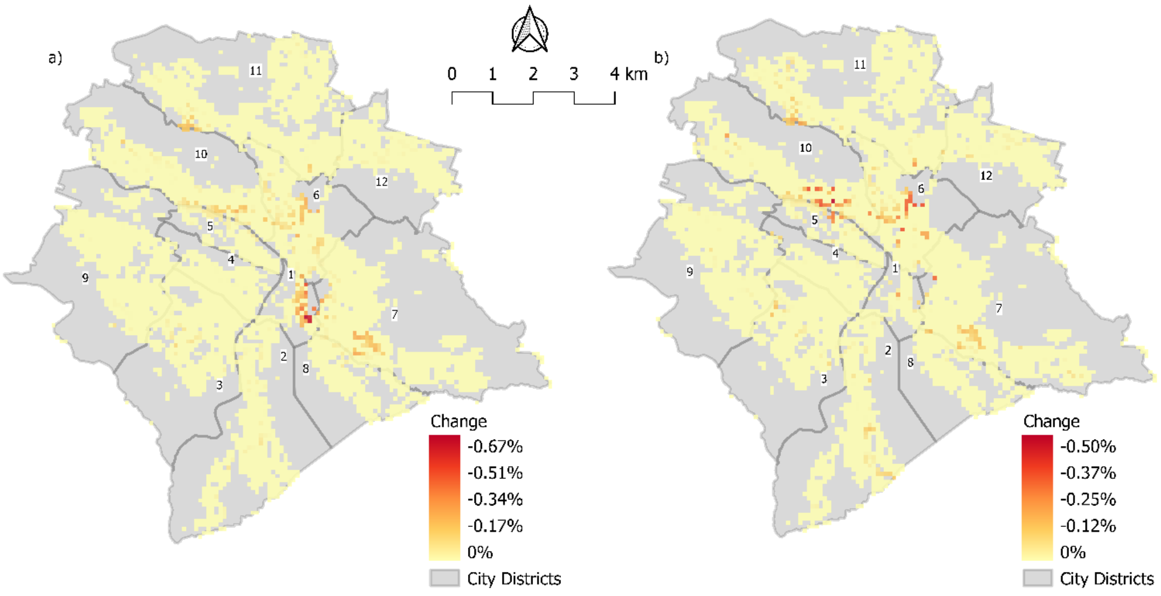

Figure A.7: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Older adults. a) Healthcare Services; b) Daily Shopping.

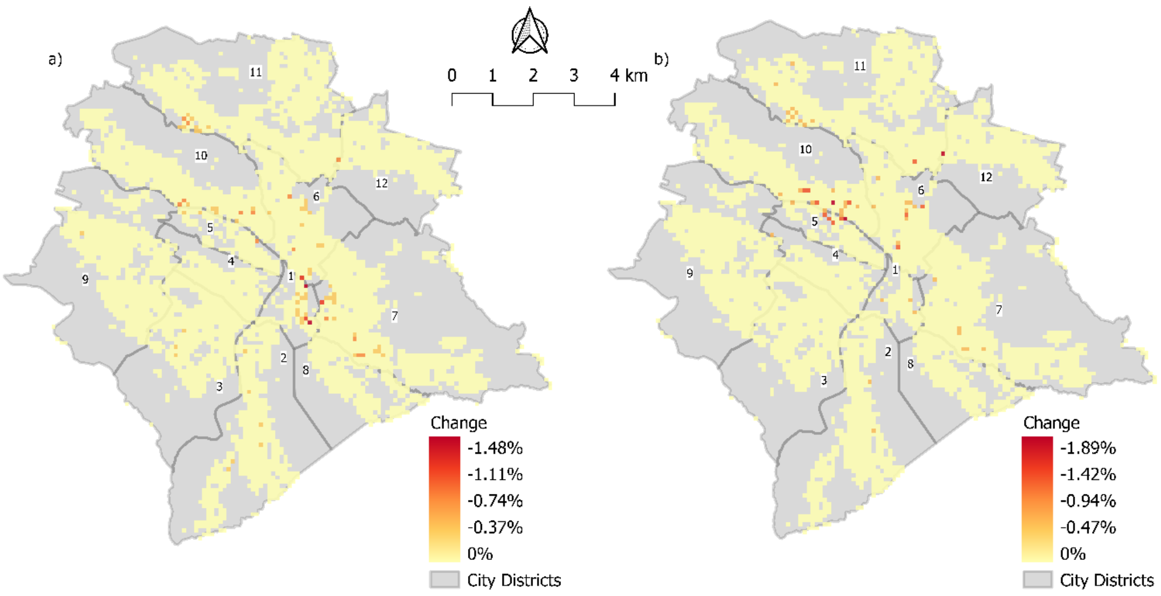

Figure A.8: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Older adults. a) Healthcare Services; b) Daily Shopping.

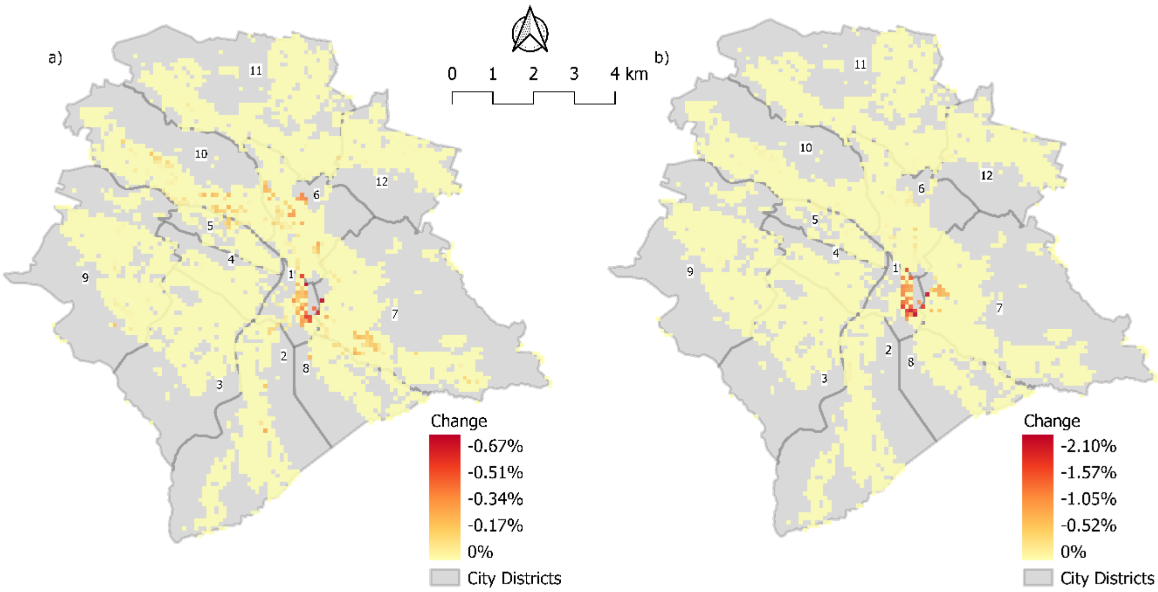

Figure A.9: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Older adults. a) Public Services; b) Education.

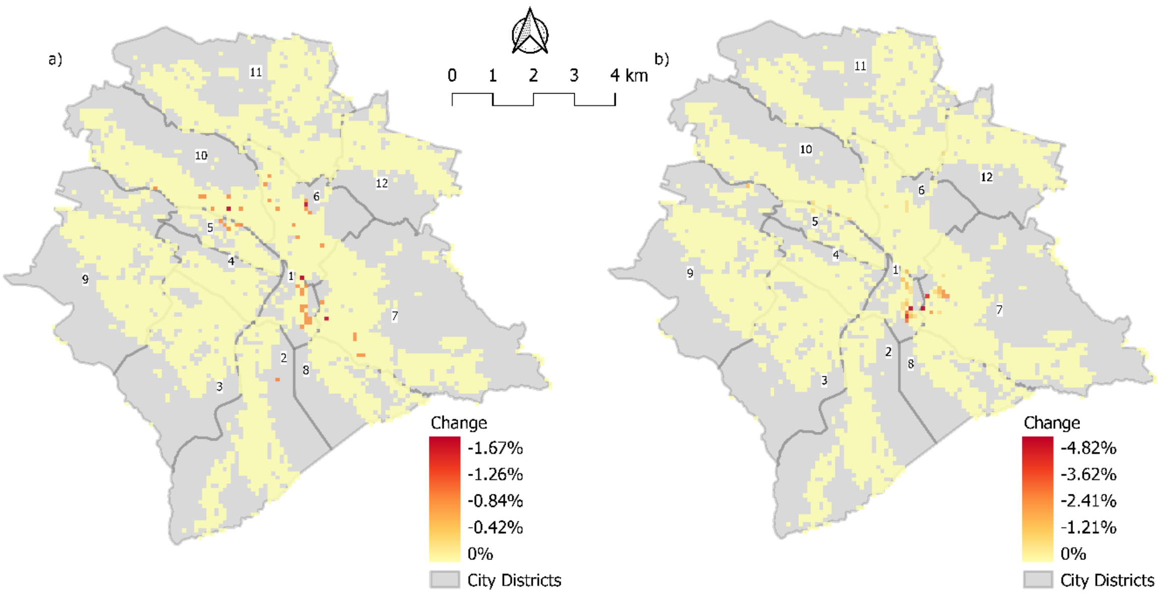

Figure A.10: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Older adults. a) Public Services; b) Education.

