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Assessing Urban Accessibility Measurement Algorithms within the X-Minute City in Zurich

GEO 511 Master's Thesis

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Abstract

Urbanization and the growing demand for accessible infrastructure underscore the need for inclusive urban planning, particularly for individuals with mobility limitations such as wheelchair users. Despite the increasing focus on equitable access, traditional accessibility assessments often overlook contextual elements, such as physical barriers, that can significantly impact mobility. This thesis addresses this gap by analyzing pedestrian spatial accessibility within the *x-minute city* framework, specifically for wheelchair users in Zurich's District 1. The study applies three different Floating Catchment Area (FCA) methods — 2SFCA, E2SFCA, and KD2SFCA — to evaluate how methodological choices influence accessibility outcomes for different population groups.

The methodology included enhancing the pedestrian network by integrating slope information and key accessibility features, such as stairs, surface conditions, and curb ramps, collected as part of a citizen science project. To further refine the analysis, a survey of 29 wheelchair users was conducted to assess their perception of accessibility features. The responses were used to weight the accessibility features in the enriched network, allowing for a more user-centric analysis. The enriched network was analyzed using the three FCA methods to assess the impact of data enrichment on accessibility evaluations.

The results reveal significant spatial accessibility disparities between the general population and wheelchair users. Applying the *x-minute city* concept with a 10-minute threshold revealed that, while accessible to the general population, wheelchair users experienced substantial limitations caused by physical barriers, demonstrating the importance of incorporating detailed accessibility data. Among the FCA methods, E2SFCA emerged as the most effective in capturing accessibility disparities, particularly for populations with mobility restrictions, as it accounts for distance decay within subzones, unlike the binary approach of 2SFCA or the continuous decay of KD2SFCA.

This study advances urban accessibility research by demonstrating the impact of integrating localized data and selecting appropriate methodological approaches. Refining accessibility models based on user needs leads to more precise and equitable evaluations for inclusive urban environments.

Keywords: *Floating Catchment Area Methods, Accessibility Analysis, x-Minute City, Wheelchair Users, Zurich, Physical Barriers, Sidewalk*

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List of Abbreviations

2SFCA	2-Step Floating Catchment Area
3SFCA	3- Step Floating Catchment Area
E2SFCA	Enhanced 2-Step Floating Catchment Area
B2SFCA	Balanced 2-Step Floating Catchment Area
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DEM	Digital Elevation Model
EVSFCA	Enhanced Variable-Width Floating Catchment Area
FCA	Floating Catchment Area
KD2SFCA	Kernel Density 2-Step Floating Catchment Area
M2SFCA	Modified 2-Step Floating Catchment Area
MAUP	Modifiable Area Unit Problem
MH3SFCA	Modified Huff 3- Step Floating Catchment Area
OGD	Open Government Data
OSM	Open Street Map
POI's	Points of Interest
SPAI	Spatial Accessibility Index
TIFF	Tagged Image File Format
ZuriACT	Zurich Accessible CiTy

1. Introduction

1.1 Motivation and Background

Urbanization and the increasing demand for accessible infrastructure are two major global trends that characterize the 21st century (WHO, 2007).

Cities play a central role in ensuring accessibility to every segment of society, contributing to increased equality by providing widespread access to services and facilities that meet people's basic needs (Gaglione et al., 2021). It is important to note that within the concept of accessibility, there are diverse definitions with varied objectives (Biazzo et al., 2019). The most common and widely used definition is by Hansen (1959), who defines accessibility as "the opportunity that an individual or a type of person, in a given location, has to participate in a particular activity or set of activities." Moreover, accessibility can address various dimensions, including spatial and aspatial accessibility (Khan, 1992) or potential and realized accessibility (Subal et al., 2021). This thesis focuses on spatial accessibility, the ability to interact with opportunities, considering the travel cost between demand and supply (Demitiry et al., 2022; Subal et al., 2021). In this context, spatial accessibility is a crucial indicator for determining if public facilities are distributed equally within the city (Liu et al., 2022).

Among different population groups affected by urbanization and spatial accessibility, wheelchair users are particularly exposed, as they face significant barriers to mobility in urban spaces. With over 65 million people worldwide relying on wheelchairs every day (Tannert & Schöning, 2018), urban infrastructure often fails to meet their mobility needs. Physical barriers, such as kerbs, steps, and uneven surfaces, can significantly limit their ability to navigate cities, particularly in crowded urban areas (Bromley et al., 2007). Accessibility in cities is not merely a matter of mobility; it is about independence, dignity, and full participation in social and economic life (Sahoo & Choudhury, 2023). Therefore, the limitations mentioned above not only restrict physical mobility but also limit access to essential services, social participation, and employment opportunities, which are fundamental for an inclusive society (Sahoo & Choudhury, 2023).

Efforts to improve accessibility for wheelchair users have been particularly prominent in Western cities, most notably after the introduction of the Disability Discrimination Act in the UK in 1995, which aimed to reduce physical barriers along pedestrian areas (Bromley et al., 2007). However, much remains to be done to ensure full accessibility in both older and newly urbanized environments (Sahoo & Choudhury, 2023).

As highlighted by UNECE (2020), everyone can experience periods of reduced mobility, requiring assistive devices or accessible urban spaces. Older adults, for instance, may experience declining mobility due to age-related fragility, while parents with strollers may struggle to navigate areas without ramps or smooth pavements (UNECE, 2020). The need for accessible urban design is thus broad and impacts a wide spectrum of the population.

Several innovative measures have been adopted to assess accessibility to essential services in urban environments, often based on catchment areas. Some of these measures draw on the concept of the *15-minute city*, introduced by Carlos Moreno for Paris (Moreno et al., 2021), which envisions urban spaces where residents can access essential services within a 15-minute walk or bike ride. This model has since evolved into the more flexible *x-minute city*, which recognizes that time thresholds for service access can range from 5 to 30 minutes, depending on local context and needs (Staricco, 2022). The *x-minute city* builds upon the *15-minute city* framework but acknowledges that varying time limits, such as 10, 20, or even 5 minutes, may be more suitable for different urban environments (Rao et al., 2024; Staricco, 2022). The ultimate goal of the *x-minute city* is to ensure that all neighborhoods provide efficient access to key services such as healthcare, education, entertainment, and commerce, regardless of the specific time threshold chosen (Pozoukidou & Angelidou, 2022).

In alignment with principles of sustainable and inclusive urban planning, the *x-minute city* framework prioritizes four key features: proximity (short distances to services), diversity (a range of available services), density (a sufficient population to support these services), and ubiquity (accessibility for all individuals) (Büttner et al., 2022; Shabtay et al., 2023). This perspective of the model, advocating for equitable access to public services (Jeon & Jung, 2023), aligns with the underlying concept shared by other urban frameworks. For example, it resonates with the approach of Zurich's *City of short distances* (“Stadt der kurzen Wege”) planning, where the city's proposed model encourages pedestrian exploration while ensuring accessibility to numerous locations within the neighborhood (Kanton Zürich, 2022). To ensure inclusivity in urban environments, it is vital to consider the challenges faced by populations with limited mobility, particularly wheelchair users (Bromley et al., 2007; Logan et al., 2022). Despite the broad applicability of the *x-minute city* model, many urban infrastructures still present significant barriers to these populations (Sahoo & Choudhury, 2023).

1.2 Research Gap

In the existing literature, spatial accessibility has been increasingly studied in recent years, but research on pedestrian accessibility remains limited in scope, often lacking a complete analysis including different factors. For instance, Liu et al. (2022), emphasize that many studies have focused primarily on car-based or public transport-based accessibility, neglecting active travel-based accessibility, such as walking. Walking not only supports physical health by preventing chronic diseases (Büttner et al., 2022) but also strengthens social ties within communities (Logan et al., 2022). However, the lack of detailed pedestrian network data, particularly regarding accessibility for diverse users, including those with disabilities, remains a major gap in current research (Bolten & Caspi, 2021).

Furthermore, many accessibility-related studies rely on representations of the "general population" (Wilberg et al., 2023), without considering the individuals' diversity and mobility needs (Bolten & Caspi, 2021; Wang et al., 2019). For example, scholars argue that few studies examine how people with disabilities experience the urban environment (Bromley et al., 2007; Lid & Solvang, 2016; Vale et al., 2017). Also, Sahoo & Choudhury (2023) argue that despite the growing recognition of equality and inclusion, achieving actual inclusion for individuals with mobility restrictions remains a significant challenge. They emphasize the significance of wheelchair accessibility, as it plays a pivotal role in promoting equality, inclusion, and overall well-being for individuals with mobility limitations (Sahoo & Choudhury, 2023). Therefore, the specific needs of disabled individuals are often only briefly mentioned (Bromley et al., 2007). This oversight underscores the importance of incorporating the perspectives of people with disabilities into urban planning processes, ensuring that environments are designed to accommodate a wide range of mobility needs (Bromley et al., 2005).

Moreover, existing studies concentrate on accessibility to a single public facility, like healthcare centers (Delamater, 2013; Demitiry et al., 2022; Kim & Kwon, 2022; Lin et al., 2018; Liu et al., 2022) or grocery stores (Hosford et al., 2022; Kesarowksi & Hernández-Palacio, 2023; Smith et al., 2010), without offering a comprehensive view of accessibility to multiple essential public facilities. This gap becomes even more apparent in the context of recent urban planning models, such as the *x-minute city*, where a holistic view of accessibility is required to ensure equal access to all services.

1.3 Research Objective

From a conceptual point of view, this thesis aims to investigate pedestrian spatial accessibility to different public facilities within the concept of the *x-minute city* focusing on wheelchair users. And from a methodological point of view, it aims to understand how different accessibility measures from the Floating Catchment Area (FCA) family, namely 2SFCA, E2SFCA, and KD2SFCA respond to the accessibility needs of specific population groups, considering enriched sidewalk networks with accessibility information.

With this, the main objective of this research aims to contribute to addressing the research gaps mentioned above, highlight the existing spatial accessibility issues potentially introduced to wheelchair users, and provide insights into how accessibility could be improved to create a more inclusive and sustainable urban environment.

1.4 Research Questions and Hypothesis

Research Question 1:

How does the enrichment of the sidewalk network datasets with detailed accessibility information, specifically catering to the diverse mobility needs of wheelchair users impact the outcome of accessibility measurement algorithms?

§ Hypothesis 1: I expect that an enriched sidewalk network with accessibility data will not only provide a more reliable baseline for accessible measurements but also generate distinct responses. I expect that these responses will be characterized by paths that avoid specific obstacles, even though this may result in an increase in travel time. The hypothesis is based on the idea that incorporating detailed accessibility data, including surface conditions and topographical challenges like steep slopes or stairways, will enable more accurate route optimization and a better consideration of individual needs, helping to reduce obstacles for wheelchair users.

Research Question 2:

To what extent can District 1 of Zurich be considered a 'x-minute city', and how does this perception change with the enrichment of the sidewalk network dataset?

§ Hypothesis 2: I expect that adherence to the concept of the "x-minute city" in Zurich's District 1 will decrease with the enrichment of the pedestrian network dataset. Despite the aim of enhancing urban inclusivity, the addition of accessibility information —

covering elements like sidewalk gradients, accessibility features, and surface conditions— may reveal barriers, potentially increasing travel times. Drawing from my personal knowledge of the city, I anticipate discovering areas with varying levels of accessibility, such as Niederdorf, which might present lower accessibility due to its challenging features, including cobblestones, stairs, and slopes.

Research Question 3:

How do different Floating Catchment Area (FCA) methods affect accessibility assessment within the framework of an x-minute city for wheelchair users?

§ Hypothesis 3: I hypothesize that using different Floating Catchment Area (FCA) methods will reveal varying patterns in the assessment of accessibility within Zurich's *x-minute city* framework. The 2SFCA method is likely to show stark contrasts, producing lower accessibility values due to its simplified approach. The E2SFCA method, with its focus on weighted subareas, will likely identify pockets of higher accessibility, leading to more varied results depending on the density of services in each subzone. The KD2SFCA method is expected to produce the most uniform results, likely resulting in higher accessibility values in areas where services are more evenly distributed, as it smooths out extremes and captures more subtle differences in accessibility across the urban area.

2. Literature Review

2.1 Accessibility

2.1.1 Definitions and Concepts

Accessibility is a wide-ranging concept with multiple definitions that vary depending on the context of use. The definition of accessibility (as defined in Section 1.1) draws from Stewart's concept of *population potential*, which refers to the relationship between population and distance. In other words, it is a measure of the relative closeness or proximity between origin and destination (Ashik et al., 2020).

Biazzo et al. (2019) illustrate that, depending on the context, the term accessibility may refer to the availability of services for disadvantaged people, the capability of reaching workplaces, or the ability to participate in certain activities at specific times of the day. Given the variety of definitions, some authors have specified different aspects of the general term accessibility. One distinction is proposed by Khan (1992), who differentiates between spatial and aspatial dimensions of access. Spatial access refers to the role of spatial separation between supply and demand, while aspatial access emphasizes non-geographical barriers such as language or ethnicity (Subal et al., 2021). In addition to this first dichotomy, Khan (1992) also differentiates between potential access and realized access. While potential access refers to the possibility of accessing a service, realized access represents the actual use of the service. These two dichotomies result in a 2x2 matrix composed of potential spatial access, realized spatial access, potential aspatial access, and realized aspatial access (Khan, 1992; Subal et al., 2021). Furthermore, Langford et al. (2016) also emphasize the importance of differentiating between potential accessibility measures and actual service use, as many other factors can influence service utilization beyond the impact of geographical friction.

Another categorization is suggested by Geurs & Van Wee (2004), who identify four components of accessibility: land use, transport, temporal, and individual. The land use component concerns the quantity, quality, and spatial distribution of opportunities (e.g. services) at each destination, the demand for these opportunities in the areas of origin (where people live), and the comparison between supply and demand, which can create competition for limited resources, such as jobs or hospital beds (Geurs & Van Wee, 2004). The individual component, on the other hand, refers to personal needs, capabilities, and opportunities, which depend on factors such as age, income, education level, and physical condition (Geurs & Van Wee, 2004). This is comparable to the concept of aspatial access mentioned earlier. Some researchers focusing on the

individual component examine for example accessibility specifically for older adults (Gaglione et al., 2021; Liu et al., 2022; Ulloa-León et al., 2023). Location-based measures analyze accessibility at a macro level, describing how easy it is to access certain activities or services in an area, such as measuring the number of jobs reachable within 30 minutes of travel (Geurs & Van Wee, 2003). Finally, the temporal component reflects time constraints, including the availability of opportunities at different times of day and the time that individuals have available to participate in specific activities (Geurs & Van Wee, 2003).

2.1.2 Spatial Accessibility

What has been discussed so far leads us to define spatial accessibility as the ability to reach services or opportunities, taking into account distance and geographic location. In other words, it measures how easily people can access what they need in everyday life, considering the distance between where they are (origin) and the services they intend to reach (destination). However, to fully understand the concept of spatial accessibility, it is essential to also consider availability.

Accessibility is not just about how easily services can be reached, but also about the number of opportunities available to the population. As Delamater (2013) points out, regional availability—the number of opportunities in a given area—must be balanced with the distance separating the population from resources to gain a complete picture of access. The combination of accessibility and availability, defined by Guagliardo (2004) as "spatial accessibility", provides an integrated framework that takes into account both the distribution of opportunities and people's ability to reach them.

Thus, it becomes evident that spatial accessibility plays a fundamental role in urban planning. From this perspective, it can be interpreted as the ability of cities to allow people to move efficiently, ensuring equity in access to services (Biazzo et al., 2019). This implies that accessibility is not only about the overall efficiency of urban transport but must also be broken down into specific accessibility for different areas and groups of people with particular needs (Biazzo et al., 2019). Poor spatial accessibility to urban facilities can worsen residents' quality of life, exacerbating social inequalities (Ashik et al., 2020).

The integration of spatial accessibility into public policies aims not only to improve the distribution of opportunities and the efficiency of transport but also to reduce social inequalities and promote greater equity (Hu et al., 2020). Throughout the rest of this thesis, the term *accessibility* will be used to refer to *spatial accessibility*, which involves

both the availability of services and the capacity of individuals to reach them, accounting for spatial distances and barriers.

2.1.3 X-Minute City

In recent years, cities worldwide have sought to improve walkability and proximity to essential services, with one of the most well-known concepts being the *15-minute city*. First introduced by Carlos Moreno for Paris in the early 2010s (Moreno et al., 2021), the *15-minute city*, as defined in Chapter 1, focuses on reducing travel time to improve quality of life by enabling people to easily integrate six key social functions: living, working, commerce, healthcare, education, and entertainment (Moreno et al., 2021). Numerous studies (Büttner et al., 2022; Papas et al., 2023; Pozoukidou & Angelidou, 2022; Ulloa-Leon et al., 2023; Zhang et al., 2022) support the idea that the *15-minute city* can promote public health and create more livable, healthier cities and neighborhoods. Building upon this concept, the *x-minute city* expands the framework to accommodate varying time thresholds depending on local context and needs (Logan et al., 2022). This model proposes that all necessary services and facilities—such as healthcare, education, commerce, and entertainment—should be accessible within a defined time limit, which can range from 5 to 30 minutes depending on the city's characteristics (Staricco, 2022). This approach is designed to enhance both proximity and inclusivity, ensuring urban environments cater to the diverse needs of all inhabitants, including those with mobility challenges (Büttner et al., 2022). The flexibility of the *x-minute city* allows for time thresholds that vary across cities: Sydney uses a 30-minute model, while Stockholm applies a 1-minute version (Rao et al., 2024). Staricco (2022) notes that cities in America and Australia often use a 20-minute framework, while 15 minutes remains the norm in many European and Asian cities. These differences in time thresholds are influenced by factors such as walkability levels and the spatial distribution of services, which vary across urban environments (Staricco, 2022). Despite these variations, the ultimate goal remains the same: to create urban spaces where essential services are easily accessible to everyone, regardless of ability (Büttner et al., 2022).

The concept of spatial accessibility is central to both the *x-minute* and *15-minute city* models. As cities grow, the distribution of urban services and infrastructure becomes crucial in ensuring equitable access for all residents (Park & Goldberg, 2021). Ashik et al. (2020) highlight that achieving a sustainable system requires careful planning of how facilities are distributed in space relative to the population. Kesarowski &

Hernández-Palacio (2023) further emphasize the importance of proximity and accessibility to workplaces and daily services for all inhabitants. Without addressing these concerns, cities may experience significant disparities in the level of access available to different population groups (Ashik et al., 2020).

By focusing on the relationship between time, space, and access, cities can foster more inclusive, resilient, and sustainable urban environments (Logan et al., 2022). This effort aligns with global initiatives, such as the United Nations Sustainable Development Goals, aimed at creating cities that are not only functional but also accessible to everyone, including those with mobility restrictions (Logan et al., 2022).

2.1.4 Accessibility Features

Despite various studies and projects, current infrastructures are generally designed based on the general population, without disabilities (Gharebaghi et al., 2018). Disability arises when there is a mismatch between individual capabilities and environmental demands (Lid & Solvang, 2016). It is the social and built environment that can support or limit citizens' self-esteem, thus influencing their opportunities to participate in society (Lid & Solvang, 2016). Several studies (e.g., Gamache et al., 2019; Gharebaghi et al., 2018; Lid & Solvang, 2016; Vale et al., 2017) agree on the existence of a gap between the current design of urban environments and the way people with disabilities experience and interact with these spaces. Vale et al. (2017) emphasize that the environment can significantly reduce accessibility to opportunities, creating barriers that can be overcome at a cost (e.g., travel time) or even completely prevent access.

Various studies have analyzed the mobility of people with physical restrictions, using different methods to assess their perception of the surrounding environment and accessibility features. Some research (e.g., Ab Hamid et al., 2023; Gamache et al., 2019; Kapsalis et al., 2022) opted for a systematic literature review, while others have used questionnaires and participatory studies (e.g., Bromley et al., 2007; Gharebaghi et al., 2018; Lid & Solvang, 2016; Meyers et al., 2002; Núñez et al., 2021). Lid & Solvang (2016) conducted interviews with individuals with visual impairments or mobility restrictions. From this study, it was found that the perception of accessibility features varies depending on the person and their disability. For example, wheelchair users perceive a lowered curb on sidewalks as a facilitator, whereas visually impaired individuals perceive it as a barrier since a curb helps them to identify where the street ends and the sidewalk starts (Lid & Solvang, 2016). Ab Hamid et al. (2023) highlight

that barriers such as uneven areas or hilly terrains often have a negative impact on spatial accessibility, especially for individuals with restricted mobility. Similarly, Vale et al. (2017) explain that a lamppost on a sidewalk reduces the available space for everyone. While it may not be a problem for those without disabilities, for someone using a wheelchair, the reduced space can prevent passage, forcing them to find an alternative route (Vale et al., 2017). In a literature review, Gamache et al. (2019) identify many obstacles that people with disabilities encounter on pedestrian infrastructure, such as curb ramps, uneven surfaces, pedestrian crossings, inadequate lighting, steps or stairs, rest areas, and bus stops.

Facilitators, on the other hand, can significantly improve sidewalk accessibility for people with disabilities. For individuals with mobility impairments, features such as smooth and wide sidewalks, well-maintained curb ramps, and sufficient crossing points are essential for efficient and less exhausting navigation (Rosenberg et al., 2012). Additional facilitators include the presence of grass strips separating sidewalks from traffic, which enhances safety and comfort, and adequate lighting to ensure visibility (Renel, 2019; Rosenberg et al., 2012). For individuals with visual impairments, tactile paving, auditory signals, and clear signage play a crucial role in improving accessibility. By addressing these facilitators, urban environments can transition from merely meeting basic requirements to fostering true equity and inclusivity.

Lid & Solvang (2016) therefore stress the need for urban planners to recognize disability as a universal human condition if they want to effectively incorporate accessibility into their planning work. To this end, it is necessary to have specific pedestrian networks to measure pedestrian accessibility and identify all potential barriers (Vale et al., 2017). As highlighted by Maliszewska-Nienartowicz (2020), ensuring access to goods and services for people with disabilities is a fundamental goal enshrined in the United Nations Convention on the Rights of Persons with Disabilities (United Nations, 2006), and it represents a crucial element for sustainable development and social inclusion. Using detailed data on the accessibility features present in the built environment in urban planning can contribute to promoting equity and making public spaces more accessible.

2.2 Floating Catchment Area Methods

Several methods have been proposed to measure spatial accessibility to public services, including provider-to-population ratios (Jamtscho & Corner, 2014), distance to the nearest provider (Ngui & Apparicio, 2011), and gravity models (Du & Zhao,

2022; Rehka et al., 2020; Stacherl & Sauzet, 2023). Traditional gravity models estimate accessibility based on supply and distance, assuming that the influence of services decreases with distance (Kiani et al., 2021). However, these models do not account for demand and assume a homogeneous population distribution (Delamater, 2013). The basic gravity model formula is:

$$O_i = \sum_j S_j f(d_{ij}) \quad (1)$$

where O_i is the cumulative opportunity of location i, S_j is the supply facility (e.g., the number of doctors in the case of healthcare resources) at location j, d_{ij} is the travel cost (e.g., time or distance) between location i and location j, and $f()$ is a distance decay function that reflects the spatial impedance of travel cost (e.g., d_{ij}) (Park & Goldberg, 2021).

To address this limitation, Shen's model (Shen, 1998) introduces a demand variable, which refines the accessibility measure by considering the number of people seeking services at each location:

$$A_i = \sum_j \frac{O_j f(C_{ij})}{D_j} \quad (2)$$

where A_i is the accessibility of people living in location i, O_j is the cumulative opportunity (or supply) at location j, $f(C_{ij})$ is a distance decay function that represents the spatial impedance between locations i and j. D_j is the demand potential at location j, calculated as:

$$D_j = \sum_k P_k f(C_{kj}) \quad (3)$$

where P_k represents the number of people in location k seeking opportunities at location j, and $f(C_{kj})$ is the spatial impedance between k and j.

While functional, these models have limitations. They fail to capture spatial details within analysis units and assume no interactions beyond the area boundaries (Langford et al., 2016). These container-based analyses are also prone to the Modifiable Areal Unit Problem (MAUP), where results can be influenced by the size and location of unit boundaries (Langford et al., 2016). Luo & Wang (2003) highlight that gravity models assume all services within a zone are fully available to residents, overlooking variations in service availability and competition.

Unlike traditional gravity models, FCA (Floating Catchment Area) methods overcome many of these limitations, offering a significant theoretical advantage. These methods allow the boundaries to "float," using travel buffers or attraction areas based on distance or travel time, thus eliminating the rigidity of fixed administrative boundaries (Delamater, 2013). FCA metrics provide a more interpretable result in the form of a supply-to-population ratio, better reflecting the reality of competition among residents for services (Demitiry et al., 2022). In FCA methods, a catchment area is shifted across the region of interest, and the density of events is estimated by considering a uniform distribution from the center of that area. Like gravity models, these methods incorporate both supply information (e.g., available services) and demand (e.g., the resident population). Therefore, FCA methods successfully combine service availability with spatial accessibility, including both the capacity of services and the distance (Subal et al., 2021).

FCA methods were initially developed to evaluate accessibility to healthcare services (Delamater, 2013; Gao et al., 2021; Kim & Kwon, 2022; Liu et al., 2022) and were later adapted for many other applications, such as access to public parks (e.g. Dai, 2011), grocery stores (e.g. Chen, 2019), and educational facilities (e.g. Chen et al., 2020).

The main common features of various FCA methods are the integration of supply and demand locations, the quantification of the ratio between them, and the assessment of the spatial relationship between supply and demand, independent of administrative boundaries (Jörg et al., 2019). The result is an accessibility index that improves with a higher number of supply points, greater capacity, lower demand, and closer proximity between the population and services (Jörg et al., 2019).

An important aspect of FCA methods is the use of distance decay functions, which represent the decreasing likelihood of using a service as distance increases (Subal et al., 2021). These functions (see Figure 1) can be modeled in different ways, including binary, continuous, or hybrid forms, where the catchment area is divided into subzones to better reflect variations in accessibility (Luo & Qi, 2009; Luo & Wang, 2003). These subzones allow for the application of different weights based on distance, improving the accuracy of accessibility calculations (Luo & Qi, 2009).

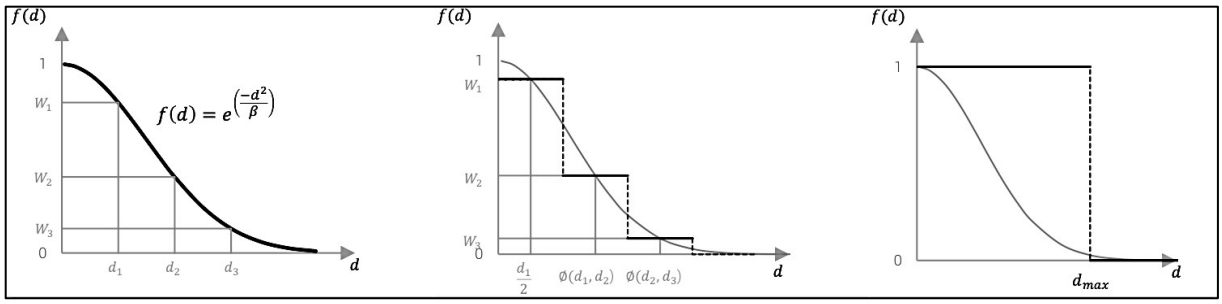

Figure 1 Distance weighting functions to operationalize the relationship between distance and accessibility. From left to right: Gaussian function (continuous function), staircase function based on a Gaussian function (hybrid function), whereby the mean values of the subzones are used to derive the distance weights, binary-discrete staircase function (Jörg et al., 2019)

There are several variants of FCA methods that further enhance this methodology. In the following sections, the Two-step Floating Catchment Area (2SFCA) method, the Enhanced 2SFCA (E2SFCA), and the Kernel Density 2SFCA (KD2SFCA) will be presented in detail, along with a discussion of their applications and benefits.

2.2.1 2SFCA

The Two-step Floating Catchment Area (2SFCA) method, introduced by Luo and Wang (2003), represents an important advancement in characterizing spatial accessibility. It combines information on demand, supply, and distance in two stages, producing a binary measure of travel impedance to evaluate accessibility (Luo & Wang, 2003).

In the first stage, the method calculates the supply-to-demand ratio R_j, dividing the capacity of a facility S_j (supply) by the population P_i (demand) within the threshold distance d_0 which represents the size of the catchment area (Luo & Wang, 2003). This stage determines the ability of a facility to meet the needs of the population within its service range:

$$R_j = \frac{S_j}{\sum_{i \in \{d_{ij} \leq d_0\}} P_i} \tag{4}$$

In the second stage, the accessibility index A_i for each demand point i is calculated by summing the ratios R_j obtained in the first stage for all facilities j within the threshold distance d_0 from i:

$$A_i = \sum_{j \in \{d_{ij} \leq d_0\}} R_j = \sum_{j \in \{d_{ij} \leq d_0\}} \frac{S_j}{\sum_{j \in \{d_{ij} \leq d_0\}} P_i} \tag{5}$$

This binary approach considers all populations within a predefined threshold as having the same access to facilities, without accounting for variations in the distance between the population and the facilities (Chen & Jia, 2019; Luo & Wang, 2003).
In practical terms, the steps of the 2SFCA method can be clearly visualized in the diagram in Figure 2 proposed by Park & Goldberg (2021).

