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Spatio-temporal accessibility analysis of service provision: A comparison of the cities Zurich and Winterthur

GEO 620 Master's Thesis

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Abstract

Accessibility research has been an ongoing topic of multi-disciplinary research since the 1960s. Advances in GIS and GIScience have expanded the methods available and the application scope of the research topics. Therefore, many novel accessibility research methodologies have been developed in the last two decades; such as the two-step floating catchment area and its successors. The service of accessibility research is that it allows us to gain insight into the spatial structure and logic of many systems vital to everyday life for the population. Most of the existing accessibility research has been focused on healthcare. However, the improvement in methods and approaches allows for the application of accessibility research on a much wider range of services. Furthermore, the latest research in accessibility analysis has been theoretically founded on the time-geography research of the 1970s and hence the individual has been brought back into the focus of research. This theoretical shift and methodological expansion have increased the variety of research topics, which has accentuated the differences between accessibility research variants.

The aim of this thesis is to implement the latest accessibility research methods on a wide variety of services. Through this process, we will differentiate the different types of accessibility research recognized in the literature and establish a continuity between them. The methodology applied in this research is the Enhanced two-step floating catchment area method (E2SFCA) by Luo & Qi (2009). With it, we will conduct a spatio-temporal accessibility analysis of service provision within the Canton of Zurich, Switzerland. However, the E2SFCA does not include a spatio-temporal aspect initially. Therefore, the second aim of this thesis is to include spatio-temporality into the E2SFCA method through input parameters in accordance with the time-geography theories of Thorsten Hägerstrand (1970). Also, the novelties introduced will be tested through a sensitivity analysis to ascertain the impact of each parameter on accessibility research results.

The spatio-temporal E2SFCA (S-T E2SFCA) method developed within this research has produced spatially logical results for the study areas in the Canton of Zurich, the City of Zurich and Winterthur. The concentration of all services is as expected in the southwestern part of the Canton where the City of Zurich is located, and in the inner city areas of the Zurich and Winterthur. However, the input parameters have a significant influence on the final results which is an issue since there is no defined framework on parameter value designation in the literature. By using different values, one can derive opposite results. Nonetheless, the results produced within this research have been consistent with expected spatial logic and have detected intra-regional differences which would not necessarily have been intuitively predicted.

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Chapter 1: Spatio-temporal accessibility analysis

1.1. Introduction

The spatial distribution of content, flows, and structures in a region conforms to a particular logic conditioned by the physical setting and social superstructure of the region (Šterc 2015). One of the purposes of geography is to provide us with insight into the spatial logic of a region. Therefore, every human built system can be perceived as a logical construct of geospatially determined content. There are innumerable spatial systems which form an intricate weave within our daily reality. They are unperceivable to the individual person. Yet, spatial systems are also indispensable for proper functioning of our societies. One such spatial system is the provision of services to the population of a region. While the majority of our time is spent either at home or at work (Hägerstrand 1970), there is reason and incentive to engage with other activities outside of these two points. While work and habitation are essential for life, the ability to engage in other, auxiliary activities, is central to personal development and quality of life (Neutens et al. 2013). However, one can only engage in auxiliary functions if one has access to them within his or her spatio-temporal reach. Be it leisure, shopping, education, socialization etc., access to services depends on their existence and connection to, and also distance from our points of work or habitation. These parameters represents the spatial aspect of spatio-temporal accessibility analysis.

The spatial model of reality used to imagine the system of service provision is that of Geographic space (Šterc 2015). Geographic space is a continuous multi-dimensional sphere of possibility within which objective reality may manifest at a given time through content, relations, flows, and structures. Therefore, service provision within a region is a spatial system of population nodes, connected to service nodes through a network, with particular flows and distributions which conform to existing spatial logic. Human existence is a constant process of navigating Geographic space, each moment is defined by a location and a position, and each location has its own unique moment in the life path of an individual (Hägerstrand 1970; Massey 2005). Therefore, the access to services for a population is determined not only by spatial parameters of distance and connectivity, but also by time. The time needed to access services in a region is of equal importance as an accessibility constraint as is spatial connectivity through a network (Neutens et al.2010b). Access to a service through a network is meaningless if the service cannot be reached and utilized within a reasonable timeframe which is based on the time resources a person has available during a day. These considerations represent the temporal aspect of spatio-temporal accessibility analysis.

Through this Master thesis I will research the spatio-temporal accessibility to services within the Kanton of Zurich and its two prime cities; Zurich and Winterthur. I will seek insight into the spatial logic of service distribution and provision, as well as the resulting accessibility values. Both governmental and private services will be modelled in order to provide a holistic evaluation of service availability in the study region. The spatial network through which the population will seek access to services will include multi-modal travel, pedestrian and motor vehicle networks, public transport and personal transport. The purpose of this research is to provide insight into the spatial logic of service accessibility and its temporal variations; so as to recognize underserviced and overserviced spaces, as well as to critique and inform service distribution planning.

1.2. Content overview

This Thesis is divided into six chapters. The First chapter introduces the topic of the research. The Second chapter outline the state of the art and the chosen research questions and hypothesis. The Third chapter describes methodology of the research as well as the data and study region used. The Fourth chapter presents the results of the research and sensitivity analysis. The Fifth chapter presents the discussion about the results, their meaning, the outlook of the research, and the final conclusion. The Sixth chapter contains the list of literature and supplementary information necessary for reproducibility or results comprehension.

The Master thesis will begin with a brief introduction to spatio-temporal accessibility and relevant concepts (1.1.). The following section will provide a theoretical overview of the topic and examine its components in detail (1.3.). Furthermore, the research topic section will establish the definitions chosen by the author for the purpose of the research. This is important since the definition of spatio-temporal accessibility will guide methodology considerations. Furthermore, this will set the approach to interpreting the final research results and corresponding discussion chapter.

The Second chapter will present the state-of-the-art concerning spatio-temporal accessibility analysis and its recurring definitions in the relevant literature. The first section (2.1.) will be the review of relevant literature consulted during the writing of this thesis. It will examine the topics and methods of accessibility research and the evolution of scientific interest in terms of research scope and complexity. The second section of the State of the Art chapter will outline the research gaps recognized by the author (2.2.). The final section of the Second chapter will establish the definite research questions, aims, and hypothesis of this research (2.3.).

The Third chapter will present the methodological framework of the research. Within the first section the chosen methodology will be described by its strengths, weaknesses, and relation to the research gap (3.1.). Next, the study region will be presented by geographic scope and content (3.2.). The third section will present the implementation of the chosen methodology within the GIS framework of ArcMap (3.3.). The following section will outline the services modelled in the research, their functional categorization, and reasoning behind their inclusion (3.4.).

The Fourth chapter will present the results of the accessibility analysis implementation within the study region and the implications of the sensitivity analysis. The first section will describe the Meritum of the results as well as outline the challenges encountered (4.1.). The research produced a great number of maps, hence chosen examples per service category will be provided in larger scale with commentary (4.2.). The final section of the Results chapter will contain the results of the sensitivity analysis conducted to test the methodology and data used (4.3.).

The Fifth chapter will present the discussion of the results and the research outlook. The first section describes the relation between the results and spatial logic of the study region (5.1.). The following section will reflect on the research questions and hypothesis of the research (5.2.). The third section of the Discussion presents the Outlook of the research, the unrealized possibilities, and future research challenges and possibilities (5.3.). The final section contains the conclusion of the Master thesis (5.4.).

The Sixth chapter presents the auxiliary information regarding the rest of the thesis. The bibliography (6.1.) and the service data sources (6.2.), and methodology relevant resources (6.3.).

1.3. Research topic

Spatio-temporal accessibility to services within a region is based on the interaction between the population within the region and the service provision system within the region. Service provision is a concept which encompasses the systems of essential and auxiliary services within space. The raison d'etre of a service provision system is the demand for various services by the population of a region. Therefore, service provision involves a multitude of services in constant interaction with the population and other services. The spatial systems generated through this interaction form some of the integral systems of geographic space which directly influence quality of life, possibilities, and individual mobility (Neutens et al. 2013). Hence, comprehension and insight into the spatial logic of such systems and the factors which influence them are a scientific interest. Likewise, it is of popular interest that spatial systems are understood so that they may be better managed for the common good. In order to conduct a spatio-temporal accessibility analysis it is first necessary to establish the "subjects", "objects", and definitions within the research.

Services and the population co-exist within geographic space. However, it is the population that which accesses services within the region. Therefore, the logical hypothesis would be that the distribution of services is conditioned by the distribution of the population. While axiomatic, it is not clear whether each individual service conforms to this logic. Nor is it clear that the simple presence of services means they are accessible to the population which they conform to.

Therefore, the Meritum of this research can be summed up by the following research question:

How are services accessible, spatio-temporally, to the population of the chosen study region?

The answer to this research question should be more than a binary "they are / they are not". Indeed, rather than providing a concise answer, this question provides us with a subset of questions which have to be answered in order to inductively derive a final conclusion. Thankfully, the subset questions are more precise in their subject, and thus withstand a relatively concise, deductive answer. In order of appearance within the thesis, the subset questions are: *What are services? What is the population? What is accessibility?*

These three questions represents the outer object of scientific interest; the domain relevant questions and categories which have to be understood, classified, and defined (Šterc 2015). This is necessary in order to address the inner object of scientific interest; the logic which governs and structures (to geography immanent) existence (Šterc 2015). The outer objects of interest within this thesis are thus defined within the following subsections of the First chapter. This is done to facilitate reader (and author) topic comprehension, which is a necessary prerequisite in the pursuit of the inner object of scientific interest. The inner object of scientific interest within this research is epitomized by the presented research question;

How are services accessible, spatio-temporally, to the population of the chosen study region?

"How?" as in; what is the underlying logic of service accessibility; not only the degree to which services are accessible. Therefore, the subjects of this research are services, the population, and spatio-temporal accessibility. Conversely, the object(ive) of this thesis is to gain insight into the spatial logic of spatio-temporal accessibility to services. Finally, it is of further interest whether the chosen methodology provides reasonable insight into spatial logic and how do the input parameters affect results generated through the chosen methodology. The applied topic of this research is spatio-temporal accessibility to services in urban and peri-urban areas of the Canton of Zurich; the city of Zurich and the city of Winterthur; with an adjoined 5km buffer in order to lessen edge effects.

1.3.1. Services and the population

Apart from homes and workplaces, there are numerous other locations which a population has a need or desire to access for various reasons (Neutens et al. 2013). Such locations are considered services within this research. This designation is based on the consideration that the minimum requirements for sustainable individual existence is a place of work and a place of habitation (Hägerstrand 1970; Goodchild et al. 1993). Therefore, all other places accessed and utilized by an individual are a service to the individual for the purpose of self-investment and development (Townsend 1987). This hypothesis reduces and abstracts human existence into two categories; locations of work and living, and locations of service utilization. If we transform the meaning of these two categories from *what* (location), to *why* (purpose), we can argue that they both serve a certain function in life. Therefore, the categories of workplace, home, and service are functions in the life of an individual. Drawing on the central place theory by Walter Christaller and from it derived functional regionalisation principles, the functions in the life of an individual may also be ordered by centrality. In fact, the centrality of services is evident in the existing literature; accessibility analysis most often concerns access to healthcare.

The home of an individual represents the location with the highest degree of functional centrality. The home fulfils the function of habitation from which and to which an individual "flows" within geographic space (Hägerstrand 1970). It is foremost from the point of habitation that one would seek other services, including work. The workplace fulfils the function of work, which is necessary to sustain life within our prevailing socio-economic environments (Hägerstrand 1970). Due to this fact, the workplace represents the second highest degree of centrality. Therefore, the functions of habitation and work are conditions *sine qua non* for the average individual. There are certainly exceptions to this hypothesis, but such individuals are undoubtedly outliers rather than a relevant demographic. Work and habitation are functions essential to an individual's existence. The essential nature of work and living is primordial and has been the basis which marks most of Terran fauna (Townsend 1987); there exists a safe "home base" from which individuals venture into the unknown (geographic space) to procure sustenance (and for other reasons) (Hägerstrand 1970). Thus, of the two essential functions, habitation is more significant and spatially entrenched, while work can exhibit spatial and temporal variation. Far from simplifying human existence with such a conception, defining working and habitation as essential functions recognizes all further functions (services) as consequences of evolution and civilization. Hence, we shall consider services as auxiliary functions of human existence, which are accessed from the point of habitation or work.

Since services are accessed from points of habitation or work, the population of the study region is modelled by resident and workplace demographies. The demographic data is aggregated within equally spaced points within the study region and it is from these points that the population ventures out to access and utilize services. The points containing demographic data for resident or workplace demographies are considered population points. Conversely, auxiliary functions which represent services within a region are modelled by irregularly positioned, discrete points. Each service point pertains to an individual service provision node (e.g. a bank branch, or a clinical practice etc.), which existed at the moment of data generation (Q2 2018).

1.3.2. Accessibility

Accessibility analysis has the potential to provide insight into the interaction between a population and its essential and auxiliary functions. This interaction, and the spatial distribution of population and service points, forms the spatial system of service provision within a region. As any spatial system, the system of service provision is an ongoing process in constant transformation as it adapts to changes in population and service distribution. If we could gain a better understanding of the spatial logic which conditions such a system, we could better inform the society and decision makers on the transformation of service provision and accessibility. Hence, they could be better predicted and controlled.

1.3.2.1. Population and service points

To facilitate insight and comprehension of any spatial system, it is useful to abstract it through a simplistic model which uses few categories. The fundamental categories of spatial representation in geography are the point, the line, and the polygon (Longley et al. 2010). Of these, the point is the foundation upon which all other spatial models are developed (Kemp 2008). Through the location and position of a point (Hägerstrand 1970; Šterc 2015), complex relations can be modelled. Therefore, the population and services can both be represented in geographic space as discrete points, interconnected with links of a transport network. The service provision within a region involves a multitude of services in constant interaction with the population and other services. Therefore, a region always has a measurable demand for certain auxiliary functions based on demographic and socio-economic factors. Likewise, there is also a finite and measurable supply of certain services. Hence, a supply and demand relationship defines the system of service provision (Luo & Wang 2003). This duality necessitates two core components for accessibility research; the population component (demand), and the service component (supply). Consequently, both these components are manifested in geographic space by unique locations; a service point which represents the local supply of a function, and a population point which represents the local demand for a function. Therefore, auxiliary functions should be considered as services which the population of a region dynamically creates and consumes, represented as service points (one of the points of interest for accessibility research).

These two fundamental locations (the population and the supply point), and the relations between them, have been the basis for all accessibility research in one way or another. Since the service component is generated due to an evident functional utility it represents for the population component (Gregory et al. 2009), services should further be considered spatial resources in order to exemplify their finite and measurable nature in relation to the population (Apparicio & Seguin 2006). This expands the meaning of accessibility to encompass social and economic considerations. Much of the existing accessibility research is focused on this aspect of accessibility; e.g. spatial equity (Townsend 1987; Talen & Anselin 1998; Smoyer-Tomic et al. 2004; Apparicio & Seguin 2006; Smith et al. 2009).

1.3.2.2. Defining accessibility

Spatio-temporal accessibility is not the same as accessibility. Accessibility research can be subset into several instances, each of which represents a stage in the evolution of the topics, methodologies, and technology applied. These are (Neutens et al. 2012a): availability, accessibility, temporal accessibility, and spatial accessibility. Each of these accessibility research instances builds upon the earlier ones through adding additional dimensions of reality (space, time, interaction etc.). Thus, the historical evolution of scientific interest within accessibility research has developed spatio-temporal accessibility as a logical whole representing complementing structures of geographic space (Miller 2017). Thus, the concept of spatio-temporal accessibility must be broken down into its components and analysed in order to elucidate its main differences to the earlier instances of accessibility research, as well as its advantages. Each individual word of the expression "*spatio-temporal accessibility"* represents another dimension and value added to the whole. Hence, spatio-temporal accessibility is a superset of spatial accessibility, temporal accessibility, accessibility, and availability. This superimposition of dimensions adds both depth and complexity to the base notion of accessibility, which is essential for improving the application scope, validity and veracity of the results. Simply stated, the evolution of scientific interest in accessibility analysis both within and without geography follows a trend of expanding on the base notion of accessibility through adding both more complex methods and additional dimensions of reality, such as time.