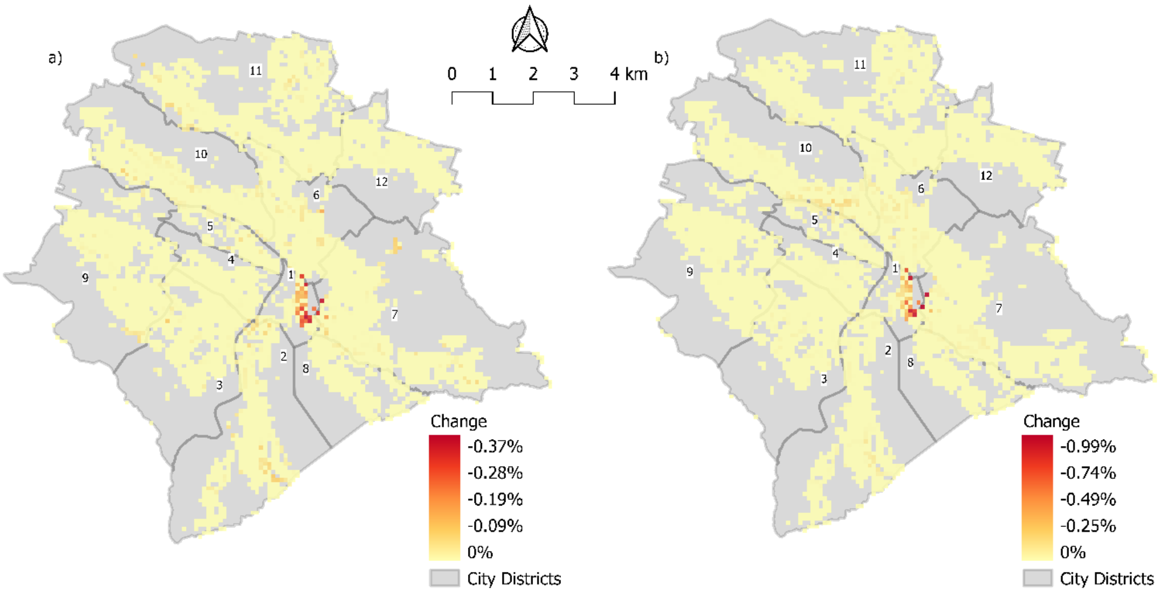

Figure A.11: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Older adults. a) Leisure and Sports; b) Food and Drinks.

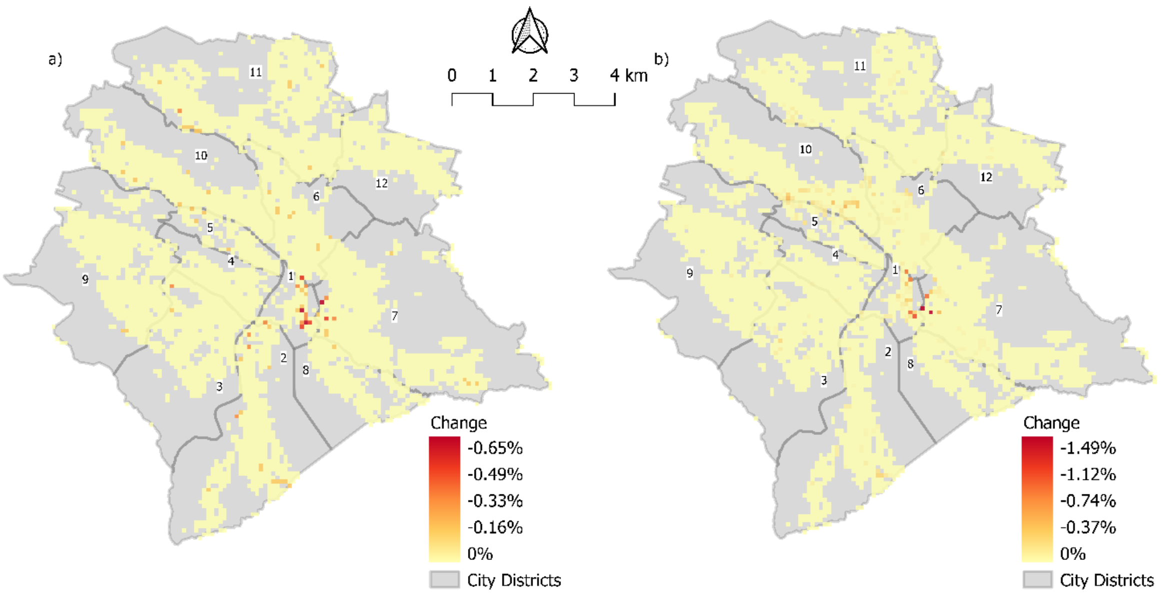

Figure A.12: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Older adults. a) Leisure and Sports; b) Food and Drinks.

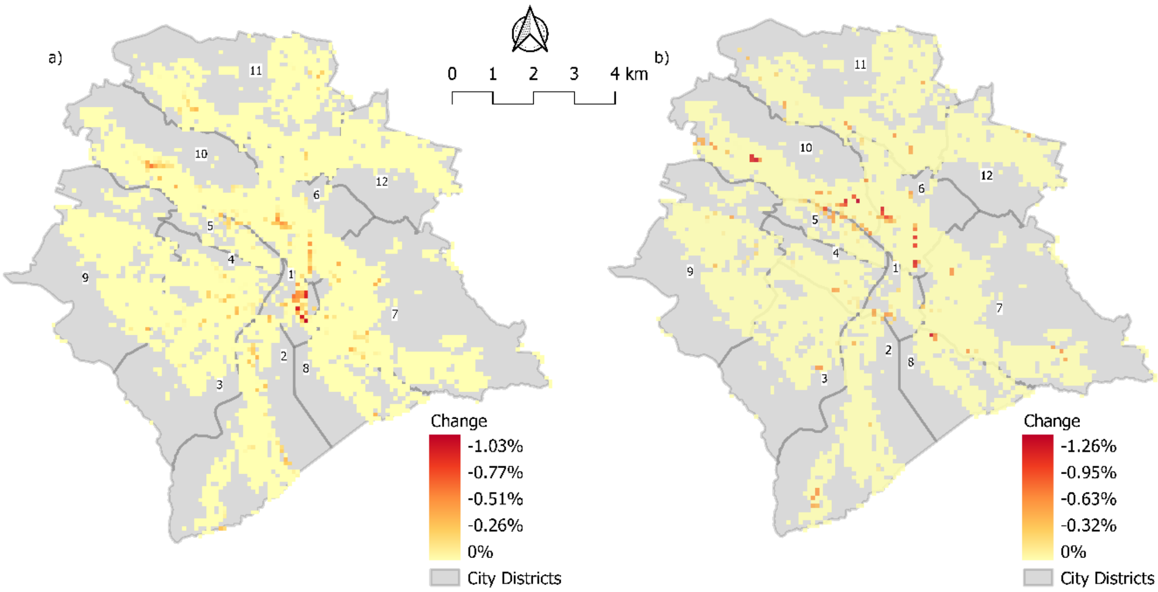

Figure A.13: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Manual wheelchair users. a) Healthcare Services; b) Daily Shopping.