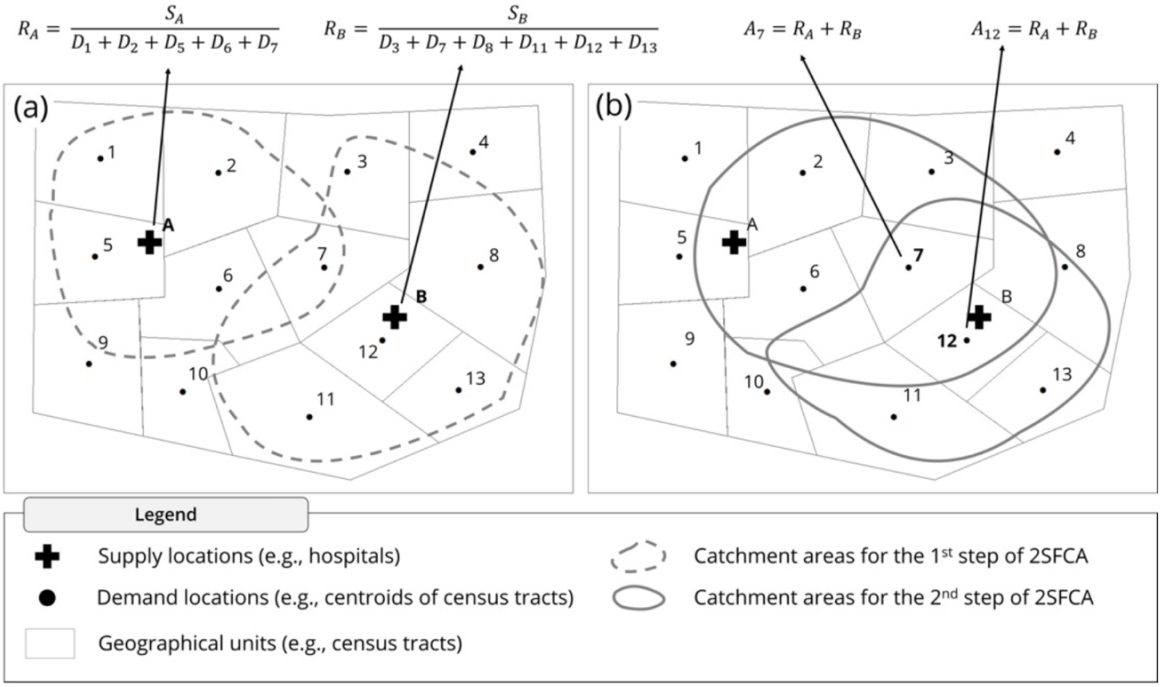

Figure 2 Diagram of the two-step floating catchment area (2SFCA) method. (a) First, the supply-to-demand ratio is calculated for each facility within a set travel time. (b) Next, the total supply-to-demand ratios of all facilities within the travel time are summed up for each location (Park & Balgberg, 2021).

In the first step, the providers, represented by A and B (the black crosses), are considered, and their catchment areas are identified, as indicated by the dashed lines. For each provider, the ratio between the supply capacity and the demand from the points within their catchment area is calculated. For example, for provider A, serving points 1, 2, 5, 6, and 7, the ratio is calculated by dividing the capacity of provider A by the total demand of those points. The same is done for provider B, who serves other demand points such as 3, 7, 8, and so on.
In the second step, the focus shifts to the demand points, represented by the small black dots. For each point, the total accessibility to nearby providers is calculated. For instance, demand point 7 lies within the catchment areas of both A and B, so its total accessibility will be the sum of accessibility to both providers. The same applies to point 12, which is influenced by both providers. In this way, each demand point receives a measure of total accessibility, considering all providers within its range.

The 2SFCA method was developed to address the limitations of traditional place-based accessibility measures, but it has been criticized for its reliance on the fixed size of the catchment area. One of the main limitations, as highlighted by Langford et al. (2016), is that locations outside the catchment area are considered completely lacking access, creating sharp and artificial boundaries in accessibility scores (Luo & Qi, 2009). Another limitation is that 2SFCA does not account for distance impedance within the catchment area: all people within the threshold are treated as having equal access, regardless of their actual distance from services (Wang, 2012).

2.2.2 E2SFCA

The Enhanced Two-Step Floating Catchment Area (E2SFCA) method, introduced by Luo & Qi (2009), is an improvement of the 2SFCA developed to overcome some of its limitations. While the 2SFCA uses a binary approach where all facilities within a certain travel time threshold are considered equally accessible, the E2SFCA introduces weights for different travel time thresholds to better reflect spatial impedance (Demitiry et al., 2022). This improvement accounts for distance, differentiating access opportunities based on proximity (Luo & Qi, 2009). In this context, the E2SFCA adopts a hybrid approach, combining binary and continuous aspects, where closer zones receive higher weights and farther zones receive lower weights (Luo & Qi, 2009).
The E2SFCA uses a geographic weighting function to assign weights in both stages of the calculation process. The Formula (6) for the first stage calculates the supply-to-demand ratio R_j considering three different travel time subzones, each with a specific weight W_r:

$$R_j = \frac{S_j}{\sum_{i \in \{d_{kj} \in D_r\}} P_i W_r} = \frac{S_j}{\sum_{i \in \{d_{ij} \in D_1\}} P_i W_1 + \sum_{i \in \{d_{ij} \in D_2\}} P_i W_2 + \sum_{i \in \{d_{ij} \in D_3\}} P_i W_3} \quad (6)$$

where Sj is the capacity of facility j, P_i is the population at point i, and W_1, W_2, W_3 are the weights assigned to the three travel time subzones (e.g., 0-10 minutes, 10-20 minutes, and 20-30 minutes). This approach allows for a better differentiation of accessibility based on distance and the attractiveness of the facility (Luo & Qi, 2009).
In the second stage, the spatial accessibility index A_i is calculated for each demand point i by summing the supply-to-demand ratios R_j of accessible facilities j, weighted based on their distance from the demand point:

$$A_i = \sum_{k \in \{d_{kj} \in D_r\}} R_j W_r = \sum_{k \in \{d_{kj} \in D_1\}} R_j W_1 + \sum_{k \in \{d_{kj} \in D_2\}} R_j W_2 + \sum_{k \in \{d_{kj} \in D_3\}} R_j W_3 \quad (7)$$

This approach addresses the limitations of the 2SFCA, particularly its reliance on a binary system that does not account for differences within the same catchment area (Jörg et al., 2019; Luo & Qi, 2009). While the 2SFCA treats all facilities within a defined radius as equally accessible, the E2SFCA differentiates the influence of facilities based on their actual distance from the demand point, thus producing a more realistic accessibility index (Jörg et al., 2019).

However, two main limitations of the E2SFCA method emerge. The first concerns the sensitivity of results to the chosen impedance coefficients, which can lead to significant variations in access scores (Lin et al., 2018). This variability introduces uncertainty about the accuracy of the results and their dependence on the selected coefficient rather than the actual configuration of the access system (Lin et al., 2018). The second limitation relates to the assumption of a single mode of transport, generally based on the use of private cars. This reduces the flexibility of the method in contexts where alternative modes of transportation, such as public transport or pedestrian mobility, are used (Lin et al., 2018).

2.2.3 KD2SFCA

The Kernel Density Two-Step Floating Catchment Area (KD2SFCA) method represents a further evolution of the 2SFCA and was developed to address the limitations related to the binary and zonal approach of previous methods. Unlike the 2SFCA and E2SFCA, which use discrete time or distance thresholds to divide catchment areas, the KD2SFCA introduces a continuous approach through kernel density estimation (Dai & Wang, 2011). This method allows us to model the influence of distance in a continuous way, providing a more realistic representation of spatial accessibility compared to methods that divide areas into subzones (Jörg et al., 2019).

In the KD2SFCA, the influence of the distance between demand and supply points is modeled with a kernel function, often the Epanechnikov kernel (Jörg et al., 2019). This kernel is commonly used because it optimizes the balance between bandwidth and distance decay, offering a more intuitive and realistic representation of accessibility (Jörg et al., 2019). Unlike the binary or zonal approaches of 2SFCA and E2SFCA, the KD2SFCA ensures that accessibility decreases gradually as the distance from the supply point increases (Dai & Wang, 2011).

The bandwidth *h* defines the catchment area, but unlike the 2SFCA, the influence of distance is not uniform (Dai & Wang, 2011). The kernel function guarantees a progressive reduction of accessibility towards the boundaries of the area, becoming zero beyond that limit (Dai & Wang, 2011).

The first stage of the KD2SFCA method uses the kernel function to rescale the population within the catchment area based on the distance from a supply point. In the second stage, the kernel function is applied again to rescale the accessibility ratio *Rj*, weighting the accessibility of each facility according to the distance between the demand and supply points:

$$A_i = \sum_{j \in \{d_{ij} \leq d_0\}} R_j f(d_{ij}, h) = \sum_{j \in \{d_{ij} \leq d_0\}} \frac{S_j f(d_{ij},h)}{\sum_{j \in \{d_{ij} \leq d_0\}} P_i f(d_{kj},h)} \quad (8)$$

where *Sj* represents the service capacity at the supply point *j*, P_i is the population at the demand point *i*, and $f(d_{ij})$ is the kernel function that depends on the distance d_{ij} between points *i* and *j*. In this context, the bandwidth *h* defines the threshold within which accessibility is calculated.

One of the most relevant aspects of KD2SFCA is that it produces higher accessibility scores in areas with a higher density of supply points, such as shops or clinics, and lower scores in more distant areas or those with fewer access opportunities (Dai & Wang, 2011). This continuous approach allows for greater precision compared to the 2SFCA, as it not only considers areas inside or outside a catchment area but also accounts for spatial variations within the area itself (Jörg et al., 2019).

2.2.4 Other Variants

Several variants of the 2SFCA method have been developed to improve spatial accessibility analysis. For instance, the Modified 2SFCA (M2SFCA), proposed by Delamater (2013), reduces errors in accessibility estimation by considering the suboptimal placement of facilities. Another key variant, the Balanced 2SFCA (B2SFCA), introduced by Demitiry et al. (2022), balances demand and service distribution by assigning fractional populations to multiple facilities. The Enhanced Variable-Width Floating Catchment Area (EVSFCA), developed by Luo & Whippo (2012), refines accessibility calculations by adjusting catchment widths to account for varying geographical contexts, which is particularly useful in areas with complex facility distributions (Hu et al., 2020). The 3-Step Floating Catchment Area (3SFCA),

introduced by Wan et al. (2012), adds an extra layer to the model by considering competition between facilities, though this can lead to more complex calculations and potential errors in accessibility estimation (Delamater, 2013). The Modified Huff 3SFCA (MH3SFCA), as proposed by Jörg et al. (2019), incorporates Huff's probability model to better account for the attractiveness of facilities in determining accessibility. Despite the advances these methods represent, they still face limitations, especially in terms of technical complexity, as seen in the 3SFCA and MH3SFCA, where the choice of parameters such as distance and facility attractiveness can greatly influence the results. Table 1 summarizes some of the FCA methods and the parameters used in each. In this master's thesis, the 2SFCA, E2SFCA, and KD2SFCA variants will be considered.

Table 1 Overview of the properties of a traditional indicator and FCA methods (Jörg et al., 2019).

Criteria	**Simple supply-population ratios**	**2SFCA**	**E2SFCA**	**3STFCA**	**E3SFCA**	**M2SFCA**	**MH3SFCA**
Consideration of the demand competition	✗	✓	✓	✓	✓	✓	✓
Results are independent of the unit of analysis (e.g., administrative boundaries)	✗	✓	✓	✓	✓	✓	✓
Dependencies between the analysed regions are reflected in the results	✗	✓	✓	✓	✓	✓	✓
Consideration of several supply options	✗	✓	✓	✓	✓	✓	✓
Consideration of relative distance differences (within the maximum radius)	✗	✗	✓	✓	✓	✗	✓
Supply competition is considered	✗	✗	✗	✗	✗	✓	✓
Consideration of relative and absolute distances	✗	✓	✓	✓	✓	✓	✓
Constant total demand per population	✓	✗	✗	✗	✗	✗	✗

2.3 Travel Time

This section reviews various studies on walking and wheeling speeds. These studies provide the basis for calculating travel times for each edge of the network (see Section 3.3.2), which are necessary for applying Floating Catchment Area (FCA) methods in accessibility analysis.

2.3.1 Walking Speed

Walking is an essential and accessible mode of transport in many cities, but the perception of walking distances can vary significantly between individuals. Vale & Lopes (2023) highlight that a 15-minute walking distance may not always correspond to the same physical distance for everyone, with differences emerging based on individual characteristics and the environment.

Several studies have examined how factors such as age, gender, and physical condition affect walking speed. Giannoulaki & Christoforou (2024) note that these individual characteristics are closely linked to mobility capacity, with older adults tending to walk more slowly than younger individuals. The environmental and urban context also has a significant impact. For example, slopes can influence walking pace. According to Aghabayk et al. (2021), gentle slopes do not have a significant impact, but steeper slopes, both uphill and downhill, cause substantial variations in speed. Walking uphill requires more effort while walking downhill requires greater control to maintain balance, as highlighted by Thomson et al. (2019). Moura et al. (2017) emphasize that aspects including pedestrian density, terrain characteristics, and weather conditions directly influence average walking speed. People tend to walk more slowly on uneven surfaces or when they perceive a risk of slipping, while higher pedestrian density can reduce walking speed due to the need to avoid obstacles (Moura et al., 2017).

Abdullah & Al-Qemaqchi (2021) estimated that the average walking speed in urban environments is 1.33 m/s, but this speed can vary depending on the context and pedestrian characteristics. Caselli et al. (2022), on the other hand, recommend a lower speed of around 1.0 m/s for urban settings with an older population, reflecting a more inclusive approach to ensure accessibility for all road users. Finnis & Walton (2008) found that walking speed increases on slopes up to 6°, both uphill and downhill, with a maximum recorded speed of 1.92 m/s downhill. Aghabayk et al. (2021) observed that steep uphill slopes (+12%) significantly reduce walking speed, while downhill

slopes (-12%) increase it, confirming that terrain gradient is one of the main factors influencing walking speed.

For this master thesis, the focus was placed exclusively on walking in everyday conditions, with particular emphasis on speed variations related to slope, but without further distinctions based on gender or age. Table 2 summarizes the average walking speeds found in the literature for a general population, highlighting speeds on flat surfaces as well as on different slopes.

Table 2 Average walking speeds for daily activities on flat surfaces and slopes from various studies, including speed variations based on the gradient of the slope.

Source	Average Speed Flat Surface [m/s]	Average Speed for different slopes [m/s]
Abdullah & Al-Qemaqchi (2021)	1.33	-
Aghabayk et al. (2021)	1.352	Gentle downhill (-3.43°): 1.363 Steep downhill (-6.84°): 1.422 Gentle uphill (3.43°): 1.338 Steep uphill (6.84°): 1.268
Caselli et al. (2022)	1.0 to 1.39 (depending on area)	-
Finnis & Walton (2008)	1.468	Downhill: 1.509* Uphill: 1.461
Fossum & Ryeng (2021)	1.6	Downhill (4.57°): 1.611 Uphill (4.57°): 1.470
Giannoulaki & Christoforou (2024)	1.13**	-
Sun et al. (1996)	1.142***	Downhill (-3.43°): 1.130 Uphill (3.43°): 1.155

* Not specified for which gradient of inclination

** Average value of different literatures (only the one of European countries)

*** Average between the value for men and the one for women

2.3.2 Wheeling Speed

In calculating travel times for wheelchair users, it is necessary to account for their wheeling speed, which likely differs from that of the general population and directly impacts the accuracy of the accessibility analysis in the FCA method. Several studies (Cooper et al., 2008; Da Silva Bertolaccini et al., 2022; Oyster et al., 2011; Slowik et al., 2015) have analyzed the propulsion speed of wheelchair users, both in everyday conditions and more challenging situations, such as ramps or inclined surfaces. These studies focus on different population groups. For example, Cooper et al. (2008) analyzed the mobility of children in wheelchairs, while another study (Tolerico et al., 2007) focused on wheelchair athletes. There are a limited number of studies examining

the specific relationship between slope and propulsion speed, a factor that can significantly influence users' autonomy (Slowik et al., 2015).

The slope of roads is particularly crucial for wheelchair users, as it not only determines propulsion speed but also the very possibility of accessing certain routes or infrastructure. In this context, the study by Kim et al. (2014) analyzed various proposals in the literature, concluding that the maximum acceptable slopes for ramps range from 1:8 to 1:12, corresponding to inclinations between 4.76° and 7.13°, depending on the ramp height.

In Switzerland, the Swiss Center for Barrier-Free Building establishes that the maximum slope for new constructions should be 6%, while for existing installations, it can reach up to 12%, corresponding to inclinations of 3.43° and 6.84°, respectively (Schmidt & Manser, 2008). These standards indicate how the slope of the terrain plays a fundamental role not only in determining speed but also in assessing accessibility.

As observed for walking speed, the inclination of the terrain also has a significant impact on propulsion speed for wheelchair users. Slowik et al. (2015) studied wheelchair propulsion on an ergometer under three conditions: free, fast, and inclined. During the free condition, the average speed was 1.04 m/s, while in the fast condition, participants reached a speed of 1.90 m/s. On an inclined surface, the average speed was 1.05 m/s, simulating an 8% slope. Da Silva Bertolaccini et al. (2022) compared different wheelchairs and observed variations in performance based on the type of wheelchair used and environmental conditions. The study by Oyster et al. (2011) found that people with spinal injuries traveled an average of 1,877.59 meters per day at a speed of 0.63 m/s, while Cooper et al. (2008) observed that children using manual wheelchairs traveled about 1,602.31 meters per day at a speed of 0.67 m/s. In another study, Tolerico et al. (2007) found that adults in wheelchairs traveled an average of 2,457 meters per day at a speed of 0.79 m/s. Finally, Boyce et al. (1999) observed one user able to move autonomously on ramps, with recorded speeds of 0.7 m/s uphill and 1.05 m/s downhill.

Table 3 presents data from representative studies, examining speeds on both flat and inclined surfaces. Only active wheelchair users, i.e., those who move without assistance from others, were considered. Additionally, regarding average speeds, only data related to everyday wheelchair use were included, excluding special or experimental situations that do not represent daily routines.

Table 3 Average wheeling speeds for active wheelchair users on flat surfaces and slopes from various studies, including speed variations based on the gradient of the slope.

Source	Average Speed Flat Surface [m/s]	Average Speed for different slopes [m/s]
Boyce et al. (1999)	0.69	Downhill (-3-4°): 1.05 Uphill (3-4°): 0.7
Cooper et al. (2008)	0.67	-
Da Silva Bertolaccini et al. (2022)	1.3	-
Oyster et al. (2011)	0.63	-
Slowik et al. (2015)	1.04	-
Tolerico et al. (2007)	0.79	-

3. Materials and Methodology

This chapter outlines the data and methods used in this thesis. Figure 3 shows both the data sources (in blue) and the steps taken throughout the methodology. The left side of the flowchart specifically refers to the analysis of the sidewalk network for the wheelchair population, which has been enriched with both slope information and accessibility point data, resulting in a fully enriched network. The right side of the flowchart begins with the enrichment of the sidewalk network using slope information, a step performed for both the wheelchair and general populations. The subsequent steps using the partially enriched network, however, pertain exclusively to the general population. Each step in the process is connected to the corresponding section of this thesis, where these methodologies are discussed in greater detail (refer to the Section numbers in parentheses).

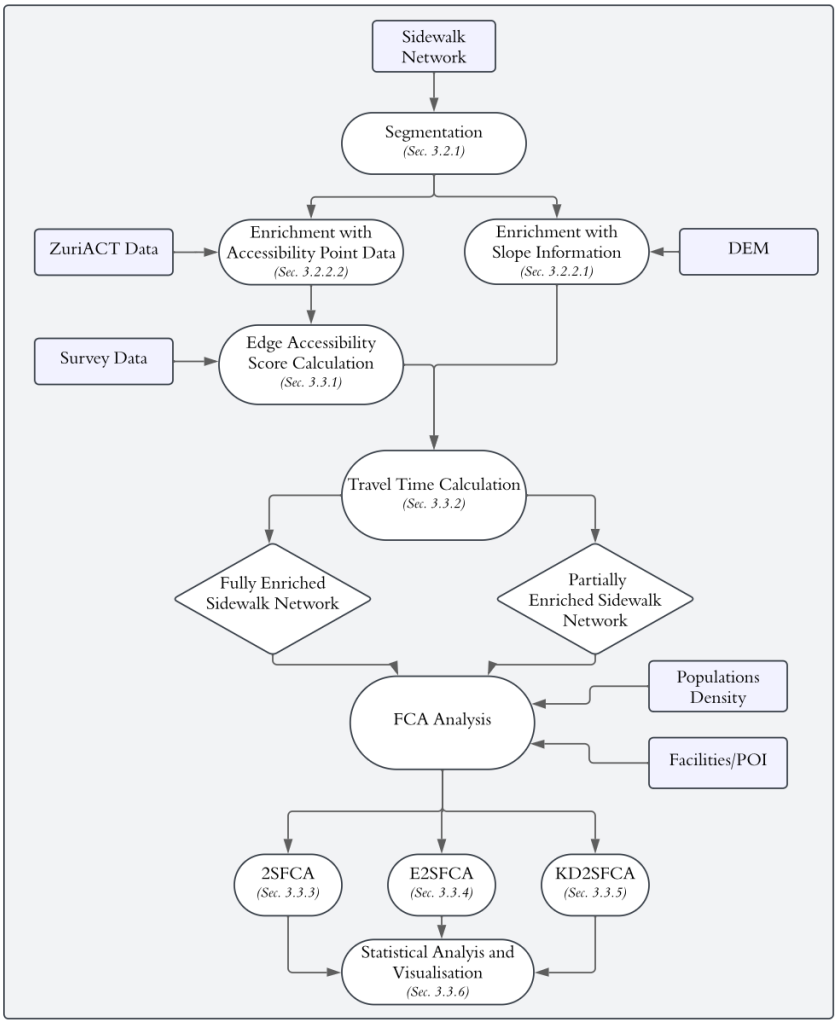

Figure 3 Flowchart of data and methods: sidewalk enrichment for wheelchair users (top left) and steps for both populations (top right). Section references are shown in parentheses.

For this master's thesis, various tools were used depending on the purpose. In the pre-processing phase related to network segmentation, the process was carried out in Python (Version 3.11.5). For the steps involving the enrichment with altitude information, QGIS (Version 3.34.11) was used. QGIS also served to pre-process the facilities data previously downloaded from OpenStreetMap (OSM). Finally, the rest of the data processing, analysis, and visualization were carried out in R (Version 2023.09.1+494).

3.1 Data

3.1.1 Supply

For the various services used as supplies in spatial accessibility analysis, the categories of services and Points of Interest (POIs) as shown in Table 4 and visualized in Figures 4 and 5 are used. The POIs were downloaded from OSM via OverpassTurbo and included point, polygon, or line data types. In this process, for each POI, the specific key (e.g., "amenity") and its corresponding value (e.g., "hospital") were defined to accurately extract the relevant data.

This dataset was pre-processed in QGIS to individually check whether the points corresponded to the indicated facility and to verify the presence of duplicates. Furthermore, since the data types included points, segments, and polygons, they were all converted into point data by taking the centroid.

Table 4 Points of Interest (POIs) categorized by facility type, with associated attributes.

Facility Category	Key	Value
Healthcare	amenity	pharmacy
	amenity	hospital
	amenity	doctors
	amenity	clinic
	amenity	dentist
	amenity	nursing_home
Education	amenity	school
	amenity	university
	amenity	college
	amenity	library
	amenity	kindergarten
Transportation Services	railway	tram_stop

	public_transport	station
	amenity	bus_station
Administrative Services	amenity	post_office
	amenity	townhall
	amenity	bank
	amenity	social_facility
Commercial Services	shop	general
	shop	kiosk
	shop	mall
	shop	supermarket
	shop	departement_store
	shop	food
	shop	beverages
Social Interaction	amenity	bar
	amenity	biergarten
	amenity	cafe
	amenity	fast_food
	amenity	food_court
	amenity	restaurant
	amenity	pub
Cultural	amenity	cinema
	amenity	theatre
	tourism	museum
	tourism	gallery
Sport	leisure	fitness_centre
	leisure	swimming_pool
	leisure	sports_centre
	leisure	stadium
Outdoor Leisure	leisure	park
	leisure	playground
	amenity	bbq
	tourism	zoo
	tourism	picnic_site

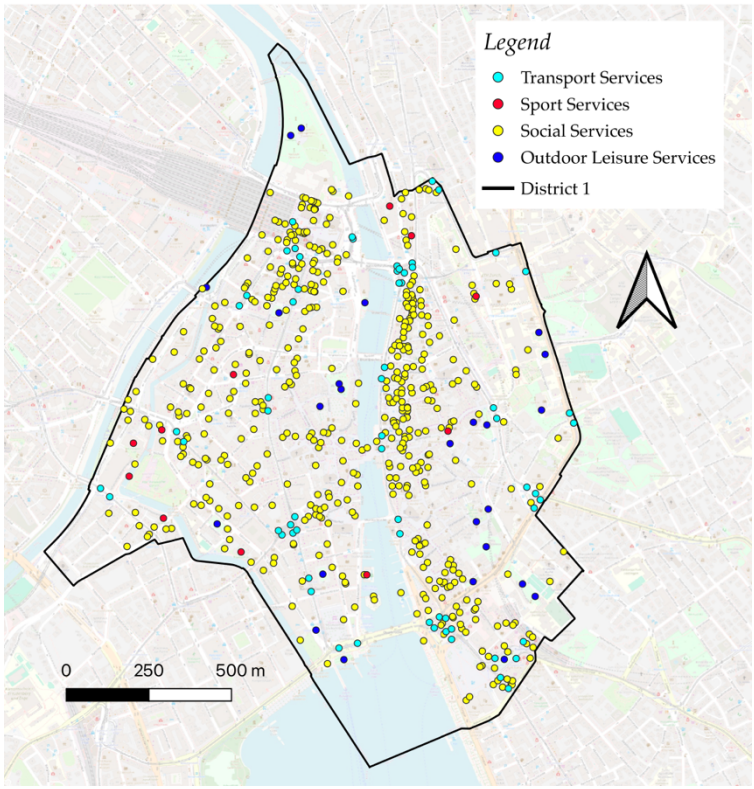

Figure 4 Spatial distribution of services in District 1: Transport Services, Sport Services, Social Services, and Outdoor Leisure Services.

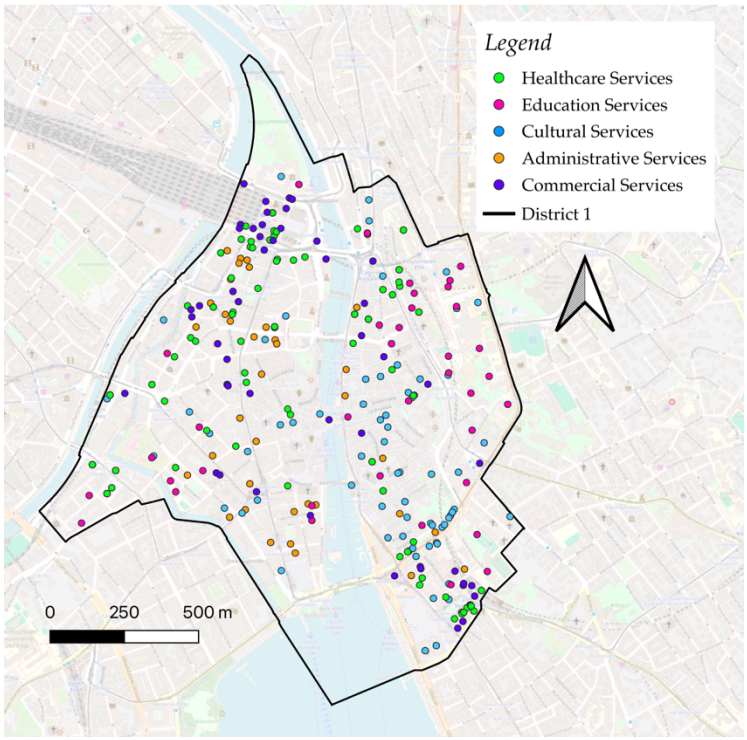

Figure 5 Spatial distribution of services in District 1: Healthcare Services, Education Services, Cultural Services, Administrative Services, and Commercial Services.

3.1.2 Demand

For the demand, the population dataset *Räumliche Bevölkerungsstatistik (OGD)* (Open Data Zürich, 2023) as shown in Figure 6 was used, which was taken in ESRI shapefile format from Open Data Zurich. This dataset includes a polygonal grid layer with 100x100m cells, and a point dataset with the centroids of the cells. Each cell contains the population size. The dataset also includes an age breakdown, but no specific data regarding people in wheelchairs is provided. For this reason, and based on the assumption that the environment should provide equal opportunities for all individuals regardless of mobility restrictions, the same population dataset was used for both the general population and individuals using wheelchairs, as no specific dataset exists for the latter group.