1.3.2.3. Availability and accessibility

Availability is the simplest component and concept in accessibility research. It concerns the quality of being able to be utilized by other spatial content. For example, a service is available to a population point if a service point is reachable within the chosen geographic scope, regardless of considerations about supply/demand, time budgets, or network connectivity. Therefore, availability research is interested in the existence, quantity and quality of a spatial resource in a study region (Luo & Wang 2003). The results of availability research for a spatial resource, e.g. a hospital in a region, is a binary indicator; the resource either does not exist (is not available), or it exists (is available) in *x* amount of *y* quality. Consequently, availability analysis was the earliest research topic concerning accessibility to services and is the foundation of modern, more advanced approaches (Guagliardo 2004). Availability research was the logical baseline concern in the historical context of first scientific interest in service accessibility during the late 20th century. During that timeframe, there were wide spatial disparities due to few public services offered at all, the foremost concern being healthcare (Joseph & Bantock 1982; Guagliardo 2004; Mao & Nekorchuk 2013). The advantage of availability research is that it provides decision-makers with an easy to understand method for comparing different administrative units according to their available spatial resources (Luo & Wang 2003). However, due to the innate mobility of humans and their ability and willingness to cross borders, comparing the service availability of small scale geographies does not provide a realistic insight into spatial reality (Yang et al. 2006; Salze et al. 2011). Instead, availability research is most informative when comparing large and medium sized regions (Guagliardo 2004). This inability to properly model availability of services on smaller scales or border regions has directly prompted the development of spatial accessibility research (Joseph & Bantock 1982). However, availability research does not concern only administrative units, but also catchments for unique locations. Thus, availability research can be conducted with minimum data and techniques (Luo & Wang 2003). For example, a buffer analysis would suffice to test service availability for a population. If a service exists within the buffer, it is available in x amounts of y quality; which can then be compared to other population point buffers. To conclude, availability is concerned only with the existence, quality, and quantity of a spatial resource in a study region. Availability is the starting premise for accessibility since if there are no available spatial resources in a study region at all, we cannot measure or model accessibility.

Conversely, accessibility concerns not only the existence, quality, and quantity of a spatial resource in a study region, but also its relation to the population of the same study region. In the consulted literature, what is designated as accessibility appears in two principal modes; as a binary function of existence of choice in a study region, and as a measure of the quality or quantity of choice in a study region. Hence, this creates the duality of meaning in which an inaccessible location might indicate a complete lack of access to something (Guagliardo 2004), or a relative deprivation in relation to other locations within the scope of the research (Townsend 1987). As explained in the previous paragraph, we have defined the first mode as availability to differentiate the subtle, yet fundamental difference. Building on availability, accessibility concerns the utilization potential (Hansen 1959) or actual utilization of spatial resources by a population (Neutens et al. 2012a, 2011, 2012b). One of the first definitions for accessibility (Hansen 1959): "*the potential of opportunities for interaction*", conceptualizes accessibility as a measure of spatial potential, an intersection of provider and receiver (Tenkannen 2017). In the context of spatial analysis, accessibility models the utilization potential of a service by a population based on spatial, temporal, and other factors. Therefore, accessibility is the measure of service utilization potential pertaining to a service or a population point (Neutens et al. 2012a, 2011, 2012b, 2013), and it represents a relative deprivation value in relation to other service and population points (Smith et al. 2009). Thus, an inaccessible point indicates below average accessibility, not necessarily complete a lack of access as it would in an availability research. Conversely, an accessible point indicates above average accessibility. Hence, accessibility introduces the supply and demand relationship of service provision.

Although accessibility research may focus on actual utilization of services, in practice it is predominantly (Guagliardo 2004) the research of service utilization potential. Therefore, we define accessibility as the measure of service utilization potential in a study region, which takes into account the amount and quality of services available and their supply and demand relationship with the demographic factors of the study region (Bertolini et al. 2005). However, accessibility does not model network connectivity between the population and services within the study region. Furthermore, the greatest weakness of simple accessibility research is that it assumes equal accessibility scores for the entire study region as well as limiting choice to only those services within the study region.

1.3.2.4. Spatial accessibility

Spatial accessibility is a fundamental methodological and conceptual expansion of the notion and application of accessibility research. While accessibility research introduces regional supply and demand considerations and is useful for inter-regional comparison, spatial accessibility recognizes intra-regional accessibility variation (Joseph & Bantock 1982). Furthermore, spatial accessibility allows trans-boundary accessibility which lessens edge effects and better models spatial reality of population mobility. This is all enabled by the necessary prerequisite of any spatial accessibility research; a network dataset. Per the book "The Geography of Transport Systems" (2017), accessibility is defined as: "The measure of the capacity of a location to be reached by, or to reach different, locations. Therefore, the capacity and the arrangement of transport infrastructure are key elements in the determination of accessibility." Hence, spatial accessibility introduces a transport network overlaid on population and service points. Accessibility scores are derived in part based on the network catchments of population and service points, while the size of the catchment is calculated by network travel costs instead of linear distance. Due to the network travel calculations, spatial accessibility research emerged with the spread of GIS during the nineties of the 20th century (Miller 1991; Yang et al. 2005; Neutens et al. 2012b). Without the application of computer based methods (GIS in this case), it is was unfeasible to reliable calculate the necessary spatial interpolations between many control points (Warntz 1964).

Spatial accessibility analysis provides better measures of accessibility potential within a study region, while also minimizing edge effects. Another advantage of spatial accessibility research is that it eliminates the problem of assigning uniform accessibility scores to an entire study region since each population point can have its own score calculated based on network position in relation to service points. Furthermore, the addition of a transport network allows for greater control of analysis parameters through network constraints; variable network speeds (travel impedance), network distances (length or time), multi-modal transport, inaccessible network sections, different network edge types, etc.

Therefore, spatial accessibility is a measure of accessibility based on considerations of population service demand, service point capacity, and network constraints.

1.3.2.5. Temporal accessibility

Spatial accessibility maintains the research trend of expanding complexity and scope for both availability and accessibility. Temporal accessibility is the intermediate step between spatial accessibility and spatio-temporal accessibility. It appears in the consulted literature through three approaches. The first approach is the research on daily or weekly variations in spatial accessibility (e.g. Neutens et al. 2012b). This approach segments the day or week into contrasting timeframes which would expectedly yield different spatial accessibility results due to variations in traffic congestion, population demand, or service supply. For example, network travel costs differ during rush hour and off-peak hours of the day (Neutens et al. 2012a; Tenkannen 2017), hence the natural catchments of service/population points are dynamic on both the daily and weekly basis. The weekly basis assumes also different working hours for workdays and weekends. This introduces the second approach to temporal accessibility which assigns opening and closing hours to service points (e.g. Neutens et al. 2011). It further assumes likely timeframes during which population points would seeks services based on the typical working hours of 8:00/9:00 to 16:00/17:00. The third temporal accessibility approach is the addition of multi-modal transport (Townsend 1987; Mao & Nekorchuk 2013). It is logical that part of the population would access service points not only by car, but also by public transport, on foot, or by bicycle. Temporal accessibility models multi-modal transport through different network travel speeds, which either constrict or expand a service/population point network catchment. Essentially, a temporal accessibility analysis builds on the spatial accessibility analysis in the form of temporal case scenarios, as opposed to temporally uniform spatial accessibility.

Therefore, temporal accessibility is the measure of temporal variation in spatial accessibility.

1.3.2.6. Spatio-temporal accessibility

Spatio-temporal accessibility is the most recent instance of accessibility research and it draws upon all previous research and approaches. Unlike temporal accessibility which is implemented through modifying temporal parameters of spatial accessibility, spatio-temporal accessibility combines spatial and temporal accessibility analysis in the baseline methodology. Instead of case scenarios which demonstrate temporal variations in accessibility, temporal constraints are built into the spatial accessibility through time budgets and service utilization costs. The theoretical foundation of spatio-temporal accessibility is the work by Swedish time-geographer Thorsten Hägerstrand (1970). Hägerstrand (1970) argues that individual spatial mobility is temporally constrained by time budgets for service utilization between fixed activities, such as work or sleep. Hence, when seeking a service, an individual needs to traverse space to reach the service point from his "home base", which deducts a certain amount of time from the individual's temporal resources based on network constraints. Based on the distance to a service point, the time budget of the individual might not be sufficient to traverse the space in-between his location and the service point. Likewise, if less temporal resources are needed to access a service point, that service point is more accessible than another service point which requires a greater investment of temporal resources. However, this is where classic spatial accessibility stops, and spatio-temporal accessibility begins. Upon reaching the service, the individual has to expend further temporal resources to utilize the service. Furthermore, upon utilizing the service, the individual has to return to the "home base". The return trip potentially requires the same time it took to reach the service, although network cost dynamism might also change during the time it took to utilize a service. The way availability manifests within spatio-temporal accessibility is that a service is unavailable to a population point if it cannot be reached, utilized, and returned from within a fixed time budget. The total time budget is an assumption of the time an individual might allocate to utilizing a certain service. It varies based on the function which a service fulfils, and it varies from person to person. Hence, the individual would probably be willing to expend more time accessing a service of higher functional centrality; e.g. healthcare. Likewise, accessing a lower order service such as provision is likely to be assigned a smaller time budget. The variation of time budgets between individuals may vary on their socio-economic and demographic characteristics. An unemployed person will have a greater time budget than an employed person (Hägerstrand 1970), hence his or her spatial reach is greater. Also, a senior individual is likely to have slower walking speed than a juvenile individual (Mao & Nekorchuk 2013). Hence, the senior individual will expend a greater amount of time on network mobility and thus have a smaller spatial reach. The entire process of service utilization is therefore expanded to include realistic considerations which are absent in spatial accessibility and temporal accessibility. In fact, spatio-temporal accessibility is structured around considerations of the temporal and spatial constraints a person would encounter when accessing service (Neutens et al 2010b, 2011, 2012a, 2012b; Delafontaine et al. 2013; Miller 2017). That is why the measure of spatio-temporal accessibility is often described as "person-based" accessibility (Neutens et al 2010b, 2011, 2012a, 2012b; Delafontaine et al. 2013; Miller 2017; Tenkanen et al. 2017).

The term "spatio-temporal" is synonymous with "space-time", and is used intermittently within the literature concerning it (Hägerstrand 1970; Miller 1991; Delafontaine et al. 2012; Neutens et al. 2012a, 2011, 2012b, 2013; Miller 2016; Tenkannen 2017). However, "space" and "time" are nouns acting as adjectives in conjunction with accessibility, while the proper adjective form; "spatio-temporal", places greater connotative emphasis on accessibility. This is in line with our chosen definition of spatio-temporal accessibility:

Spatio-temporal accessibility is the measure of temporally constrained spatial accessibility.

Therefore, a complete spatio-temporal accessibility analysis should include both spatial and temporal constraints; service based time budgets, dual network travel costs, service utilization costs, considerations of multimodal transport, variable network travel speeds, daily and weekly variations in the parameters, and considerations on the intersections of individual space-time pyramids when utilizing services.

Spatio-temporal accessibility analysis is the state of the art in accessibility analysis. The following section on the State of the art will outline the historical and conceptual process which culminated with spatio-temporal accessibility research.

Chapter 2: State of the art

2.1. Accessibility research

We consider accessibility research as the general scientific field of interest within which spatio-temporal accessibility has been developed and within which it is positioned. Therefore, this section will present the history of accessibility research, its evolution, and challenges. Afterwards, the main topics of accessibility research will be presented. This subsection is followed by an overview of the methodologies applied in accessibility research; from earlier to more recent. Finally, the recognized research gaps will be presented in the last subsection of the State of the art. The focus during the literature investigation was on scientific works in the field of geography and its subdivisions. However, the topic of accessibility is multidisciplinary in its interest and application. Hence, it is a recurring topic in other sciences as well; particularly urban planning, healthcare, sociology, and transport science. Therefore, the compiled readings could have missed important scientific work on the topic of accessibility and what is presented within this section is to the best knowledge of the author.

Spatio-temporal accessibility is the most recent iteration of accessibility research which originated in the 1950s (e.g. Hansen 1959) and 1960s (e.g. Warntz 1964), during the quantitative revolution and early computerization of geography (Miller 1991; Radke & Mu 2000; Gregory et al. 2009). Fifty years of research, in combination with technological advances, has yielded significant improvements in the approaches and methodologies within accessibility research. However, the foundations upon which modern research is based have been a steady evolution in terms of scope and application. Therefore, spatio-temporal accessibility is in a way the compilation of best practices developed through the years within accessibility research. However, the novelty of spatio-temporal accessibility presents challenges as well. Having been developed on the basis of accessibility research, spatio-temporal accessibility is focused on those research topics which are prolific in classic accessibility research (primarily healthcare). This is not necessarily a limit on the scope, but simply a challenge to be overcome in future research. Furthermore, spatio-temporal accessibility necessarily implements the most complex methodologies and datasets, due to drawing on multiple different approaches and considerations in accessibility research.

Scientific interest in accessibility emerged due to the rapid changes in human living standards and population patterns brought upon by urbanisation and globalisation (Farrington & Farrington 2005), and rise of dual earner families (Neutens et al 2011). More importantly, during the second half of the 20th century, computer assisted research was becoming widely available to researchers in the USA where some of the first proper, wide-scale accessibility research began. However, pioneer research on accessibility within geography began in the beginning of the 20th century on the topic of accessibility to railways (fig. 1), which was considered as a measure of civilization and a spatial resource which can improve quality of life for the population which have access to it (Jefferson 1928; Kolars & Malin 1970; Wang et al. 2009; Kraft 2016; Tenkanen 2017).

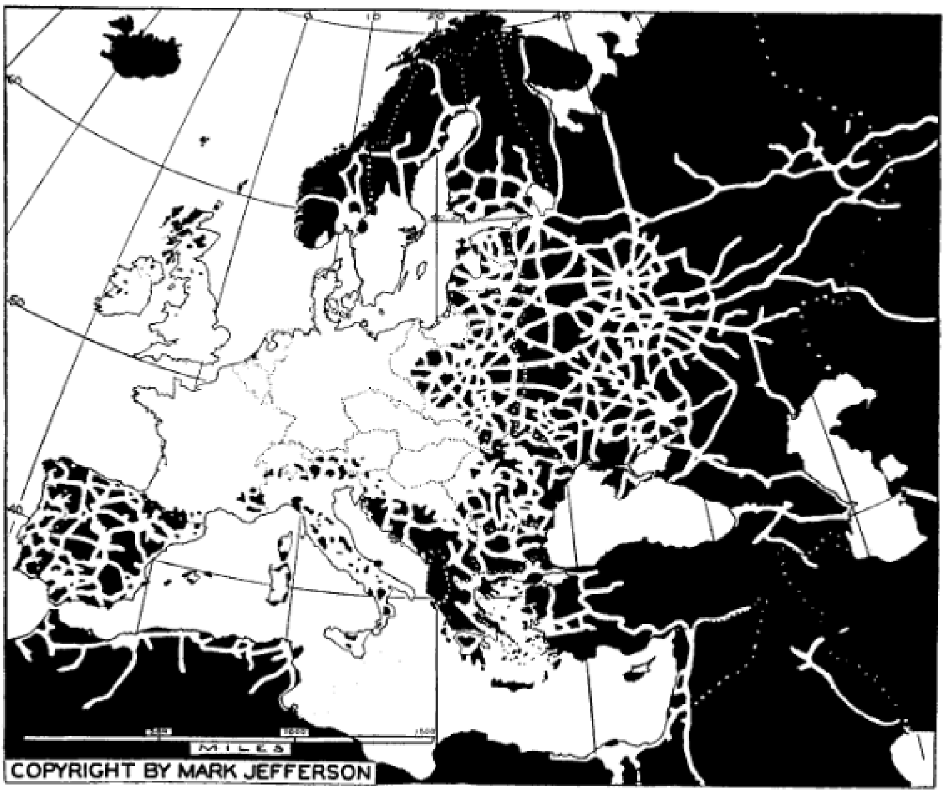

FIGURE 1.—Europe within ten miles of a railway is white. Black regions are farther from the rails. The continuous white area is called a *railweb*, the network of lines as in Spain and Russia a *railnet*.