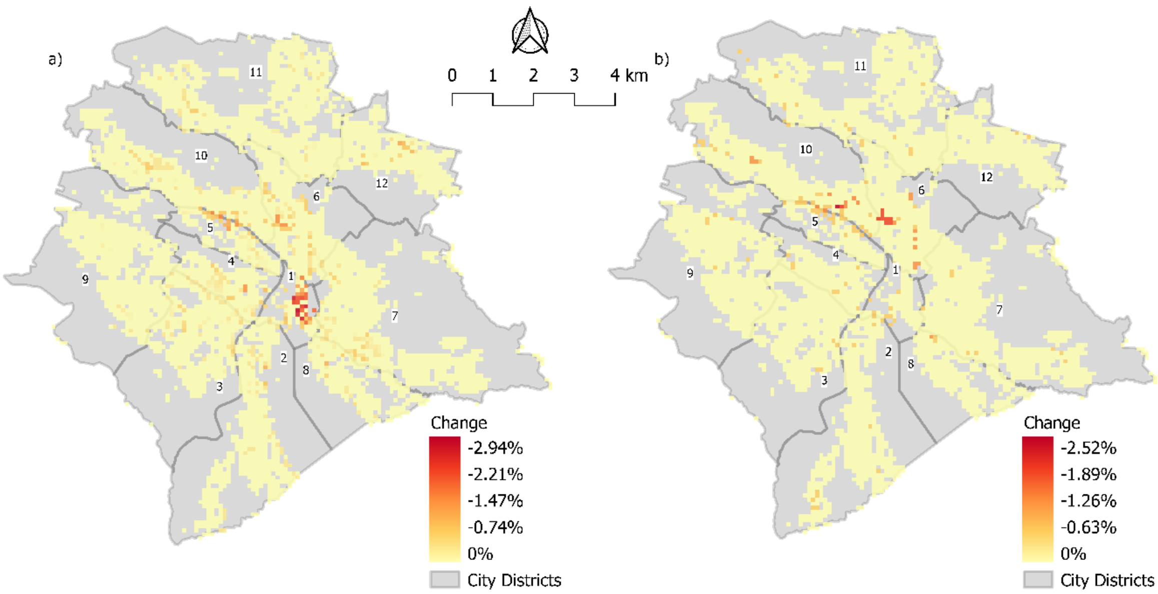

Figure A.14: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Manual wheelchair users. a) Healthcare Services; b) Daily Shopping.

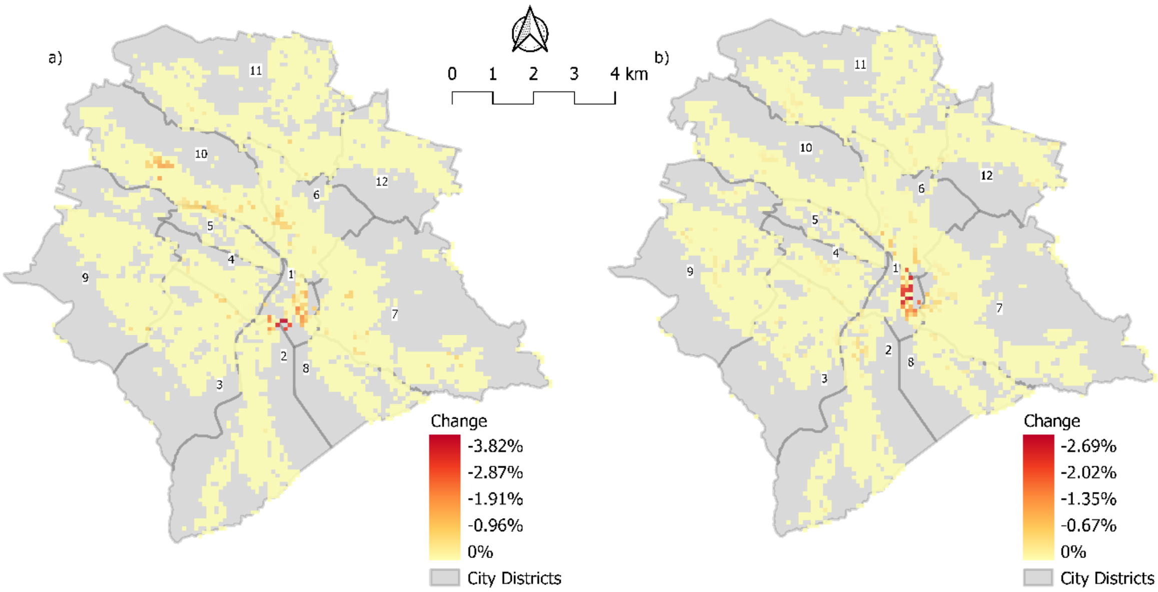

Figure A.15: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Manual wheelchair users. a) Public Services; b) Education.

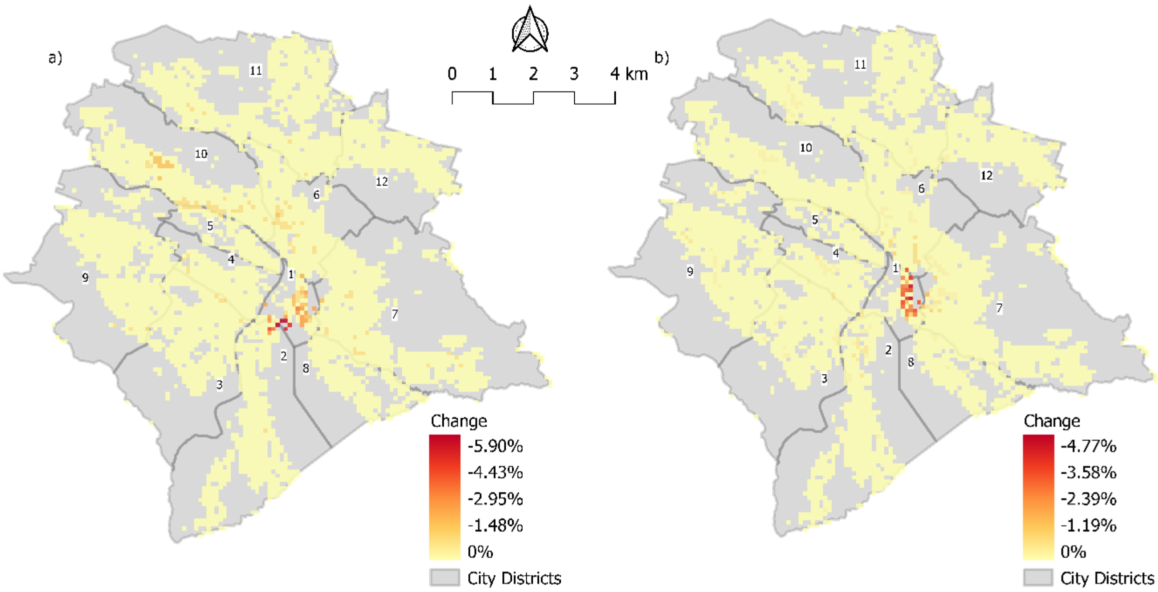

Figure A.16: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Manual wheelchair users. a) Public Services; b) Education.

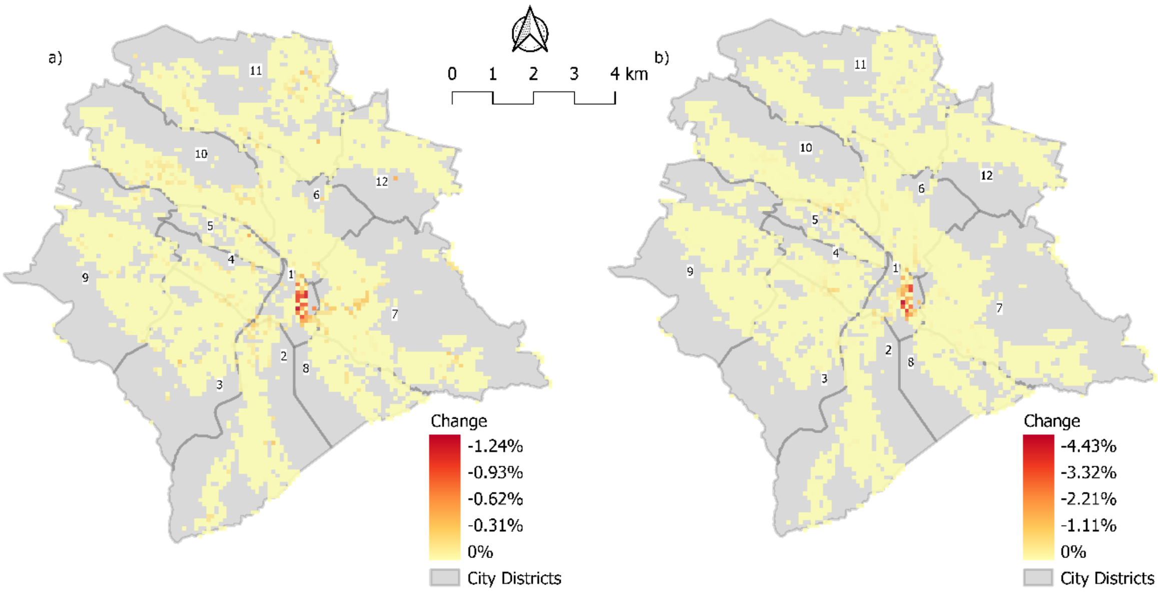

Figure A.17: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. KD2SFCA Method. Manual wheelchair users. a) Leisure and Sports; b) Food and Drinks.