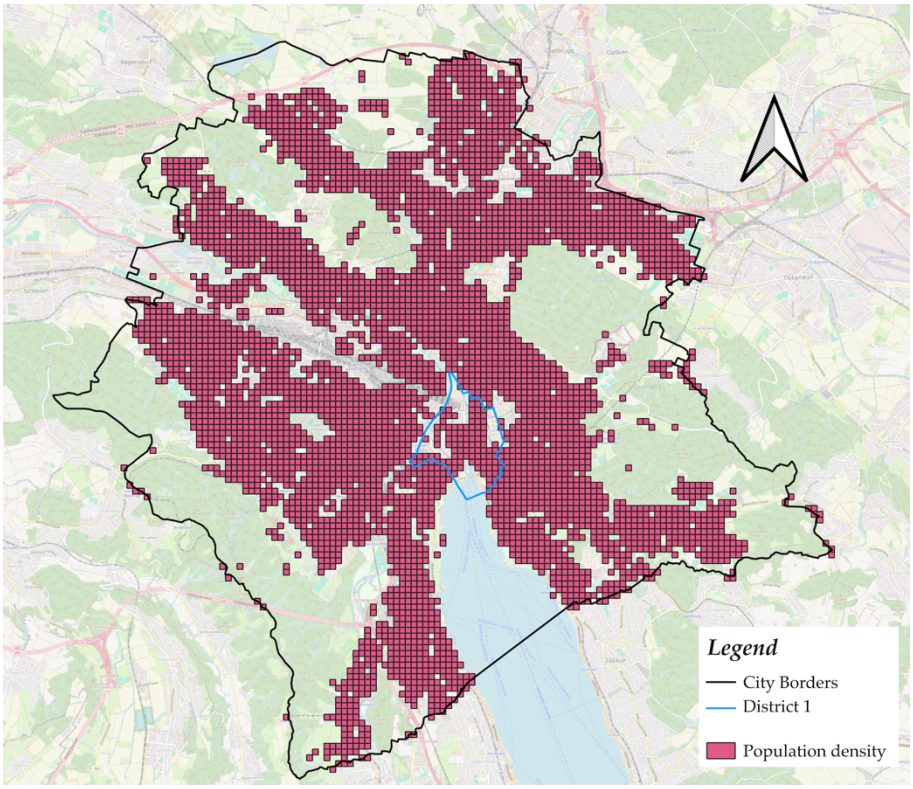

Figure 6 Population density in Zurich, with city borders and District 1 highlighted. Data is based on the Räumliche Bevölkerungsstatistik (OGD) dataset, obtained as an ESRI shapefile from Open Data Zurich (2023).

3.1.3 Travel Time

To calculate the travel time, various data were required, including the pedestrian network, slope, accessibility feature points, and the corresponding speeds. For the pedestrian network, the dataset *Fuss- und Velowegnetz* (Open Data Zürich, 2022)

was used, downloaded from the Open Data Zurich catalog in ESRI shapefile format and is show in Figure 7.

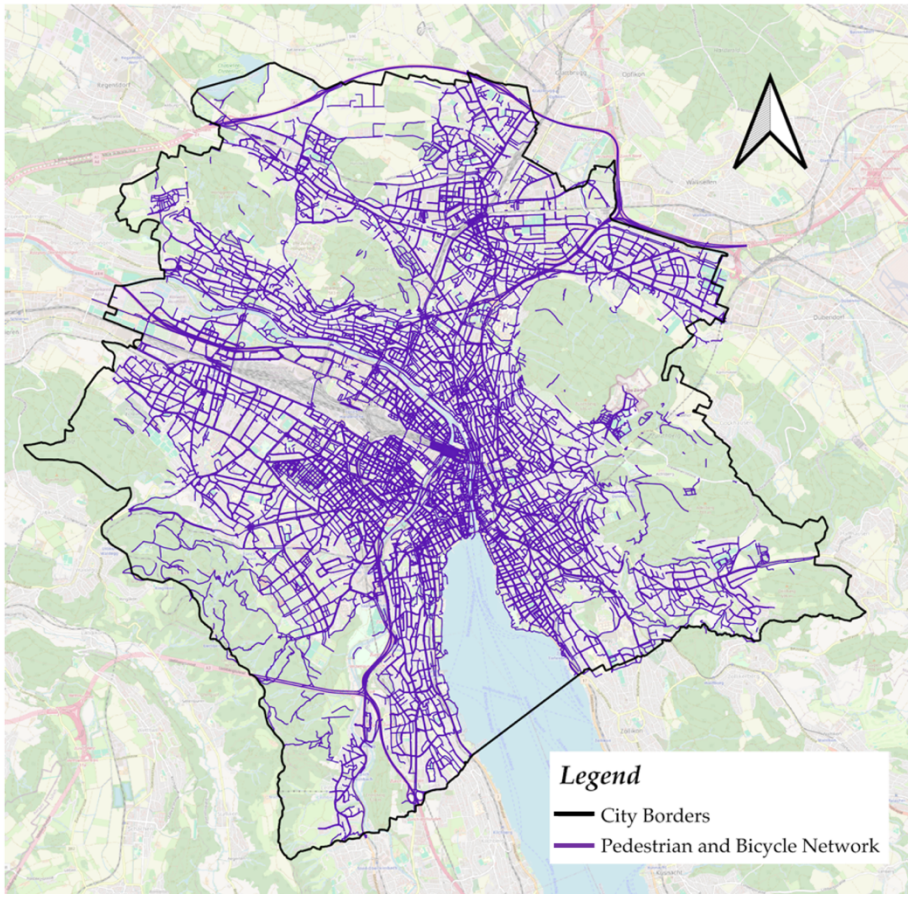

Figure 7 Zurich's pedestrian and bicycle network, with city borders highlighted. Data sourced from the Fuss- und Velowegnetz dataset (Open Data Zürich, 2022), downloaded in ESRI shapefile format.

To determine the slope of individual segments, the *swissALTI3D* Digital Elevation Model (DEM) (Federal Office of Topography, 2017) with a 0.5m resolution was used. This highly accurate digital elevation model was obtained from Swisstopo in TIFF format, which describes the surface of Switzerland without vegetation and buildings (Federal Office of Topography, 2024).

Finally, to include accessibility information, a point dataset from the *ZuriACT (Zurich Accessible CiTy)* project (Allahbakhshi, 2023; Allahbakhshi & Ardüser, 2024), led by Dr. Hoda Allahbakhshi, was used. The project was a collaboration between the University of Zurich and the City of Zurich. This project aims to contribute to providing a systematic and enriched dataset of accessibility features in District 1 of the city of Zurich as part of a citizen science project.

Using a digital web application (Project Sidewalk, 2024), participants contributed to collecting information on the accessibility of Zurich's city center by assessing it

through digital street view images. Project participants included older adults with age related mobility restrictions, individuals with situational mobility limitations (e.g., parents with pushchairs or caregivers), persons with mobility impairments, and others without mobility restrictions who contributed by adopting the perspective of wheelchair users. Together, they contributed to mapping a wide range of accessibility features, represented as point labels, within District 1 (Allahbakhshi, 2023).

These points label correspond to various sidewalk elements, including ramps, stairs, and surface issues. Users labeled accessibility features using Google Street View images, choosing from seven main label types: 'curb ramp', 'no curb ramp', 'Obstacle, 'surface problem', 'absence of sidewalk', 'crosswalk', and 'pedestrian signal'. Additionally, specific tags could be assigned to each accessibility feature to categorize and describe the feature characteristics. For example, in the 'Obstacles' category, the tags specify the type of obstacle, such as '*trash/recycling can*' or '*tree*', while in the 'Surface Problem' category, the tags describe issues with the surface, such as '*sand/gravel*' or '*very broken*'. These tags help classify the features and provide more detailed information, enabling a comprehensive analysis of both accessibility challenges and facilitators within the environment. These distinct categorizations aim to offer a clear understanding of the nature of obstacles encountered (Saha et al., 2019). These point labels, validated using the Infra3D tool and amounting to approximately 9,000 points, are used throughout this thesis and will hereafter be referred to as accessibility features.

3.1.4 Perception of Sidewalk Elements

To assign accessibility information to the pedestrian network, data from a survey conducted by Alexandra-Ioana Georgescu, as part of her PhD project, in collaboration with myself, was used. The survey, available in both German and English, was distributed via LimeSurvey and targeted people living in Switzerland who have or have had mobility difficulties. These individuals may have various types of impairments, such as using a wheelchair, having age-related mobility issues, being visually impaired, or even being a parent with a stroller. However, only the responses from individuals using wheelchairs were utilized to determine the severity of various accessibility features present in the urban environment.

The participant recruitment process involved contacting various associations related to the target population to ensure the survey reached a wide audience. A pivot study began in July, allowing refinement of the methodology and structure of the survey.

The official survey was launched online on October 11, 2024, and responses collected up to November 17, 2024, were considered for the analysis. During this period, participants provided valuable data to inform the study.

The questionnaire is structured into four parts:

- In the first part, basic information about the participants is collected, such as age, education level, income, and specific details regarding their mobility limitations, including the type and duration of the impairment. This section helps to profile the participants and understand their general background in relation to their mobility challenges.
- In the second part, participants are asked to classify and assess the severity of various barriers present in the urban environment. This information is crucial as it can highlight how different population groups, depending on their type of disability, perceive barriers differently and how these obstacles impact their ability to navigate urban spaces.
- In the third part, participants evaluate elements that facilitate accessibility (facilitators) and how these elements affect their mobility. This section also provides insights into differences between population groups, as participants with varying mobility impairments may identify different features as beneficial.
- Finally, the fourth part of the survey focuses on participants' overall perception of Zurich, with specific questions about their experiences in the urban environment. This part serves to contextualize their daily interactions with the city, helping to evaluate how accessible Zurich feels to them on a broader scale.

This survey aims to highlight the differences in the perception of street elements among various population groups and provide useful insights to improve urban accessibility, making it more inclusive for all citizens.

3.2 Pedestrian Network

This section describes the steps necessary for creating the network used in the spatial accessibility analyses (see Section 3.3), in which the different FCA methods are applied. A graph was created for both the general population and people using wheelchairs. During the creation of the two pedestrian networks, a clip was applied to extract data related to District 1, evaluating and considering various buffers to account for the edge effect. However, the main analysis was limited to District 1.

Only the dataset corresponding to footways was used, filtering for the variable *foot=1*, thereby excluding paths designated for bicycles. Additionally, pathways located within the "Hauptbahnhof" (main train station) area were excluded to focus the analysis on the city's urban environment. Including such routes, such as those on the train tracks or within the station premises could result in misleading accessibility patterns. It is important to mention that all data used in the research were set in the Swiss coordinate system CH1903+ / LV95 to ensure proper georeferencing and spatial alignment with the coordinates used in the local datasets.

3.2.1 Segmentation

The segmentation of the pedestrian network is necessary to avoid errors when enriching the data with information on slopes (see Section 3.2.2.1). When considering segments of significant length, the overall slope can appear distorted. For example, if the elevation at the starting point of a segment is higher than at the endpoint, the slope will appear negative. However, along the segment, the road might have an ascent followed by a descent, making the elevation profile more complex than suggested by the simple difference between the two endpoints.

Therefore, dividing the segments into smaller parts allows for a more accurate capture of internal elevation variations, reducing the risk of distorted slopes. This approach makes it possible to accurately represent the actual terrain fluctuations along the path. The segmentation not only ensures accurate handling of inclination data but also allows for more precise allocation of accessibility features. By dividing the network into smaller segments, the exact locations of features can be assigned accurately. The segmentation was primarily carried out using Python, utilizing the *geopandas*, *shapely*, *numpy*, and *pandas* packages. The pedestrian network dataset was divided into segments of 10 meters or less. The 10-meter value was set to ensure uniform segment lengths. In cases where an original segment could not be evenly divided by 10, the remainder was assigned to a shorter segment.

This method allowed for the creation of segments as uniform in length as possible, while maintaining the maximum length constraint of 10 meters. In addition to segmentation, start and end points were assigned to each segment, creating two geodata frames: one containing the points and one containing the segments.

3.2.2 Enrichment sidewalk network with accessibility information

This section focuses on the enrichment of the sidewalk network with additional data to improve the accessibility analysis. Section 3.2.2.1 outlines the process of incorporating elevation data to calculate slopes, enriching the sidewalk network for both the general population and the wheelchair population. Section 3.2.2.2 then discusses how accessibility point data is added specifically for the wheelchair population.

3.2.2.1 Adding Slope Information

After the segmentation of the pedestrian network, the segments were enriched with slope information. Elevation was assigned to the start and end nodes of each segment using the digital elevation model (DEM) in QGIS, through the *Sample Raster Value* function. The updated dataset with elevations was then imported into R Studio for further calculations.

The slope was calculated using the Pythagorean theorem, by taking the elevation difference between the start and end nodes of the segment and relating it to the length of the segment itself. The formula used is:

$$Slope = \frac{(h_1 - h_2)}{l} \tag{9}$$

where h_1 and h_2 represent the elevations of the starting and ending points of a segment, and l is the length of that segment.

After calculating the slope for each segment, it was necessary to consider the direction of the path. Since the slope varies depending on the direction (uphill or downhill), a bidirectional structure was adopted, where each segment was duplicated: one with a positive slope for the ascent and one with a negative slope for the descent. This approach ensures an accurate representation of the terrain conditions along the path in both directions.

The resulting bidirected graph, containing information about the segments and their slopes, was created using the *igraph* package in R. The final data were organized into two geodata frames: one containing the points (POINT) and one containing the segments (LINESTRING), each with geographic coordinates, segment lengths, and slopes.

To establish accessible slopes and categorize the streets, further research was conducted to determine the maximum accessible slope values. Guidelines from the Swiss Center for Barrier-Free Building (Schmidt & Manser, 2008) were applied. These

guidelines suggest maintaining slopes at a maximum of 6%, allowing exceptions up to 12% only in existing structures where changes are not feasible. However, slopes exceeding 6% typically require assistance for most users.
Based on this information and the available literature (see Section 2.3), the values were assigned as described in Table 5.

Table 5 Slope categorization and assumed wheeling speed based on inclination ranges for accessibility assessment.

Slope Categorization	**Inclination Range [°]**	**Inclination Range [%]**	**Assumed Speed [m/s]**
Steep downhill	< (-3.43)	<(-6%)	inaccessible
Gentle downhill	(-3.43) – (-2.9)	(-6%)-(-4%)	1.050
Flat	(-2.9) – (2.9)	(-4%)-(4%)	0.853
Gentle Uphill	(2.9) – (3.43)	(4%)-(6%)	0.700
Steep Uphill	> (3.42)	>(6%)	inaccessible

For each slope category, an average speed was assigned based on findings in the literature, as outlined in Section 2.3. For the general population, different limits were applied for slope categorization, as it is assumed that people without mobility restrictions are capable of navigating steeper slopes compared to wheelchair users. However, the division of categories was kept the same (see Table 6) to ensure consistency and coherence between user groups, while adjusting the values to reflect different capabilities.

Table 6 Slope categorization and assumed walking speed based on inclination ranges for accessibility assessment.

Slope Categorization	**Inclination Range [°]**	**Inclination Range [%]**	**Assumed Speed [m/s]**
Steep downhill	< (-6.84)	<(-12)	1.4655
Gentle downhill	(-6.84) – (-3.43)	(-12%)-(-6%)	1.368
Flat	(-3.43) – (3.43)	(-6%)-(6%)	1.337
Gentle Uphill	(3.43) – (6.84)	(4%)-(6%)	1.321
Steep Uphill	> (6.84)	>(12%)	1.3645

3.2.2.2 *Adding Point Data Accessibility Information*

The ZuriACT data was restructured to emphasize accessibility challenges encountered by wheelchair users, with the recorded features being refined and grouped to better align with the study's objectives.

The removal of temporary elements was based on the *tags*, excluding those containing words like '*parked*', '*sign*', and '*construction*', which were deemed representative of temporary elements. Outdoor dining areas were retained, as many restaurants in Zurich maintain these areas permanently, even during nighttime.

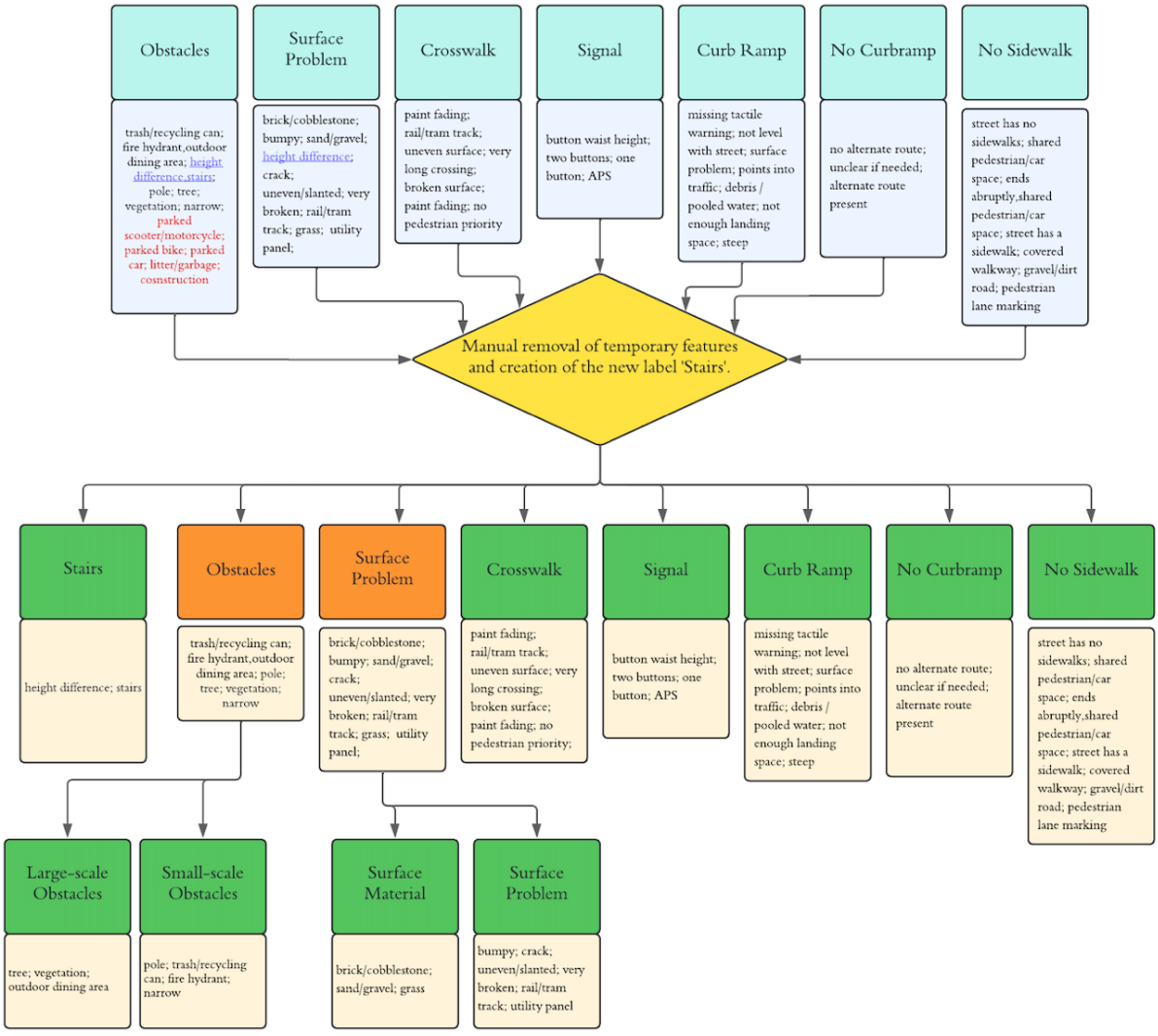

Figure 8 Classification and refinement process of pedestrian network features for accessibility analysis, highlighting categorization and subcategorization steps. The original categorization is indicated in blue, while the final categorization is shown in green.

Next, a specific approach was taken for elements related to stairs and height differences. Elements in the 'Obstacles' category with the '*stairs*' tag were extracted and assigned to a new data frame called 'Stairs', as stairs represent a significant obstacle for wheelchair users. Additionally, elements with the '*height difference*' tag,

found in both the 'Surface Problem' and 'Obstacles' categories, were added to this new category, assuming they represent difficult-to-overcome height differences. Within the 'Obstacles' category, all elements with the *litter/garbage* tag were removed, as they were considered to represent temporary or easily removable situations. Another transformation involved creating a new category for surface materials. Elements in the 'Surface Problem' category with the tags *'brick/cobblestone'*, *'sand/gravel'*, *'crack'*, *'uneven/slanted'*, *'very broken'*, *'grass'*, and *'utility panel'* were extracted and assigned to a new category called 'Surface Material', distinguishing surface material-related issues.

Additionally, features in the 'Obstacles' category were further subdivided into two subcategories: 'Large Obstacles', containing large elements such as *'outdoor dining area'*, *'tree'*, *'vegetation'*, and *'narrow'*, and 'Small Obstacles', containing smaller obstacles. A visualization of these changes is presented in the diagram in Figure 8. The collected data includes instances where the same element can be labeled multiple times, either from different perspectives or by different users. This means that the same accessibility feature can be represented by multiple points in the dataset, creating duplicates for the same real-world element. To address this situation and appropriately merge the duplicated points, a clustering method was used, to represent each element with a single point.

The method chosen for this process was DBSCAN (Density-Based Spatial Clustering of Applications with Noise), which is particularly suitable for situations where the number of clusters is not known in advance and the points may be distributed irregularly.

DBSCAN allows for identifying groups of points representing the same element while offering the advantage of handling noise points. Unlike other clustering methods, DBSCAN does not force all points into clusters, enabling the detection of outliers or unique features that do not conform to the density criteria. As described by Cao et al. (2022), DBSCAN is a typical clustering algorithm that uses data density as a measure, allowing the identification of clusters of arbitrary shape and noise points within datasets. The parameters *MinPts*, representing the minimum number of points in a neighborhood, and *Eps (Epsilon)*, the neighborhood radius, are crucial for determining the clustering structure (Cao et al., 2022).

Regarding the parameters used, *MinPoints* was set to 1. This choice is motivated by the fact that a real element could be represented by a single point. Since the data can be collected by different users or from different perspectives, a single point can still represent a real feature. Setting *MinPoints = 1* ensures that such isolated points are not

excluded from the analysis, ensuring that every element is considered. A similar study was conducted by Saha et al. (2019), which addressed the issue of data duplication during the collection of accessibility labels. By using a clustering method, the study successfully aggregated labels related to the same issue, even when collected from different perspectives or users. This approach validated *MinPoints = 1*, as it allows for considering cases where an element is represented by only one point.
The second key parameter is *Eps*, which determines the maximum distance within which points can be considered part of the same cluster. Initially, *Eps* was set to 2 meters and then manually adjusted. The goal was to achieve optimal separation between points representing distinct but closely located elements, avoiding the aggregation of points related to different elements into a single cluster. Visual observation of points on nearby streets helped adjust this parameter, ensuring that each cluster accurately represented a single element.
After clustering, the *medoid* method was used to uniquely represent each cluster. This method selects the most central point within each cluster as the representative, preserving the original information of the point. Unlike the centroid method, which calculates an average of the points, the medoid does not create new points but maintains the position of existing ones.
The representative points, obtained through the medoid method, were subsequently added to the edges of the pedestrian network using the *st_nearest_feature* function in R. This function allowed for associating each accessibility point with the closest pedestrian network segment (edge).
As a result, a new variable was created for each edge of the pedestrian network, listing all the accessibility features present in that specific section. This step is crucial as it enriches the network for wheelchair users with detailed information about obstacles and accessibility-relevant features. These data will then be used to establish an accessibility score for each edge of the network (see Section 3.3.1), assessing the accessibility of the various segments based on the collected features and specific accessibility needs.

3.3 Spatial Accessibility Analysis

This section outlines the process of spatial accessibility analysis, starting with the enrichment of the sidewalk network. Further, it details the application of the Floating Catchment Area (FCA) methods to assess accessibility for both the general population and those using wheelchairs. The section concludes with a comparative analysis,

which includes statistical techniques, such as paired scatter plots and correlation coefficients, to evaluate the results and provide deeper insights into the accessibility patterns.

3.3.1 Edge Accessibility Score Calculation

Once a comprehensive list of accessibility features was added as a variable for each edge of the pedestrian network, the next step focused on assigning an accessibility score to the corresponding segments. This process required assigning specific weights to each identified feature, considering the impact each had on the overall accessibility of the segment.

Analyzing the data collected through the survey (see Section 3.1.4) enabled the identification and quantification of the perceived severity / facilitating levels associated with different street elements, which can either hinder or facilitate the daily mobility of individuals with mobility impairments. For simplicity, the term *severity level* will be used from this point onward to describe both barriers and facilitating elements, replacing the term *facilitating* used previously.

Survey participants were asked to evaluate the severity with which different street elements affected their daily mobility, ranging from fully passable to completely impassable for barriers and from very facilitating to barrier for facilitators. These evaluations were converted into numerical scores, with barriers rated from -5 (completely impassable) to -1 (fully passable) and facilitators rated from +1 (not facilitating) to +5 (very facilitating). The use of both positive and negative values in the table reflects the dual nature of the features, distinguishing between those that improve mobility (facilitators) and those that hinder it (barriers).

For barriers, the median severity level was calculated for each street element to establish a representative value of the perceived hindrance. Similarly, for facilitators, the median value was determined to reflect the level of support they provided. This approach ensured that the accessibility scores were grounded in direct user experience, realistically reflecting both challenges and improvements encountered in different urban contexts.

A particular case is the 'Crosswalk' label, where the severity level is not fixed but varies depending on the associated tag. The survey categorized 'Crosswalk' into different types based on specific characteristics, such as '*uneven surface*', '*rail/tram track*', '*very long crossing*', and '*no pedestrian priority*'. For each tag, a weight was assigned that reflects its impact on accessibility. For example, a crosswalk with uneven surface will

have a more negative weight compared to one with paint fading, which represents a less severe obstacle. This differentiation was possible due to the distinctions made in the survey.

Once these final severity levels were determined for each accessibility feature, they were ready to be applied to the pedestrian network. At this point, each edge of the network was analyzed to identify the presence or absence of accessibility features. Any edge without identified features (represented by NA values) was assigned a weight of 0, meaning it was considered free of any barriers or facilitators. This approach ensured that every segment of the network was assigned a score, which allowed for a smooth transition to the next phase: assigning weights to each label.

Each feature type was then assigned its respective weight to reflect its impact on accessibility. Features that represented obstacles, such as an uneven surface on a crosswalk, reduced the accessibility score, while features that facilitated mobility, like a curb ramp, increased it. These weights, which were derived from the severity levels taken from the survey responses, were used to quantify the accessibility of each edge in the network. Features that impeded accessibility were assigned a high negative weight, reflecting their significant impact on reducing accessibility. On the other hand, features that facilitated accessibility received a positive weight, improving the overall accessibility score of the segment.

The overall score for each edge was calculated by summing the weights of the labels present on that segment. For each label, the number of occurrences of that feature on a given segment was multiplied by its severity level, and all results were summed to obtain a raw score. For example, in the segment from A to B (see Figure 9), which has a 'SurfaceProblem' with a weight of -2, a 'Surface Material' with a weight of 1, and a 'No Sidewalk' with a weight of 2, the raw score would be:

$$\begin{aligned} raw\ score = \quad & (NoSidewalk * weight_{NoSidewalk}) \\ & + (SurfaceMaterial * weight_{SurfaceMaterial}) \\ & + (SurfaceProblem * weight_{SurfaceProblem}) \\ & = -3 + (-3) + (-3) = -9 \end{aligned} \tag{10}$$

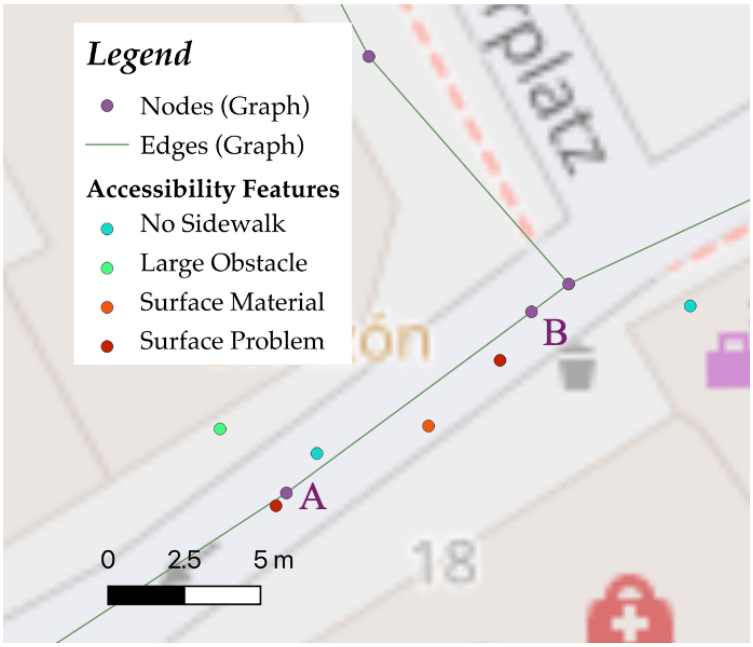

Figure 9 Example of accessibility raw score calculation for a segment within District 1.

After calculating the raw score for each segment, it was scaled to an accessibility score ranging from 0 to 2. On this scale, a score of 2 represents excellent accessibility, 1 indicates normal accessibility, such as in the absence of barriers or facilitators, and 0 represents an area that is not accessible. This scaling system is essential for the travel time calculations described in the next section.