Figure 1. 1919 Map of European railway availability by 10km Euclidean distance from railway lines. (Jefferson 1928)

The concept that accessibility to transportation services improves quality of life through increased individual mobility has persisted as a research topic to this day (Guagliardo 2004; Salze et al. 2011; Neutens et al. 2012b; Mao & Nekorchuk 2013; Kraft 2016; Tenkanen et al. 2016; Tenkanen 2017). Likewise, increased accessibility to other functions could improve quality of life as well (Apparicio & Seguin 2006; Smith et al. 2009; Zhang et al. 2011; Neutens et al. 2013), which is why accessibility research steadily expanded in its topics of interest. First healthcare, then public services, provision, and other functions regularly important in the life of an individual.

During the first half of the 20th century, various demographic, socio-economic, and economic data was becoming available in the USA (Warntz 1964). This enabled new approaches to appraising geographic space and spatial resources both in business and science. For example, the practice of redlining became a recognized and enforced spatial trend (Eisenhauer 2001). Based on population socioeconomic and social factors, businesses adjusted their distribution of service points to achieve highest utility, which left certain areas underserviced. The economic rationale behind this business sponsored accessibility application is one of the great potentials of accessibility research: to derive optimal facility locations based on supply and demand relationships within a region (Leonardi 1978; Radke & Mu 2000). However, optimal facility (service point) placement need not always be from the business optimization perspective. It is possible to apply the same approach inversely and derive optimal facility (service point) location for better accessibility to the population (van den Berg et al. 1976; Neutens et al. 2012a). This is especially relevant with public healthcare (Joseph & Bantock 1982) and governmental service delivery (Radke & Mu 2000; Neutens et al. 2012a, 2011). Nevertheless, the initial business outlook regarded accessibility to services as the propensity of the population to consume (utilize) a service in quality and quantity dependent on issues such as race or income (Eisenhauer 2001; Zenk et al. 2005). This was not limited to private business but also informed public service distribution (Apparicio & Seguin 2006). This can be understood through Hughes (1936) description of spatial resources as institutions which vie for customers in an open or a closed space. Some institutions form power structures which express degrees of unilateral sovereignty over individuals (e.g. the racket or the state) and operate in a mutually exclusive, closed or delimited space (Allen 2009). However, most institutions are not exclusive in their spatial scope and their influences overlap a mutual clientele (Hägerstrand 1970) for which they perform a specialized service (Mao & Nekorchuk 2013). That is, the spatial institutions fulfil a functional need of the population through providing a service. Hughes further posits (1936): "Customer institutions tend to be located with reference to the probable movements of population, and also with reference to their competitors, in the struggle to be equally accessible to the people whose wants they exploit." Hence, the distribution of services in a region, in the absence of fiat intervention, would follow a certain logic (Domanski 1979) based on the spatial distribution of populations and other services, almost a market logic driven spatial equity (Apparicio & Seguin 2006). Hence, the notion of a spatial logic, akin to market logic, was gradually introduced in accessibility research. Such a spatial logic trends towards spatially balanced accessibility as services dynamically position themselves until a region is sufficiently saturated (Domanski 1979). The integration of population mobility and choice with the concept of spatial logic necessitated the abstraction of the population into aggregated figures (Hägerstrand 1970). Hereafter, accessibility research has primarily concerned potential accessibility to services for a population (Hansen 1959; van den Berg et al. 1976; Domanski 1979; Joseph & Bantock 1982; Townsend 1987; Luo & Wang 2003; Guagliardo 2004; Smoyer-Tomic et al. 2004; Yang et al. 2005; Zenk et al. 2005; Apparicio & Seguin 2006; Luo & Qi 2009; Smith et al. 2009; Salze et al. 2011; Zhang et al. 2011; Delafontaine et al. 2012; Neutens et al. 2012a, 2011, 2013; Mao & Nekorchuk 2013; Tenkanen et al. 2016; Masy 2017; Tenkanen 2017; Järv et al. 2018), as opposed to realized accessibility of the population (Neutens et al. 2012b).

This data driven theoretical and practical shift in perception of accessibility potential gave credence to the notion of a logical distribution of spatial content. Examples in both geographic (Stewart 1942) and sociologic (Zipf 1946) research considered distance and size as the principal dimensions governing this logic. Spatial relations exhibited patterns which indicated a "force of attraction between two populations based on their size and mutual distance" (Zipf 1946). Two points are more likely to be interrelated if their mutual distance is lower since this facilitates accessibility. Also, spatial interrelation increases if their combined population is greater since this creates more supply and demand potential. John Q. Stewart (1942) provided a potential explanation for George K. Zipfs (1946) theory by drawing an analogy to Physics. The electrostatic potential (charge divided by distance) and gravitational potential (mass divided by distance) could be observed in geographical phenomena (Stewart 1942). Hence, the influence of a spatial point (be it a service or a population point) would extend a gravitational force according to its relative size (e.g. position in functional hierarchy or demographic potential for population points, or supply capacity/quality for service points), dependent on the distance to other points. Instead of merely discrete points, both population and services could now be understood as continuous spaces of equal potential (fig. 2), based on which business and public decisions could be informed (Warntz 1964).

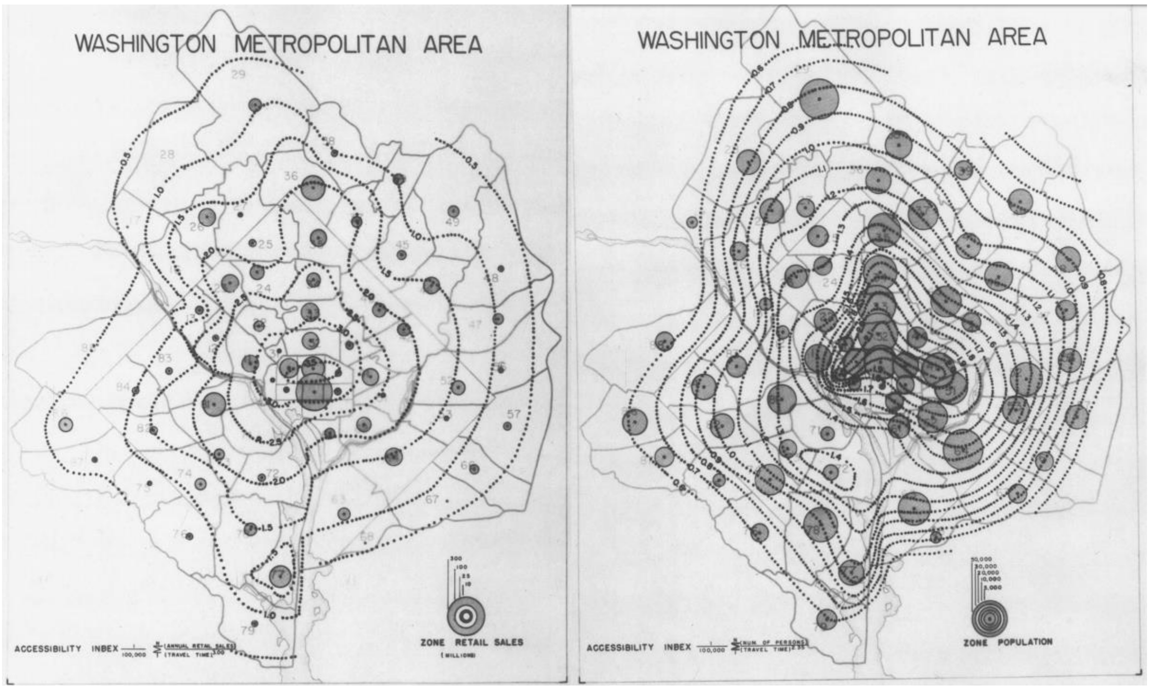

Figure 2. Accessibility potentials to provision (retail) in the Washington Metropolitan area by Hansen (1959). Left map visualizes accessibility potential by service supply, right map visualizes accessibility potential by population demand.

The inter-relation and inter-dependence of geospatial content would later be postulated by Waldo Tobler (1970) as the First Law of Geography (n.b. the conceptual analogy to laws in Physics);

“*Everything is related to everything else, but near things are more related than distant things*.”

However, there was an absence of widespread scientific interest for the relation of demographic factors and spatial resources until after World War II (Warntz 1964). This surge of scientific interest coincided with the quantitative revolution paradigm shift in Geography and subsequent introduction of computers and digital statistics in Geography (Gould 1979; Miller 1991; Gregory et al. 2009). Calculating large scale spaces of potential was unfeasible manually, the necessary interpolation between multiple control points would only be achieved through the application of computers (Miller 1991). Pioneer Geographic research on population potential using an early IBM computer (Stewart & Warntz 1958) produced continuous potential maps for the entirety of the continental USA which demonstrated logical spatial demographic patterns. However, Stewart & Warntz (1958) recognized population size is not the only aspect which influences the gravity potential of a location. The gravity is potential is conditioned also by, as they termed it, total “social mass”; anything produced or transported for social purposes. Hence, the social mass is also the spatial content created, valorised, exchanged, and sought after by the population of a region. Social mass in this context basically represents the material and virtual resources which constitute the service provision system and the demand for service provision. This represents the uniqueness of regions, each is marked by a unique setting, a milieux (Latham 2000), which makes up service provision alongside service points supply and distribution. Therefore, a need to weight the gravity potential of population was introduced (Stewart & Warntz 1958; Warntz 1964). Weighing populations produced better results in relation to spatial logic and expected patterns (Warntz 1964). However, a definite approach to weighing gravitation decay has been an issue ever since in all methodologies involving gravitational concepts (Hansen 1959; Warntz 1964; Domanski 1979; Guptill 1975 as cited in Guagliardo 2004; Joseph & Bantock 1982; Guagliardo 2004; Yang et al. 2006; Luo & Qi 2009; Salze et al. 2011; Mao & Nekorchuk 2013). The notion that population can be viewed as a continuous spatial potential was logically followed by the view of functions as continuous spatial potential as well (Hansen 1959). Walter G. Hansen (1959) regards the intersection of population potential and service potential as accessibility potential (fig. 2). Accessibility potential is thus based on the supply and demand relations between supply capacity and population demand, inversely proportional to the distance between them. Indeed, the gravitational model used to calculate accessibility potential by Hansen (1959) is one of the basis of most of the modern gravitational accessibility models, alongside the model by Joseph & Bantock (1982) (per Guagliardo 2004).

2.1.1. Accessibility research challenges

The phase of applied accessibility research started in the 1970s based on the theoretical and methodological frameworks set up in the previous two decades (Guagliardo 2004). The most prolific application of accessibility research has been, and remains, accessibility to healthcare. This is logical since healthcare is of indubitable public interest. Furthermore, in most countries healthcare is a predominantly governmental service and thus should be equitably distributed (Townsend 1987). Also, the parameters of healthcare capacity and demand are well established (Lee 1991; Mao & Nekorchuk 2013). For that reason, healthcare accessibility analysis inputs have less uncertainty involved (Joseph & Bantock 1982) than applications on other services, private or governmental. The progress of urbanisation and functional centralisations in Angloamerica and the UK during the 1980s increased the urban-rural divide in terms of service accessibility and deprivation (Townsend 1987). Also, healthcare was increasing centralized in large hospitals, mostly in urban spaces (Joseph & Bantock 1982). The accessibility research of the day mostly addressed these two concerns and thus introduced new challenges in accessibility research. The spatial logic of rural and urban regions is fundamentally different (Joseph & Bantock 1982), as are the socioeconomic and demographic factors of the populations (Townsend 1987). Hence, the rural-urban imbalance in actual healthcare supply and demand (Thouez et al. 1988) cast doubt on the outcomes of simple analysis of accessibility potentials (Radke & Mu 2000). It was evident that using the same methods on these two cases was a subpar solution. The differences in the human factor of urban and rural space had to be addressed in the methodologies. This induced a refocus on the human aspect of accessibility, as opposed to accessibility potentials. The problem was set: does accessibility potential have any relevance to actual, realized accessibility by the population about which the research is conducted (Joseph & Bantock 1982)? Accessibility was thus divided into two stages (Guagliardo 2004); potential accessibility, and realized/achieved/actual accessibility. This was compounded by the waning of the "*Augean period*" of the quantitative revolution in geography and accessibility research by the end of the 1970s (Gould 1979). Ideological and politicised topics were returning to prominence within the science (Gould 1979). Concepts such as: equity, inequality, class, deprivation, sexism, racism etc. were co-opted and instrumentalized to justify research motivation and outcomes (Townsend 1987). Thus, it was necessary to relate the results of potential accessibility with the ground truth. This was only possible through an empirical research on realized accessibility which would accompany the research on potential accessibility (Guagliardo 2004). Realized accessibility is thus by default regarded as the "Holy Grail" of accessibility research. Most of the consulted literature regularly defines the difference between potential and realized accessibility, almost as a form of disclaimer to what follows; research on potential accessibility. Thus, we shall present several definitions of realized and potential accessibility from the literature:

- Realized accessibility is measured based upon actual utilization of services, whereas potential accessibility supposes no actual interaction between the population and services. (Joseph & Bantock 1982)
- Revealed accessibility focuses on actual use of services, whereas potential accessibility signifies the probable entry into the service provision system based on spatial and aspatial access factors. (Luo & Wang 2003)
- Accessibility potential is based upon the coexistence in space and time of a population service demand, and a willing supplier of the service. Realized accessibility is based upon the actual delivery of the needed service to the population in an area. (Guagliardo 2004)
- Distance between supply and demand is one of several indicators of accessibility to healthcare; a long waiting list or crowded waiting rooms may be a better indicator of accessibility. (Yang et al. 2006)
- Realized accessibility focuses on actual use of services, whereas potential accessibility focuses on aggregate supply of services in an area. (Luo & Qi 2009)

However, realized accessibility research has rarely been undertaken despite the implied added value of testing the validity of potential accessibility research. This is due to a lack of data on realized accessibility of individuals (Joseph & Bantock 1982). Such a dataset needs to be purposely produced, whereas potential accessibility research can be undertaken with readily available datasets. Furthermore, the downside of realized accessibility research is due to the arbitrary nature of aspatial factors conditioning individual choice (Joseph & Bantock 1982; Guagliardo 2004; Delafontaine et al. 2012). It is simpler to model and argue spatial logic based on constant, spatial factors; rather than idiosyncratic human behaviour (Hägerstrand 1970). Nevertheless, scientists remain cognizant of the downside pertaining to research on potential accessibility.

Early accessibility research thus considered accessibility to be primarily defined by distances between supply and demand of services (e.g. Jefferson 1928). Thus the main parameter and accessibility barrier was Euclidean distance (Guagliardo 2004; Tenkanen 2017). However, potential accessibility based on fixed distance measures tends to assume equal accessibility potentials within the entire catchment derived from such a distance based approach (Joseph & Bantock 1982; Luo & Wang 2003; Guagliardo 2004; Yang et al. 2006; Luo & Qi 2009; Mao & Nekorchuk 2013). Every location in space has not only a different coordinate, but also a different position in relation to every other location (Hägerstrand 1970; Massey 2005; Šterc 2015). A uniform regional accessibility score is in contrast with spatial reality. The spatial constraint of distance had to be reformed in order to produce better potential accessibility results. Joseph & Bantock (1982) addressed the issue of uniform regional accessibility by introducing distance weighted accessibility. They assumed, logically, that the farther away a service point is, it would be correspondingly less likely that it would be utilized barring absence of multiple choice. This assumption is corroborated by the First Law of Geography (Tobler 1970); the intensity of spatial relations is inversely proportional to distance between spatial content. However, the solution by Joseph & Bantock (1982) still produced isochronally concentric accessibility scores (Guagliardo 2004). Nevertheless, Toblers first law is central to the theory of spatial logic (Šterc 2015). If a population point has access to multiple equal quality service points, it is most likely it would utilize the closest one. This is due to individual utility; the least time is invested into traversing space, the more time remains for other activities (Hägerstrand 1970). Indeed, medical research indicates that patients prefer to use closer services rather than farther, out of increased security and convenience (Guagliardo 2004). However, with services of lower functional centrality the population is more willing to invest time in order to access higher quality services, as demonstrated by Smith et al. (2010) on the example of accessibility to fresh produce selling grocery stores. Therefore, distance constraints are modelled as temporal parameters. However, the temporal parameters have to be weighted and adjusted according to the topic of the research (Joseph & Bantock 1982).