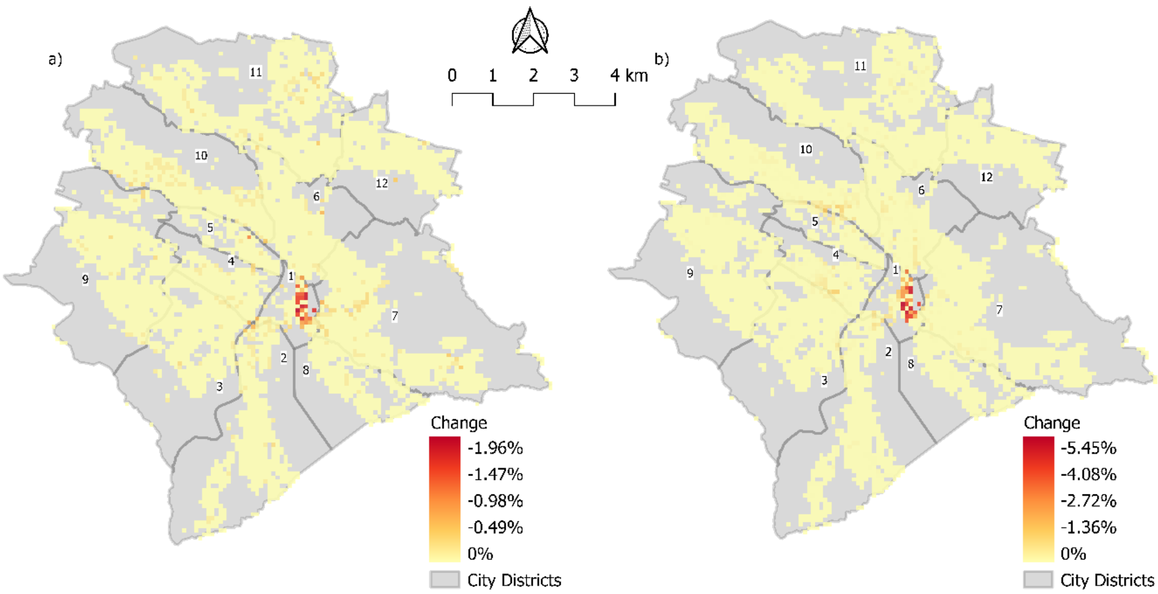

Figure A.18: Distribution of locations where SPAI values changed due to the enriched accessibility data in the city of Zurich. 2SFCA Method. Manual wheelchair users. a) Leisure and Sports; b) Food and Drinks.

A.2 Spatial Accessibility in Zurich – Other FCA Methods

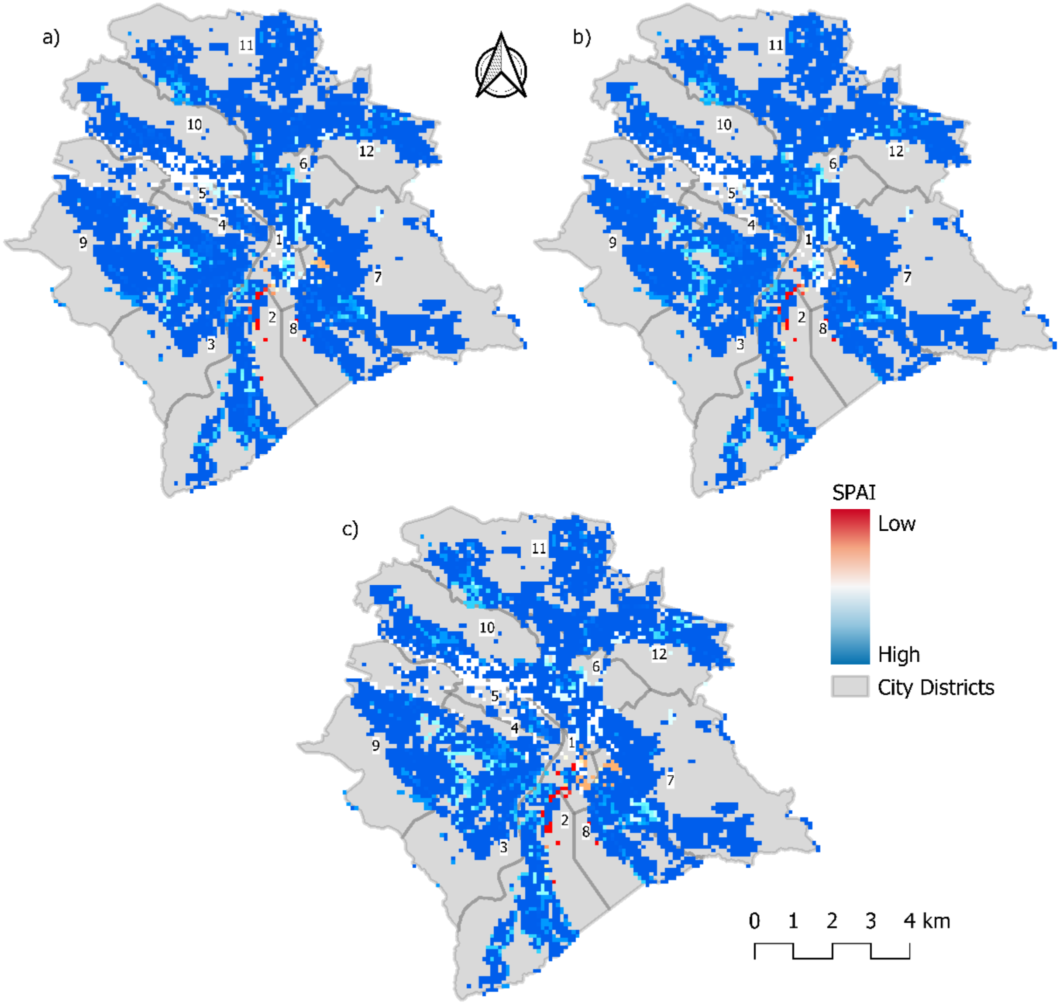

Figure A.19: Distribution of SPAI in the city of Zurich. Healthcare Services. KD2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

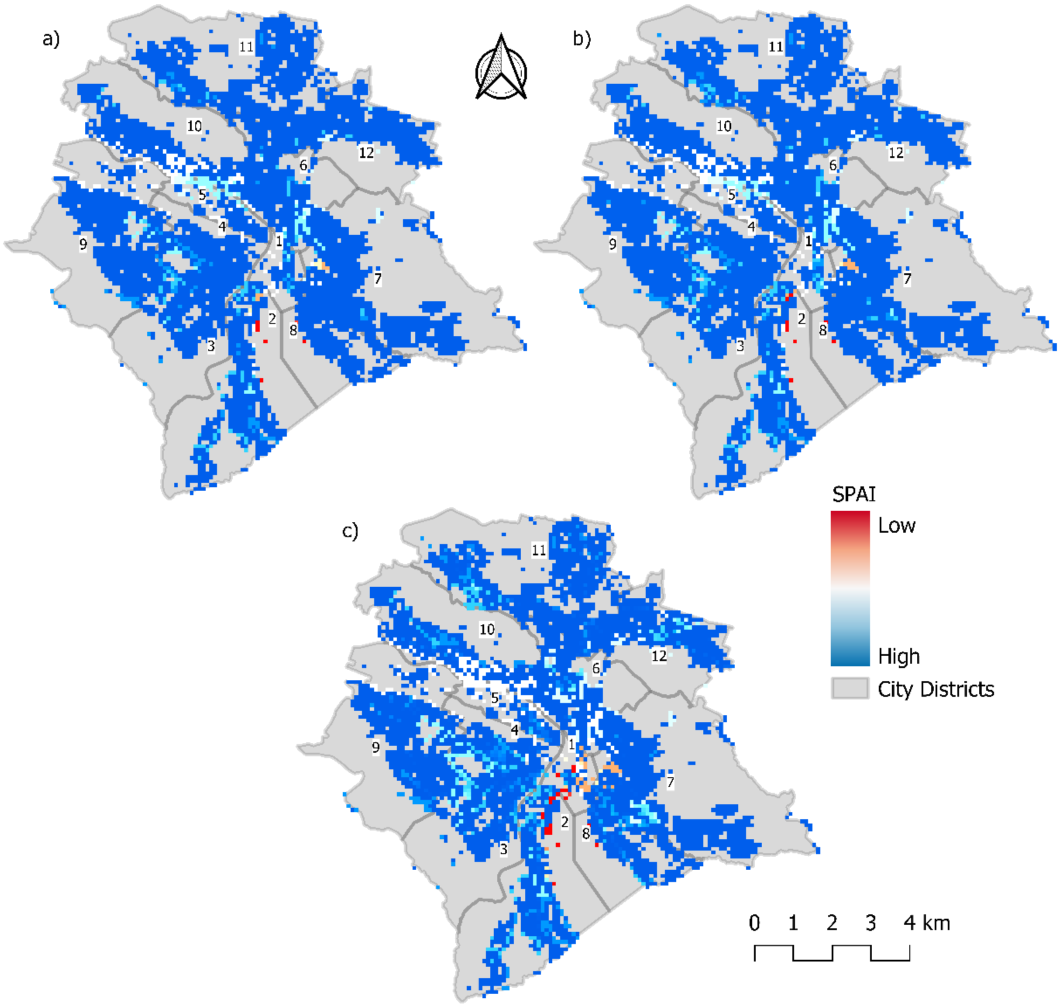

Figure A.20: Distribution of SPAI in the city of Zurich. Healthcare Services. 2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