3.3.2 Travel Time

The travel time for each edge is calculated by dividing the length of the segment by the walking speed, which is determined based on the slope of the segment (see Section 3.2.2.1). Subsequently, the result of this division is further divided by the normalized access score. This mechanism accounts for the level of accessibility of the segment: if a segment has an access score greater than 1, indicating the presence of facilitators, the resulting travel time will be reduced because the segment is more accessible and facilitates movement. Conversely, if the access score is less than 1, indicating poor accessibility, the travel time will increase, reflecting the difficulties encountered in traversing that segment.

3.3.3 2SFCA

The first spatial accessibility measure conducted in this study is the 2-Step Floating Catchment Area (2SFCA) method. The formulas and approach for this method were applied as explained in the theory (see Section 2.2.1), without reiterating the detailed description here.

In this analysis, the capacity of each service was assumed to be 1. This assumption was necessary due to time constraints in obtaining specific data related to the actual capacity of each type of service and the likely lack of data in some cases. While the actual capacity of each service might vary depending on its type (e.g., a hospital compared to a store), collecting such information for District 1 would have required considerable time and might have excluded certain services due to limited data availability. The assumption of uniform capacity allowed the analysis to proceed without significantly compromising the overall accuracy of the model.

The 2SFCA method was applied separately for each type of service described in Section 3.1.1, and the results were combined to produce a comprehensive accessibility index (SPAI). The analysis was conducted for both the general population and wheelchair users to account for the different accessibility needs of each group.

For each population group, accessibility was analyzed using time thresholds of 5, 10, and 15 minutes. This allowed an evaluation of which time threshold best represents the concept of an *x-minute city* for District 1. Considering the specific spatial characteristics of the district, it was crucial to determine the most suitable time interval for this type of analysis.

To address the edge effect issue, which can distort results near the boundaries of the study area, the analysis was initially conducted by including a 10-minute buffer beyond District 1's boundaries. This comparison helped evaluate how the inclusion of areas outside the district affected the results compared to an analysis limited exclusively to the district itself. As the street accessibility features data were limited to District 1, this phase of the analysis only considered the slope of the sidewalks as the accessibility variable.

The results were normalized and visualized on maps to enable comparisons of accessibility between the general population and wheelchair users, as well as across the different services analyzed. The normalization was performed using the formula:

$$SPAI_{norm,i} = \frac{SPAI_i - \min(SPAI)}{\max(SPAI) - \min(SPAI)} \tag{11}$$

where $SPAI_i$ represents the raw accessibility score for a specific point *i*, and *min(SPAI)* and *max(SPAI)* denote the minimum and maximum accessibility scores across all points, respectively. This approach follows the normalization method described by Han et al. (2012), ensuring comparability across different scales and population groups. The same normalization method was also applied to the other FCA methods used in this study, E2SFCA (see Section 3.3.4) and KD2SFCA (see Section 3.3.5).

3.3.4 E2SFCA

For the E2SFCA analysis, a single time threshold was chosen to balance the accessibility needs of both the general population and wheelchair users, while streamlining the process by avoiding repeated calculations for multiple thresholds and focusing on method comparison.

The Gaussian weighting function was used to modulate the accessibility gradient according to the following formula:

$$f(d) = e^{\frac{-d^2}{\beta}} \tag{12}$$

where d represents the distance between demand and supply points, and β is the distance decay coefficient (Jörg et al., 2019). This function was chosen because it allows for a gradual reduction in accessibility as distance increases, reflecting the fact that the influence of services decreases continuously but not linearly.

The β coefficient was calculated based on the following condition:

$$f(d_{max}) \approx 0.01 \tag{13}$$

This threshold value was indicated by Jörg et al. (2019) as a critical point for determining when the Gaussian function tends toward zero. The specific β value obtained is 78173.01, ensuring that accessibility decreases significantly when the distance from the service reaches the maximum defined, but without reaching zero completely, thus realistically reflecting urban conditions.

As shown in Formula (6) in Section 2.2.2, the E2SFCA method applies differentiated weights to various subzones to better reflect accessibility based on distance. The weights W_j were calculated based on the average distances in seconds (d_j) within each of the 4 subzones using the decay function. For instance, the weight for the first subzone, covering distances up to 150 seconds, was:

$$W_1 = e^{\frac{(-75)^2}{78173.01}} \approx 0.931 \tag{14}$$

The weights for the other subzones, W_2, W_3 and W_4, were calculated using the same approach, with their respective average distances shown in Figure 10. The results are as follows:

- W_2 for an average distance of 225 seconds: **0.523**
- W_3 for an average distance of 375 seconds: **0.165**
- W_4 for an average distance of 525 seconds: **0.029**

These values reflect the decreasing influence of service accessibility as the distance increases, as demonstrated by the curve in the graph.

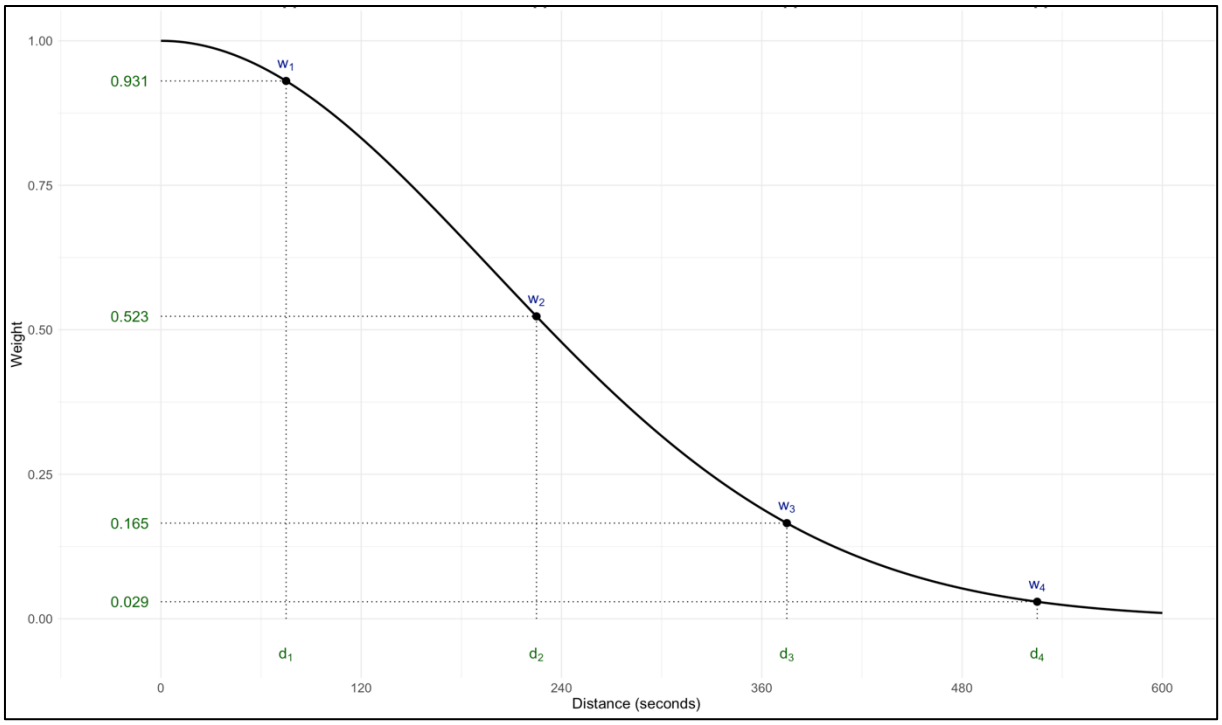

Figure 10 Gaussian weighting function applied in the E2SFCA analysis for District 1, with weights W_1, W_2, W_3, and W_4 calculated at average distances d_1, d_2, d_3, and d_4 in seconds. The curve reflects the weight decay across increasing distances, using a decay coefficient β=78173.01 to modulate accessibility.

Using Formula (6) in Section 2.2.2, the supply-to-demand ratio R_j for each facility is calculated as:

$$R_j = \frac{1}{P_j\,(0.931) + P_j(0.523) + P_j(0.165) + P_j(0.029)} \tag{15}$$

Here, the capacity of the services *Sj* was set to 1 due to the lack of more specific data. The population in each subzone (P_j) was weighted by the corresponding weights (0.931, 0.523, 0.165, 0.029), ensuring that the influence of population decreases with increasing distance from the service.

In the second stage, the accessibility index A_i is calculated by summing the R_j ratios of the services accessible to each demand point, weighted by the distance weights in their respective subzones, as shown in Formula (7) in Section 2.2.2:

$$A_j = R_j(0.931) + R_j(0.523) + R_j(0.165) + R_j(0.029) \quad (16)$$

This two-stage process ensures that accessibility is gradually reduced as distance increases, avoiding the abrupt cutoff typical of binary approaches.

3.3.5 KD2SFCA

In the calculation of accessibility using the KD2SFCA method, as previously illustrated in Section 2.2.3, a kernel function is applied to model the influence of distance between demand and supply points. In this analysis, a single time threshold was used for both populations, and the chosen kernel function was Epanechnikov. The Epanechnikov function, defined as (Dai & Wang, 2011):

$$f(d_{ij}, h) = \begin{cases} \frac{3}{4}\left(1 - \left(\frac{d_{ij}}{h}\right)^2\right), & if\ d_{ij} \leq h; \\ 0, & if\ d_{ij} > h, \end{cases} \quad (17)$$

was selected for its ability to optimally weight the distance between points, progressively reducing accessibility as the distance from the service increases. The first stage of the calculation involves the use of a distance matrix and the decay function to determine the kernel weights for each distance between demand and supply points. These weights decrease as the distance between points increases, following the Epanechnikov function $f(d_{ij}, h)$, which ensures a gradual reduction in accessibility. Subsequently, for each service j, the supply-to-demand ratio R_j is calculated by dividing the service capacity S_j by the sum of the weighted population within the catchment area, as shown in Formula (8) in Section 2.2.3. In this analysis, the service capacity S_j was set to 1 due to the lack of more specific data.

In the second stage of the KD2SFCA method, the spatial accessibility index (SPAI) is calculated for each population point by summing the R_j ratios of all accessible services. This step, as described in Formula (8) in Section 2.2.3, applies the kernel function again to weight the influence of each service based on its distance from the population point. The resulting SPAI values reflect not only the distance to services but also their availability, with closer services contributing more significantly to the accessibility score, while the influence of more distant services is progressively reduced.

3.3.6 Comparison of FCA Methods

The first phase of comparison between the different accessibility calculation methods was carried out through a visual analysis. Maps were created representing the SPAI values for each type of facility and for each method used (2SFCA, E2SFCA, KD2SFCA), visually highlighting the differences in spatial accessibility.

In addition to the visual comparison of SPAI value maps for each facility and method, difference maps were generated to highlight the discrepancies in results between the various methods. These difference maps were created by subtracting the SPAI values obtained with the KD2SFCA and E2SFCA methods from those obtained with the 2SFCA method for each facility. Using the 2SFCA as the reference point made it possible to directly visualize the areas where the alternative methods deviate the most in terms of accessibility.

Subsequently, to quantify the discrepancies between the methods, a statistical analysis of the results was performed. Pairwise scatter plots were used to compare the SPAI results obtained for each method. These scatter plots provide a graphical representation of the relationships between the methods, allowing the identification of possible over- or under-estimations of accessibility. Next, correlation analyses were conducted, using both Spearman's and Pearson's correlation coefficients, to evaluate the strength of the relationships between the results obtained with each method. The use of Spearman's coefficient is particularly suitable for checking the rank correlation between accessibility models, as suggested by Kim & Kwon (2022), while Pearson's coefficient allows for the analysis of the linear relationship between the SPAI values obtained from each method. Spearman’s coefficient, based on ranks, is less influenced by outliers compared to Pearson’s coefficient, which can be significantly affected by extreme values in the data (Bocianowski et al., 2024). In the study by Chen & Jia (2019), the correlation between six distance decay models—rectangular cumulative-opportunity, negative-linear cumulative-opportunity, inverse-power gravity-type, exponential gravity-type, Gaussian gravity-type, and kernel density—was found to be significant. The findings provide a solid basis for using comparison techniques across different accessibility methods.

4. Results

This chapter highlights the main outcomes obtained through the methodologies described in Chapter 3. The pedestrian network map of Zurich's District 1 in Figure 11 serves as a reference when mentioning specific streets or key locations throughout the results section, providing spatial context for the accessibility patterns observed.

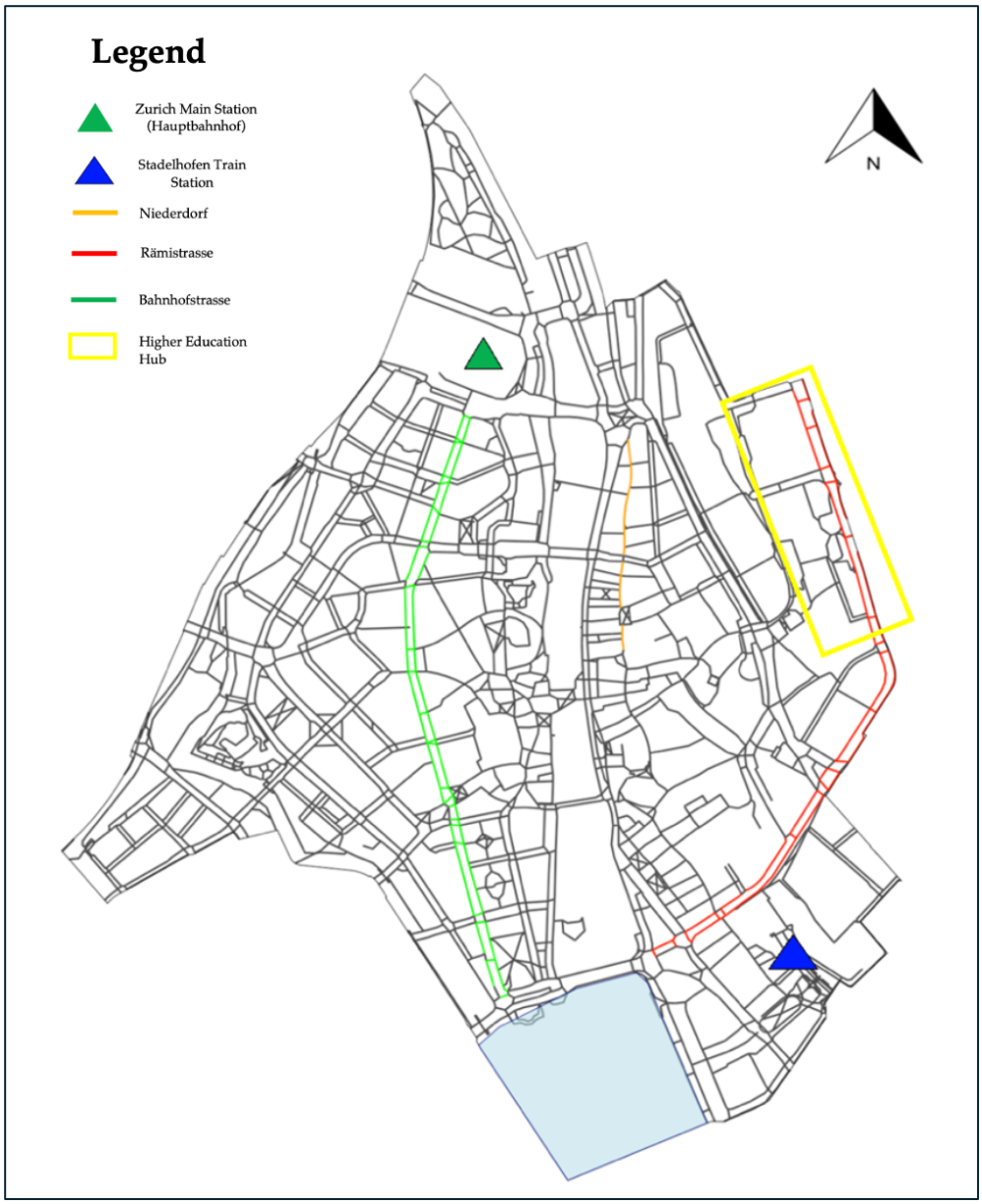

Figure 11 Pedestrian network of Zurich's District 1, showing highlighted main streets and the central station. This map provides a reference for the study area and the key locations analyzed in the accessibility assessment.

4.1 Demographic Profile of Survey Participants

The following section provides an overview of the demographic and mobility characteristics of the survey participants. The data analyzed includes responses from 29 individuals who use wheelchairs. The participants' ages ranged from 22 to 72 years, with a mean age of 39.4 years (SD = 15.8) and a median age of 34 years. The distribution shows that most participants were in their late twenties to early fifties, with some outliers in older age groups. Regarding gender identity, 51.7% of participants identified as female (n = 15), 41.4% as male (n = 12), and 6.9% as other genders (n = 2). These results indicate a diverse sample in terms of both age and gender, which is relevant for assessing varying mobility needs and accessibility challenges faced by wheelchair users.

Participants were also asked to report on their mobility impairments and the duration for which they have been affected. Of the total sample, 89.7% of respondents reported having permanent mobility impairments (n = 26), while 10.3% (n = 3) indicated temporary mobility restrictions. Among those with permanent impairments, 46.2% stated that they had been affected since birth (n = 12), while the remaining participants reported experiencing mobility restrictions for a range of years, with a mean duration of 10.6 years (SD = 9.5). These responses suggest that the sample includes individuals with both lifelong and more recently acquired mobility impairments, allowing for a broader understanding of accessibility needs.

In terms of mobility assistive devices, 86.2% of participants (n = 25) reported using a manual wheelchair at least occasionally, making it the most commonly used device. Among these, 58.6% (n = 17) identified the manual wheelchair as their primary device. An electric wheelchair was reported as the main device by 27.6% of participants (n = 8), while 13.8% (n = 4) indicated using a manual wheelchair with an electric attachment as their primary means of mobility. These results highlight the prevalence of manual wheelchairs, either as a primary or secondary device, suggesting that this assistive technology plays a central role in the mobility of most participants.

The demographic profile of the survey participants demonstrates a diverse group in terms of age, gender, and mobility experiences. While not all participants use a manual wheelchair as their primary mobility device, the survey responses in this thesis are analyzed under the assumption that participants are manual wheelchair users. This assumption is grounded in the rolling speeds employed in the analysis, which are sourced from literature specific to manual wheelchair users.

4.2 Enriched Pedestrian Network

This section presents the results of enriching the pedestrian network with accessibility information, as described in Section 3.2.2. The enrichment process involved integrating detailed data on slopes, barriers, and other accessibility features to evaluate the network's accessibility for wheelchair users. The results of the slope categorization for wheelchair users are shown in Figure 12. The map highlights the distribution of slopes across the network (without differentiating between uphill and downhill), with segments in red indicating steep inclines and declines. These sections are of particular interest as they represent inaccessible areas for wheelchair users due to the significant physical challenges posed by such gradients.

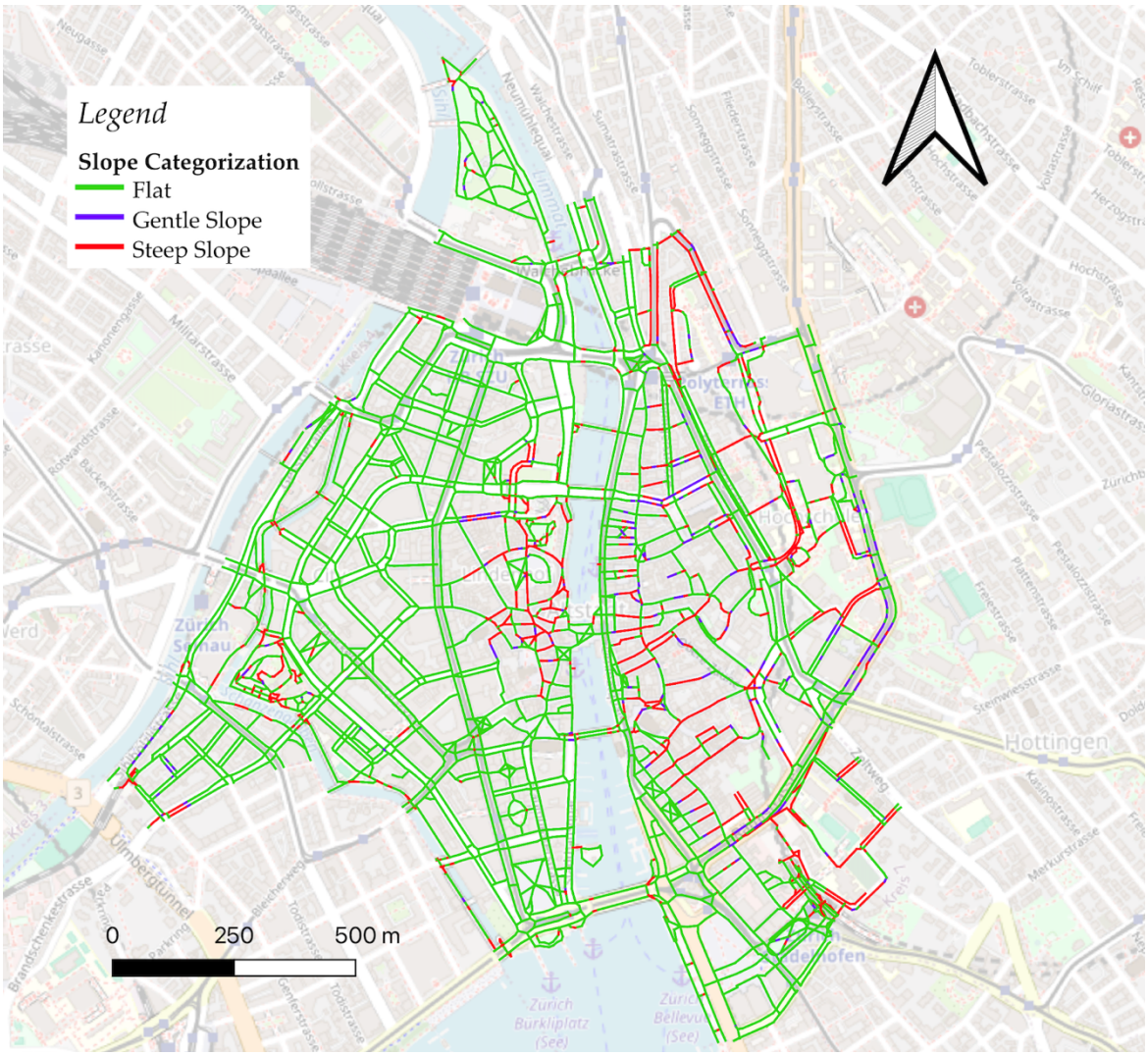

Figure 12 Spatial distribution of slope categories for wheeling accessibility across the city network of District 1 in Zurich.

To ensure the accurate integration of accessibility features into the pedestrian network, the clustering of data points was performed first, as explained in Section 3.2.2.2. This step reduced the initial 8,191 data points to a total of 2,829 clusters, effectively consolidating duplicated observations into unique points.

Table 7 summarizes the results, showing the number of points before and after clustering for each label category. The reduction is most notable for categories such as "Surface Problem", and "Curb Ramp," where large numbers of duplicate points were merged into single representative clusters.

Table 7 Pre- and post-clustering summary of point counts by label category.

	Number of Points	
Label Category	**Before Clustering**	**After Clustering**
Surface Problem	2669	817
Crosswalk	1156	460
Obstacle Stairs	28	15
Signal	936	244
Curb Ramp	2573	737
No Curb Ramp	63	43
No Sidewalk	420	325
Surface Material	38	30
Large Obstacle	21	15
Small Obstacle	287	143
Total	8'191	2'829

Following the clustering of accessibility features, severity levels were assigned to each feature, as described in Section 3.3.1. These severity levels, derived from survey responses, reflect the perceived impact of barriers and facilitators on the mobility of individuals with impairments. Barriers, such as 'No Curb Ramp' or 'Stairs', were assigned negative values, while facilitators, such as 'Curb Ramp' or 'Crosswalk', received positive values. Table 8 provides a summary of the accessibility features and their corresponding severity levels. Notably, features like 'Stairs' were rated as the most severe barrier (-5), while 'Curb Ramp' received the highest facilitating score (4.9).

Table 8 Accessibility features with their assigned severity/facilitating levels based on survey responses. Negative values indicate barriers that hinder mobility, while positive values represent facilitators that enhance accessibility.

Accessibility Features	**Severity/Facilitating Levels**
Surface Problem	-3
No Sidewalk	-3
No Curb Ramp	-4.1
Obstacle Small	-3
Obstacle Large	-4
Stairs	-5
Crosswalk	4.2
Curb Ramp	4.9
Signal	3.8
Surface Material	-3
Crosswalk: paint fading	-1
Crosswalk: very long crossing	-2.2
Crosswalk: uneven surface	-3
Crosswalk: brick/cobblestone	-3
Crosswalk: broken surface	-3
Crosswalk: bumpy	-3
Crosswalk: rail/tram track	-2
Crosswalk: no pedestrian priority	-2

The assumption that the severity levels derived from electric wheelchair users could be treated similarly to those of manual wheelchair users was validated by the survey responses. Overall, the two groups exhibited comparable perceptions of accessibility features, with no significant differences emerging for most barriers and facilitators. However, a notable exception was the evaluation of "Uneven Sidewalk", where electric wheelchair users consistently rated the feature more negatively. Specifically, 7 out of 8 electric wheelchair users rated it as "Almost Not Passable", with only one rating it as "Fully Passable". In contrast, manual wheelchair users showed greater variability in their responses: 2 rated it as "Not Passable", 11 as "Passable with Some Difficulties", 4 as "Almost Not Passable", and 1 as "Almost Fully Passable". These findings suggest that, while electric wheelchair users tend to perceive "Uneven Sidewalk" as a more severe barrier, this difference does not significantly impact the overall validity of the assumption, given the general alignment between the two groups for other features.

The severity levels were subsequently used to assign a weight to each edge of the pedestrian network, accounting for all accessibility features present on each segment. The sum of the weights for each edge was then scaled to a range of 0 to 2, resulting in an accessibility score. A score of 0 indicates that the segment is completely inaccessible, with barriers that prevent mobility. A score of 1 represents neutral accessibility, which can occur either when there are no significant barriers or facilitators present or when

barriers and facilitators counterbalance each other. Finally, a score of 2 indicates excellent accessibility, with features that facilitate mobility without significant hindrance. The resulting accessibility scores are visualized in Figure 13, providing a comprehensive overview of the network's accessibility.

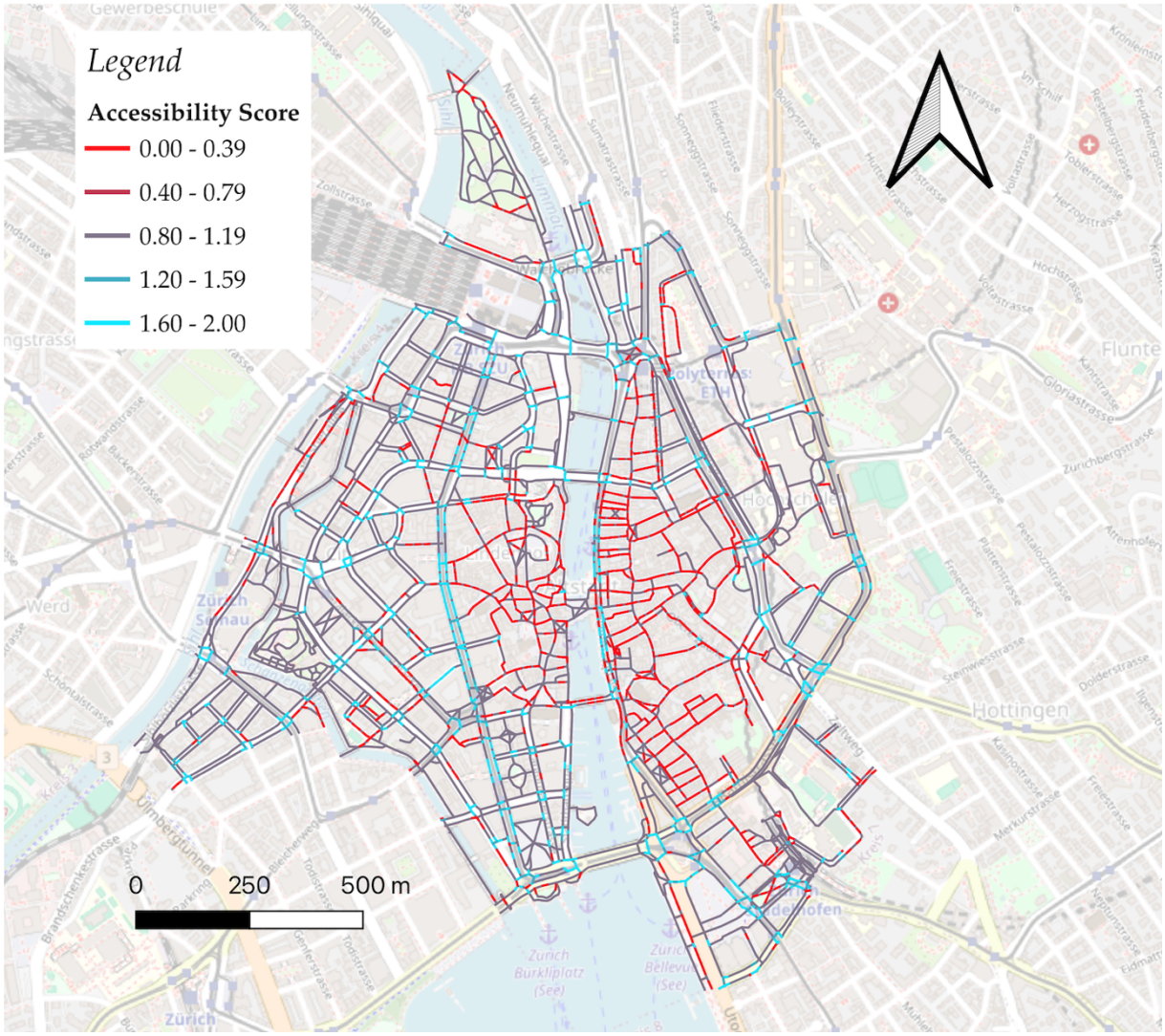

Figure 13 Accessibility scores scaled from 0 to 2 for the pedestrian network of Zurich's District 1.