The solution to uniform regional accessibility is to model distance as time necessary to traverse space (Luo & Qi 2009). As defined in the section on the Thesis research topic (1.2.); spatial accessibility is a measure of accessibility based on considerations of population service demand, service point capacity, and network constraints. A purely distance based accessibility analysis could be undertaken with only the service demand and service supply values. However, by transforming linear distance based catchments into catchments based on temporal reach, different accessibility scores can be described for locations based on their spatial relation to the point of origin. To properly model the complexity of spatial relation based on temporal constraints, one requires more data (Joseph & Phillips 1984 per Luo & Wang 2003). What is necessary is a network dataset and adequate (GIS) software (Radke & Mu 2000; Luo & Wang 2002; Guagliardo 2004; Yang et al. 2006). This is why complex, network based accessibility approaches became prevalent on the turn of the millennia (Radke & Mu 2000). The implementation of transport networks and multimodal transport (Mao & Nekorchuk 2013; Tenkanen et al. 2016; Tenkanen 2017) allowed for variable regional accessibility based on realistic spatial logic. Zones of higher accessibility follow zones of lower network friction, i.e. lower travel costs (Guagliardo 2004). Thus, a population point origin for an accessibility analysis has access to an ***n*** amount of service points, based on the spatial and temporal reach within the given transport network. Accessibility scores propagate from population points based on network catchments parameters. The expected spatial logic of accessibility results would exhibit a radial spread of higher accessibility zones along corridors of lower network travel impedance (Domanski 1979; Mao & Nekorchuk 2013).

The application of GIS and network distances marks the beginning of the penultimate phase in accessibility research. The seminal work of this phase is the polygon-polygon location allocation method developed by Radke & Mu (2000), coined by Luo & Wang (2003) as the Two-step floating catchment area (2SFCA). The original 2SFCA by Radke & Mu (2000) calculated optimal placement of public service facilities to achieve maximum coverage for the population of Northern California. The novelty compared to the previous methods was in the application of accessibility research on a polygon-to-polygon basis, as opposed to point-point or point-polygon which was the norm (Radke & Mu 2000; Guagliardo 2004). This methodology will be described in detail in the following subsection on methodologies since a variation of it is used in this Master thesis. However, the challenge for the 2SFCA method was that it reintroduced the uniform regional accessibility problem. Essentially an overlay of two buffers; one for demand and the other for supply, the 2SFCA did not include distance decay to model gravitational effects despite using a road network and temporal travel costs to generate the catchments. This was addressed in the second iteration of the 2SFCA, the enhanced 2SFCA (E2SFCA) by Luo & Qi (2009). By adding distance decay weights to accessibility scores of the generated catchments (Guagliardo 2004). Distance decay models expected spatial logic per Toblers First Law; services closest to the population point are assigned the highest accessibility score, i.e. closest by network derived distance. While solving the problem of uniform regional accessibility, the inclusion of distance decay measures and weights introduced a new challenge (Joseph & Bantock 1982; Luo & Wang 2002; Guagliardo 2004; Luo & Qi 2009): What are the correct values for distance decay? They vary from service to service, from study region to study region, topic to topic, space to space etc.

In summary, the challenges encountered within accessibility research up to spatio-temporal accessibility implementation are:

- The difference between availability and accessibility.
- Implementation of service supply and population demand.
- The inability to model realized accessibility.
- Uniform regional accessibility of potential accessibility research.
- Lack of distance decay with which to model variable regional accessibility and Toblers First Law.
- Distance decay weighting framework.

The following subsubsection will outline the most recent phases of accessibility research which are based on time-geography theories.

2.1.1.1. Space-time implementations

An alternative interpretation of realized accessibility has become popular in recent literature; that of person-based accessibility (Delafontaine et al. 2012; Neutens et al. 2012a,2012b,2013; Tenkanen et al. 2016). Person-based accessibility analysis concerns the spatial and temporal possibilities and constraints of the average individual (Delafontaine et al. 2013; Tenkanen et al. 2016). Conversely, place-based accessibility concerns the spatial and temporal accessibility of location; its locational benefit based on innate potential accessibility (Neutens et al. 2011). Essentially, both place-based and person-based accessibility measures are types of potential accessibility, but with a greater emphasis on temporal rather than spatial constraints. Neutens et al. & Delafontaine et al. define person and place based accessibility as:

- Potential accessibility is deemed a static measure, temporally and spatially, whereas realized accessibility should focus on person-based accessibility based on time geography. (Neutens et al. 2012a)
- Place-based accessibility indicators are based on the proximity of service points to population points, whereas person-based measures are based on observations of individual activity and travel behaviour. (Neutens et al. 2012b)
- Place-based accessibility measures concern the physical separation of key locations for individuals and the key services locations sought by those individuals. Person-based accessibility is based on detailed observations of individual spatiotemporal constrains and their temporal fluctuations. (Delafontaine et al. 2012)

- Realized social interaction is based on frequency of interaction with other people, memberships in clubs and religious communities etc., whereas potential social interaction is based on the intersection of individual space-time prisms within daily routines (fig. 3). (Neutens et al. 2013)

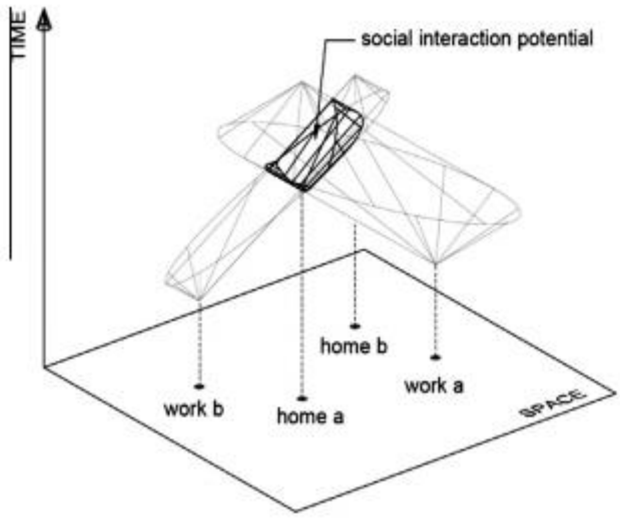

Figure 3. Potential for social interaction (potential accessibility to social interaction) at the intersection of two space-time prisms. (Neutens et al. 2013)

The theoretical foundations of person-based approaches are theories of time geography (Delafontaine et al. 2012), particularly the work by the Swedish geographer Thorsten Hägerstrand (Miller 1991, 2017; Delafontaine et al. 2013; Neutens et al. 2011, 2012a, 2012b, 2013; Tenkanen 2017). Hägerstrand (1970) developed a holistic theory of spatial reality which views existence as a concatenated sequence of locations which all spatial content occupies at a given moment in temporal continuity. The purpose of this theory was to return the focus of social geography on the individuals, rather than "dividuals". Hence, the issues of quality of life, choice, and possibility were put forward as the central issues in this seminal work. This was done by emphasising the temporal dimension in geography, and the meaning of every moment in time-space (Massey 2005; Šterc 2015; Miller 2017). The important contribution to accessibility research is in the form of spatio-temporal constraints; abstract rules of behaviour which manifest in spatial reality as locations, extents, or durations in time. Three sets of constraints are presented (Hägerstrand 1970): capability constrains which pertain to the innate limits of an individual; coupling constrains which pertain to the inter-personal obligations which limit choice and mobility (e.g. mandatory meetings); and authority constraints which pertain to the time-space domain of an individual. Thus, spatio-temporal constraints necessarily set limits on person-based accessibility through conditioning participation in service utilization. The interrelation of these three sets of constraints in spatial reality is modelled by the time-space prism (Hägerstrand 1970). Figure four visualizes the concept and shape of the time-space prism: it is described by three axii; two horizontal axii representing space (geographic location), and a vertical axis representing time (geographic position). The 3D geometric shape represents the part of geographic space accessible at each moment of the given time budget and spatio-temporal constraints. The potential path area describes the maximum extent accessible without breaking any spatio-temporal constraint which, while possible, induces chaos into the system. Therefore, the space-time prism models the maximum accessible spatio-temporal extent for an individual or a location, provided a certain time budget to traverse the space and therein contained spatio-temporal constraints.

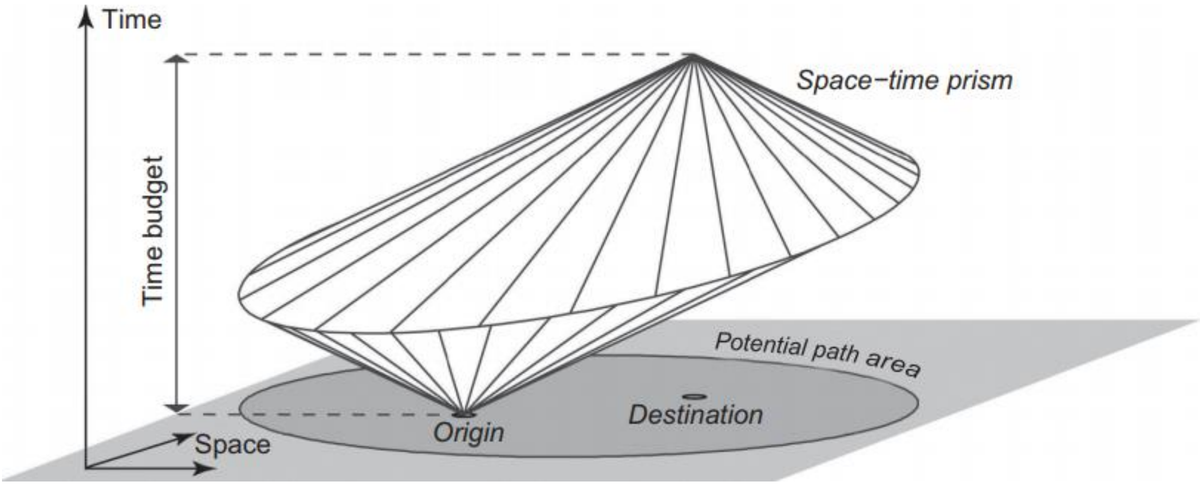

Figure 4. Illustration of the Space-time prism, the three axii, and its projection in space as a potential path area at a given moment (the 3D shape). (Delafontaine et al. 2012)

Person-based accessibility approaches benefit from the theoretical framework set by Hägerstrand, which justifies the emphasis on personal time budgets, network travel constraints (speeds, links, availability), and the spatio-temporal scope of possibility represented by the shape of the space-time prism. Thus, in the research on social interaction within Flanders by Neutens et al. (2013), social interaction potential is defined as the intersection of two individual's space-time prisms between fixed activities. This demonstrates that person-based accessibility is a type of potential accessibility research since the approach does not assume actual interaction (which is unlikely as pointed out by the authors), but establishes the space and time this interaction may be achieved (fig. 3). However, the space-time prism is applicable to place-based accessibility research as well (fig. 4). Delafontaine et al. (2012) apply the time-geography concept in their research on Ghent public library accessibility. The spatio-temporal accessibility research is based on the locations of the public libraries, as opposed to the population points. Instead, the population points are accessed by the library and the cumulative demand of accessible population points contributes to the accessibility scores of the service points. Since this phase of accessibility research is the most recent; all the best practices of previous phases are implemented within spatio-temporal accessibility research (Delafontaine et al. 2012). These practices include: variable regional accessibility due to using network distance and constraints, multi-modal transport, weekly variations in accessibility due to differing service point supply/availability, daily variations in accessibility due to different opening and closing hours, total time budgets for traversing space and utilizing services, variable service utilization temporal costs, maximum travel extents based on space-time prism calculations, all implemented on the newest software and hardware available.

The time-geography theoretical framework by Thorsten Hägerstrand has a central position in the considerations and choices within this Master thesis as well. Hence, the theory will be revisited in the Second chapter.

2.1.2. Accessibility research Methodologies

Accessibility research methodologies can be divided into two categories: regional availability and accessibility; and discrete unit (individual) accessibility and availability (Guagliardo 2004). This differentiation is guided by the primary focus of the accessibility analysis and, to a lesser degree, by the scope of the research. Regional accessibility analysis models accessibility for geographic or administrative units, while discrete unit accessibility models accessibility at discrete points or even for individual persons. Of the two, regional approaches are more prevalent in older literature, while individual approaches are more prevalent in recent literature. This is due to regional approaches being simpler to implement (Guagliardo 2004), and also possible to visualize without advanced software (Miller 1991; Radke & Mu 2000). Thus, regional accessibility has emerged as a research interest earlier than individual accessibility. Regional accessibility methodologies concern accessibility values aggregated at the administrative or geographic unit level (Radke & Mu 2000; Guagliardo 2004; Delafontaine et al. 2012). Regional accessibility can be further subdivided into regional availability and regional accessibility methodologies. This is due to the fact that certain methodologies do not take into account the relation between supply and demand, but merely the existence of supply in arbitrary proximity to demand, and the quality and quantity of existing supply. Regional availability methods are simpler than regional accessibility and require less data, which is their main advantage. However, this is invalidated by the superficial insight they provide into the spatial systems of service provision. Nevertheless, regional availability is simple to implement, and it is useful when comparing scores between regions. In fact, availability methodologies are most appropriate for comparing regions of greater geographic scope; e.g. countries or mid-tier local governance.

Conversely, regional accessibility methods models the full relation between supply and demand within a study region, not just their intersection. This means that both the quantity and quality of service points is modelled and it is put in relation to the present population demand for the service in question. Regional accessibility methodologies are most common in accessibility research since they provide a relatively good insight into the spatial logic of a service provision system (Joseph & Bantock 1982; Joseph & Phillips 1984 per Luo & Wang 2003; Guagliardo 2004). This is especially true for more recent iterations of regional accessibility, e.g. the 2SFCA method (Radke & Mu 2000) and its successor, the E2SFCA (Luo & Qi 2009). Furthermore, regional accessibility has been established as a norm in service public delivery evaluation (Thouez et al. 1998) and optimization (Radke & Mu 2000). The introduction of network travel costs into accessibility analysis introduces the spatial aspect, while transforming distance into time costs introduces the temporal aspect. As outlined in the previous subsection, spatio-temporal accessibility methodologies include service utilization costs and total time budgets.

Individual accessibility (discrete unit accessibility) requires more complex datasets than regional accessibility, hence it is more difficult to implement (Neutens et al. 2012b, 2013). However, due to the rise of big data and large-scale individual geographic information gathering, discrete unit accessibility will increase in presence and prevalence within accessibility research (Tenkanen 2017). Regional accessibility thus concerns the accessibility (or availability) scores for continuous administrative or geographic units; such as counties or catchments, while individual accessibility most often corresponds to person-based approaches (Delafontaine et al. 2012; Neutens et al. 2012a, 2012b), however it can be applied to place-based approaches as well if accessibility is calculated for service or population points in space (Delafontaine et al. 2013). This thesis focuses on place-based individual accessibility potential of population points in the study region. Based on the calculated discrete point accessibility scores, a regional average will be derived for the Kanton, cities of Zurich and Winterthur, and city quarters of Zurich.

2.1.2.1. Service availability methods

The simplest service availability methods are various catchment analysis methods which project a geographic scope from a point, line, or a polygon of origin. Everything which falls within this projected spatial scope, i.e. the catchment, partakes in the availability calculations. GIS methods to calculate availability include the baseline methods which support spatial analysis on feature classes (Longley et al 2010). These are the buffer, the distance to feature, the convex hull, the bounding box, the isochrone, and the thiessen (Voronoi) polygon. Furthermore, in the case we are calculating regional availability for polygons representing geographic or administrative units, it is enough to select services by locations (intersect or contain), to calculate a basic availability indicator.