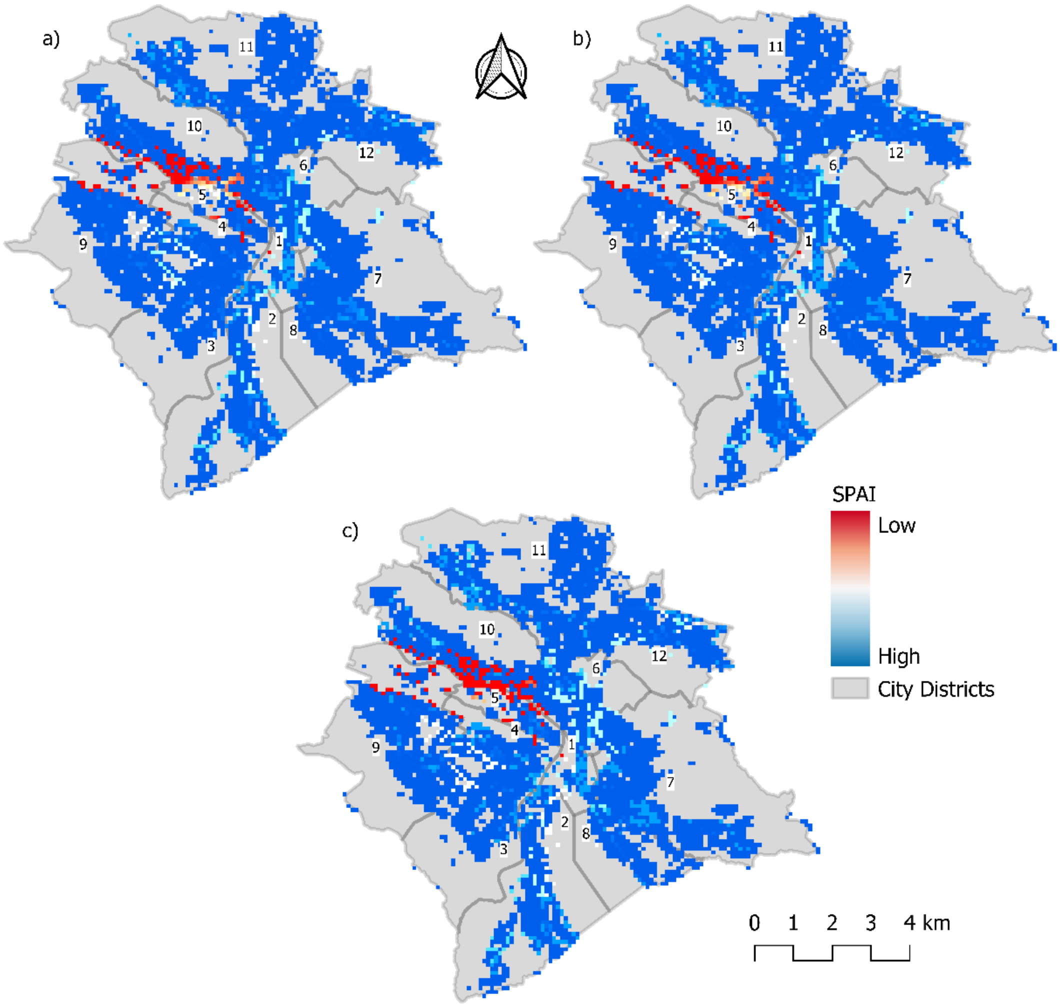

Figure A.21: Distribution of SPAI in the city of Zurich. Daily Shopping. KD2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

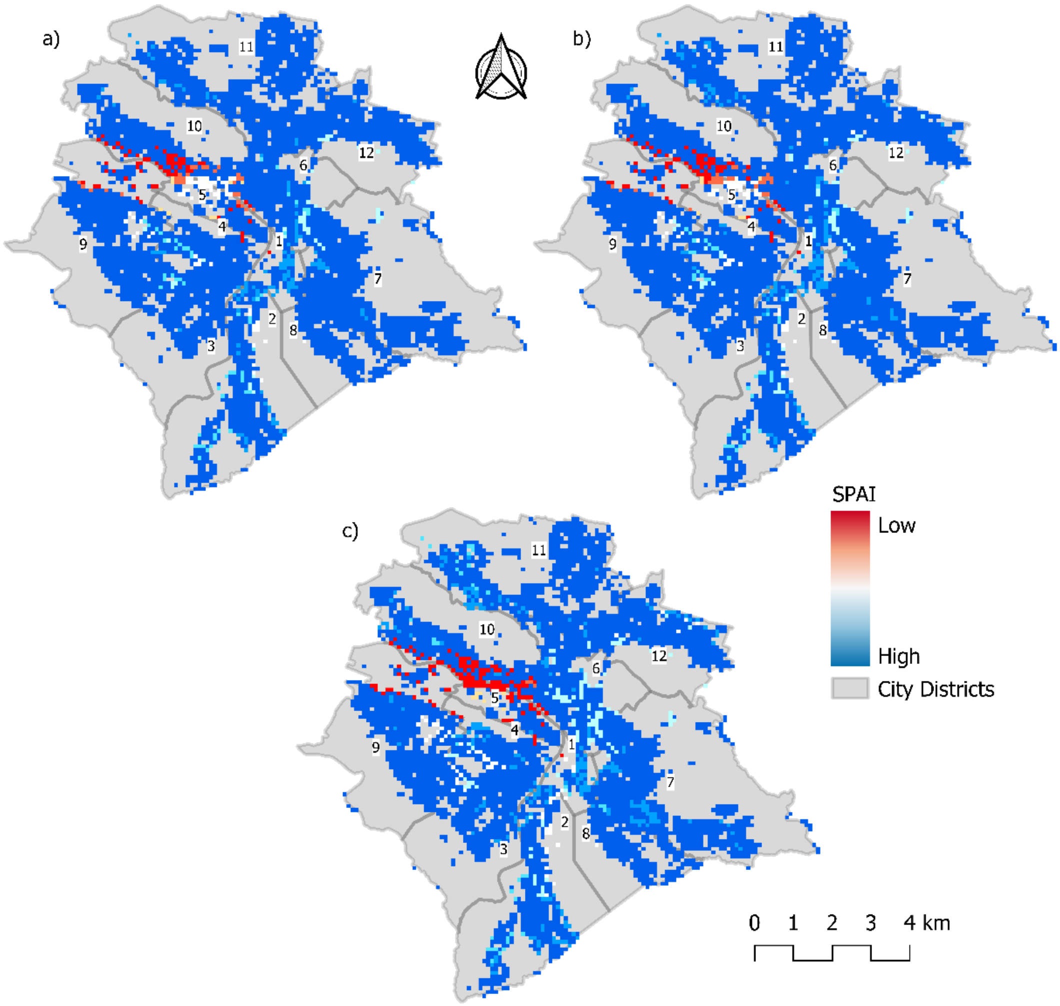

Figure A.22: Distribution of SPAI in the city of Zurich. Daily Shopping. 2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