The least accessible areas are concentrated in the central part of the district, including the Niederdorf and its surrounding zones extending toward the lake, with scores predominantly in the range of 0.00–0.39. Segments in the range of 1.60–2.00, indicating high accessibility, are scattered throughout the district, particularly in locations with crosswalks and curb ramps.

Notably, the Bahnhofstrasse stands out for its generally good accessibility, primarily within the intermediate range (1.20–1.59), with several edges achieving the highest

range (1.60–2.00). However, a few exceptions are present, with segments scoring in the lowest range, reflecting localized barriers.
While the district's pedestrian network offers a range of accessibility levels, with many edges in the neutral range, a significant number of areas score in the lowest range. This highlights a lack of adequate accessibility for wheelchair users, underlining the importance of addressing barriers to ensure equitable access to the urban environment.

4.3 Time Limit Analysis by Service Type

This part of the analysis examines the accessibility of various services for both the general population and wheelchair users, using the 2SFCA method and considering three time thresholds: 5, 10, and 15 minutes. The goal is to identify which of these thresholds is most suitable for the *x-minute city* analysis, by analyzing how accessibility varies in relation to walkable distance. The services examined include administrative, commercial, cultural, education, healthcare, sports, social, transport, and outdoor leisure services.

4.3.1 General Population

The analysis of accessibility using the SPAI index highlights how service coverage within District 1 changes as different time thresholds are applied. For the general population, a 15-minute threshold results in near-complete coverage of the study area, indicating that most services are accessible within a reasonable walking distance. However, at shorter thresholds of 5 and 10 minutes, accessibility patterns become more granular, revealing localized areas with higher accessibility, known as "hotspots". These hotspots vary by service type, reflecting the spatial distribution of different facilities across the district.
At the 5-minute threshold, the accessibility patterns are particularly detailed, with hotspots clearly identifiable for each service type. Administrative and commercial services (see Figures 14a & 14d) show their highest values around the Hauptbahnhof, reflecting the concentration of offices, shops, and administrative buildings in this key transport hub. Cultural services (see Figure 14g), on the other hand, present their main hotspot near Stadelhofen, where several museums and cultural institutions are located.

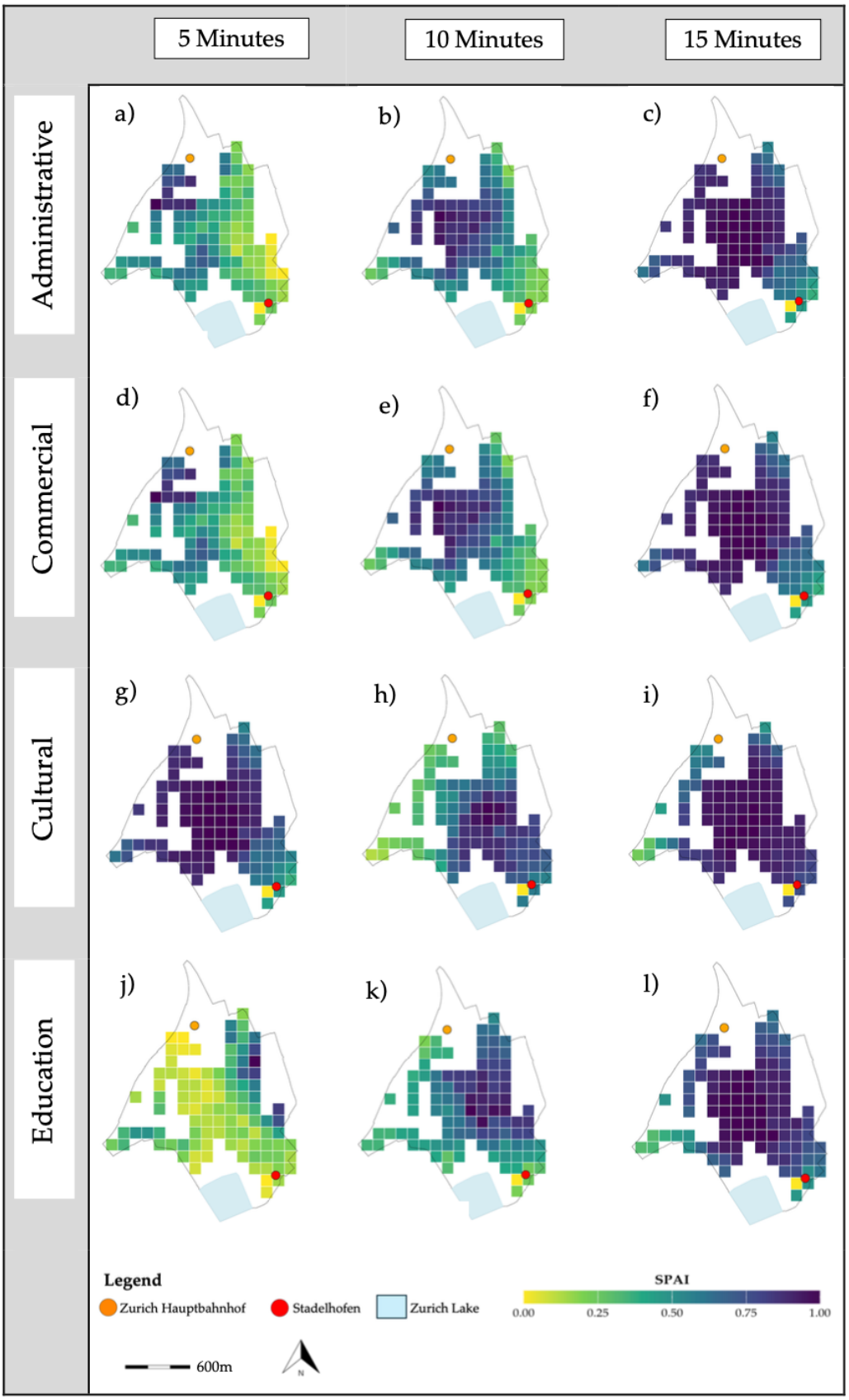

Figure 14 SPAI values for the general population, calculated using the 2SFCA method, with different time thresholds (5, 10, and 15 minutes) for various facilities: Administrative (a-c), Commercial (d-f), Cultural (g-i), and Education services (j-l). The maps display the accessibility levels for each facility type, with the main stations and Zurich Lake marked for reference.

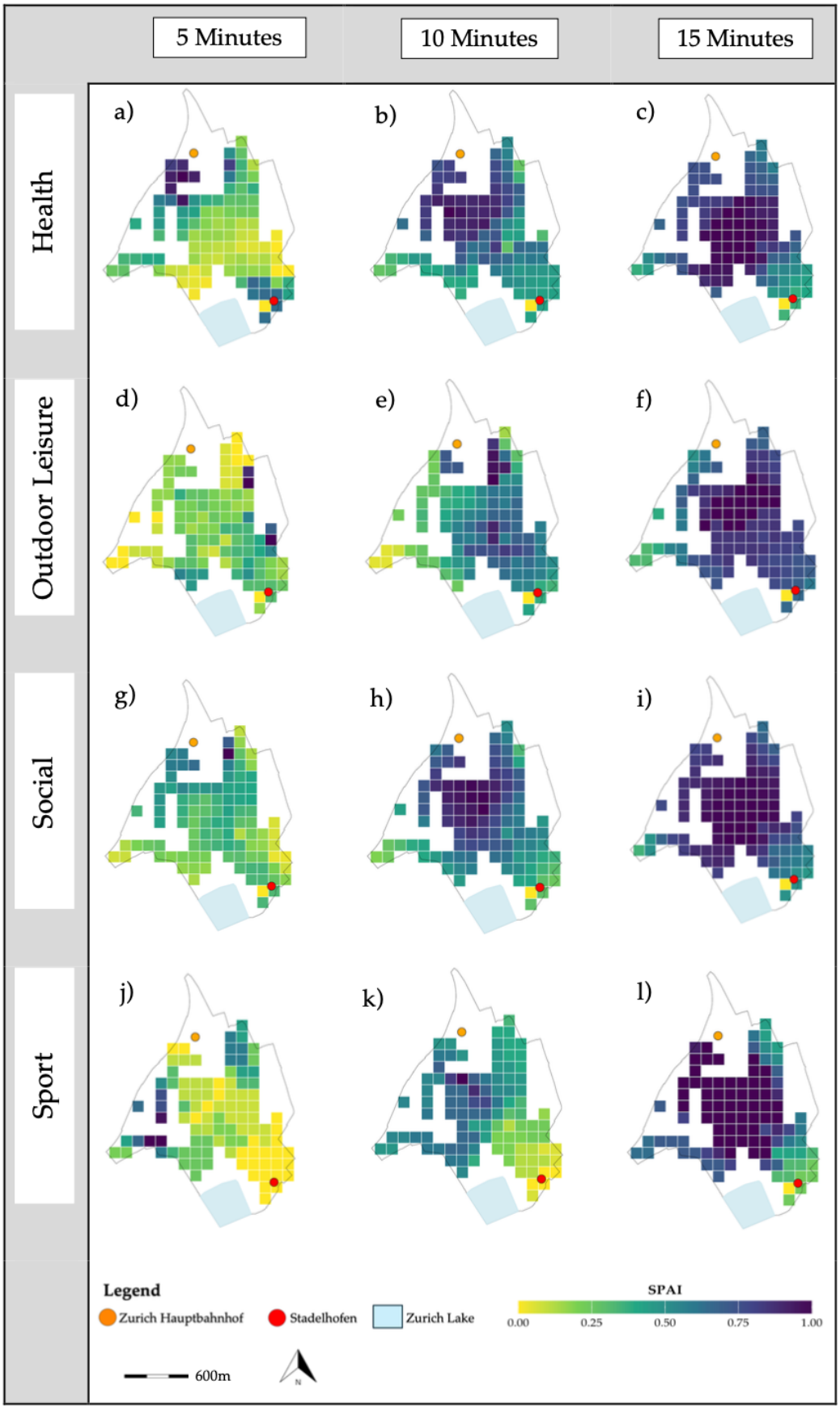

Figure 15 SPAI values for the general population, calculated using the 2SFCA method, with different time thresholds (5, 10, and 15 minutes) for various facilities: Health (a-c), Outdoor Leisure (d-f), Social (g-i), and Sport (j-l) services. The maps display the accessibility levels for each facility type, with the main stations and Zurich Lake marked for reference.

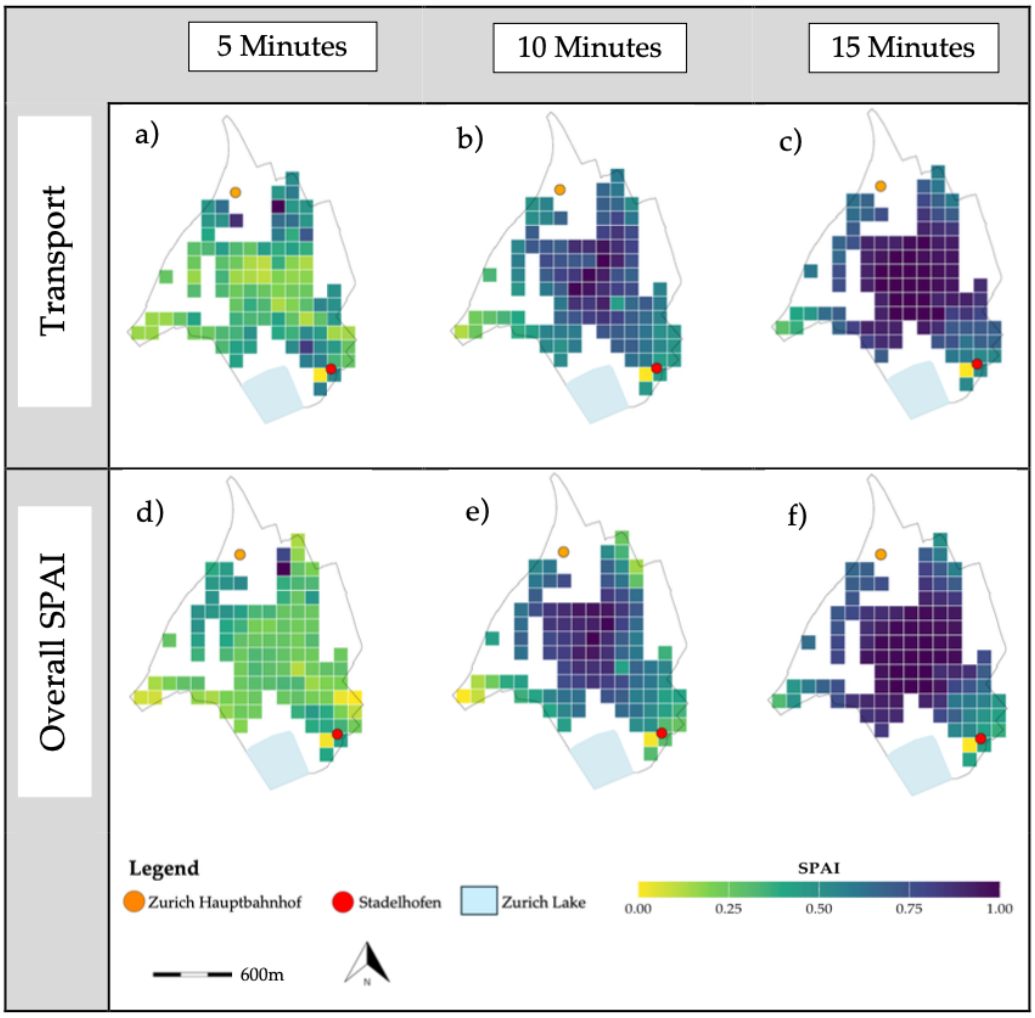

Figure 16 SPAI values for the general population, calculated using the 2SFCA method, with different time thresholds (5, 10, and 15 minutes) for the Transport Services (a-c) and the Overall SPAI Index (d-f). The maps display the accessibility levels for each facility type, with the main stations and Zurich Lake marked for reference.

Social and transport services (see Figures 15g and 16a) are more evenly distributed across the district, resulting in a consistent spread of medium SPAI values within a short walking distance.

Educational services (see Figure 14j) show higher accessibility around the higher education hub near Rämistrasse (see Figure 11), as expected given the presence of multiple educational institutions. Healthcare services reveal two distinct hotspots (see Figure 15a): one around the Hauptbahnhof and another near Stadelhofen, reflecting the locations of pharmacies and medical centers. For sports services (see Figure 15j), a smaller cluster of high values is observed in the western part of the district, where a few key sports facilities are located. These hotspots are easy to identify at the 5-minute threshold, and each type of service forms its own distinct accessibility pattern. Notably, no specific area of the district consistently shows low accessibility across all

service types. Instead, each service has its own distribution, creating unique hotspots that are highly localized and service-specific. This level of detail highlights the varied spatial distribution of services within the district and allows for a better understanding of where accessibility is highest for each service type.

When the threshold is increased to 10 minutes, accessibility improves across the district, and the previously observed hotspots expand. However, a noticeable shift occurs in the distribution of the highest SPAI values. For example, while cultural services (see Figure 14h) continue to show high accessibility near Stadelhofen, the highest values now concentrate more toward the central parts of the district, particularly around the Hauptbahnhof. This trend is not limited to cultural services but can be observed across multiple service types, as central areas benefit from their proximity to a broader range of facilities. The shift in maximum accessibility values toward the district's center highlights the increasing importance of centrally located services as the catchment area expands.

At the 15-minute threshold, this shift becomes even more evident. Accessibility is nearly uniform across the district, with most areas achieving high SPAI values. However, the highest values are now clearly concentrated in the central parts of the district, particularly around the Hauptbahnhof and its surroundings. This pattern reflects how increasing the time threshold allows population nodes in central areas to benefit from their proximity to a larger number of services compared to more marginal areas.

It is important to note that the SPAI values are normalized (see Formula 11 in Section 3.3.3) to allow for relative comparisons across locations. This normalization ensures that accessibility patterns are comparable within each threshold but does not necessarily reflect absolute differences in accessibility levels. For example, a point with a normalized value of 0 (minimum) may still have a relatively high SPAI score in absolute terms, but the normalization process amplifies the relative differences between locations. Similarly, when comparing maps from different thresholds or methods, areas with a normalized value of 0 do not necessarily represent the same absolute level of accessibility. The purpose of normalization is to highlight the spatial distribution of accessibility values, making it easier to identify where accessibility is highest and where it is most limited within a given threshold.

When considering the overall SPAI, which represents the combined accessibility for all services, a more balanced distribution of values is observed at the 5-minute threshold (see Figure 16d). This is due to the diversity of individual service hotspots, which tend to compensate for each other when aggregated into a single overall score.

As the threshold increases, the overall SPAI distribution becomes more concentrated in central areas, reflecting the higher density of services in these locations. At the 15-minute threshold (see Figure 16f), the overall SPAI values become nearly uniform across the district, although marginal areas still show slightly lower values compared to the center. In general, increasing the threshold makes accessibility more uniform but with an increasing concentration in central areas.

4.3.2 Wheelchair Users

The accessibility analysis for wheelchair users shows significantly lower SPAI values compared to the general population across all thresholds. At shorter time thresholds, accessibility remains particularly limited, with almost the entire study area showing very low values. Unlike for the general population, no clear hotspots or patterns emerge, and the distribution of higher values appears fragmented. Physical barriers, such as streets with excessively steep slopes (>6%), pose a major challenge, limiting the ability of wheelchair users to travel further distances. Even as the time threshold increases, accessibility improves only marginally, and many areas remain difficult to reach.

Specifically, when analyzing accessibility to various services with a 5-minute threshold, the study area is dominated by minimum values of 0. There are isolated points with medium-low or high values as a result of normalization, which emphasizes relative differences rather than absolute accessibility levels. This suggests that points appearing highly accessible after normalization are a result of their values standing out relative to the distribution, rather than reflecting absolute accessibility. These points are likely located near a service, allowing them to still reach the point of interest within the 5-minute time limit.

Educational services (see Figure 17j) stand out as having a slightly better distribution at this threshold. The area around Rämistrasse, home to educational institutions such as the Federal Institute of Technology (ETH) and the University of Zurich (UZH), displays medium to high SPAI values, suggesting that some wheelchair users can access these facilities within a short timeframe.

For healthcare services (see Figure 18a), accessibility is generally low, with most areas showing minimum values. Only a few isolated points, primarily near hospitals and healthcare centers, display slightly higher values. These points remain scattered and do not form identifiable clusters, suggesting that access to healthcare services remains limited within a 5-minute walking distance.

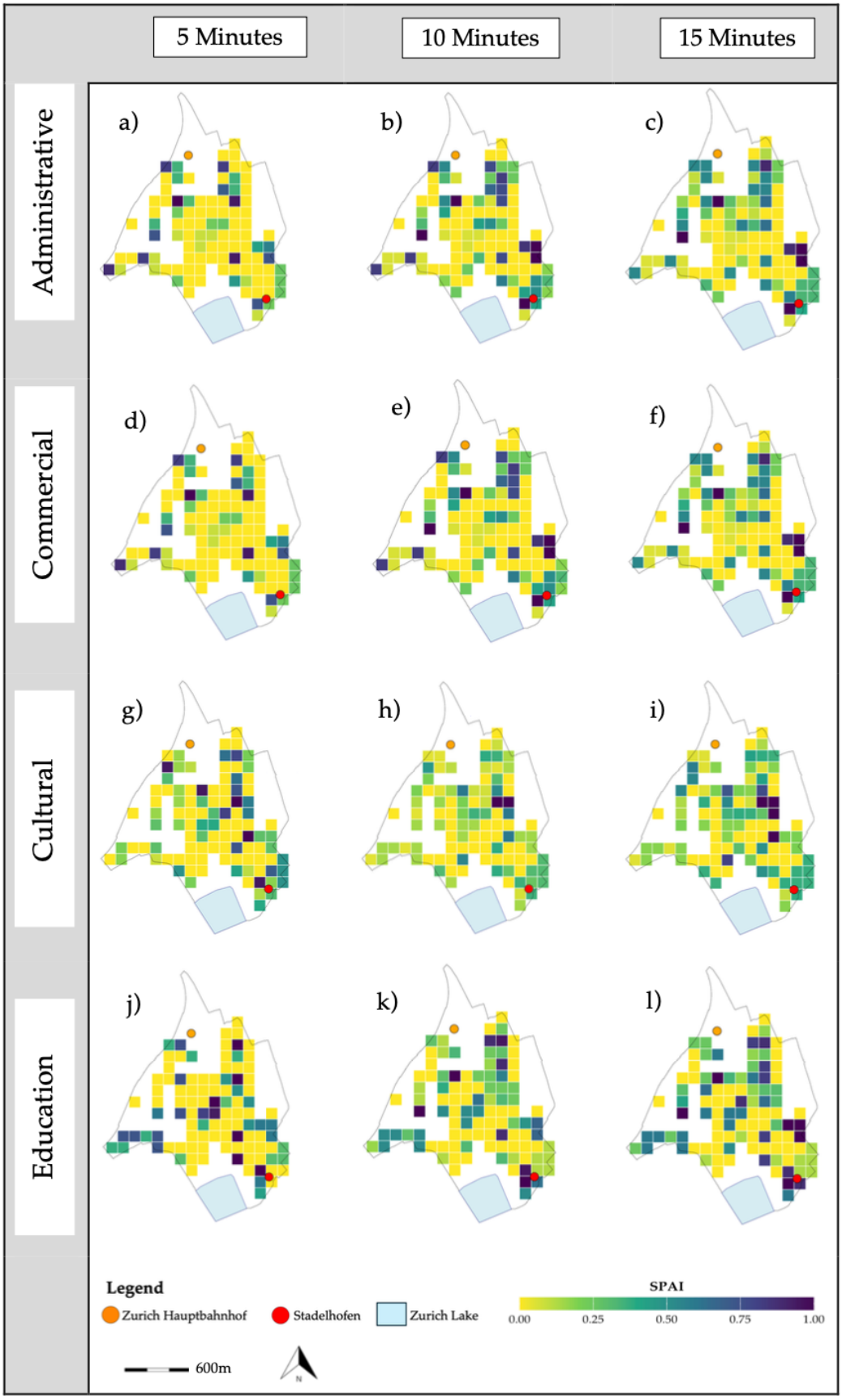

Figure 17 SPAI values for wheelchair users, calculated using the 2SFCA method, with different time thresholds (5, 10, and 15 minutes) for various facilities: Administrative (a-c), Commercial (d-f), Cultural (g-i), and Education (j-l) services. The maps display the accessibility levels for each facility type, with the main stations and Zurich Lake marked for reference.

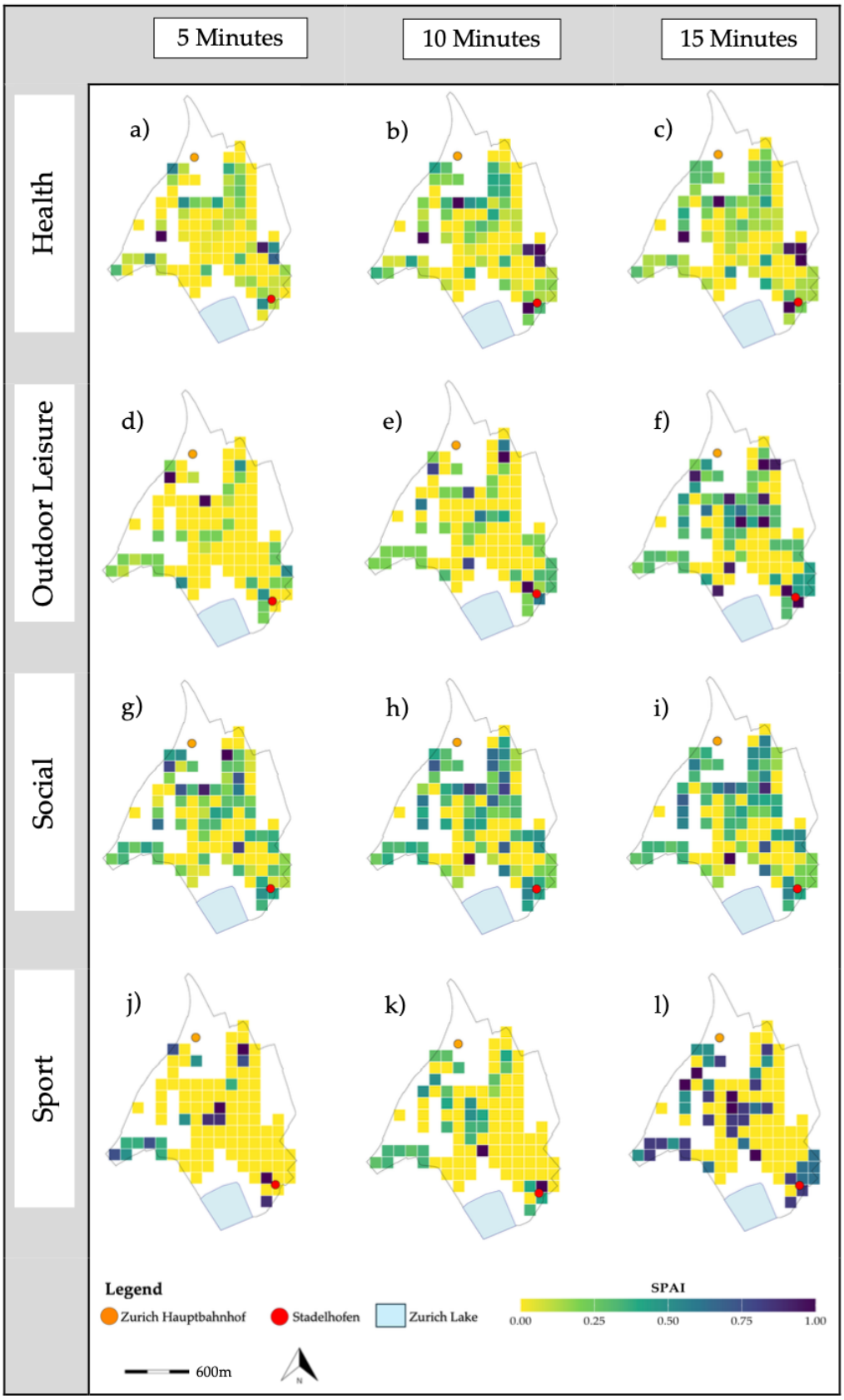

Figure 18 SPAI values for wheelchair users, calculated using the 2SFCA method, with different time thresholds (5, 10, and 15 minutes) for various facilities: Health (a-c), Outdoor Leisure (d-f), Social (g-i), and Sport (j-l) services. The maps display the accessibility levels for each facility type, with the main stations and Zurich Lake marked for reference.

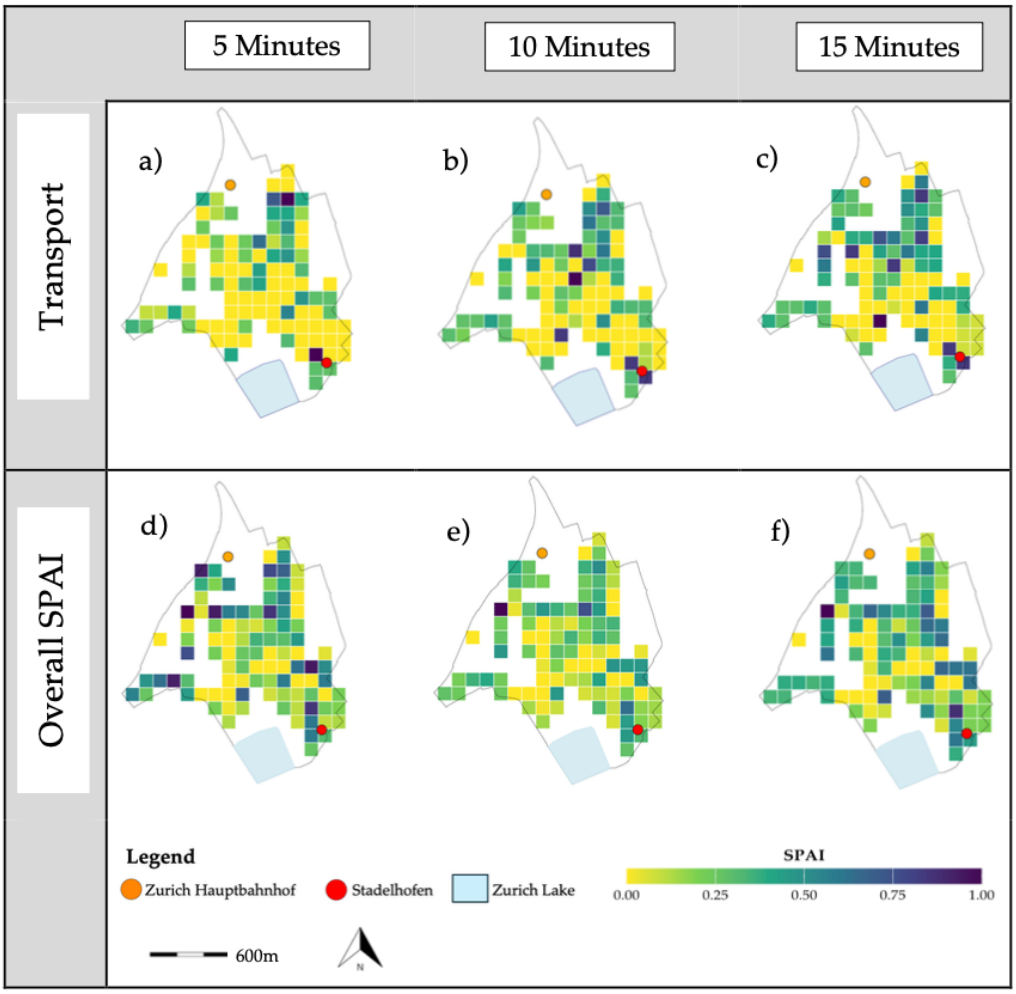

Figure 19 SPAI values for wheelchair users, calculated using the 2SFCA method, with different time thresholds (5, 10, and 15 minutes) for the Transport Services (a-c) and the Overall SPAI Index (d-f). The maps display the accessibility levels for each facility type, with the main stations and Zurich Lake marked for reference.