Buffering calculates a new polygon which covers the part of space specified by distance, Euclidean or spherical, from the feature which is being buffered (Kemp 2008). Thus, calculating the availability to services for a population point would require the input of a distance parameter for its buffer. Once generated, the buffer would extend from the population points into nearby space and represent the linear distance to the population point. Every service point which is overlaid by the population point buffer partakes in the availability measure for the population point (e.g. fig. 5). Likewise, if no services are present in the generated buffer, the population point does not have any available services. Similarly, Thiessen (or Voronoi) polygons are generated between input features and divide space into catchments by equidistance from input features (Longley et al. 2010). Thus, when used with irregularly spaced population points, the Voronoi analysis will generate catchments which will extend to the point of equidistance to other population points within a region. Every service point which is overlaid by the Thiessen polygon contributes to the service availability for the population point the polygon is based on. Likewise, Voronoi analysis can be based on service points to calculate the likely service demand (e.g. fig. 6) for which the service point is closest (Radke & Mu 2000). The distance to feature method calculates the linear distance to the nearest target feature from the location of the input feature (Longley et al 2010). In the case a maximum allowed distance is defined, the method will create a table listing all target features within the range and the linear distance between them and the input feature. The distance to feature method is an alternative to the buffer analysis in final outcome. The advantage of the distance to feature method over buffers is in lower processing loads (Radke & Mu 2000). Finally, the convex hull and the bounding box are examples of affine geometry application in GIS (Kemp 2008). They are both based on the topological concept of betweenness, whereas geometry of the generated shape is based on the spatial extent of input features. Based on the input features, the convex hull generates a catchment which includes the space between the input features (Kemp 2008; Longley et al. 2010). Thus, the convex hull method is useless for point features, unless it is a multipoint feature. Similarly, the bounding box generates a polygon feature based on the maximum and minimum coordinates of the input feature (Longley et al. 2010). Again, this method is useless for point features, unless it is a multipoint. The majority of recent place-based and person-based accessibility research is based on calculating accessibility scores for individual locations in space (Delafontaine et al. 2012); points. Thus, the convex hull and the bounding box have been considered only from the theoretical perspective. In the case they were to be applied, the convex hull method is superior since it produces a more realistic catchment for the purpose of accessibility analysis. An example of a convex hull application would be when calculating service availability between two line or polygon features; e.g. transport corridors, or bodies of water (Kemp 2008).

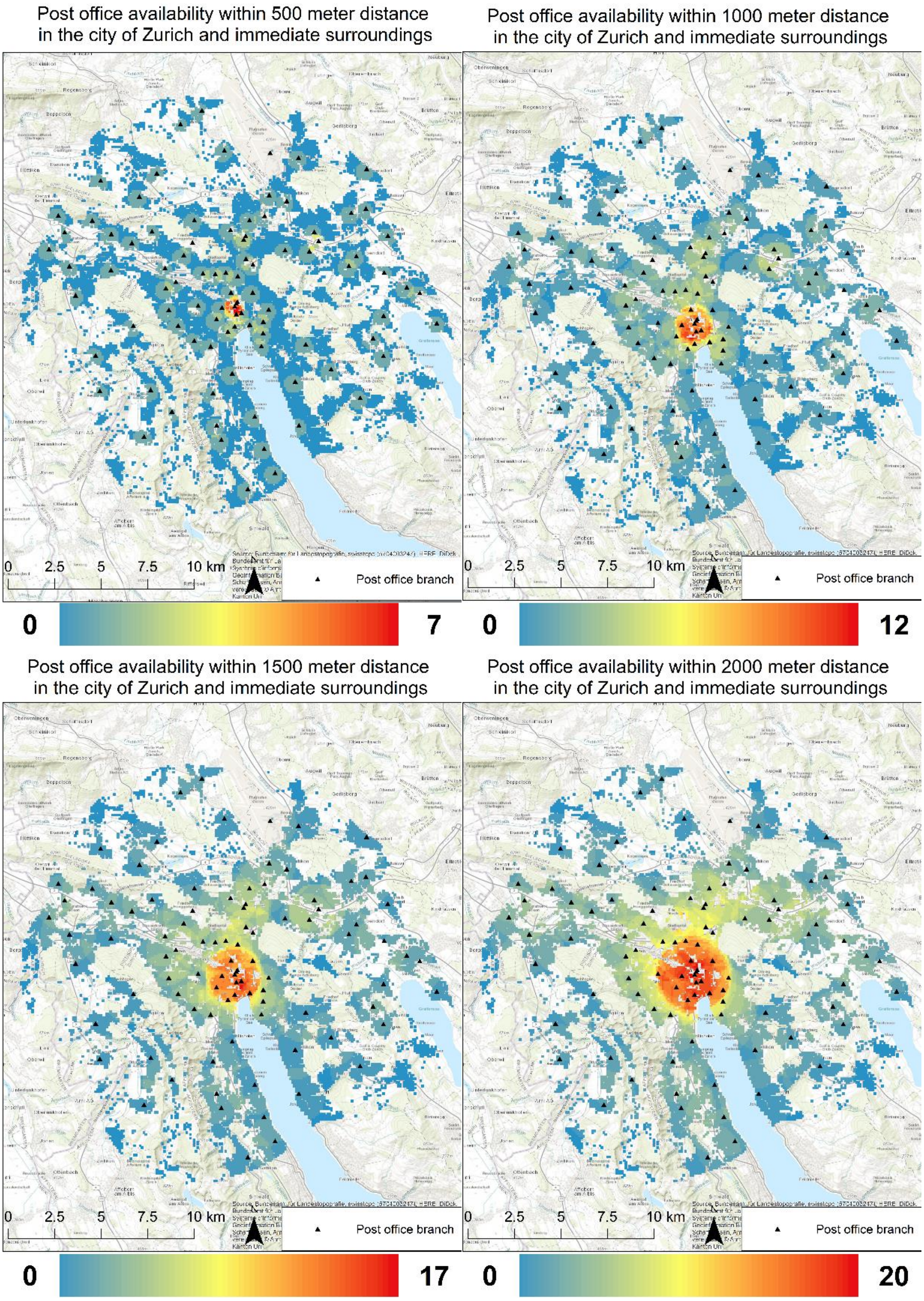

Figure 5. Author example of availability analysis by buffers of 500, 1000, 1500, and 2000 meter distance, colour ramp indicates number of post offices available for a population point.

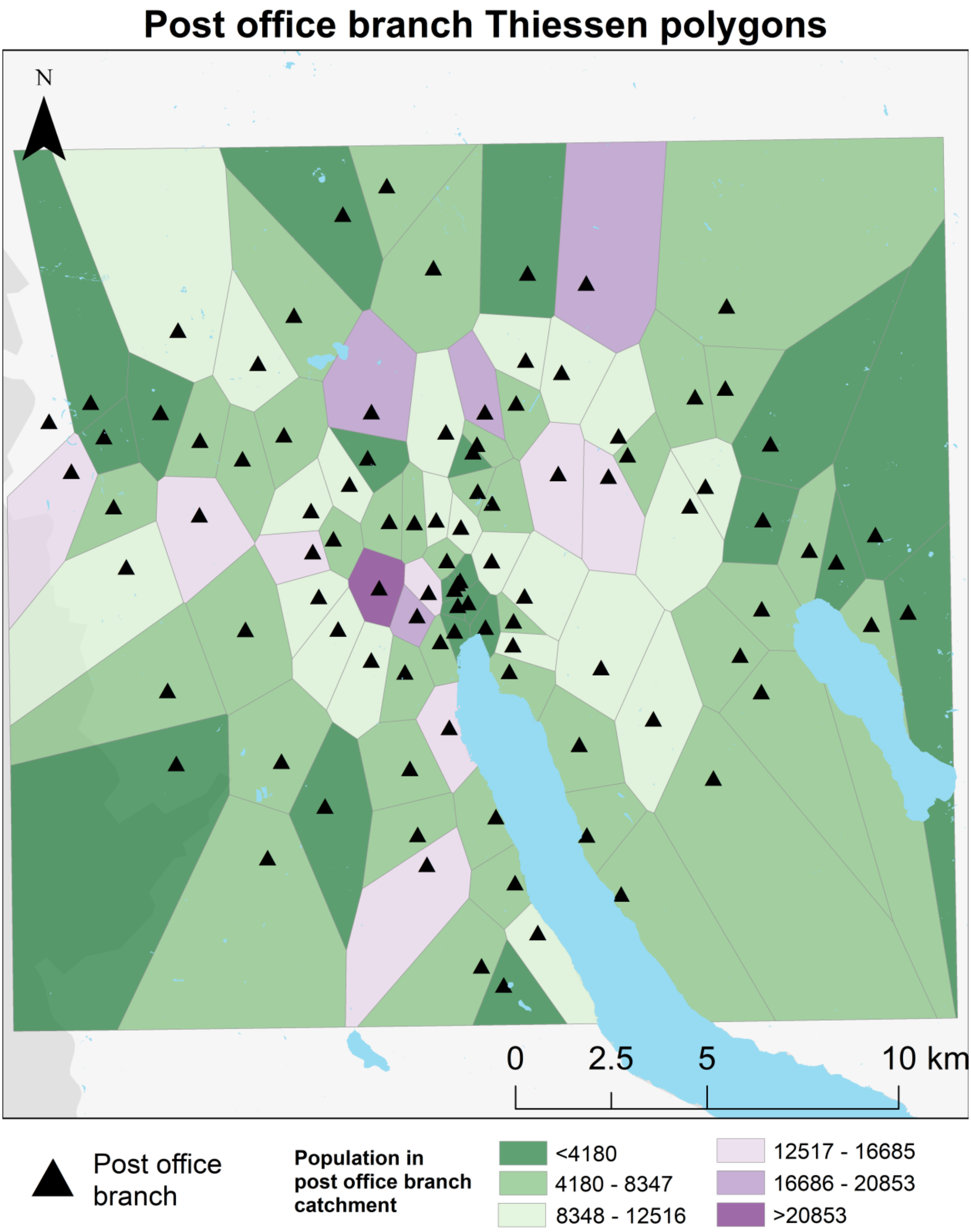

Figure 6. Author example of Voronoi analysis for resident population demand allocation to post office branches in Zurich.

The greatest downside of the above provided method examples is that each uses linear (often Euclidean) distance to calculate input feature catchments (Radke & Mu 2000). Hence, the generated catchments are not realistic in terms of actual spatial reality and how humans traverse space. Since flight is an avian domain, humans are forced to reckon with the geographic reality of relief and mobility constraints which are not modelled when using linear distance. Furthermore, the generated catchments suffer from edge effects (Kemp 2008; Longley et al. 2010). For example, the Voronoi polygons in figure 6 assign the entire population demand within the polygon to the service point which was used to generate it. The fact is that these methods segment geographic space into islands between which there is no interaction. The edge effect problem is most significant for the side of the population demand (fig. 6). The population living on the edge of a Voronoi polygon is equidistant from two service points. Hence, it is unrealistic that it would 100% of the time utilize the service point which happens to be 1 meter closer. In reality, the probability that the population on a Voronoi edge would choose either of two service points is more likely 50% (n.b. when both service points are of equal quality and centrality). Edge effects are a recurring challenge in accessibility research (Guagliardo 2004) and will be touched upon again in the following subsubsections.

The solution to edge effects, uniform regional scores, and the impossibility of multiple choice is to implement distance calculations based on network, not linear distance (Guagliardo 2004). Thus, the simplest implementation of network distances is through an isochronal analysis. Isochrones are isolines which connect points of equal temporal values (Kemp 2008). In the case of availability research, an isochrone would connect locations equally distant by network distance from a service or population point. Figure 7 demonstrates an example of isochronal analysis using walking distance and driving distance to calculate availability scores for population points in Zurich, Switzerland. The isochronal catchments are derived from the network distance value input parameter, and the network times calculated for each network edge. The movement speed is of central importance when generating isochrones since it determines network times for each segment (length/speed). Furthermore, it is possible to model different transport methods by assigning different speed limits to network edges (fig. 7). Movement speeds are assigned within the network dataset. Vehicular mobility can thus be assigned according to street classification, or official speed limits (Delafontaine et al. 2012; Mao & Nekorchuk 2013). Conversely, pedestrian movement is marked by a constant speed equal across all segment of the transport network. The question of network movement speeds is an ongoing challenge in accessibility research (Mao & Nekorchuk 2013; Neutens et al. 2013), and movement speeds vary from author to author. The pedestrian speed used in Figure 5 is 3 kilometres per hour, or circa 0.83 meters per second. Walking 10 minutes at the speed of three kilometres per hour approximately equates to a projected reach of a 500m linear distance buffer (fig. 5 for comparison). Conversely, the movement budget of 10 minutes (600 seconds) has a different catchment isochrone shape than its equivalent buffer. The network budget is expended according to the length of network segments traversed and the speed assigned to each segments. Therefore, the least-cost path chosen by the methodology to generate the isochronal catchments may differ profoundly to a buffer. The discrepancy between buffer analysis and isochronal analysis catchment shapes increases as the buffering distances and network budgets increase (fig. 5 & fig. 7).

The problem with isochronal analysis applied for accessibility research is that it does not model distance decay and it assumes uniform catchment accessibility scores. Although edge effects are addressed by essentially allocating the highest service accessibility scores to population points equidistant to multiple service points, the implication of this is misinformed. Just because multiple services are within reach with the allocated distance budget that does not mean the population point has good accessibility to those service points. For example, if the isochronal catchments are calculated for 20 minute driving distance, there could be many service points available depending on the service. The accessibility score will be highest for population points positioned on the intersection of multiple service point catchments. However, is accessibility to a service in reality better when one has access to ten services within 20 minutes driving distance, or if one has access to one service point within one minute walking distance? That is why isochronal analysis has been defined as a method better suited for analysing service availability. Most of the recent accessibility analysis methods apply an isochronal analysis based on network travel costs as a step in the process of calculating final accessibility scores (Guagliardo 2004). However, the network analysis step is supplemented by additional stages wherein various measures are applied. Measures such as distance decay, variable network friction, service utilization costs, supply and demand weighting of accessibility scores, etc.