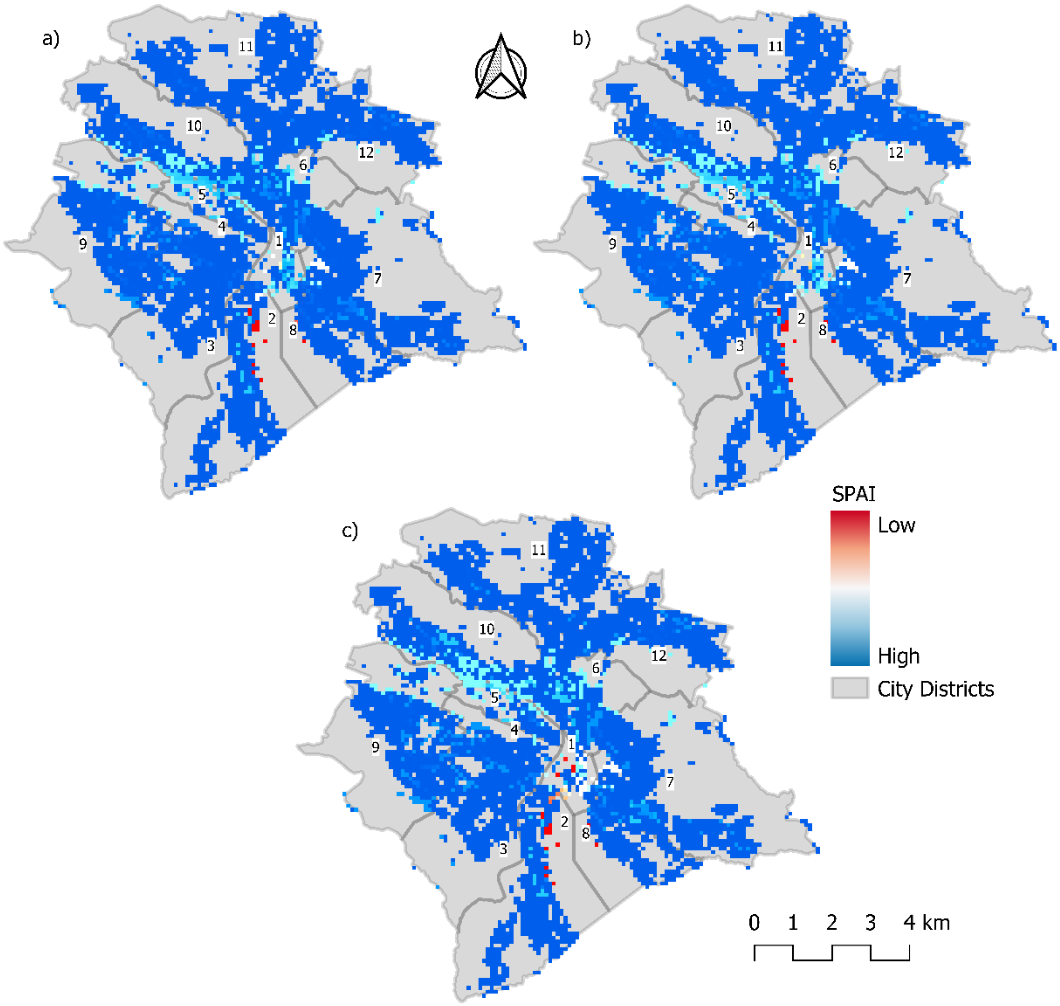

Figure A.23: Distribution of SPAI in the city of Zurich. Public Services. KD2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

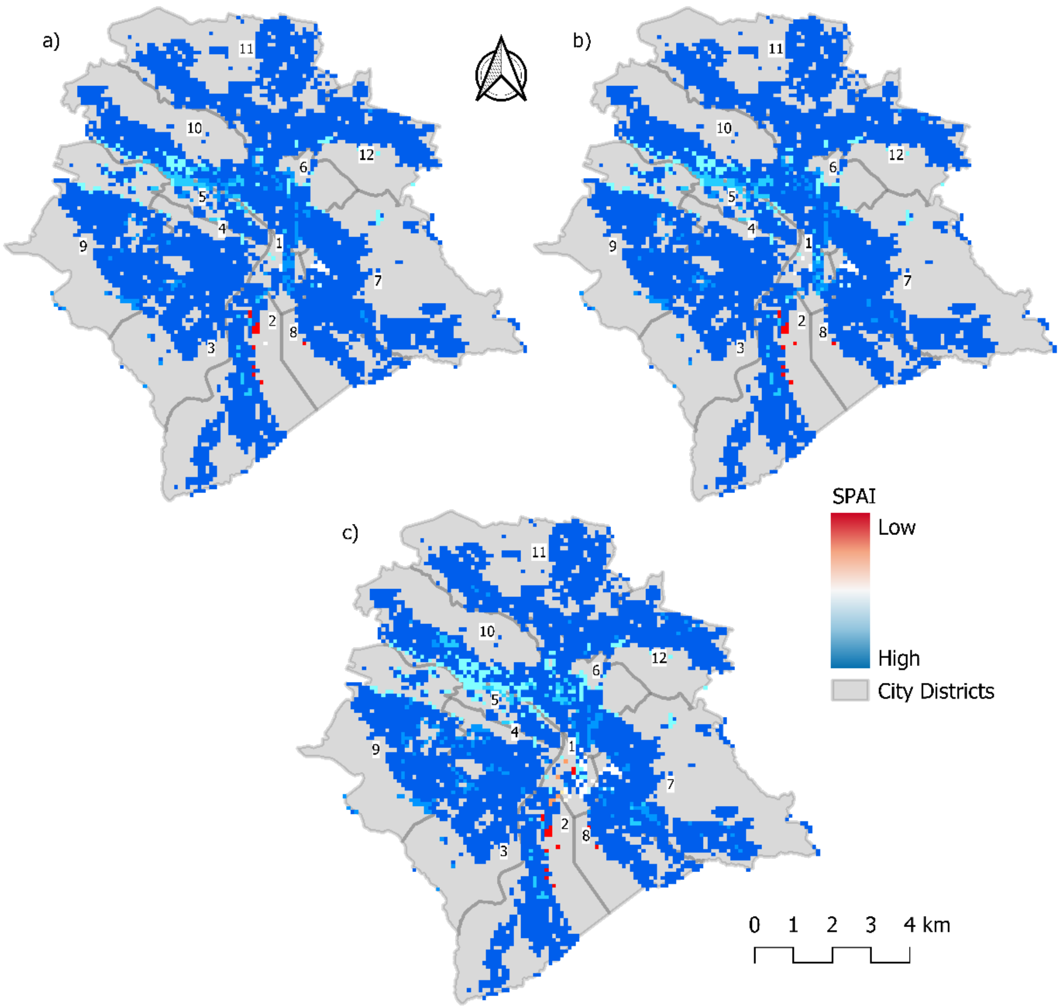

Figure A.24: Distribution of SPAI in the city of Zurich. Public Services. 2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

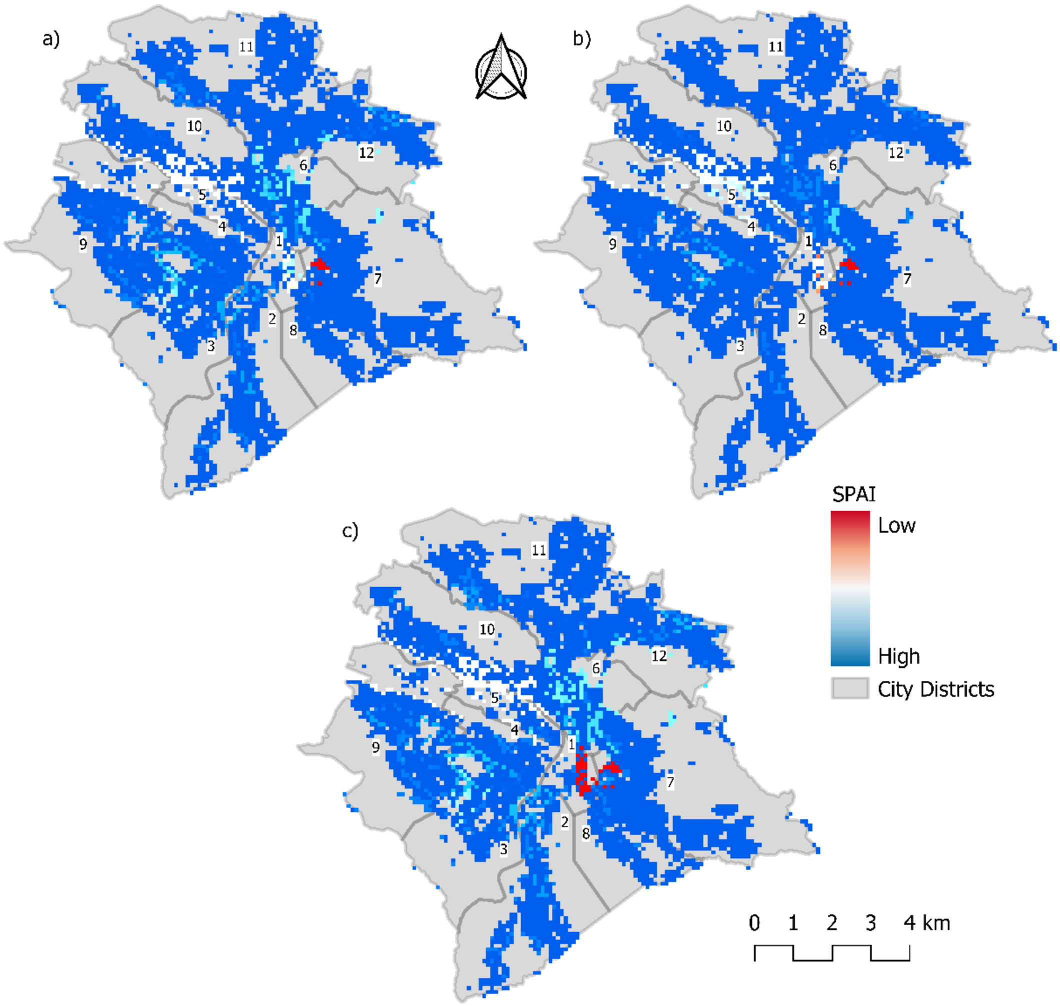

Figure A.25: Distribution of SPAI in the city of Zurich. Education. KD2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