Social and transport (see Figures 18g & 19a) services show a relatively broader distribution compared to other services, with some areas displaying medium values. However, even for these services, accessibility remains more fragmented than for the general population. The 5-minute threshold highlights that wheelchair users are heavily restricted by their immediate surroundings, with limited opportunities to access services beyond nearby locations.

When the threshold is increased to 10 minutes, accessibility improves slightly, with some areas shifting from very low to medium-low values. However, the improvements remain modest, and the distribution of SPAI values continues to appear fragmented, with isolated points of higher accessibility scattered across the district. No drastic changes in patterns are observed, and wheelchair users still face significant limitations in accessing services.

For educational services (see Figure 17k), the increase in the threshold results in a more balanced distribution of medium to high SPAI values. Areas near educational institutions continue to show higher values, and the gaps observed at the 5-minute threshold start to close.

Healthcare services (see Figure 18b) also show a slight improvement at the 10-minute threshold, with higher values expanding beyond the immediate vicinity of hospitals and healthcare centers. However, these improvements remain limited to specific locations, and large parts of the district still show low accessibility. The scattered distribution of higher values highlights that even with additional travel time, healthcare services remain difficult to access for wheelchair users.

Social and transport services (see Figures 18h & 19b), which were relatively well-distributed at the 5-minute threshold, show further improvements at 10 minutes. Medium SPAI values become more widespread, reflecting the broader availability of these services. However, accessibility still does not match the levels observed for the general population.

At the 15-minute threshold, accessibility improves further, but the overall distribution of SPAI values remains fragmented. The areas with higher values expand slightly, but accessibility remains limited to specific locations, particularly near central service points. The increase in travel time allows wheelchair users to reach more services, but physical barriers continue to restrict their movement, preventing a uniform improvement across the district.

For educational services (see Figure 17l), the 15-minute threshold results in a more even spread of medium to high SPAI values across the district. The previously identified gaps narrow, and accessibility improves in more areas. However, some parts of the district still show medium or low values, indicating that even with extended travel time, wheelchair users face challenges in accessing educational services in certain areas.

Healthcare services (see Figure 18c) continue to show predominantly low SPAI values at the 15-minute threshold, with isolated points of higher accessibility near hospitals and healthcare centers. Although coverage improves slightly, the scattered distribution of higher values persists, and accessibility remains concentrated in specific locations.

Social and transport services (see Figure 18i & 19c) show further improvements at the 15-minute threshold, with medium values becoming more widespread across the district. However, these improvements remain insufficient to match the accessibility levels experienced by the general population.

The analysis of overall SPAI (see Figure 19d-f) confirms these observations. With a 5-minute threshold, SPAI values are generally low across most of the area, with some isolated points showing higher values. These points do not follow a specific pattern, unlike what was observed for the general population, but appear randomly distributed. This suggests that, although some areas have good access, the distribution is not uniform and does not favor wheelchair users. With an increase in the threshold to 10 and 15 minutes, the situation remains largely unchanged. SPAI values remain low across most of the area, with an expansion of higher values, though these continue to be randomly distributed. Even with the increase in the travel time, the primary issue is not resolved: the difficulty of covering a sufficient area to access all services. In fact, increasing the threshold does not ensure adequate coverage for wheelchair users, who continue to face limited access, despite having a larger range of accessible distances.

4.3.3 Time Threshold Choice

A 15-minute threshold, when applied to the general population, covers nearly the entire area but is too extensive for a detailed accessibility analysis. At this threshold, the distribution of SPAI values becomes too uniform, with near-total coverage, making it difficult to distinguish between more or less serviced areas. On the other hand, a 5-minute threshold is too restrictive, especially for wheelchair users as the reduced mobility capabilities and the accessibility features present along the sidewalk severely limit the access to services. SPAI values remain low across most of the area, with some isolated regions showing higher values, but without a clear concentration, as observed in the general population. The distribution of points with higher values appears random, and accessibility remains highly limited due to the short distance that can be covered in just 5 minutes.

Finally, a 10-minute threshold seems to represent a good compromise between the two extremes. For the general population, it allows for a fairly complete coverage while maintaining significant differences in accessibility between various zones. For wheelchair users, a 10-minute threshold includes a significant portion of the peripheral zones, while still maintaining a clear distinction between central areas and more distant ones, where access is more challenging. A 10-minute threshold offers a balanced compromise: it provides wheelchair users with realistic access to a sufficient range of services, while avoiding an excessively large threshold that would flatten accessibility differences for the general population. In conclusion, a 10-minute threshold proves to be the most suitable for a balanced and informative accessibility

analysis in relation to District 1. All subsequent analyses discussed in the following sections are carried out using a 10-minute threshold.

4.3.4 Differential Map: Population Group Comparison

When applying the 2SFCA method with a 10-minute threshold, significant differences emerge in the comparison between the general population and wheelchair users, particularly when considering the distribution of SPAI values and the impact of obstacles on mobility.

The map in Figure 20 displays the SPAI difference, obtained by subtracting the overall SPAI values for wheelchair users from those of the general population. Analyzing the results, it can be observed that red areas indicate places where the general population has greater access to services compared to wheelchair users, with SPAI differences approaching 0.5 or even higher. These areas primarily represent zones where the general population benefits from better access to services, due to higher mobility capacity and the lower impact that obstacles in the infrastructure have on their movement, compared to wheelchair users.

On the other hand, purple areas show where wheelchair users have superior access to services, with negative SPAI differences around -0.5. However, these areas are very isolated and do not concentrate in a specific central zone, but rather in scattered points. This suggests that the normalization process, along with differences in the spatial distribution of services and the accessibility constraints faced by wheelchair users, influences the two groups differently. For wheelchair users, isolated points can achieve maximum values due to the limited number of accessible locations within the threshold, amplifying relative differences. Conversely, for the general population, maximum values concentrate in central areas, where nearly all services are accessible. This is because the general population can reach services at greater distances, resulting in significantly higher accessibility values in the central parts of the area, as also evident in the comparison. Peripheral points for this group, by contrast, receive lower relative values after normalization. As a result, the comparison highlights areas where wheelchair users appear to have better access in relative terms. However, it is important to note that this effect, stemming from the normalization process, may not fully reflect actual accessibility levels in absolute terms (see Formula 11 in Section 3.3.3).

White areas represent a neutral zone, where there are no significant differences in accessibility between the two populations. Overall, the map highlights how the

general population has a clear advantage in terms of accessibility, with most of the city's areas, especially central ones, showing higher SPAI values. On the other hand, wheelchair users continue to face difficulties accessing services, with some exceptions in specific areas.

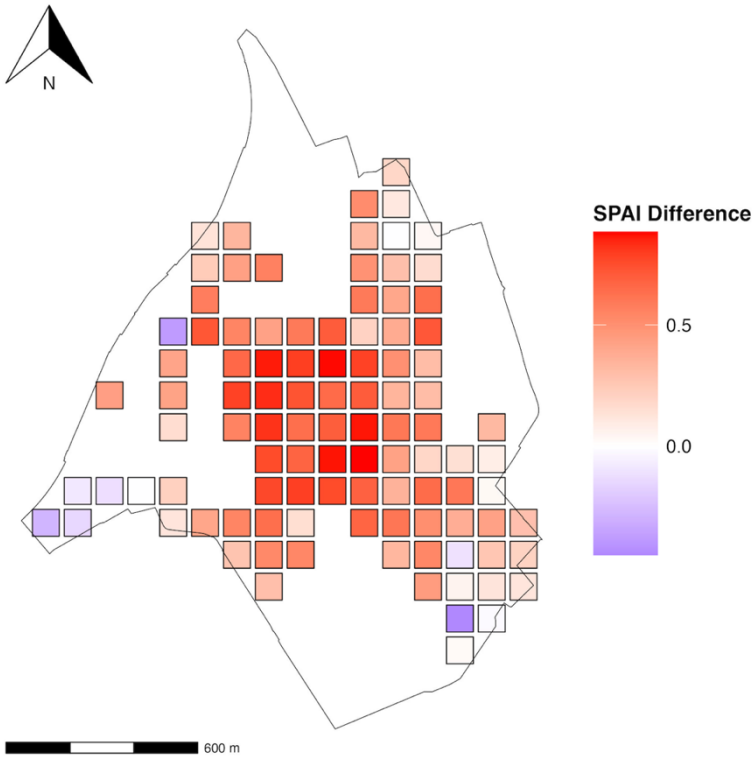

Figure 20 Overall SPAI difference in accessibility between the general population and wheelchair users for the 10-minute threshold. The color gradient represents the SPAI difference, with red indicating higher accessibility for the general population, and purple indicating higher accessibility for wheelchair users.

4.3.5 Edge Effect

To demonstrate the limitations associated with the edge effect, a comparison was made between the SPAI values obtained by applying a 10-minute buffer around the district boundary, extending outward, and those obtained without a buffer. This brief analysis was conducted for the general population, considering only information related to slope. The case with the buffer includes facility points outside the district boundary, meaning population points located at the edges can access services that are closer to them but fall outside the district.

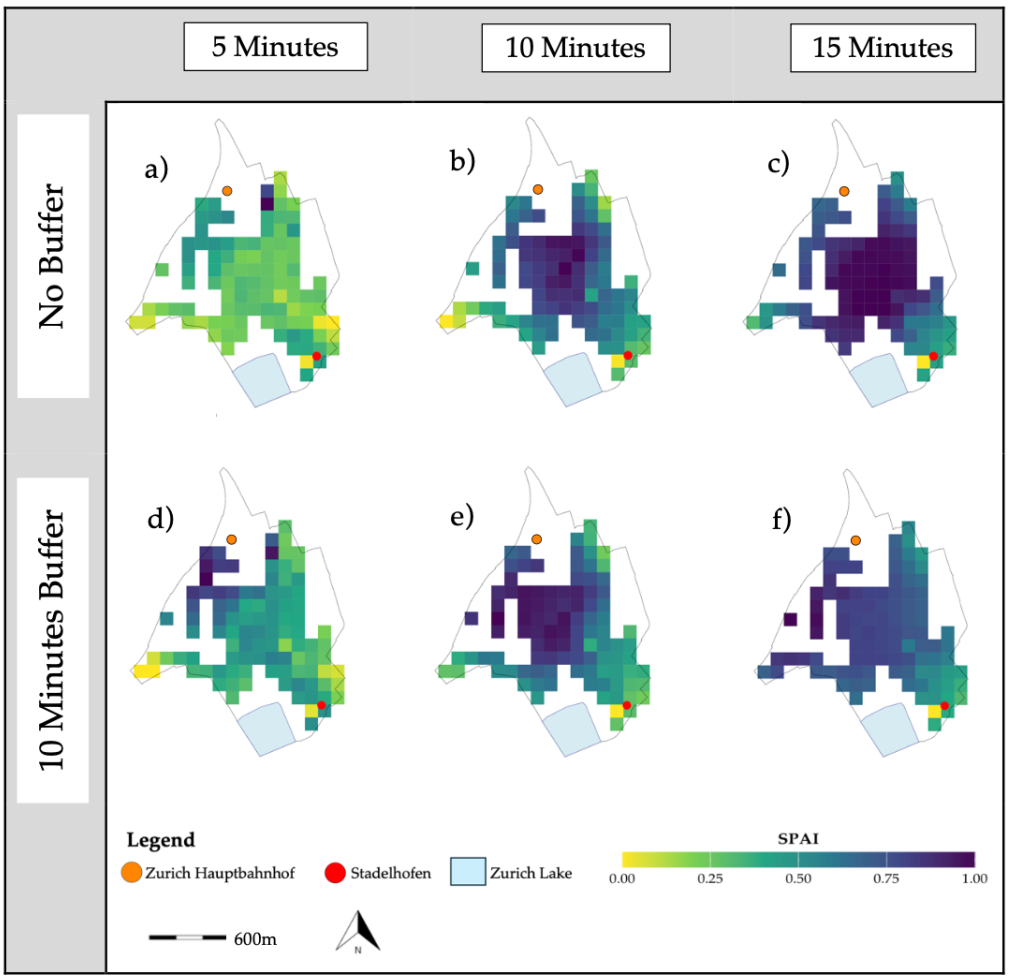

Figure 21 Edge effect visualized through SPAI values for different time thresholds (5, 10, and 15 minutes) with and without a 10-minute buffer. The main stations (red dots) and Zurich Lake (light blue area) serve as reference points for the study area.

As seen in Figure 21a&d, with the 5-minute threshold, the north-western area shows very high values, indicating better accessibility in this area due to the presence of services just outside the boundary. Overall, the entire district appears to have higher SPAI values when the buffer is considered, compared to when it is not.

A similar trend is observed with the 10-minute threshold (see Figure 21b&e), although the difference is less pronounced. Notably, the highest accessibility values in the center are slightly shifted westward compared to the analysis without the buffer.

An interesting observation is made with the 15-minute threshold (see Figure 21c&f), where, despite the overall high values across the district, the SPAI values are lower when the buffer is considered. This is because the highest SPAI values are found outside District 1 (see Figure 22), where populations points can access much larger areas. In the western part of the area, the availability and accessibility of services are higher.

This analysis highlights the edge effect, showing that when the buffer is considered, accessibility values can be skewed, leading to higher values near the district boundary. However, in the subsequent analysis comparing the FCA methods, no buffer was considered due to the lack of accessibility data outside District 1.

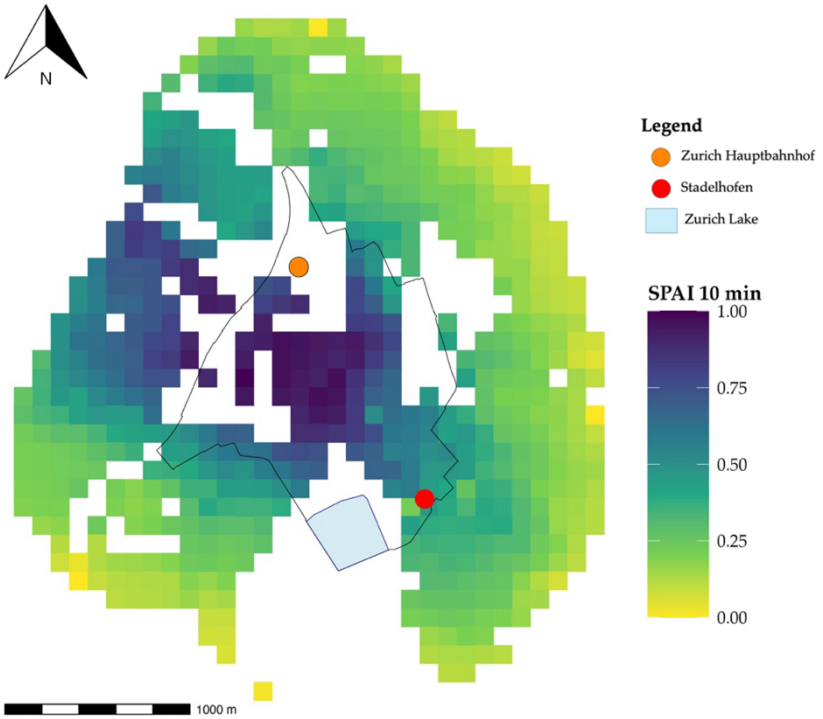

Figure 22 Edge effect representation with SPAI values visualized for a 15-minute threshold, including accessibility values within the 10-minute buffer zone beyond District 1. Main stations (red dots) and Zurich Lake (light blue) provide spatial reference.

4.4 FCA Methods Comparison

This section presents the results of the accessibility analysis conducted using three different FCA methods based on various distance decay functions. A time threshold of 10 minutes, established in the first part of the analysis, is consistently applied across all methods. The analysis includes both the general population and wheelchair users, providing insights into how different methods impact accessibility patterns for each group.

In each section, the first part discusses the results for different facility types, focusing on cases where notable differences between the methods were observed. To compare the methods in more detail, differential maps were created by subtracting the SPAI values of the KD2SFCA and E2SFCA methods from those obtained with the 2SFCA, which serves as the reference method.

4.4.1 General Population

The comparison of SPAI values across the KD2SFCA, 2SFCA, and E2SFCA methods reveals significant differences in how accessibility is distributed within District 1. In most cases, the results show a distribution pattern of accessibility that is very similar between the KD2SFCA and 2SFCA methods. In contrast, the E2SFCA method tends to display lower SPAI values in areas farther from services, with a notable concentration in the southeastern part of the district, and higher values in smaller, isolated areas. When examining individual services, more specific and different behaviors between the methods can be observed.

For instance, in the case of education, healthcare and social services (see Figures 23j-l, 24a-c and 24g-i), it can be observed that E2SFCA presents significantly lower SPAI values overall. The E2SFCA method shows a small area with higher values, while the majority of the district is dominated by medium-low values. In contrast, the 2SFCA method exhibits a much larger area with high values, with the rest of the area displaying medium-high values. Finally, the KD2SFCA also presents a relatively large area of high values, though slightly smaller than the 2SFCA. Overall, the area is dominated by medium-low values.

In the case of commercial services (see Figure 23d-f), however, the discrepancy between the different FCA methods is less pronounced. The E2SFCA still shows lower values but is largely dominated by medium values, aligning more closely with the patterns observed in the other two methods.

For sports services (see Figure 23j-l), the KD2SFCA method displays the highest accessibility values compared to the other two methods. Across all three methods, the area with lower accessibility values is the most extensive among all service types, with a large low-value area notably concentrated in the southeastern part of the district. In contrast, high accessibility values are more concentrated in the western area. The 2SFCA method shows a distribution pattern generally similar to the KD2SFCA method, though some differences can be observed in specific areas. Specifically, the 2SFCA method identifies its hotspot in the northwestern part of the district, while both the KD2SFCA and E2SFCA methods locate their hotspots farther south.

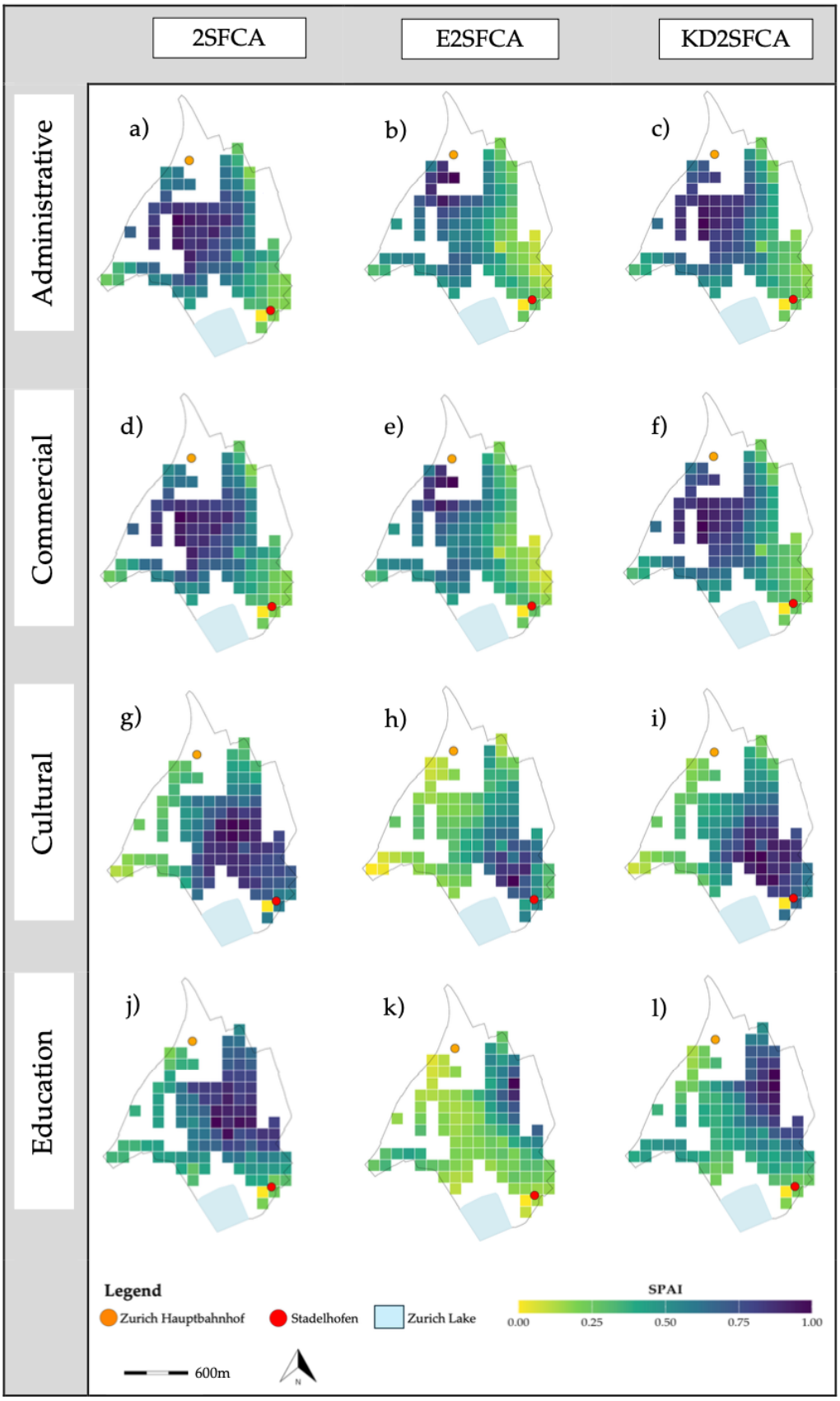

Figure 23 SPAI values calculated with different FCA methods (2SFCA, E2SFCA, and KD2SFCA) for a 10-minute threshold for the general population, shown separately for Administrative (a-c), Commercial (d-f), Cultural (g-i), and Education (j-l) services in Zurich's District 1.

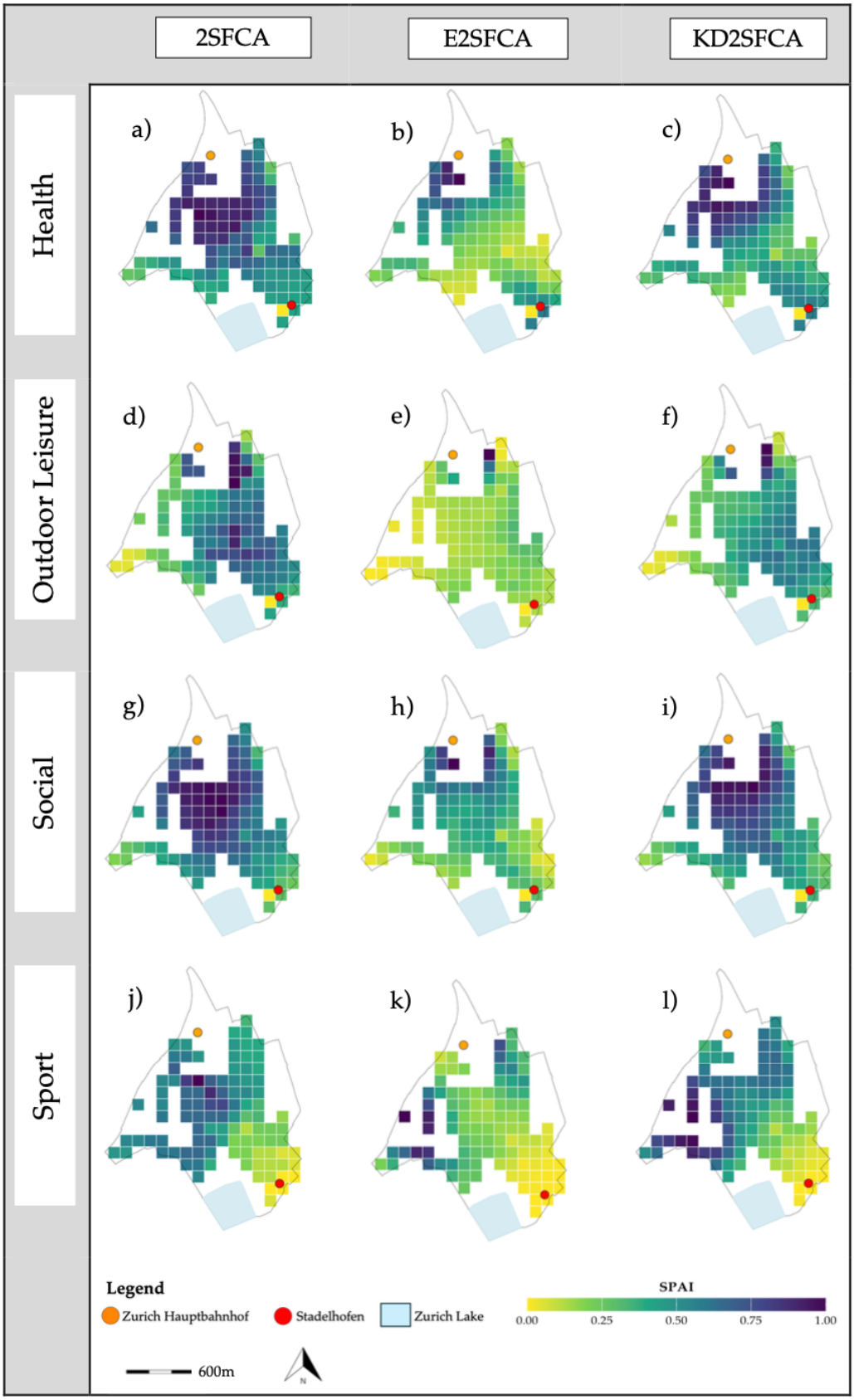

Figure 24 SPAI values calculated with different FCA methods (2SFCA, E2SFCA, and KD2SFCA) for a 10-minute threshold for the general population, shown separately for Health (a-c), Outdoor Leisure (d-f), Social (g-i) and Sport (j-l) services in Zurich's District 1.

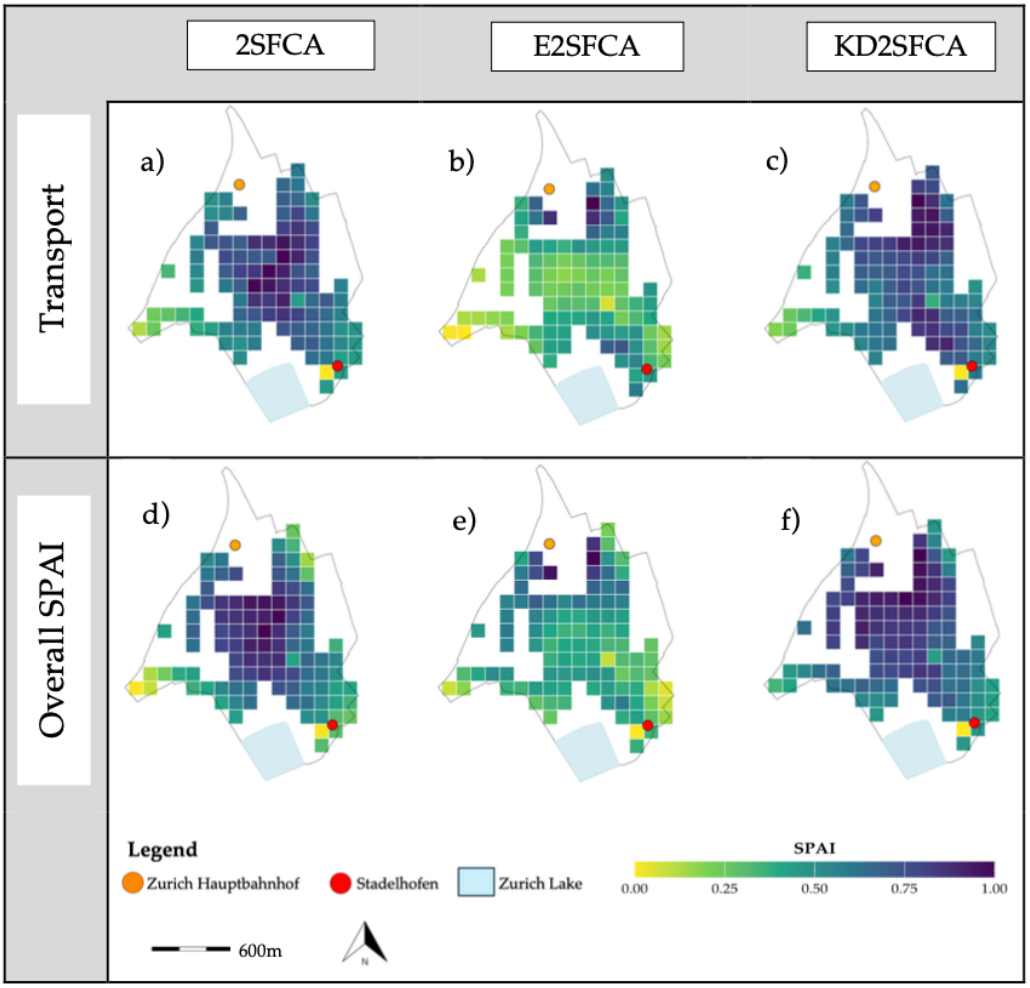

Figure 25 SPAI values calculated with different FCA methods (2SFCA, E2SFCA, and KD2SFCA) for a 10-minute threshold for the general population, shown for Transport services (a-c) and the Overall SPAI in Zurich's District 1.