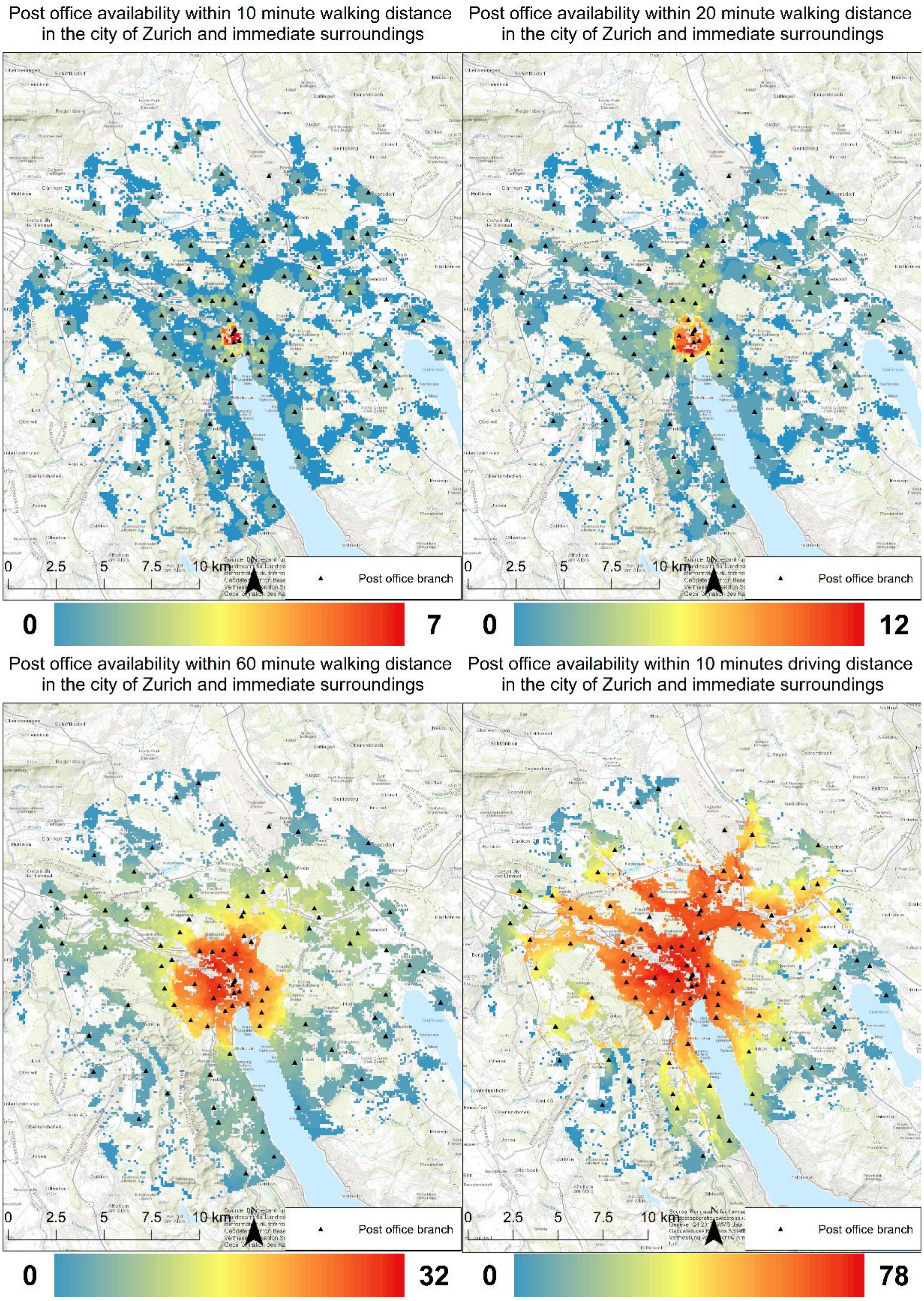

Figure 7. Author example of isochronal analysis modelling walking and driving distance catchment derived availability, colour ramp indicates number of post offices available for a population point.

In general, catchment analysis methods yields more informative results when applied on larger geographic scales. Furthermore, service availability is best applied when comparing regions (Guagliardo 2004). Hence, larger geographic scales improve the impact of the results. In either case, network distance based methods are especially susceptible to variations when applied to urban space, due to distances tending to be small and network friction values reflecting profoundly on the results (Radke & Mu 2000).

2.1.2.2. Service accessibility methods

Service accessibility methods introduce proper supply and demand relations by modelling service supply and putting it in relation to estimated service demand, which is almost exclusively based on data of resident populations (Hansen 1959; Domanski 1978; Joseph & Bantock 1982; Townsend 1987; Talen & Anselin 1998; Radke & Mu 2000; Nicholls 2001; Hewko et al. 2002; Luo & Wang 2003; Guagliardo 2004; Smoyer-Tomic et al. 2004; Zenk et al. 2005; Apparicio & Seguin 2006; Yang et al. 2006; Luo & qi 2009; McGrail & Humphreys 2009; Smith et al. 2010; Salze et al. 2011; Zhank et al. 2011; Delafontaine et al. 2012; Neutens et al. 2012a, 2011, 2012b; Mao & Nekorchuk 2013; Kraft 2016; Tenkanen et al. 2016; Tenkanen 2017). An alternative approach by Tribby & Zandbergen (2012) estimated service demand for public transport by average income of administrative units. The results indicated that optimization of public transport accessibility provides greater utility to lower income areas in terms of percentage of time saved on public transit. Another alternative to resident population are daily activity spaces (Hägerstrand 1970; Delafontaine et al. 2012; Neutens et al. 2012a, 2012b, 2013). Daily activity space is the part of geographic space within which the locations of fixed activities are positioned for individuals. Individuals would spend considerable portions of the day during such fixed activates; e.g. at home for sleeping, at the workplace for working, etc. This corresponds to the capability constraints by Hägerstrand (1970), which can manifest in space as fixed daily activities around which time has to be planned and used (Neutens et al 2012a, 2011, 2012b). The parameters and components of accessibility research will be considered in detail within the Second chapter. This subsubsection will provide an overview of the most relevant accessibility methods and authors which contributed to the development of the methodology chosen for this master thesis.

Guagliardo (2004) emphasises that availability concerns the number of service points while (spatial) accessibility necessitates some type of travel impedance, either distance or time, between supply and demand. Further, he outlines four categories of spatial accessibility methods (Guagliardo 2004):

- Provider-to-population ratios: These are methods which focus on the supply and demand relationship within an administrative or a geographic unit. The supply and demand ratio is calculated by dividing total region supply with total region demand. The outcome is a robust indicator of service provision (Joseph & Bantock 1982), which is suitable for comparison with other regions. Hence, the provider-to-population ratio methods are basically catchment analysis methods which take into account not only service supply, but also population demand. However, this is in contradiction with the definition of accessibility requiring some measure of travel impedance (Guagliardo 2004). Furthermore, Guagliardo (2004) stresses the simplistic nature of these methods, as well as their numerous deficiencies; edge effects, the MAUP, lack of distance decay, service points choice weights, and spatial uncertainty due to differing region shapes.

- Travel impedance to nearest service: This is essentially a set of distance to feature measures which derive accessibility scores based on network distance, supply and demand ratios, and basic distance decay. Thus, accessibility is weighted inversely proportional to distance. It is possible that a farther service point, which has greater supply than a closer service point, could be assigned a higher accessibility score than the closer service point. However, if the accessibility score is weighted by distance, the closer service point can have a better accessibility score despite lower supply. This models the higher likelihood of the population choosing closer service even if quality is lower than farther services (Joseph & Bantock 1982; Guagliardo 2004; Mao & Nekorchuk 2013). The travel-impedance to nearest service methods are better suited for individual accessibility research, rather than research on regional accessibility. This group of methods avoid uniform regional accessibility problems and edge effects due to aggregating scores onto population points. However, to properly model the intra-regional accessibility variation, a very granular dataset of population points is necessary which frustrates application (Luo & Wang 2003).

- Average travel impedance to provider: These methods seek to derive regional accessibility scores from individual accessibility scores. First, the individual accessibility scores are calculated for all population or service points within a region. Then, these scores are summed up, averaged, and interpreted as the regional accessibility score. The purpose of these methods is to facilitate comprehension of the accessibility situation in the region and enable comparison with other regions. However, when assigning an average accessibility score to a region, uniform regional accessibility is assumed and the accessibility of service points on the edges of the region is overestimated (Guagliardo 2004).

- Gravity decay models: The final group of spatial accessibility methods defined by Guagliardo (2004) are gravity decay models. This group is described in greatest detail and presented as the state of the art. Gravity decay models are used to calculate potential accessibility of individual points to all other individual points within a region. The gravity decay model was introduced in accessibility research by Joseph & Bantock (1982) when calculating potential accessibility to healthcare. The potential accessibility is based on a combination of supply and demand ratio, and the travel impedance to nearest service method. Once the accessibility score is calculated based on supply and demand within network catchments, the scores are weighted according to the network distance traversed. The accessibility of farther services is lower while the accessibility of closer services is increased. The manner of this weighting is an ongoing challenge and varies from author to author. Examples are linear distance decay, proportional decay (e.g. inverse distance), Gaussian decay, or concentric decay thresholds (Guagliardo 2004). Essentially, gravity decay models compound combine accessibility and methodology aspects of the other three categories. Hence, their application scope is the greatest and the calculated results better conform to spatial logic.

Therefore, of these four methods, gravity decay models are the most prevalent (Radke & Mu 2000; Luo & Wang 2003; Guagliardo 2004; Yang et al. 2006; Luo & Qi 2009). Guagliardo (2004) presents the basic structure of a supply and demand weighted gravity decay model with the following formula:

$$A_i = \sum_j \frac{S_j}{d_{ij}^{\beta} V_j}$$

Where, A_i is the accessibility score of population point i. S_j is the supply at service point j. d represents the travel impedance (time or length) between the population and the service point. β represents the gravity decay coefficient. Lastly, V_j is the cumulative demand of all population points within assigned travel impedance to service points j. Thus, the individual potential accessibility at point $\boldsymbol{i}$ is derived from the sum of service supply in service points j within travel impedance d, divided by the total competition from other population points which are within d distance to j (Joseph & Bantock 1982). The Achilles heel of gravity models are the gravity decay coefficients. No theoretical framework exists on which weights to assign to which service (Guagliardo 2004), and there are several viable options available. With this model, accessibility improves if more service points and more service supply is available, or if less demand utilized the same service points. Likewise, accessibility would improve if travel impedance decreased due to more or better network links, faster travel speeds, and larger network travel budgets.

2.1.2.2.1. FCA - Floating catchment area methods (FCA) and variants

The Floating catchment area method (FCA) was first applied (per Luo & Wang 2003; Guagliardo 2004) by Zhong-Ren Peng (1997) in his research on the balance of jobs and housing in Portland, Oregon. The jobs-housing balance is the spatial relationship between the number of jobs and housing units within an area (Peng 1997). However, the existing methods for calculating this balance were overly geodeterministic and precluded the possibility of trans-boundary commuting. Hence, Peng (1997) applied the then novel GIS to calculate buffer catchments over local traffic zones (akin to small scale census tracts). Each traffic zone was essentially a service and population point in one. The FCA method applied in this scenario calculated the cumulative number of jobs and housing within a 5 mile buffer around traffic zone centroids. These values were then put into relation as the job-housing ratio and aggregated at the corresponding traffic zone polygon. The derived ratio represented the commuting potential of a traffic zone (Peng 1997; Luo & Wang 2003). The application of the FCA method avoided the issue with edge effects, trans-boundary commute, and arbitrarily defined analysis units (MAUP) (Peng 1997).

Similarly to the application by Peng (1997), a variation of FCA was applied when generating the isochronal availability scores in figure 7 within the previous subsection. Service layer zones were generated with network analyst for post office branches in Zurich. The chosen travel impedance were 10 minute driving distances at municipal speed limits. Each generated isochronal catchment contained the service supply capacity of the post office branch from which it was generated. Thus, the regional service supply was floated above population points, with lots of overlaying polygons in certain areas of the city. The overlaid supply values were spatially joined with the population points (merge parameter was set to "SUM" for the field of supply capacity). The result was an individual availability value derived from a regional availability model. However, it is possible to transform the availability score into an accessibility score if the ascribed supply capacity for each population point is divided by the demand, i.e. the number of people within the population point. The values calculated tend to be miniscule since population demand is modelled by resident population size. Thus, in most cases the numerator (the service capacity) is many times smaller than the denominator (population demand) (e.g. Radke & Mu 2000; Luo & Wang 2003; Luo & Qi 2009). For ease of comparison, the accessibility values are normalized to a range between 0 and 1. In any case, the accessibility scores generated within potential accessibility research are not necessarily intuitive values, nor are they readily comparable to other regions (Luo & Qi 2009). They should be considered indices of deprivation (Townsend 1987) relative to the study region accessibility averages and the accessibility scores of all other points within the study region. Therefore, normalizing the values into the value range between 0 and 1 facilitates comprehension while not deducting from the meaning nor application of the results. Figure 8 presents the side-by-side comparison of 10 minute driving distance isochronal availability scores (left map) and accessibility scores (right map). Although generated with one of the simplest accessibility methods available (Guagliardo 2004), the accessibility score map in figure 8 exhibits results profoundly different in meaning and logic than the availability score map. Spatial accessibility methods produce results of greater relevance to expected spatial logic and allow for greater intra-regional accessibility score variance. Although edge effects are still presents (and unless the entirety of geographic space is analysed, edge effects will remain), the supply/demand ratios allocated significantly lower potential accessibility scores to inner city areas (fig. 8 right), as opposed to the availability calculation (fig. 8 left) which does not implement supply/demand ratios.

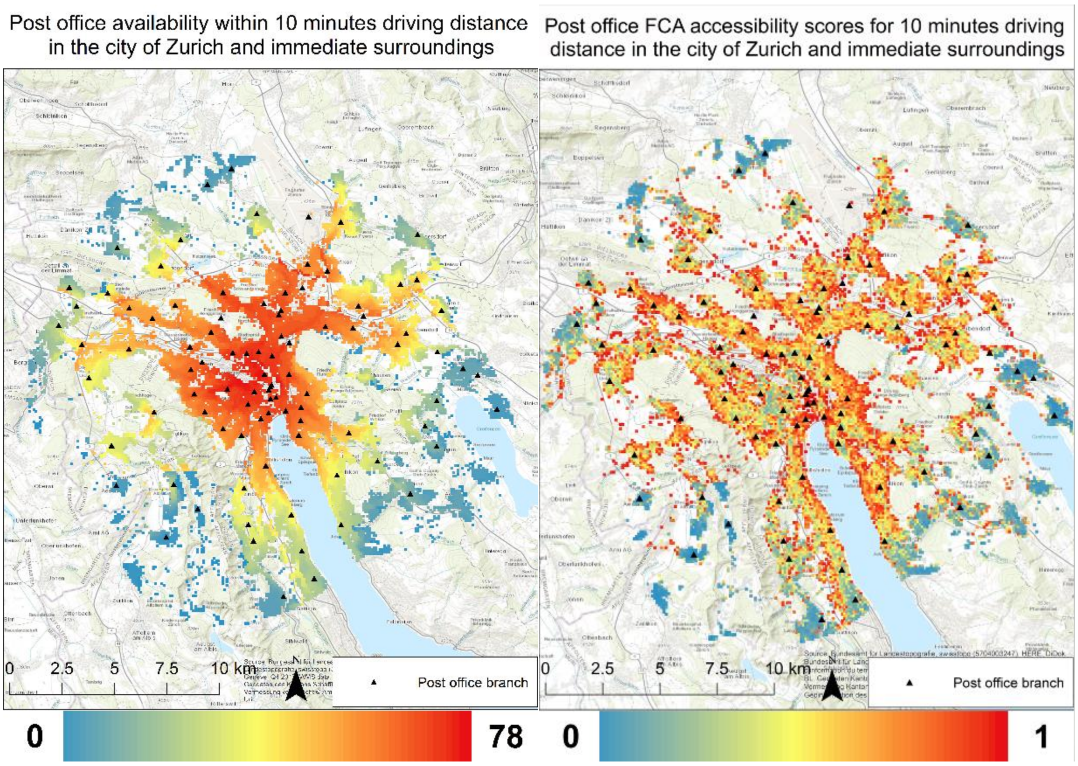

Figure 8. Comparison of isochronal availability scores and from them derived FCA accessibility scores. Colour ramps represent number of available post office branches for population points (left map), and the post offices accessibility score for population points (right map).

2.1.2.2.2. 2SFCA – Two step floating catchment area method

The two-step floating catchment area method (2SFCA) of spatial analysis was first implemented by Radke & Mu (2000) with the purpose of allocating public service supply within a region so that maximum coverage was achieved for the population. The existing system of public service delivery in Northern California relied on an unevenly distributed network of service points. The goal of the 2SFCA method was to redistribute the service points in order to achieve a spatially more equitable distribution. However, the method applied was described by Radke & Mu (2000) as a variant of polygon feature-to-polygon feature location allocation and defined as a spatial decomposition model (Luo & Wang 2003; Luo & Qi 2009). The term two-step floating catchment area (2SFCA) was coined three years later by Luo & Wang (2003) to reflect the conceptual and methodological continuity of the 2SFCA with the FCA methods. In any case, the Meritum of the 2SFCA method is that it is a multi-staged catchment analysis which distributes supply and demand over an area in order to achieve results more in line with spatial logic and expectations.