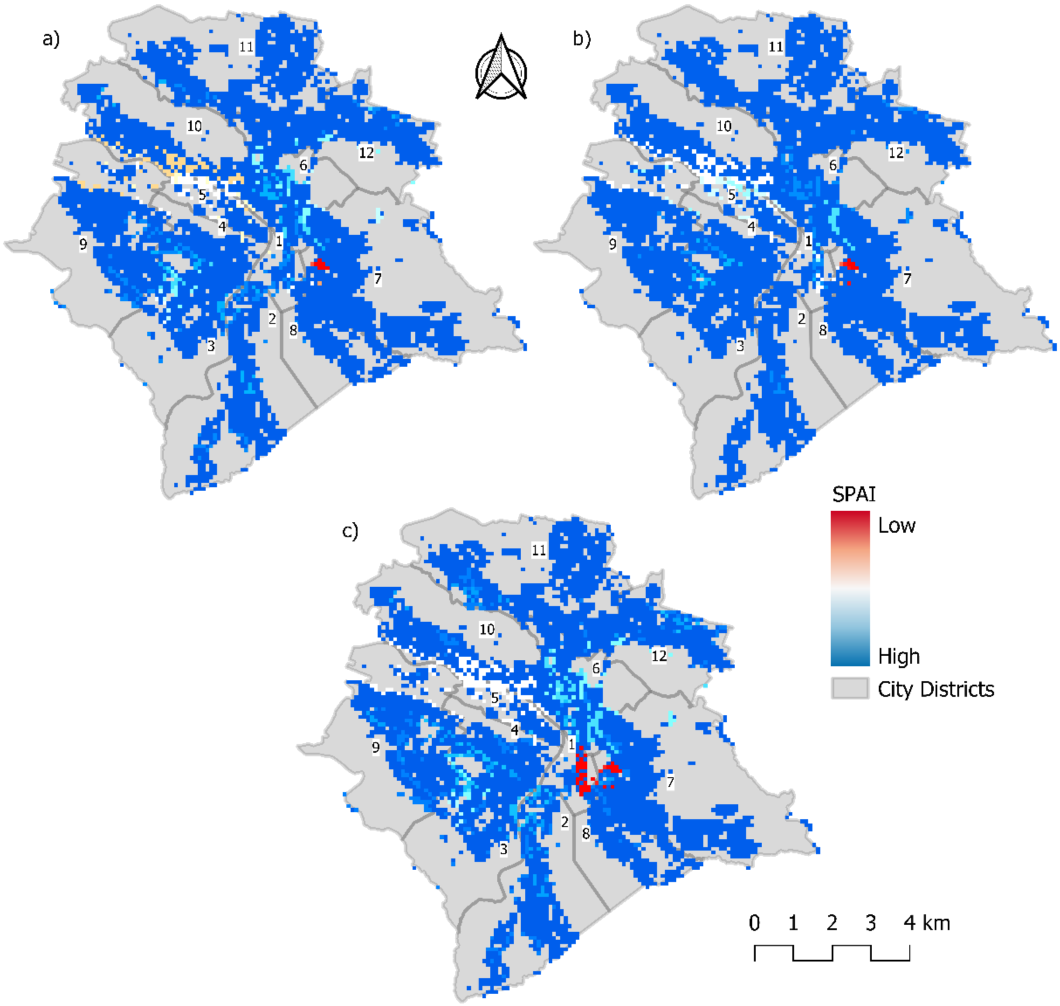

Figure A.26: Distribution of SPAI in the city of Zurich. Education. 2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

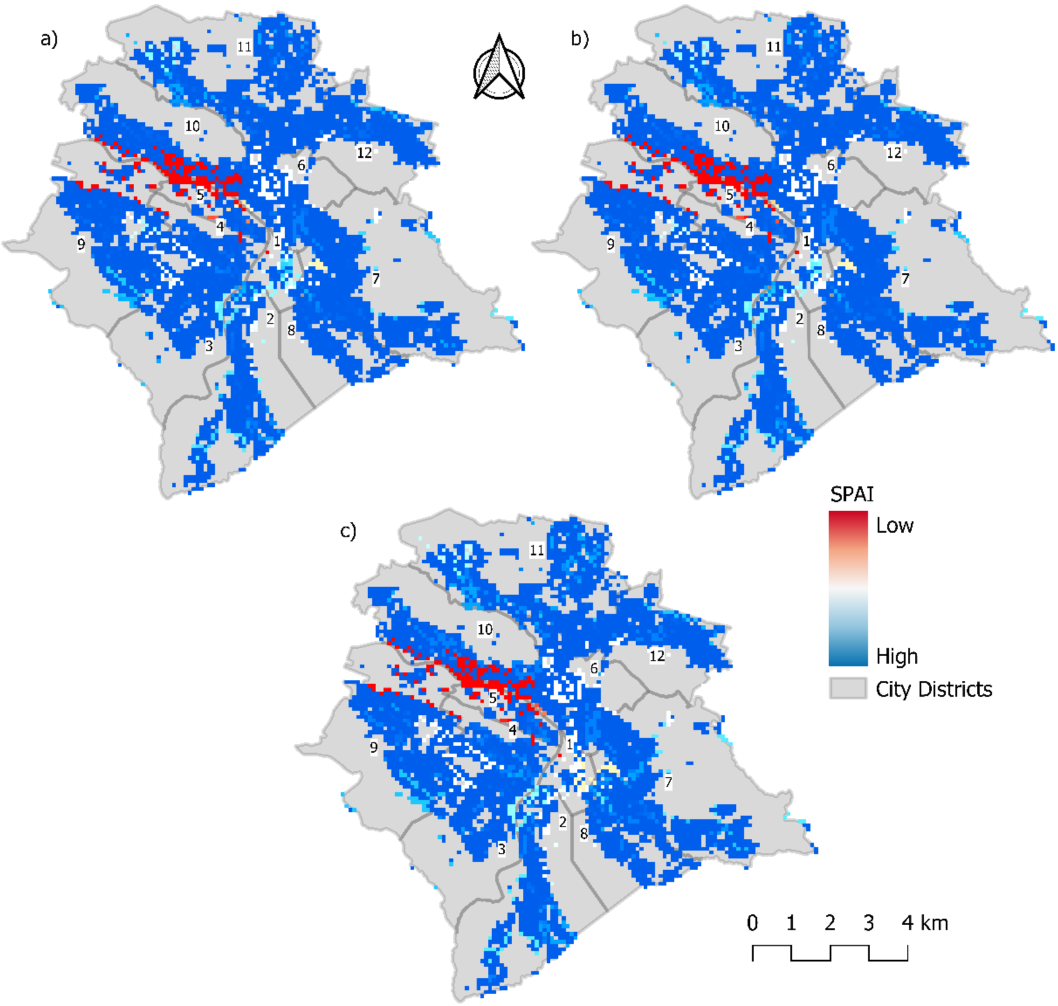

Figure A.27: Distribution of SPAI in the city of Zurich. Leisure and Sports. KD2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