As observed in the analysis with different time thresholds in Section 4.3, the transport category (see Figure 25a-c) exhibits good accessibility across the entire district, and this is confirmed in the results obtained with the KD2SFCA method. High and medium-high values are observed across nearly the entire district, with a small exception in the southwest. In contrast, the result from the E2SFCA method presents a pattern predominated by values within the first two quartiles of the SPAI range across almost the entire area. Some higher values are noted in the northern part and a small area in the southeast, but overall, the accessibility does not match the higher levels observed with the other two methods. More specifically, the 2SFCA method produces results much more similar to the KD2SFCA, with generally high values across the district. However, while the KD2SFCA shows two distinct hotspots — one slightly north of the center and another in the south extending towards Stadelhofen — the 2SFCA presents

a more centralized concentration of maximum values in the core of the district. Despite these differences in the spatial distribution of high values, both methods provide consistently higher SPAI values compared to the E2SFCA method.

The analysis of outdoor leisure services (see Figure 24d-f) shows some variation in the distribution of SPAI values across the three methods, with more noticeable differences than for other service types. The E2SFCA method produces predominantly medium-low values across the district, with slightly higher values in the northern part. The KD2SFCA method displays a more balanced distribution within the second and third quartiles, with some isolated areas of very low or very high values. Interestingly, unlike in most cases, the 2SFCA method identifies a much larger area of high values compared to the KD2SFCA. In particular, it highlights a distinct hotspot in the central part of the district that is not captured by the other methods.

For administrative and cultural services (see panels a-c and g-i in Figure 24), no significant variations are observed, and therefore they will not be discussed in detail here. The overall SPAI (see Figure 25d-f) for the three methods follows the patterns observed in the individual service types. E2SFCA is the method with the lowest SPAI values, dominated by values from the second quartile (greenish colors). Some lower values are seen in the southeast, and maximum values are concentrated in the northern part of the district. The 2SFCA method, on the other hand, exhibits a good extension of high values in the central part of the district, with medium values in the more outlying areas, especially in the east, and minimal values in a small southwest area. Finally, KD2SFCA also demonstrates a good extension of high values located in the center, with a further extension to the north. The rest of the area is characterized by medium SPAI values and does not show areas with low values as seen in the 2SFCA method.

Building on these observations, the differential maps (see Figure 26) provide further insights into the differences between the methods by visualizing the variations in overall SPAI values across District 1. These maps highlight two distinct patterns that were previously observed: KD2SFCA tends to yield higher accessibility values compared to 2SFCA, while E2SFCA generally results in lower values. This is evident from the predominance of purple points on the KD2SFCA map, which indicate negative differences, while the majority of red points on the E2SFCA map suggest positive differences.

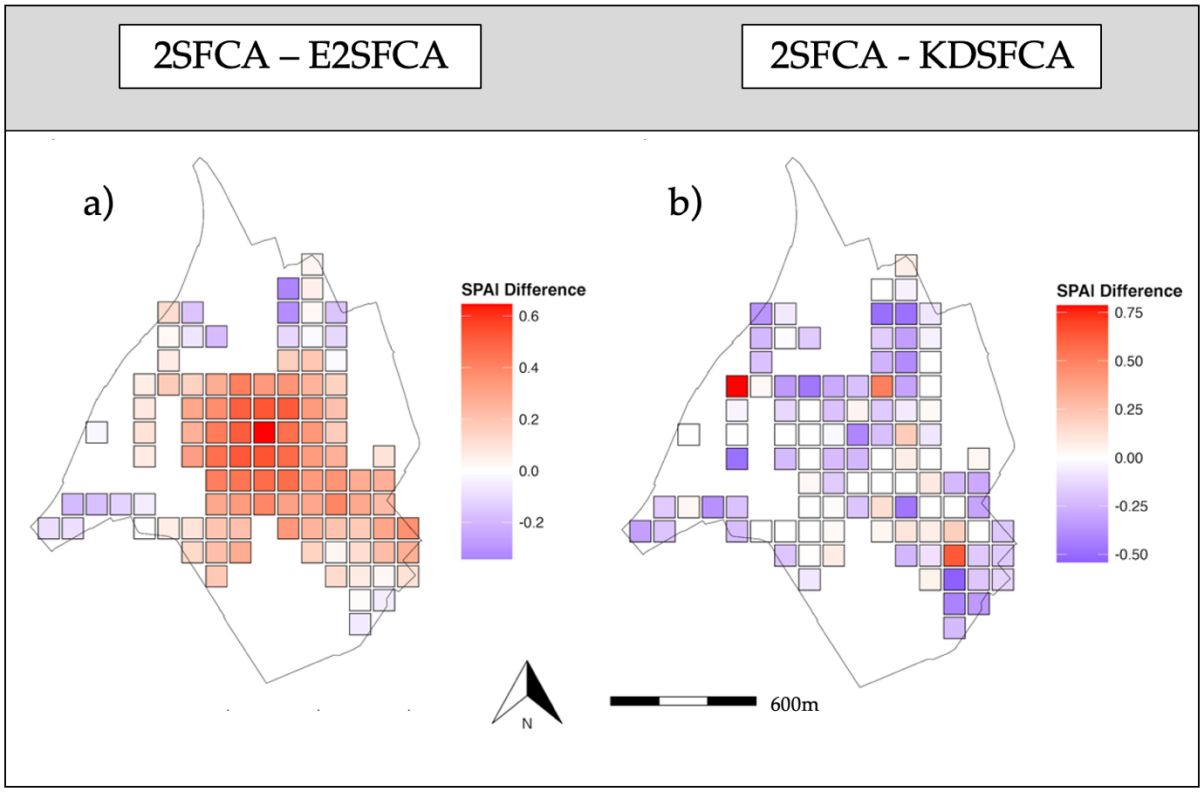

Figure 26 SPAI differences for a 10-minute threshold for the general population, calculated using overall SPAI values and 2SFCA as the reference method. The left panel (a) shows differences between 2SFCA and E2SFCA, while the right panel (b) compares 2SFCA and KD2SFCA.

The disparities are more pronounced in the case of E2SFCA, where the maximum differences exceed 0.6. By contrast, the differences for KD2SFCA rarely surpass 0.3, indicating a more moderate variation. This suggests that E2SFCA, with its differentiated weighting approach, exerts a stronger influence on accessibility distribution compared to KD2SFCA, which shows more consistent results across the area due to its smoother decay function.

An interesting observation regarding KD2SFCA (see Figure 26b) is that the most significant negative differences occur in the peripheral zones of the district, where this method tends to produce higher accessibility values. In contrast, the central areas display positive differences, indicating that 2SFCA leads to higher SPAI values in those zones. However, the magnitude of these positive differences is relatively small, reaching a maximum value just above 0.1. This can be attributed to KD2SFCA's approach, which applies a spatial decay function that distributes accessibility more evenly across the area, particularly in the peripheral zones.

For E2SFCA (see Figure 26a), the situation is reversed. The central areas exhibit a relatively large positive difference, implying that 2SFCA provides higher accessibility there. On the other hand, the peripheral areas show several cells with negative

differences, indicating that E2SFCA produces lower accessibility values in those regions. This is a direct result of E2SFCA's use of differentiated weights, which place less emphasis on distant areas, making it more sensitive to proximity to services in central locations. As a result, E2SFCA tends to overestimate accessibility in the core areas while underestimating it in more peripheral zones.

The combined analysis of individual service types and the differential maps shows that the KD2SFCA and 2SFCA methods generally produce wider areas with higher accessibility values, while the E2SFCA method results in more localized variations and distinct hotspots.

4.4.2 Wheelchair Population

For wheelchair users, it can be initially observed that the results from the 2SFCA and KD2SFCA methods are quite similar across almost all services, both showing a mix of low and high SPAI values. The KD2SFCA, however, generally produces more values in the upper range, whereas the 2SFCA displays a more even spread of medium values. In contrast, the E2SFCA method generally produces significantly lower SPAI values, which are more evenly spread across the entire district. For all three methods, as discussed in Section 4.3, the distribution of SPAI values is not homogeneous and continuous but rather sporadic.

In the case of education, healthcare, outdoor leisure, and sports services (see Figures 27j-l, 28a-f and 28j-l), the E2SFCA method shows a clear dominance of low values (yellow), with a few small exceptions of medium-low values (excluding the maximum values caused by normalization). For these same services, the results from the other two methods (KD2SFCA and 2SFCA) reveal a more favorable pattern, with a wider range of medium SPAI values and, in some cases, higher values.

Another notable observation pertains to sports services (see Figure 28j-l), where the KD2SFCA method covers a larger area with high SPAI values compared to 2SFCA, which mirrors the trend seen in the general population.

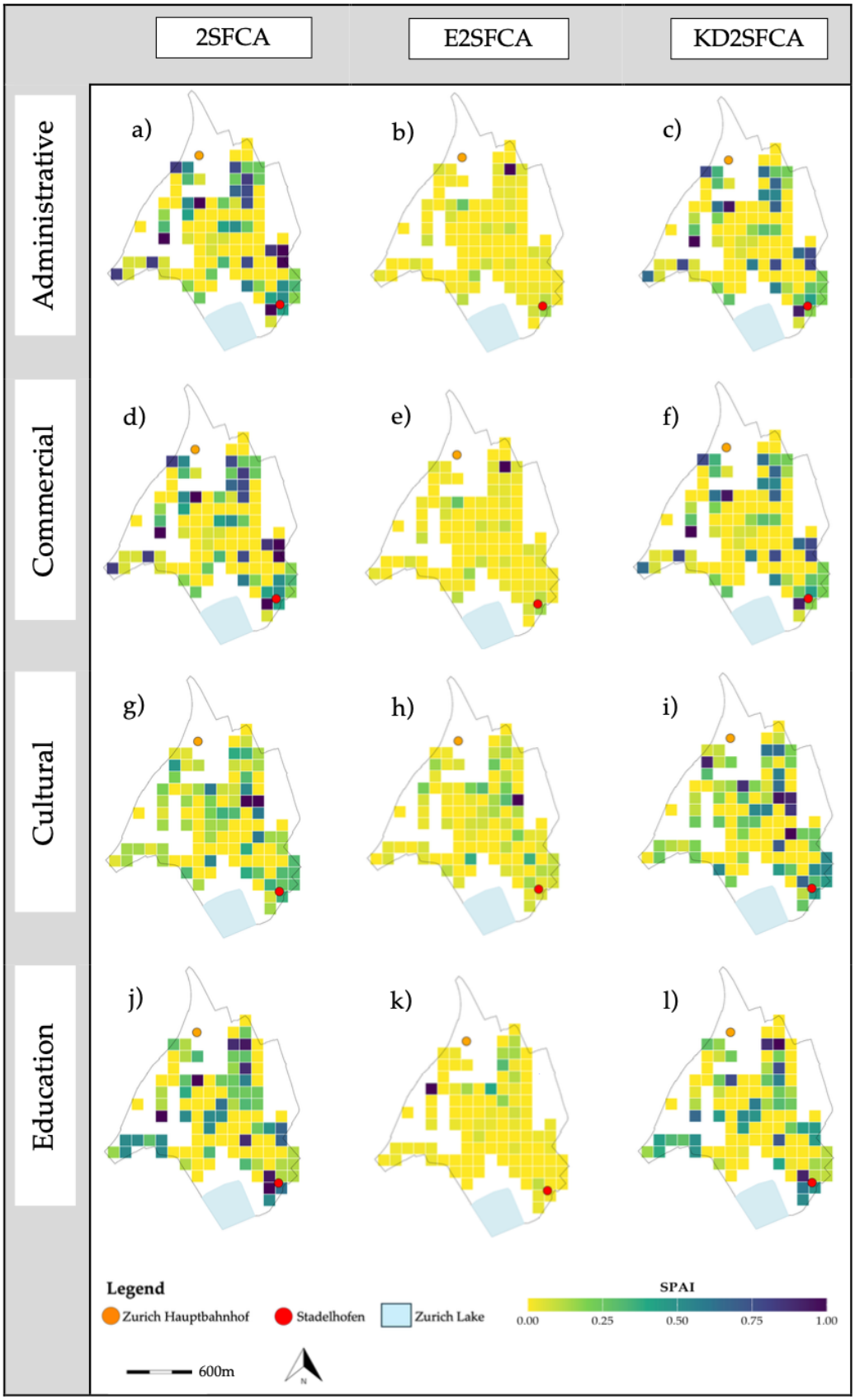

Figure 27 SPAI values calculated with different FCA methods (2SFCA, E2SFCA, and KD2SFCA) for a 10-minute threshold for wheelchair users, shown separately for Administrative (a-c), Commercial (d-f), Cultural (g-i) and Education (j-l) services in Zurich's District 1.

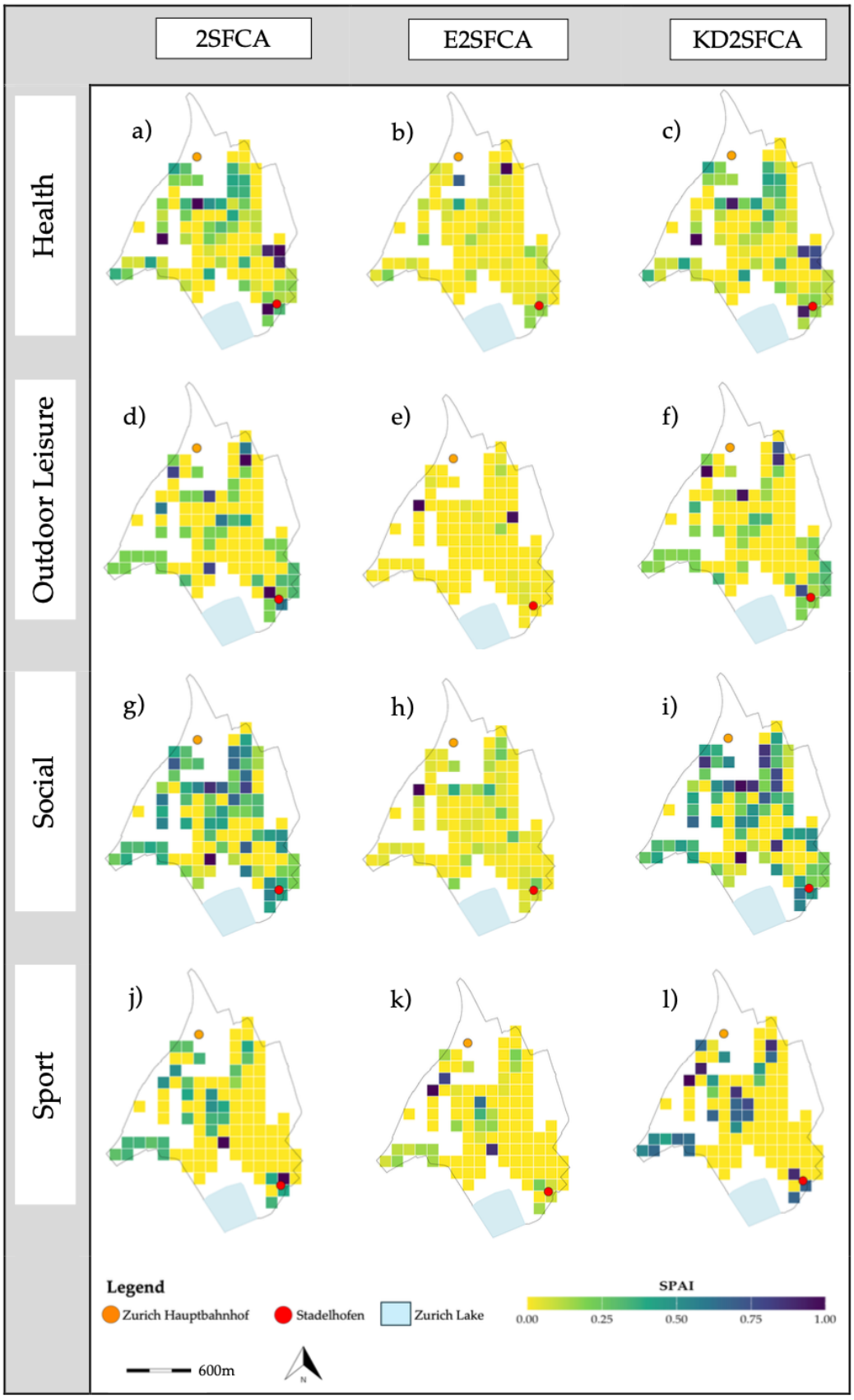

Figure 28 SPAI values calculated with different FCA methods (2SFCA, E2SFCA, and KD2SFCA) for a 10-minute threshold for the general population, shown separately for Health (a-c), Outdoor Leisure (d-f), Social (g-i) and Sport (j-l) services in Zurich's District 1.

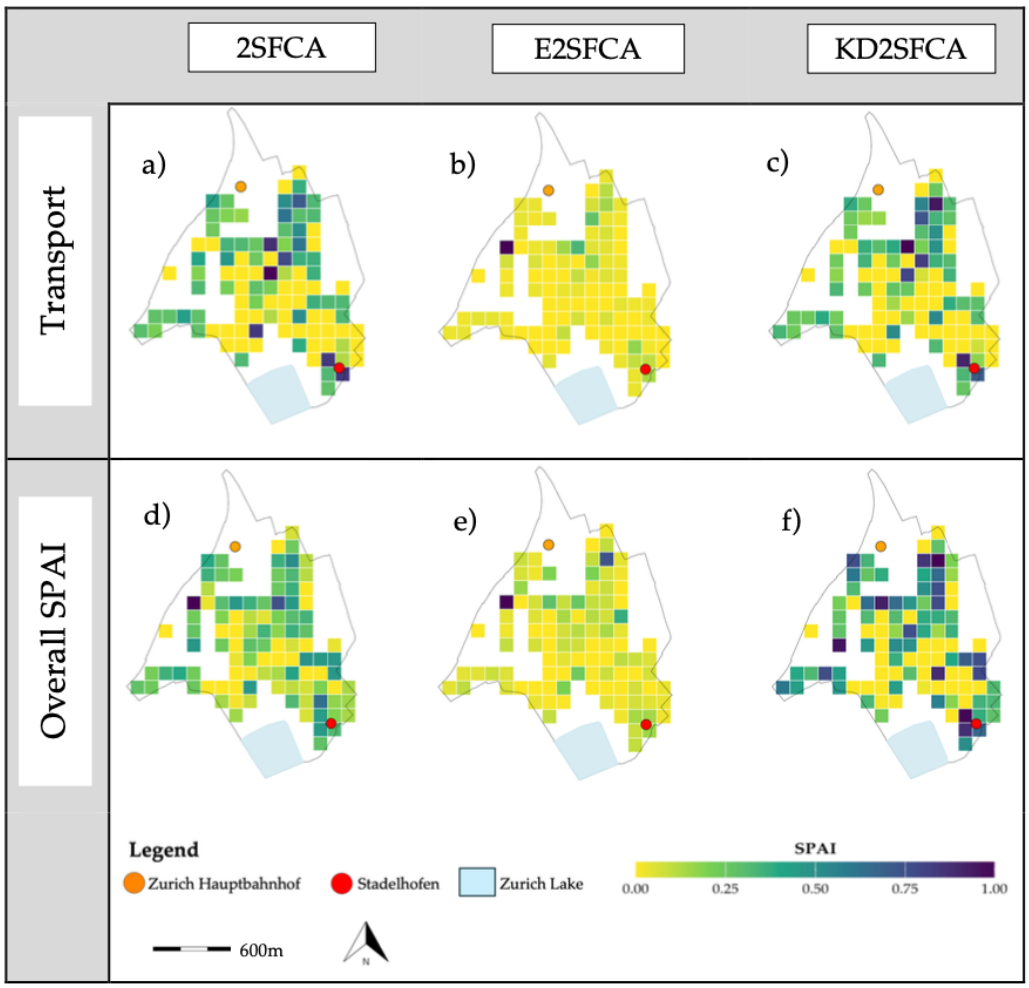

Figure 29 SPAI values calculated with different FCA methods (2SFCA, E2SFCA, and KD2SFCA) for a 10-minute threshold for the general population, shown for Transport services (a-c) and the Overall SPAI in Zurich's District 1.

The most accessible results are seen in social and transport interaction services (see Figures 28g-i and 29a-c). Across all three methods, a significant proportion of the area is covered by medium-high values, though the distribution remains somewhat sporadic. The E2SFCA method, in this case, contains a higher number of SPAI points with maximum values compared to 2SFCA. An interesting aspect here is that points with maximum values are located near areas with minimum values. This contrasts with the results for the general population, which showed a more gradual pattern with distinct zones clearly separated by higher and lower values.

When examining the overall SPAI maps (see Figure 29d-f), it can be observed that E2SFCA yields the lowest values, while KD2SFCA produces the highest. The results for E2SFCA are predominantly composed of points with minimum values, with some points reaching the second quartile, and only two points achieving high SPAI values. Conversely, KD2SFCA reveals several areas with high or medium-high SPAI values. However, many points still fall within the lower range, scattered across the district,

including some of the central areas. The 2SFCA method, while still showing fewer maximum values than KD2SFCA, covers a broader area with higher SPAI values, resulting in a predominance of medium and medium-high values, with fewer low values than the KD2SFCA method.

The differential maps (see Figure 30) provide confirmation of the patterns previously identified, further highlighting the variations in overall SPAI values between the methods for wheelchair users. Unlike the general population, there is no clear division between central and marginal areas. Instead, the distribution of SPAI values appears more heterogeneous, without following a clear pattern. Nevertheless, the differences between the methods used are still evident.

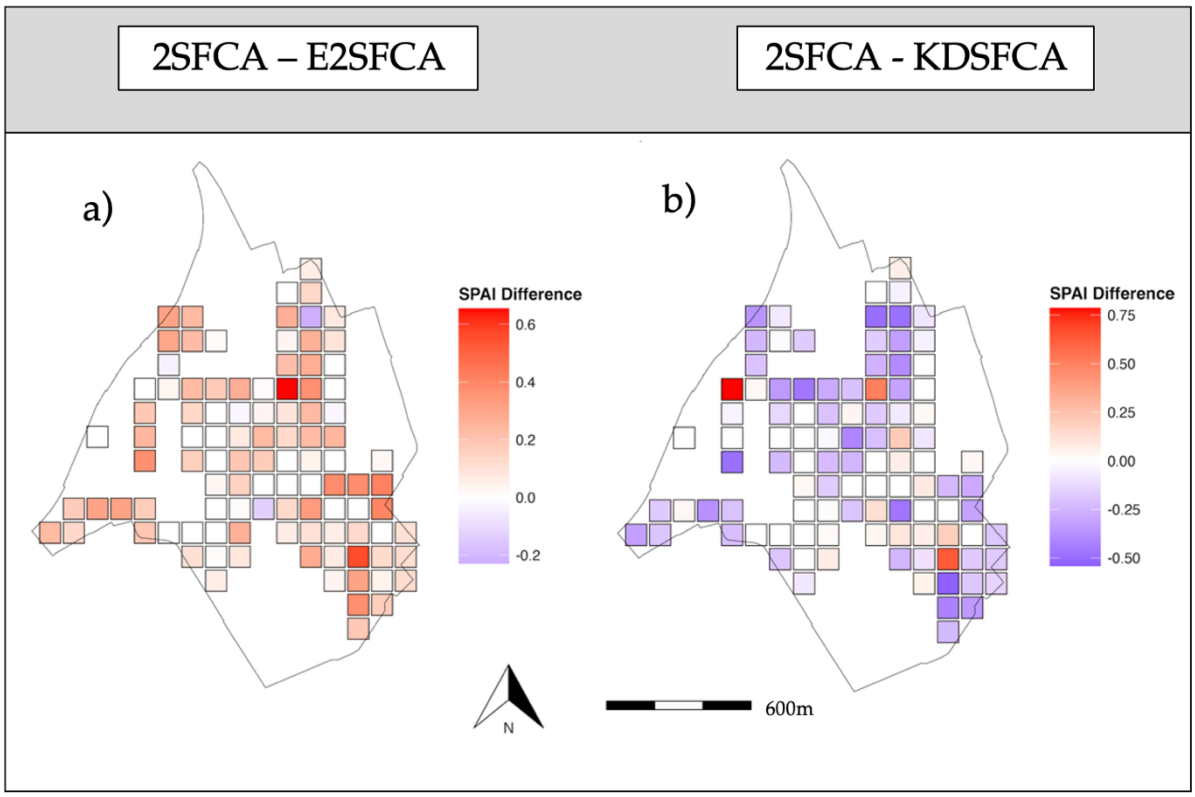

Figure 30 SPAI differences for a 10-minute threshold for wheelchair users, calculated using overall SPAI values and 2SFCA as the reference method. The left panel (a) shows differences between 2SFCA and E2SFCA, while the right panel (b) compares 2SFCA and KD2SFCA.

When comparing the 2SFCA and KD2SFCA methods (see Figure 30b), the map shows a predominance of negative differences, indicating that KD2SFCA tends to yield higher SPAI values. Some exceptions exist, with scattered positive difference points indicating instances where 2SFCA produced higher values. Interestingly, two of these points exceed 0.6, indicating significant differences in specific areas.

The comparison between 2SFCA and E2SFCA (see Figure 30a) shows the opposite trend. The differential map highlights a predominance of positive differences, suggesting that 2SFCA generally provides higher SPAI values than E2SFCA. Only two points exhibit negative differences, and these differences are minimal, not exceeding 0.1. In contrast, positive differences surpass 0.5, suggesting that E2SFCA tends to underestimate accessibility in the analyzed areas.

Taken together, these analyses illustrate the variations in accessibility patterns for wheelchair users depending on the FCA method applied. While KD2SFCA and 2SFCA generally produce higher SPAI values across wider areas, the E2SFCA method results in more evenly distributed but lower accessibility values. The differential maps further highlight these variations, showing that KD2SFCA typically produces higher values compared to 2SFCA, whereas E2SFCA tends to yield lower values across the district.

4.5 Statistical Analysis

This section presents the statistical analysis conducted to interpret the accessibility outcomes obtained from the three Floating Catchment Area (FCA) methods presented in Section 4.4. The analysis is divided into two groups: the general population and the wheelchair population. The primary objective is to understand how the methodological approach of each FCA method, particularly the use of different decay functions, influences the resulting accessibility values and shapes the interpretation of spatial accessibility outcomes.

4.5.1 General Population

In the paired scatter plot matrix in Figure 31, density plots, scatter plots, and Pearson correlation values between the different FCA methods are shown. The density plots reveal the distribution of SPAI values across the population points. For KD2SFCA, the density plot shows a relatively flat start, indicating few population points with low SPAI values. The curve peaks between 0.6 and 0.8, suggesting that a substantial portion of the population enjoys a good level of access to services. The gradual drop in the tail shows that fewer points reach maximum SPAI values.

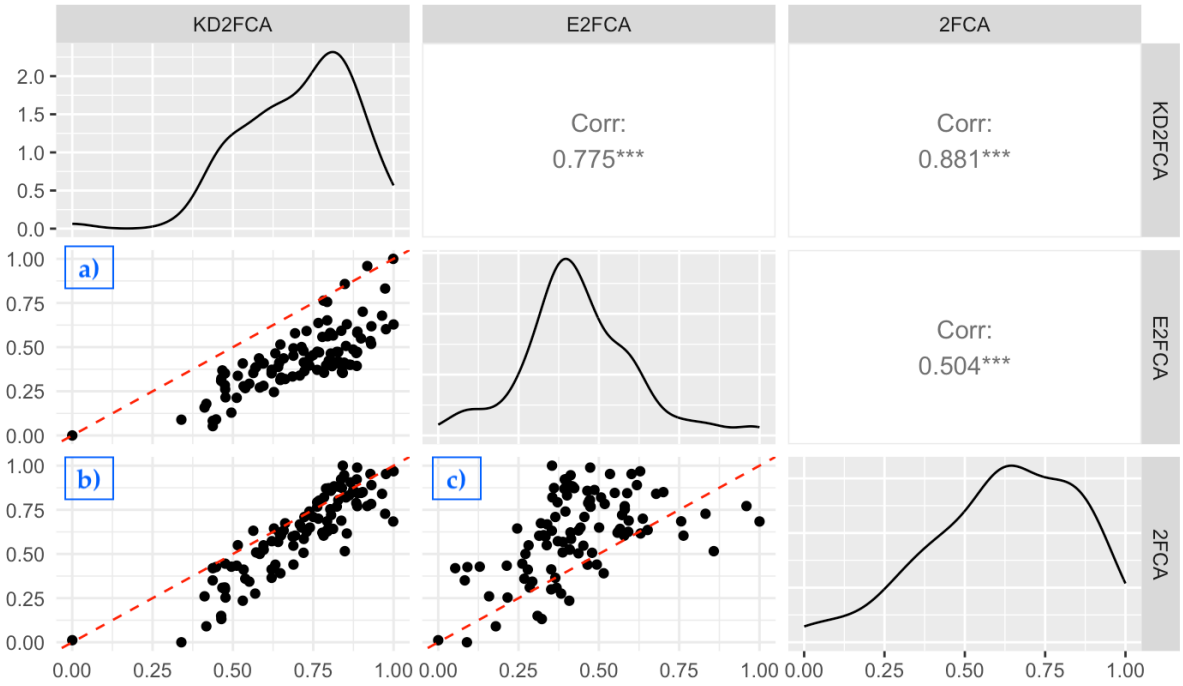

Figure 31 Paired scatter plot matrix of SPAI values for the general population across the KD2SFCA, E2SFCA, and 2SFCA methods, showing the distribution (density plots) and correlation (scatter plots). The correlation values are displayed for each pair of methods. The scatter plots show the relationship between each pair of methods, with dashed red lines representing the linear correlation. Specifically, panel (a) shows KD2SFCA plotted against E2SFCA, panel (b) shows KD2SFCA plotted against 2SFCA, and panel (c) shows 2SFCA plotted against E2SFCA.