2SFCA method flow (per Luo & Wang 2003):

Step 1: For each service point $\boldsymbol{j}$, search all population points ($\boldsymbol{k}$) that are within a threshold travel time ($\boldsymbol{d_0}$) from service point $\boldsymbol{j}$ ($\boldsymbol{k}$ intersects $\boldsymbol{j}$ catchment), and compute the service demand (capacity-to-population) ratio $\boldsymbol{R_j}$ within the catchment area.

$$R_j = \frac{S_j}{\sum_{k\in\{d_{kj}\le d_0\}} P_k}$$

Where $\boldsymbol{P_k}$ is the population demand in population point **k** which intersects with the catchment of service point $\boldsymbol{j}$, i.e. the travel time $\boldsymbol{d_{kj}}$ is less than the threshold travel time $\boldsymbol{d_0}$ $(\boldsymbol{d_{kj}} \le \boldsymbol{d_0})$. $\boldsymbol{S_j}$ is the service capacity in service point $\boldsymbol{j}$, and $\boldsymbol{d_{kj}}$ is the travel time between $\boldsymbol{k}$ and $\boldsymbol{j}$.

Hence, the first step of 2SFCA sums up the demand present in service point catchments. The value of **Rj** represents the population competing over access to limited service supply in geographic space. This process effectively decomposes demand values from discrete points into the space of the region. However, the calculated population point demand to supply ratio is uniformly distributed over the service point catchment, which is unrealistic (Wang & Luo 2003). Therefore, the first “floating” value is assigned to catchments (floating supply/demand ratio over service points).

Step 2: For each population point $\boldsymbol{i}$, search all service points ($\boldsymbol{j}$) that are within the threshold travel time ($\boldsymbol{d_0}$) from location $\boldsymbol{i}$ (that is, intersect catchment of $\boldsymbol{i}$), and sum up supply/demand ratios, $\boldsymbol{R_j}$, at these locations.

$$A_i^F = \sum_{j\in\{d_{ij}\le d_0\}} R_j$$

Where $\boldsymbol{A_i^F}$ represents the accessibility at population point $\boldsymbol{i}$ based on the two-step FCA method, $\boldsymbol{R_j}$ is the service capacity-to-population demand ratio at service point $\boldsymbol{j}$ whose centroid intersects the catchment of $\boldsymbol{i}$, that is $(\boldsymbol{d_{ij}} \le \boldsymbol{d_0})$, and $\boldsymbol{d_{ij}}$is the travel time between $\boldsymbol{i}$ and $\boldsymbol{j}$. A larger $\boldsymbol{A_i^F}$ indicates a better accessibility at population point $\boldsymbol{i}$.

Hence, the second step of the 2SFCA method sums up service capacities of all service point j catchments ($\boldsymbol{R_j}$) which overlay population point $\boldsymbol{i}$ as an accessibility measure $\boldsymbol{A_i^F}$. The larger the value of $\boldsymbol{A_i^F}$, the higher the spatial accessibility at point $\boldsymbol{i}$ is.

Figure 9 demonstrates the 2SFCA applied on the example of post office accessibility in the city of Zurich. The application of distance decay improved on the FCA results for the same region (fig. 8). The overestimation of accessibility in fringe areas with low population was negated with distance decay. Also, the lower accessibility in inner city areas with higher populations was addressed by the distance decay. Furthermore, zones of higher accessibility follow transport corridors of high speed limit roads, and multimodal transport options (bus/tram/train). Although there is less on-map variance compared to the FCA (fig. 8), the results of the 2SFCA (fig. 9) are more logical and grant a better insight into the service provision system of the study regions.

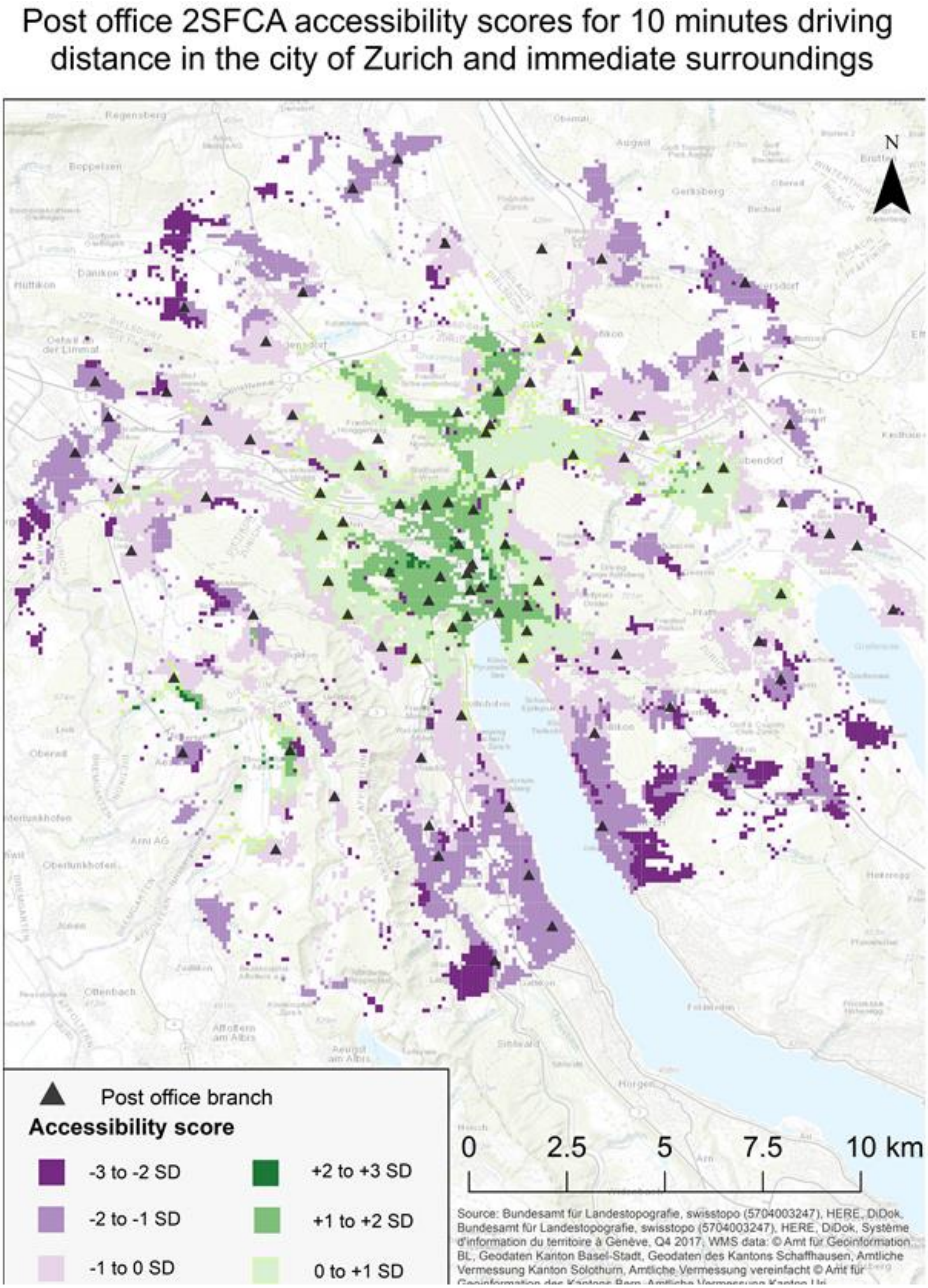

Figure 9. Author example of 2SFCA accessibility for 10 minute driving distances in the city of Zurich. Accessibility scores are normalized classified by standard deviation from the median value (pre normalization median = 0.010973).

To summarize, the 2SFCA calculates spatial demand for services and assigns them to service points during the first step. The second step generates population point catchments and sums up the service demand value of each service point within the population point catchment. The generated value is the accessibility score for the population point. When implemented, the 2SFCA (and E2SFCA) method creates a complete matrix of origin-destination data between each population point and each service point (Luo &Wang 2003; Luo & Qi 2009). Thus, the processing load of the 2SFCA methodology rises exponentially with the amount of service and population points modelled. This is compounded by the solving of the service area layers for each catchment generated, which precludes implementation of the methodology on large scales without adequate hardware.

2.1.2.2.3. E2SFCA – enhanced two step floating catchment area method

The potential of the 2SFCA method was recognized by several authors in the first decade of the 21st century. However, the deficiencies of the 2SFCA method were also scrutinized and outlined in detail (Luo & Wang 2003; Guagliardo 2004; Luo & Qi 2009; Neutens et al. 2010a, 2011, 2012a, 2012b; Delafontaine et al. 2012; Mao & Nekorchuk 2013; Tenkanen 2017). The 2SFCA assumes uniform supply/demand ratios for the generated catchments both in the first and second step. This could be addressed by introducing gravity decay to the supply/demand ratio. This was done through the enhanced 2SFCA (E2SFCA), which introduces distance decay to both steps of the method (Luo & Qi 2009). Guagliardo (2004) presented an intermediary solution of using kernel density estimators to model Gaussian distance decay on top of service and population points. He argued, and corroborated with existing medical research, that individuals are more likely to utilize closer facilities rather than farther when utilizing healthcare services (Guagliardo 2004). Most striking was that people were willing to forgo higher quality of service if sufficient utility could be gained through saving time. Since healthcare is indubitably one of the functions with the greatest degree of functional centrality, the fact that individuals are willing to forgo quality for proximity furthers the argument for gravity and distance decay in 2SFCA. The Gaussian kernel method applied by Guagliardo (2004) substituted the first step of the 2SFCA by generating a 3D catchment on top of service points, within which the service point supply was unevenly distributed as opposed to the uniform distribution in regular 2SFCA catchments. The allocated population demand was weighted by distance to the service point. Thus, the closest population points participated with the greatest proportion of their demand, while farther population point's contributions were decreased. Thus, 60% of aggregated demand was contributed by the first standard deviation of population points by network proximity. The results were accessibility patters more consistent with expected spatial logic, as well as the discovery of spatial discrepancies in primary healthcare delivery within Washington D.C. which could be ascribed to known racially or socioeconomically driven urban processes (Guagliardo 2004). Therefore, the Gaussian kernel method weights the demand side of the 2SFCA analysis for gravity decay and represents the intermediate step leading to the E2SFCA.

The enhancements to the 2SFCA method implemented by Luo & Qi (2009) are weights applied to both the supply (step 1) and demand (step 2) part of the 2SFCA method. These weights serve to differentiate different travel time zones for the purpose of modelling distance decay effect on service choice by a population. The catchments of service points j are determined as 30 minute travel time zone (per Lee 1991), and these 30 minute travel time catchments are segmented into three equal, 10 minute, zone (zone 1, zone 2, zone 3). Normally distributed distance decay according to the Gaussian function by Kwan (1998) and Wang (2007) are applied to the three 10 minute travel time zones (Luo & Qi 2009). The logic behind this choice assumes that the population is more likely to congregate at closer service points rather than farther ones (since in a 30 minute car drive catchment there is likely to be more service point choices).

Hence, the E2SFCA formula for the first (supply) step is (Luo & Qi 2009):

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

Whereas ***Dr*** is the added threshold travel time zone from service point j (d0 in 2SFCA), while $\boldsymbol{W_r}$ is the distance weight function for the individual travel zone (r = 1,2,3) calculated from the Gaussian function.

The second (demand) step of E2SFCA is:

$$A_i^F = \sum_{j \in \{d_{ij} \leq d_0\}} R_j W_r$$

where ***AFi*** represents the accessibility of population at location i to physicians, Rj the physician-to-population ratio at physician location j that falls within the catchment centered at population i (that is, ***dkjADr***), and ***dij*** the travel time between i and j. The same distance weights derived from the Gaussian function used in step 1 are applied to different travel time zones to account for distance decay. This applies a separate set of distance decay weights to the population side of the 2SFCA according to the same Gaussian function used in step 1. This effectively removes the issue of uniform regional accessibility of the 2SFCA method by modelling distance-dependent variability in choice probability. This assumption is in line with the First Law of geography and Luo & Qi (2009) have proven their E2SFCA method more effective in modelling spatial logic than the basic 2SFCA method (fig. 10). Whereas the 2SFCA more uniformly distributes accessibility across the region, the E2SFCA produces pronounced gradients and gradual dynamism in potential accessibility isolines (Luo & Qi 2009; Wan et al. 2012).

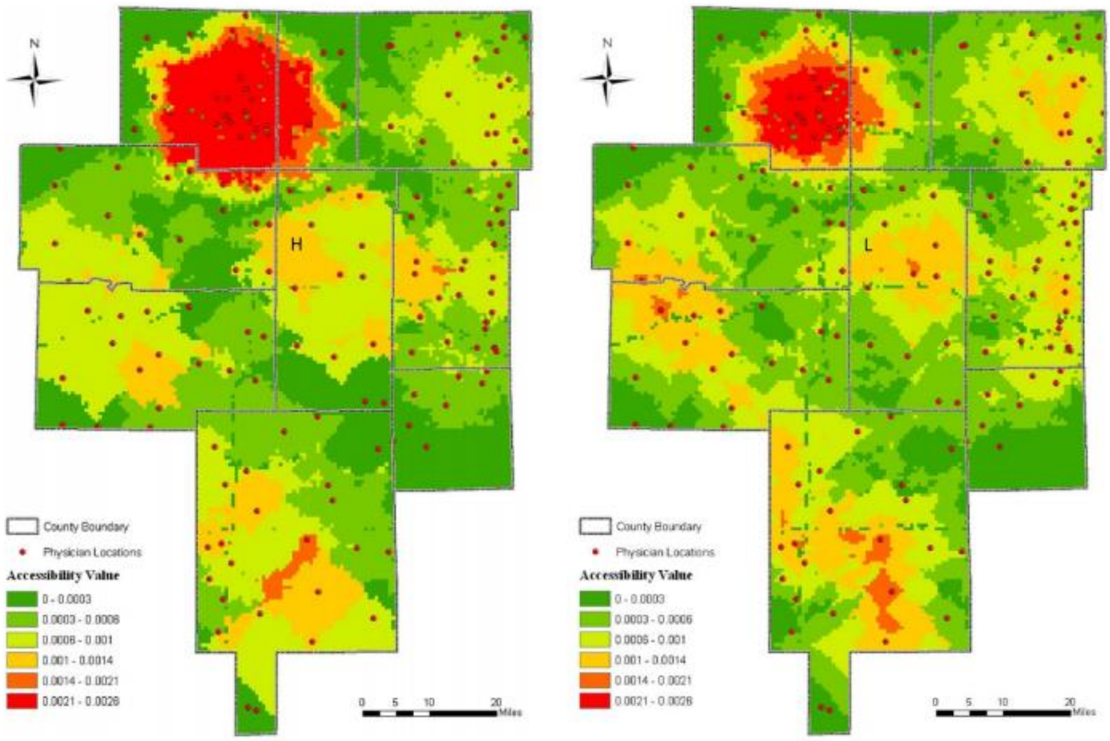

Fig. 2. Result of 2SFCA method.

Fig. 3. Result of E2SFCA method applying weight 1.

Figure 10. The difference in spatial accessibility results generated by the 2SFCA (left) and the E2SFCA (right) method. (Luo & Qi 2009)

However, the weights applied in E2SFCA are untested empirically and they are essentially arbitrary. This likely is the reason a Gaussian decay is often chosen; it is intuitive, and theoretically consistent with expected spatial logic (Tobler 1970). Nevertheless, comprehensive research on accessibility research gravity weights remains one of the greater research gaps (Guagliardo 2004; Luo & Qi 2009; Neutens et al 2011; Mao & Nekorchuk 2013). Luo & Qi (2009) present the case that the decay functions could be weighted based on reasonable assumptions about the service modelled. Thus, services of higher functional centrality (e.g. healthcare) would be assigned slower decay functions, while spatially more prolific services (e.g. leisure) could be assigned higher decay functions.

2.1.2.3. Spatio-temporal accessibility methods

What separates spatio-temporal accessibility from spatial (or temporal) accessibility are certain temporal constraints which act to modify the environment and inputs of the methodology with the goal of improving the quality of the results. The definition of spatio-temporal accessibility chosen in this master thesis is:

Spatio-temporal accessibility is the measure of temporally constrained spatial accessibility.