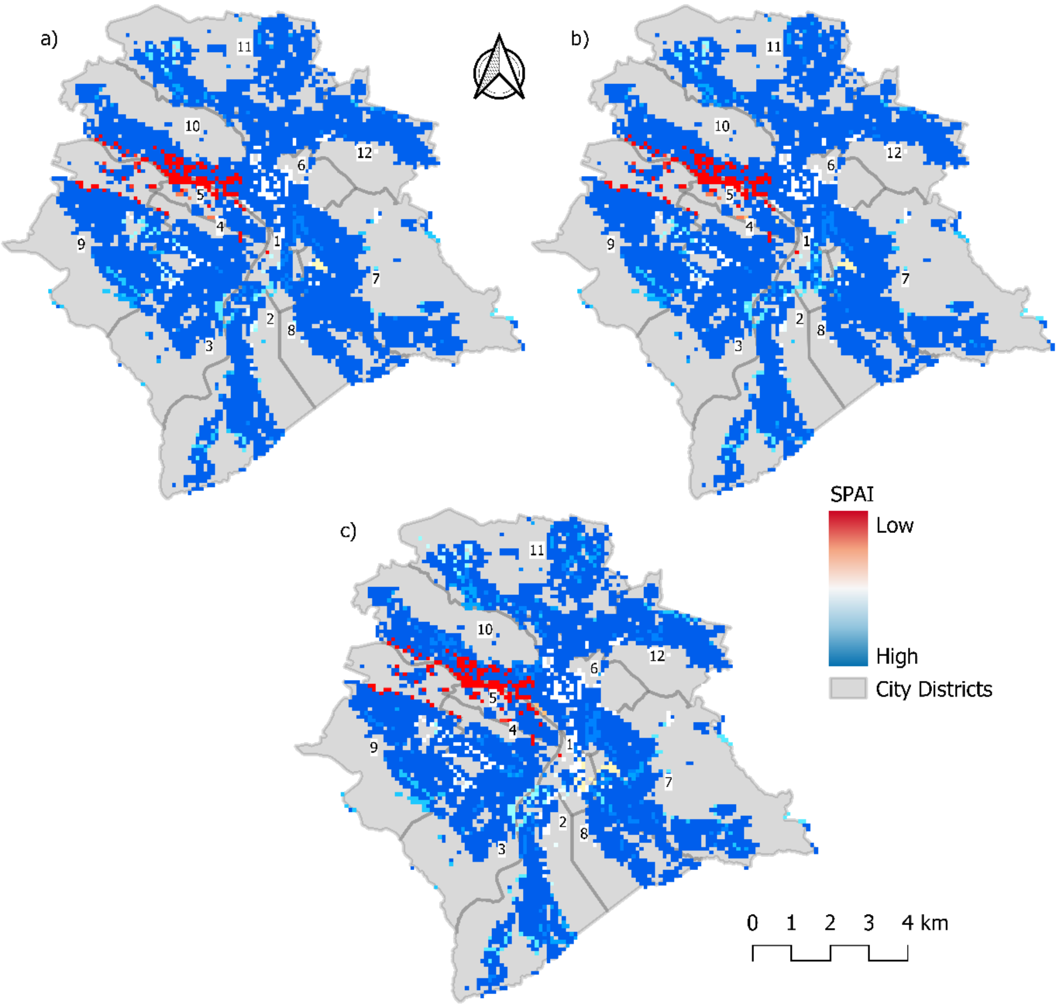

Figure A.28: Distribution of SPAI in the city of Zurich. Leisure and Sports. 2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

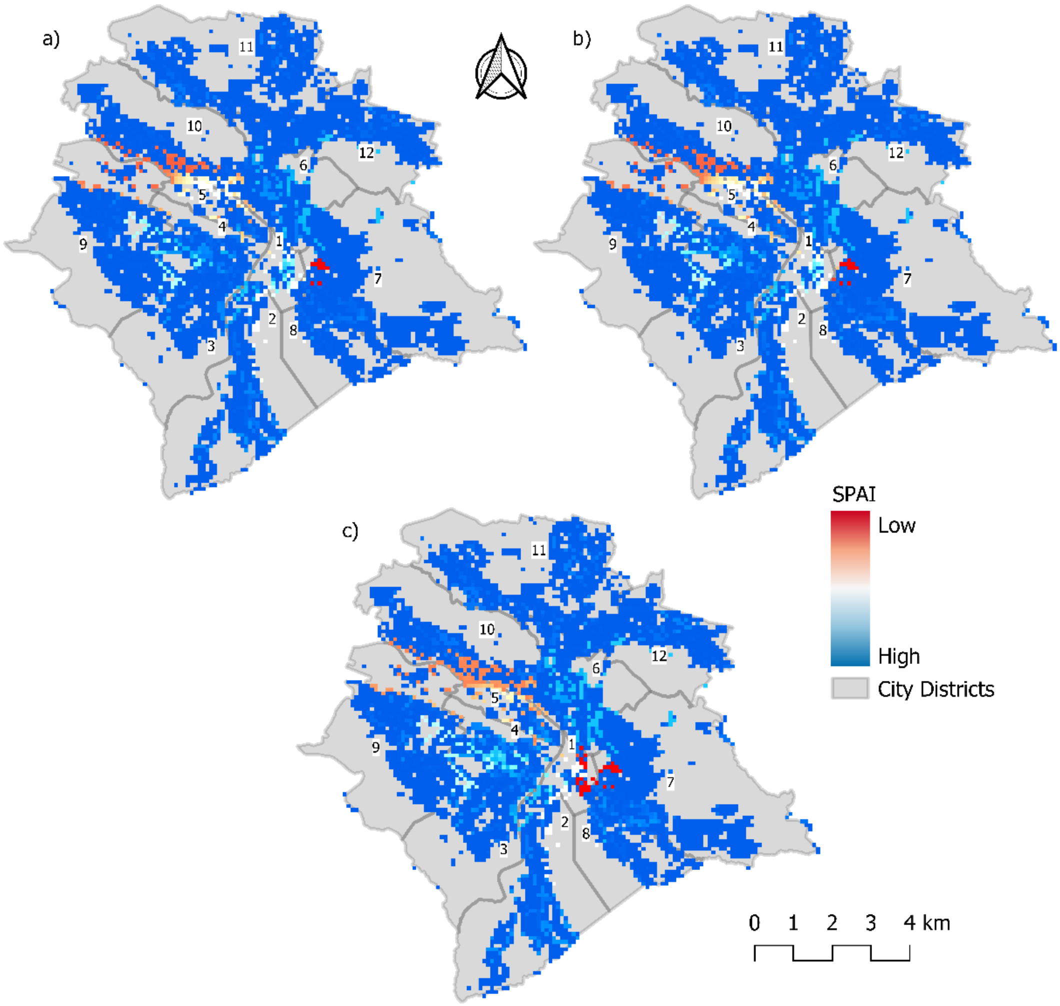

Figure A.29: Distribution of SPAI in the city of Zurich. Food and Drinks. KD2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

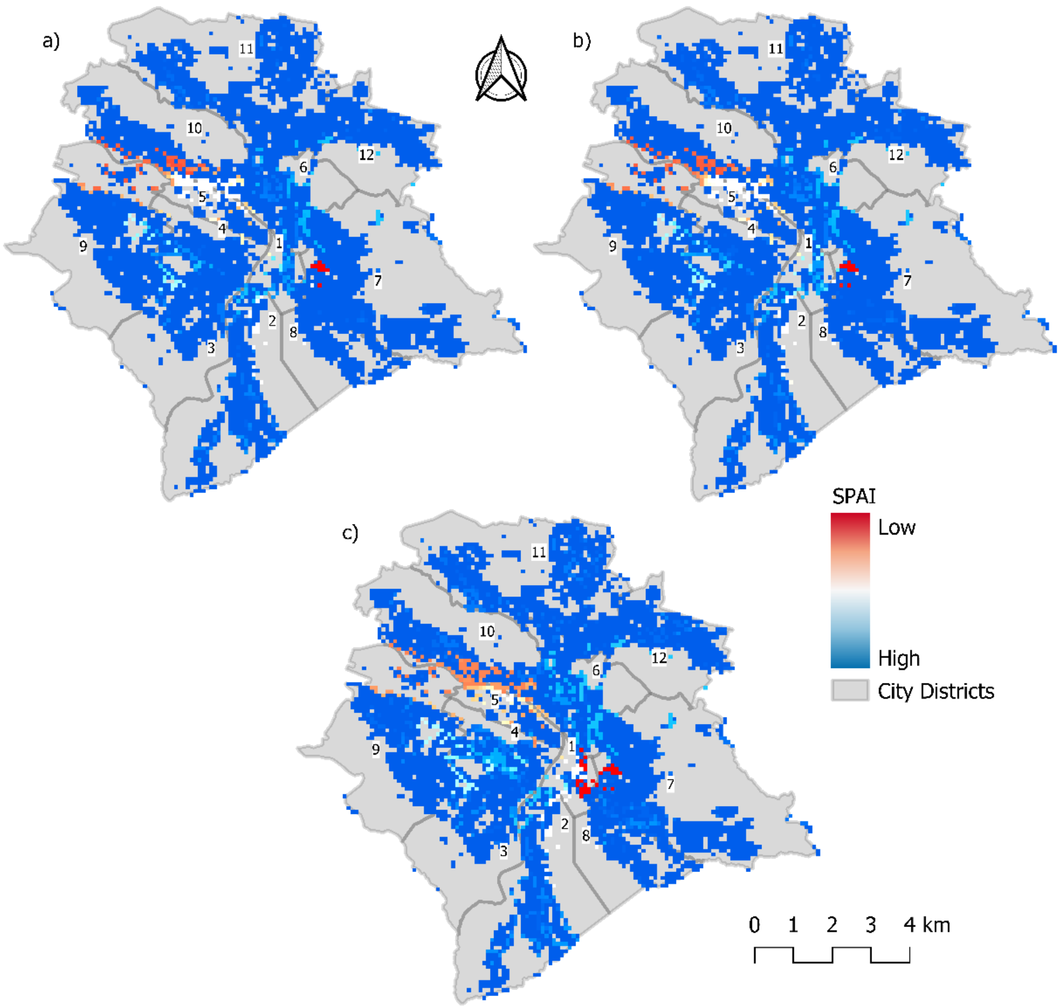

Figure A.30: Distribution of SPAI in the city of Zurich. Food and Drinks. 2SFCA. a) Younger adults; b) Older adults; c) Manual wheelchair users.

A.3 Personal Declaration

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

Yannik Joel Pude, 30.09.2022