In contrast, the E2SFCA density plot shows a more Gaussian distribution. Most population points are concentrated in the middle SPAI range, suggesting moderate accessibility. The curve starts relatively flat, similar to KD2SFCA, indicating a low number of points with very low accessibility. The downward slope confirms that high-accessibility areas are less frequent than mid-range ones.

The 2SFCA method shows a peak at an intermediate level, with a broader spread of high SPAI values than KD2SFCA. However, these values are less frequent. The tail descends gradually, indicating more high-accessibility values than KD2SFCA but with a less concentrated distribution. This suggests accessibility is more evenly distributed but with fewer extreme values.

The scatter plots illustrate the relationships between the FCA methods, showing how SPAI values correlate. Each point represents a population point, with its position based on the SPAI values from two methods. The red dashed line represents perfect correlation, providing a reference for the strength and direction of the relationship.

The scatter plot b) shows a strong positive correlation ($r = 0.881$). Points are mostly in the higher SPAI ranges, beyond the 0.5 mark, suggesting moderate to high accessibility. Points above the dashed line represent areas where 2SFCA returns higher values, while points below indicate the opposite. The scatter plot c) shows a weaker positive correlation ($r = 0.504$), with more points in the lower part of the graph, below

0.5. This suggests E2SFCA assigns lower SPAI values in lower-access areas. The final scatter plot a) shows a positive correlation (r = 0.775). The points are fairly uniform, with more below the dashed line, indicating that E2SFCA assigns lower SPAI values. This confirms E2SFCA provides more conservative estimates, while KD2SFCA tends to assign higher values.

The Pearson correlation values are all statistically significant at p-value < 0.001 (***), confirming consistent relationships. The strongest correlation is between KD2SFCA and 2SFCA (r = 0.881), followed by KD2SFCA and E2SFCA (r = 0.775). The lowest correlation is between E2SFCA and 2SFCA (r = 0.504), likely due to differences in weighting approaches.

Table 9 Spearman correlation coefficients between different FCA methods for the general population. The table compares the methods KD2SFCA, E2SFCA, and 2SFCA.

Method 1	Method 2	Spearman Coefficient
KD2SFCA	E2SFCA	0.776
KD2SFCA	2SFCA	0.876
E2SFCA	2SFCA	0.519

Spearman correlation coefficients in Table 9 confirm these findings, showing strong positive monotonic relationships. The Spearman coefficient is less sensitive to outliers and nonlinear patterns, providing a robust measure. The correlation between KD2SFCA and 2SFCA (ϱ = 0.876) closely matches the Pearson value (r = 0.881), confirming consistency across metrics. The KD2SFCA and E2SFCA correlation (ϱ = 0.776) is also similar to the Pearson coefficient (r = 0.775), showing stability even when considering nonlinear differences.

For the E2SFCA and 2SFCA comparison, the Spearman coefficient (ϱ = 0.519) is slightly higher than the Pearson value (r = 0.504), suggesting that nonlinear differences or outliers may influence the relationship. The lower correlation between these methods reflects their differing weighting and distance decay approaches, with E2SFCA applying more differentiated weights by subzones. This methodological approach results in more conservative estimates, especially in marginal areas.

In conclusion, both Pearson and Spearman correlations confirm that KD2SFCA assigns higher SPAI values, while E2SFCA produces lower values. The 2SFCA method falls in between, capturing a broader range of SPAI values with a less concentrated distribution.

4.5.2 Wheelchair Population

For wheelchair users, the distribution graph of SPAI values (see Figure 32) obtained with the KD2SFCA method shows a distinctive pattern compared to the general population. The curve highlights a downward trend, indicating a concentration towards lower values. This suggests limited access to services for wheelchair users, contrasting with the general population, where values increased in the upper range.

The frequency is higher in the lower part of the range, with isolated points reaching higher values, but not indicating uniform access.

The distribution graph for SPAI values from the E2SFCA method shows a sharper decline for higher values, indicating poor accessibility. This suggests that accessibility for wheelchair users is more limited and uneven, with few areas showing high values. The curve never reaches significantly high values, indicating that accessibility is limited to specific areas rather than widespread.

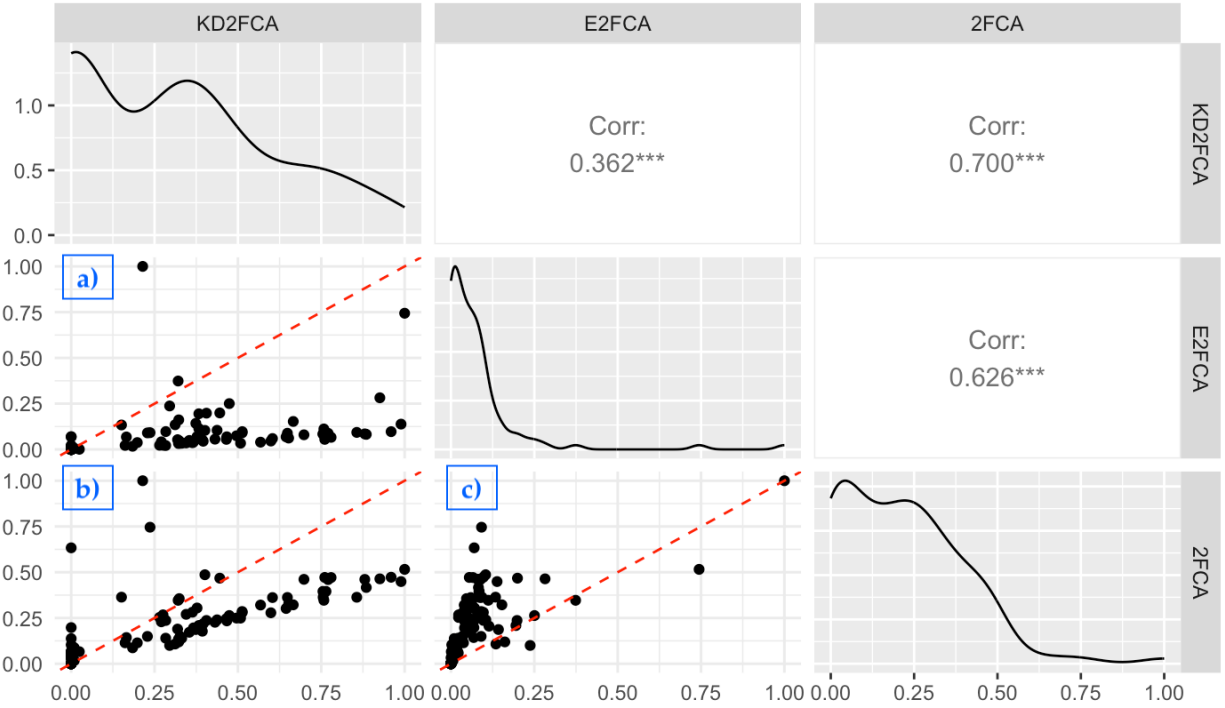

Figure 32 Paired scatter plot matrix of SPAI values for the wheelchair population across the KD2SFCA, E2SFCA, and 2SFCA methods, showing the distribution (density plots) and correlation (scatter plots). The correlation values are displayed for each pair of methods. The scatter plots show the relationship between each pair of methods, with dashed red lines representing the linear correlation. Specifically, panel (a) shows KD2SFCA plotted against E2SFCA, panel (b) shows KD2SFCA plotted against 2SFCA, and panel (c) shows 2SFCA plotted against E2SFCA.

The 2SFCA distribution graph shows a less steep decline compared to E2SFCA. Although the curve drops towards lower values, the more gradual descent suggests a slightly more homogeneous distribution. While high values are rare, the method

provides a broader spread of medium values. Compared to E2SFCA, accessibility appears more balanced, though still lower than for the general population.

The scatter plot b) shows a strong positive correlation (r = 0.700). The points mostly follow the red dashed line, with a concentration in the lower quartiles, indicating that 2SFCA produces lower SPAI values. The distribution of points shows that 2SFCA tends to produce lower values than KD2SFCA in most cases. However, in some areas with better accessibility, 2SFCA assigns relatively higher values, as reflected by points positioned above the line.

In the scatter plot c), points for E2SFCA concentrate in the first quartile, suggesting lower accessibility values. 2SFCA values are more widely distributed across the first two quartiles. The points do not closely follow the reference line, with most points above it, indicating that 2SFCA produces higher values. This confirms 2SFCA tends to assign higher accessibility than E2SFCA.

In the scatter plot a), the points show a clear distinction in distribution. E2SFCA values are mostly in the first quartile, while KD2SFCA values spread across the range. Most points are below the reference line, indicating that KD2SFCA produces higher SPAI values. However, some points lie above the line, suggesting E2SFCA returns higher values in specific cases. The weaker correlation reflects differences in how these methods measure accessibility.

Table 10 Spearman correlation coefficients between different FCA methods for wheelchair users. The table compares the methods KD2SFCA, E2SFCA, and 2SFCA.

Method 1	Method 2	Spearman Coefficient
KD2SFCA	E2SFCA	0.750
KD2SFCA	2SFCA	0.830
E2SFCA	2SFCA	0.808

The Spearman correlation values (see Table 10) show significant differences between the methods, highlighting their distinct approaches. One notable difference is between KD2SFCA and E2SFCA, with values of 0.750 (Spearman) and 0.362 (Pearson). The low Pearson correlation indicates that the two methods produce quite different results. However, the higher Spearman value suggests consistency in relative rankings between the two methods.

In contrast, the correlation between KD2SFCA and 2SFCA is significantly stronger, with values of 0.700 (Pearson) and 0.830 (Spearman). This indicates that KD2SFCA and 2SFCA produce more similar accessibility patterns. The higher Spearman value

confirms that relative rankings remain fairly stable between these methods, despite small differences in absolute values.

Finally, the correlation between E2SFCA and 2SFCA is lower than that between KD2SFCA and 2SFCA, with values of 0.626 (Pearson) and 0.808 (Spearman). The lower Pearson correlation suggests that absolute values differ more between these methods. The Spearman value shows consistency in rankings, although absolute accessibility varies. The gap between Pearson and Spearman suggests some nonlinear differences.

5 Discussion

This chapter provides a critical analysis of the findings, focusing on their implications for accessibility and mobility. The first part revisits the research questions, evaluating the results and their alignment with the initial hypotheses. The second section compares the findings with existing literature, discussing accessibility differences across population groups, the relevance of the *x-minute city* concept, and the performance of FCA methods. Finally, the discussion addresses the study's limitations and provides suggestions for future work.

5.1 Revisiting Research Questions

Research Question 1: How does the enrichment of the sidewalk network datasets with detailed accessibility information, specifically catering to the diverse mobility needs of wheelchair users impact the outcome of accessibility measurement algorithms?

The enrichment of the pedestrian path dataset with detailed accessibility information, specifically tailored for wheelchair users, confirmed the hypothesis that this added data would lead to distinct accessibility outcomes. When the network was fully enriched with accessibility features, the results differed significantly from those obtained using the partially enriched dataset, which included only slope information. For the general population, accessibility is consistently higher in the central areas of the district. The ability to cover longer distances and the absence of mobility constraints allow the general population to access a broad range of services even with challenging slopes. This results in maximum SPAI values and a more homogeneous accessibility pattern across the district, particularly in central areas where services are densely located. In contrast, the fully enriched network for wheelchair users revealed a more sporadic distribution with notably lower accessibility values. Their ability to travel longer distances is significantly restricted, making proximity to services a critical factor. Locations with nearby services achieve high SPAI values, while those farther away experience a sharp decline in accessibility, leading to a scattered and uneven pattern.

These findings are further highlighted in the differential maps (see Figure 20), which illustrate that the general population achieves significantly higher SPAI values in central areas compared to wheelchair users. This reflects their ability to maintain high accessibility throughout the district, driven by their capacity to travel longer distances

and access a wide range of services. Conversely, wheelchair users occasionally achieve relatively higher SPAI values in peripheral zones. Normalization amplifies these differences, emphasizing the sporadic patterns and higher values in peripheral areas for wheelchair users while reducing the relative values for the general population in these areas.

The inclusion of detailed accessibility features, such as surface conditions and barriers like stairs, slopes, and curb ramps, was crucial in uncovering the limitations faced by wheelchair users. While slope information was incorporated for both groups, it had minimal impact on the general population, whose ability to travel longer distances reduces the effect of topographical challenges. In contrast, for wheelchair users, these barriers significantly restricted mobility, particularly over longer distances, resulting in a fragmented accessibility pattern with low accessibility values.

The accuracy of the analysis was further enhanced by incorporating weights assigned to accessibility features through the survey conducted with wheelchair users in Switzerland. This refinement made the analysis even more precise, as the weights reflected the lived experiences and priorities of those directly affected by mobility barriers. As a result, the findings provide a more reliable representation of real-world accessibility challenges, further strengthening the certainty of the results.

These mobility limitations make proximity to services particularly important for wheelchair users. The distribution of services plays a pivotal role in accessibility, with shorter travel distances yielding better accessibility outcomes. Even areas with significant physical barriers, such as Niederdorf (Zurich's Old Town), achieved moderate SPAI values (see Section 4.3.2, Figure 19d-f). This was an expected result, as Niederdorf, located in the central-east part of the district, is characterized by cobblestone streets, narrow alleys, staircases, and a general lack of infrastructure designed with accessibility in mind, making it less accessible for individuals with mobility impairments. Despite these challenges, the area achieved moderate accessibility values due to the good distribution of services in the surrounding areas, which partially compensated for the barriers and steep sidewalks.

The findings highlight the importance of including these additional factors, as they more accurately reflect the real-world challenges faced by wheelchair users. This enriched data not only improved the model's capacity to capture mobility limitations but also underscored the necessity of detailed accessibility information for better differentiation of user needs.

Research Question 2: To what extent can District 1 of Zurich be considered a 'x-minute city', and how does this perception change with the enrichment of the sidewalk network dataset?

The concept of the *x-minute city* in Zurich's District 1 highlights significant differences in accessibility between the general population and wheelchair users. Using a 10-minute threshold as a reasonable balance between the two groups, the analysis reveals how accessibility varies depending on mobility constraints and the spatial distribution of services.

For the general population, accessibility is extensive, with large portions of the district reachable within 5 minutes and nearly full coverage achieved at 10 minutes. In contrast, wheelchair users face significant limitations. Even with a 10-minute threshold, their accessibility remains confined to small portions of the district, with only sporadic areas achieving medium-high SPAI values. This stark disparity highlights how the challenges faced by wheelchair users limit their ability to fully benefit from the *x-minute city* model.

Service distribution also plays a critical role in shaping accessibility patterns. Areas near major hubs, such as the main station ("Hauptbahnhof"), exhibit higher SPAI values due to the concentration of services and the daily foot traffic they attract. However, these patterns are not consistent across all types of services. Services with the lowest accessibility values include sports and outdoor leisure facilities, even for the general population (see Figure 14 in Section 4.3.1). For wheelchair users, this issue is further compounded, as they consistently face very low accessibility values across all types of services, highlighting the severity of access disparities (see Figures 17-19 in Section 4.3.2).

Although the central-east zone of the district often achieves medium SPAI values for wheelchair users, it is also characterized by frequent low values and significant physical barriers that make it less accessible for this group (see Figure 13 in Section 4.2). Improving infrastructure in this area could yield substantial benefits, making it more accessible and enabling wheelchair users to travel longer distances, ultimately enhancing overall accessibility across the district.

This variability emphasizes that the *x-minute city* model is highly dependent on the type and location of services, as well as the mobility needs of the population. For wheelchair users, the combination of mobility barriers and service distribution challenges renders the concept far less achievable. Accurately evaluating models like the *x-minute city* requires the inclusion of detailed accessibility information. Without

accounting for barriers and mobility constraints, the analysis risks overlooking critical disparities between population groups, particularly those with mobility impairments.

Research Question 3: How do different Floating Catchment Area (FCA) methods affect accessibility assessment within the framework of an x-minute city for wheelchair users?

The results confirm that the application of different FCA methods yields varied accessibility assessments for wheelchair users, in line with the hypothesis. The 2SFCA method generated a broader and more uniform accessibility pattern, mainly concentrated in the central areas. This method's binary approach led to a less nuanced view of accessibility, with peripheral zones underrepresented due to the strict catchment boundaries. Contrary to the hypothesis, however, the 2SFCA method did not produce significantly lower accessibility values but rather smoothed out differences within the defined catchment area.

In contrast, the E2SFCA method resulted in a more fragmented pattern, confirming the expectation that it would highlight pockets of higher accessibility. Its Gaussian weighting system prioritized central areas, with accessibility values dropping sharply in peripheral zones. This pattern reflects the method's sensitivity to the density of services in each subzone, providing a more realistic representation of distance-related declines in accessibility. However, the results also highlighted an edge effect, particularly at the catchment boundaries, where accessibility decreases steeply due to the weighting structure of the method.

The KD2SFCA method produced results that closely resembled those of 2SFCA, with marginally higher accessibility values in peripheral areas due to its continuous decay function. This approach, which gradually decreases accessibility scores with distance, offers a more advanced theoretical framework compared to the binary weighting of 2SFCA. However, the practical differences between the two methods were negligible. While KD2SFCA smooths the transitions between high and low accessibility values, its added complexity does not translate into substantial new insights in this specific urban context. The similarity in patterns suggests that, in areas with concentrated services like District 1, the continuous decay function of KD2SFCA provides only marginal improvements over the simpler 2SFCA method.

Differential maps further elucidate the differences between the methods (see Figure 26 in Section 4.4.1 and Figure 30 in Section 4.4.2). The comparison between 2SFCA and E2SFCA reveals significant positive differences in central areas, confirming that

2SFCA overestimates accessibility by failing to account for distance decay. Conversely, E2SFCA generates lower accessibility values across the district, with sharper declines in peripheral zones due to its subzone weighting approach. Comparing 2SFCA and KD2SFCA shows fewer differences, as both methods produce similar patterns. However, KD2SFCA tends to smooth accessibility transitions, resulting in slightly higher values in peripheral areas. The statistical analysis supports these findings, showing a higher correlation between KD2SFCA and 2SFCA, while the correlation with E2SFCA is notably lower.

The choice of FCA method depends on the goals of the analysis and the characteristics of the study area. Based on the findings of this thesis, E2SFCA emerges as the most suitable method for detailed urban analyses, particularly in contexts that require nuanced local variations in population needs and service access. Meanwhile, 2SFCA is well-suited for broader regional studies with homogeneous accessibility patterns, where distance decay is less relevant, though it may fail to capture local disparities. KD2SFCA, while potentially more relevant for fragmented or uneven accessibility patterns, did not provide significant new insights in this specific case, making its additional complexity less practical.

5.2 Comparison of Main Findings with Related Studies

The findings of this thesis align with previous research analyzing accessibility for mobility-challenged groups, while offering unique insights by incorporating detailed accessibility features. Gaglione et al. (2021) examined older adults in Naples and Aberdeen, concluding that proximity and density of services primarily drive accessibility. However, the study emphasized the critical role of the pedestrian network in enabling access, highlighting how barriers like poor sidewalk quality or steep slopes can hinder mobility. While Gaglione et al. (2021) did not specifically study wheelchair users, both older adults with age-related mobility restrictions and wheelchair users face similar challenges, underscoring the need for accessibility evaluations that account for pedestrian network characteristics. Similarly, Ulloa-Leon et al. (2023) analyzed accessibility for older adults in Santiago and found that central urban areas, where services are concentrated, exhibited the highest accessibility. Vale et al. (2017) demonstrated significant accessibility limitations for mobility-restricted individuals compared to others, particularly as service distance increases. These findings collectively emphasize how mobility constraints exacerbate accessibility disparities for vulnerable groups.

This thesis provided the added value of integrating detailed accessibility features, including slope information, physical barriers, and perceptions gathered through a survey of wheelchair users. These enhancements not only revealed starkly lower accessibility values for wheelchair users across all service types but also increased the validity and accuracy of the analysis. By capturing the lived experiences of mobility-impaired individuals, this thesis provided a more comprehensive understanding of the disparities in accessibility.

The concept of the *x-minute city* has been explored in other studies to evaluate accessibility across different time thresholds. Staricco (2024) tested thresholds of 5, 10, and 15 minutes and found that sports and outdoor leisure services exhibit very good accessibility, with 50% of the population able to reach them within just 5 minutes. In this thesis, however, these services were among those with the lowest accessibility values, especially for wheelchair users. This contrast highlights how incorporating detailed accessibility features, such as slope and barrier information, can reveal disparities that are not apparent in traditional evaluations.

Radics et al. (2024) adopted a flexible approach by applying thresholds from 5 to 15 minutes depending on the service category. Their findings showed that accessibility was highest in central areas of Seville. This pattern aligns with observations for the general population in Zurich's District 1. However, for wheelchair users, accessibility values were not consistently higher in central areas due to physical barriers.

The results of this thesis also resonate with findings from other studies using FCA methods. Luo & Qi (2009), who compared the 2SFCA and E2SFCA methods, observed that 2SFCA tends to overestimate accessibility due to its lack of distance decay, resulting in large high-accessibility zones that may not reflect real-world behavior. Similarly, in Zurich's District 1, this thesis found that 2SFCA produced broader accessibility patterns for the general population, particularly in central areas, which may overstate accessibility when compared to methods that incorporate distance decay. Additionally, Luo & Qi (2009) demonstrated that E2SFCA captures accessibility disparities more effectively by incorporating distance decay, particularly for services like healthcare, where proximity is crucial. In line with these findings, E2SFCA in Zurich's District 1 highlighted fragmented accessibility patterns, especially for wheelchair users, offering a more realistic representation of their accessibility challenges. Kiani et al. (2021) further confirm that E2SFCA is particularly suitable for individuals with disabilities, where accessibility heavily relies on shorter travel distances.

While Benhlima et al. (2022) noted that KD2SFCA smooths transitions between accessibility values due to its continuous decay function, the results of this thesis suggest that in dense urban contexts like Zurich's District 1, KD2SFCA provides minimal additional insights compared to 2SFCA. This aligns with observations by Yang et al. (2006), who noted that KD-based methods may add complexity without necessarily improving the assessment of accessibility in areas with concentrated services. These findings highlight how service density and spatial distribution—key characteristics of urban environments—play a critical role in shaping the relative performance of FCA methods and the nuances they reveal.

5.3 Limitations and Future Work

Despite the valuable insights provided by the results regarding accessibility for both the general population and wheelchair users, the analysis has some limitations that should be highlighted. Although this thesis analyzes a larger area compared to most research on accessibility for mobility-restricted individuals, which typically focuses on smaller areas such as university campuses (e.g. De Velasco Machado & De Oliveira, 2020; Jamtscho et al., 2015), the restriction to District 1 remains a limitation. This geographic focus, dictated by the availability of accessibility data, prevented a city-wide evaluation that could have offered a more comprehensive view of accessibility across Zurich. Additionally, the focus on wheelchair users and the general population excludes other groups with mobility restrictions or impairments, such as visually impaired individuals, whose inclusion in future studies could provide broader insights into accessibility challenges.

Another limitation of this thesis concerns the assumption regarding the survey participants who use wheelchairs. Among the 29 participants, the majority (approximately 60%) reported using a manual wheelchair as their primary device, while others relied on electric wheelchairs or other mobility aids (see Section 4.1). For the analysis, all evaluations were treated as if they were provided by manual wheelchair users, regardless of their primary mobility aid. This assumption may introduce biases, as electric wheelchair users face different accessibility challenges, particularly for features like uneven sidewalks, which they tended to rate more negatively (see Section 4.2). While these differences may influence specific results, the general alignment in evaluations across most features indicates that the validity of the analysis remains robust. Future studies could address these mobility aid-specific differences to improve the accuracy of accessibility assessments.

Furthermore, the analysis was affected by the edge effect (see Section 4.3.5): service points immediately outside the district boundary were not considered in the accessibility calculation, which impacted the results, particularly for the peripheral areas near the district's boundaries. In these zones, accessibility may have been underestimated, as services near the boundary, while relevant to the population, were not included in the distance and SPAI value calculations. This created a distortion in the analysis, as not all services that could have influenced accessibility in the adjacent areas were taken into account.

Another limitation concerns the assumption of uniform capacity for all services, which was imposed in the FCA analysis. Specifically, it was assumed that each service within the catchment area had a capacity equal to 1, without distinguishing between the actual characteristics of the services themselves, such as their capacity to accommodate users, their traffic, or their actual availability for different population groups. While this simplification was necessary for practical reasons and to manage the complexity of the data, it affected the results by limiting the analysis's ability to capture real differences between various service types. This may have resulted in failing to account for disparities in the services provided and the differences in how they are accessible to the general population and wheelchair users.

Insights from this thesis highlight areas in District 1, particularly in the central-eastern zone, where accessibility disparities for wheelchair users are most pronounced. For urban planners, targeting interventions in these zones could yield substantial improvements by addressing barriers and improving infrastructure. Incorporating such considerations into urban planning interventions can contribute to a more inclusive environment, ensuring equitable access for all population groups.

Future research could extend the scope of this analysis to a city-wide scale, incorporating more comprehensive data for all districts of Zurich. Expanding the focus to include other population groups, such as visually impaired individuals, would allow for a more holistic evaluation of urban accessibility challenges. Exploring alternative FCA methods, such as those that incorporate dynamic weighting or adjust for service-specific capacities, could provide further insights into accessibility patterns. Additionally, integrating multimodal transport options, such as public transit connections, would help capture the broader mobility landscape and its impact on accessibility. Such advancements would enhance the applicability of the findings and support urban planners in designing interventions that address the diverse needs of urban populations.

6 Conclusion

The findings of this study provide a comprehensive analysis of accessibility in District 1 of Zurich for two different population groups: the general population and wheelchair users. By enriching the pedestrian network with detailed accessibility data, this research advanced the modeling of accessibility for wheelchair users, uncovering critical barriers that are often overlooked in traditional assessments. The study applied three different Floating Catchment Area (FCA) methods — 2SFCA, E2SFCA, and KD2SFCA — revealing how methodological choices can significantly shape accessibility evaluations.

A key contribution of this study lies in demonstrating how the integration of accessibility data into network analyses transforms the application of the *x-minute city* concept. While this model demonstrated good accessibility in District 1 for the general population using a 10-minute threshold, the enriched network revealed that physical barriers reduce the *10-minute city* accessibility for wheelchair users, making it less inclusive for all population groups. These findings challenge the assumption that accessibility can be uniformly guaranteed within a set time threshold, showing instead that accessibility outcomes vary significantly based on individual mobility needs and local infrastructure.

The study further highlighted how different FCA methods yield varying accessibility patterns. While 2SFCA and KD2SFCA produced similar results, emphasizing central areas with high accessibility, the E2SFCA method offered a more fragmented view by accounting for distance decay through weighted subzones. This method proved particularly effective in identifying accessibility disparities for wheelchair users, as it better captured the influence of physical barriers on travel behavior. The comparison between the methods confirmed that the choice of FCA methodology directly impacts the evaluation of accessibility and that more advanced approaches, such as E2SFCA, provide a more refined understanding of accessibility challenges in urban contexts.

In conclusion, this research provides an important contribution to the field of urban accessibility by demonstrating that enriching sidewalk networks with detailed accessibility information significantly alters accessibility assessments, particularly for mobility-restricted populations. It also highlights the importance of selecting appropriate FCA methods, as these choices shape the results of accessibility evaluations. Future research should refine accessibility models by integrating detailed data on relevant features and user needs to promote urban inclusivity and equitable access to services.

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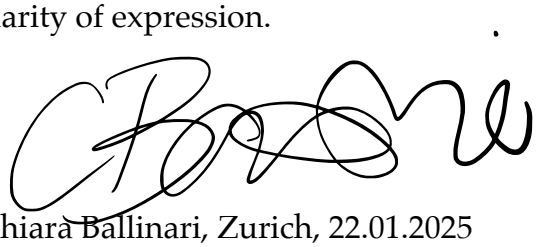
Personal Declaration

I hereby declare that the submitted thesis results from my own independent work. All external sources are explicitly acknowledged in the thesis.

AI Utilization

AI-assisted tools (ChatGPT, Grammarly) were utilized for English proofreading and clarity of expression.



Chiara Ballinari, Zurich, 22.01.2025