This definition is based on the body of research pertaining to the most recent phase of accessibility analysis. It concerns the time-geography aspect of accessibility and applies it through four temporal accessibility constraints; multi-modal transportation (Luo & Qi 2009; Mao & Nekorchuk 2013; Tenkanen et al. 2016), daily and weekly variation in supply, demand, and network parameters (Delafontaine et al 2012; Neutens et al. 2011, 2012a, 2012b; Järv et al. 2018), service utilization costs (Neutens et al. 2012b), daily fixed activities and time budgets (Neutens et al. 2010b, 2013). The mentioned authors define their work as either person-based, or place-based (spatio-temporal) accessibility research. This is in contrast with the classical division into potential and realized accessibility, or regional and individual (discrete) accessibility (Joseph & Bantock 1982; Guagliardo 2004; Luo & Qi 2009). Realized accessibility remains the goal and a great research gap even in latest phase of accessibility research. However, potential accessibility is improved by emphasising the human aspect in guiding parameter choice, values, foci etc. (Delafontaine et al. 2012; Neutens et al. 2010a, 2010b, 2011, 2012a, 2012b, 2013).

The orientation on human-based accessibility is based on time-geography theories of Thorsten Hägerstrand (1970). Humans are conditioned in their traversal of space and time by certain constraints which can manifest in reality as barriers or corridors. The capability constrains which pertain to the biological and political individual condition the possible locations and positions an individual may occupy at a given time. The most important application of this is the introduction of the concept of daily fixed activities, upon which accessibility is anchored. Instead of being dependent on a service point and a population point for calculating accessibility, it is possible to treat services as a true spatial resource which may or may not be utilized in between fixed activities (Neutens et al. 2010a, 2010b, 2011). Furthermore, by placing the emphasis of temporal constraints upon the time budgets of individuals, the approach to service point accessibility has modified as well. Instead of just the intra and inter-regional variation of potential accessibility scores, the focus is shifting to daily and weekly variation in potential accessibility (Neutens et al. 2011). For example, Tenkanen et al. (2016) analyse the variation in accessibility scores to supermarkets during work hours, the evening, and the night. They rightly point out that modern employment trends are not bound to 9-17 or 8-16 jobs anymore. Instead, night shifts are becoming more and more prevalent (Tenkanen 2017), hence night-time accessibility is a necessity. Night-time accessibility problems are compounded by lack of public transport opportunities outside of the workhours and early evenings. Therefore, the question of multimodal transport in geographic space is omnipresent within recent research (Neutens et al. 2010, 2011, 2012a, 2012b, 2013; Delafontaine et al. 2012; Mao & Nekorchuk 2013; Tenkanen et al. 2016; Tenkanen 2017; Järv et al. 2018). The variable travel speeds by multimodal transport can reveal new insights into the spatial logic of accessibility, as well as help recognize system deficiencies which might have been missed if only automobile/pedestrian travel modes were considered (Tenkanen et al. 2016; Tenkanen 2017). Thus, modern spatio-temporal accessibility research network datasets conform to both private, and public motor transport, pedestrian and bicycle movement, railroads and bus systems (Mao & Nekorchuk 2013; Tenkanen 2017).

Furthermore, in the globalised economy it is daytime somewhere on the planet at every moment of the solar day. The professional obligations of the near future might be even less constrained by the legacy of the diurnal cycle (Goodchild et al. 1993). Thus, time as a resource is gaining in value. Consequently, the question of individual temporal resources available to be invested into non-fixed activities has become the central parameter of spatio-temporal accessibility analysis. The time-budget assigned to accessibility determines the spatial extent of mobility (Delafontaine et al. 2012), increased spatial possibilities (Neutens et al. 2011), quality of life (Mao & Nekorchuk 2013), the potential for social interaction (Neutens et al. 2013), access to higher quality of services (Luo & Qi 2009) etc. For that reason, if accessibility research can facilitate the preservation of the individuals' temporal resources, it has succeeded in its civilizational mandate. Far from privatizing spatio-temporal advantage for the privileged and the informed, spatio-temporal accessibility analysis can assist in the reorganization of society and public structures so they could be of better service to the population (Neutens et al 2012a). For example, Neutens et al. (2011, 2012a) used spatio-temporal accessibility analysis to uncover gaps in public service delivery in the city of Ghent. The socioeconomic and social transformation of the family into dual earner (and thus dual worker) households has induced local government to rethink their public service delivery (Neutens et al. 2012). The researchers uncovered a discrepancy in working hours and expected fixed daily activities of the average citizen: public services were open during the time of day when the average citizen was at work. Hence, public services could be better utilized if they remained open longer (fig. 11).

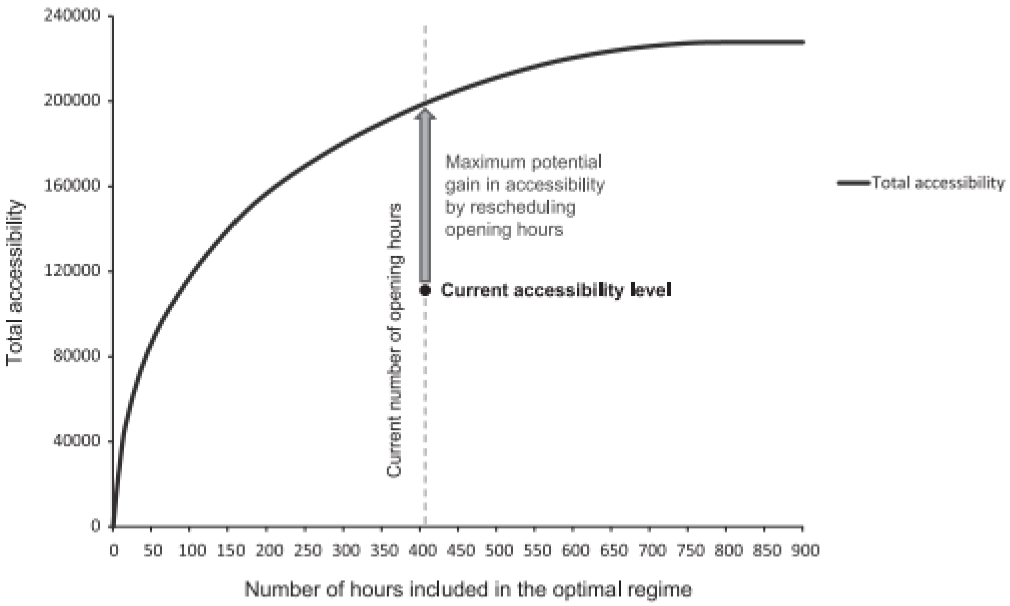

Figure 11. Calculation of grand-scale time economy benefits in optimizing public service delivery. (Neutens et al. 2011)

Conversely, Tenkanen (2017) strives to quantify public transport competitiveness. Competitiveness is equated to the spatio-temporal accessibility a transport mode enables. E.g. if public bus transport provides higher accessibility scores than private motor transport, then the public bus more competitive. Tenkanen (2017) includes multiple micro-temporal and mezzo-temporal parameters. Accessibility variation is calculated by day in week, by day, night, and evening, a further by traffic congestion. Thus, the competitiveness of different transport modes varies dynamically. The importance of quantifying the results of spatio-temporal accessibility research is in the improved impact the results will potentially have in science and society. Tangible numbers of temporal resources saved through better understanding spatial logic of service provision will help disseminate the results of accessibility research. Tenkanen (2017) demonstrated the gap in night-time public transportation competitiveness, which may be acted upon by local authorities in order to provide more consistent services to the citizenry. Furthermore, if the temporal resources are quantified in terms of monetary resources, impressive numbers can be conjured with the right time span and research implementation assumed. The conservation of 10 minutes in the daily time budget of a thousand individuals amounts to cca. 60830 hours in a year. These temporal resources can be repurposed for self-improvement or even productive enterprise from which the entire society benefits.

Lastly, the introduction of service utilization costs (e.g. Neutens et al. 2013) is the final aspect of recent spatiotemporal research which should be explained. In reality, all accessibility research ignores over half the process when deriving accessibility potentials. It is assumed that it is enough to be able to reach a service and have adequate supply and demand rations to consider that service accessible. However, when individuals utilize services, they first have to reach the service from their fixed activity locations. This part is modelled by classical methods. However, upon reaching a service, a certain amount of time has to be devoted to utilizing the service in question. This amount of time varies from service to service (Mao & Nekorchuk 2013). However, this is not the end. Upon utilizing a service, the individual has to leave the service and return to their point of fixed activates. These three components of spatio-temporal accessibility constraints all partake in the total time budget allotted for accessing the service. Thus, classic accessibility methods appropriately model only one third of the total temporal investment (Delafontaine et al. 2012). However, it is possible to introduce service utilization costs into E2SFCA, which would improve the quality of its results. This is one of the goals of this master thesis.

2.1.2.3.1. Social interaction potential

The concept of social interaction potential is the topic of spatio-temporal accessibility analysis in the body of work by Neutens et al. (2007, 2010b, 2013) which concerns the spatio-temporal windows for socialization between individuals. It is a person-based accessibility approach which sets parameters according to the expected daily routines of the average individual; two fixed activities, the commute between them, and a limited time budget to traverse space. The theoretical concepts of socialization potential (Neutens et al. 2013) are based on the work of Thorsten Hägerstrand (1970). The purpose of this application of spatio-temporal accessibility research is to uncover spatial trends conditioning social interaction and also better understand how the geography of urban areas affects spatial logic of socialization (fig. 12). The Meritum of the social interaction potential is the intersection of two individual's space-time prisms (fig. 3 on page 17).

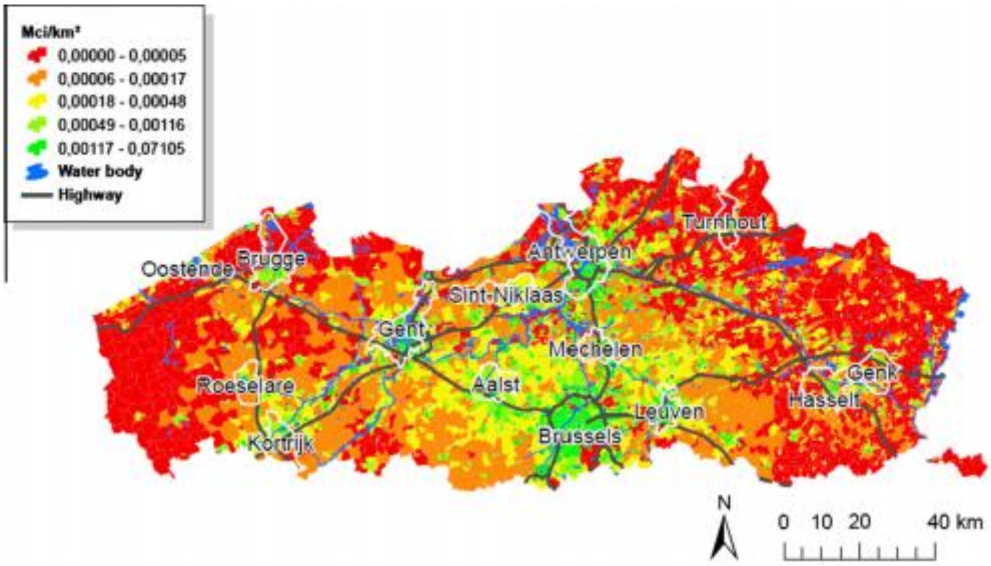

Figure 12. Map of social interaction potential in Flanders. (Neutens et al. 2013)

While an interesting application, the topic of social interaction potential requires data on realized individual accessibility and mobility (Neutens et al. 2013). In the absence of such a dataset, human activity had to be assumed to be uniform from person to person; a modal case (Hägerstrand 1970) in which an equal after-work time budget of 90 minutes was allocated to all population points. This research is unique in that is does not rely on a service and a population point to calculate accessibility to socialization (socialization potential). Instead, the service supply is derived from the intersection of the time-space prisms anchored in two fixed daily activities; work and habitation (Neutens et al. 2013). This method thus constitutes an atypical method of accessibility analysis. In due time, the datasets necessary to properly implement it might become available through remote sensing or large scale social experimentation. Hence, this application and approach is, to the best knowledge of the author, the latest accessibility research method developed. Although the 2SFCA methods are better suited for accessibility research on fixed services (Neutens et al 2013), the social interaction potential and its successors open up new applications and topics in social science and classifying human behaviour and activity zones through GIS (Neutens et al. 2013).

2.2. Research gaps

In summary, the progress and development of accessibility research methodologies has overcome a multitude of challenges. What began as simple Euclidean buffers (Jefferson 1924), has translated into GIS modelling and prediction of complex human behaviour based on time functions (Järv et al. 2018). Most significantly, accessibility research has overcome the application bottleneck of healthcare thanks to the development of new and improved methods. Thus, accessibility is becoming more and more multi-disciplinary (Tenkanen 2017). However, what began with geography has through GIS become methodologically entrenched in geography. Modern accessibility is unfeasible without GIS software (Radke & Mu 2000; Miller 2017), and GIS software is incomplete without the worldview and expertise of geography and GIScience (Duckham 2015).

However, the progress of accessibility research has not overcome several long-standing and newer research gaps. The concept of realized accessibility research remains unrealized. The logistics necessary to undertake a proper realized accessibility analysis are prohibitive to lone initiative (Joseph & Bantock 1982; Guagliardo 2004). Thus, the impulse to conduct such a research would have to originate from several sciences. Unfortunately, potential accessibility is an empirically untested concept which reduces reality to a set of uniform assumptions without which the research would be unrealistic. However, if realized accessibility could be achieved in sufficient scope, it would improve the perception and value of all accessibility research by validating or invalidating potential accessibility results.

The issue of assumptions and modelling is another research gap within accessibility research. The various spatial and temporal parameters which are necessary to conduct accessibility analysis lack proper methodological and empirical research or verification (Guagliardo 2004; Delafontaine et al. 2012; Mao & Nekorchuk 2013). Thus, accessibility research lacks a comprehensive framework which would facilitate the selection of values for gravity decay, weights, utilization costs, travel impedance, demographic subsets for demand, total time budgets, and an objective point of reference against which to evaluate results.

The question of edge effects and MAUP (Guagliardo 2004) remain a concern when deciding on spatial scope and application. Furthermore, there is still a deficit of holistic service accessibility research; research which would attempt to encompass a wide array of services the population of a study region would seek access to on a regular basis (Salze et al. 2011).

Also, most of the recent accessibility research has been undertaken within altogether four countries; the USA, Canada, the UK, and Belgium. There is a research gap pertaining to the application of modern accessibility methods in different geographic settings (Tenkanen 2017).

Finally, there is still a need to keep developing place-based accessibility measures, especially the 2SFCA family of methods. These methods have proven informative in their results (Luo & Qi 2009; Wan et al. 2012), and are likely to remain the mainstay of spatial accessibility research due to their simplicity of application and data requirements. Despite the methodological initiative being on person-based spatio-temporal accessibility, it is likely that the 2SFCA derived accessibility methods will be made available to wider scientific audiences through GIS proliferation and extension packages which automate the process (Langford et al. 2014). Therefore, there remains the research gap and interest involving the improvement of the 2SFCA methods through the implementation of spatio-temporal accessibility parameters and considerations.

2.3. Thesis aims and hypothesis

The aim of this master thesis is to apply a custom modified E2SFCA methodology to analyse the service provision system within the Kanton of Zurich, Switzerland. A further aim is to upgrade the baseline E2SFCA method with spatio-temporal accessibility parameters and thus conduct a spatio-temporal accessibility analysis. The final aim is to evaluate the applied methodology and its uncertainties through a sensitivity analysis. As the final stage in the academic journey, this master thesis is a synthesis of five years of education in geography. Therefore, goal is to further the science through fulfilling the above set aims and thus addressing several recognized research gaps as well as producing outputs relevant and interesting for the wider society.

The research process will be structured through the following research questions and their corresponding hypotheses:

RQ 1: How are services accessible, spatio-temporally, to the population of the chosen study region?

Hypothesis 1: Service accessibility will conform to the spatial logic of urban areas; inner city areas will exhibit the highest accessibility scores while the second highest will be along transport corridors due to higher network speeds. Spatio-temporal accessibility parameters will lower service accessibility in spaces between centres of concentration.

RQ 2: What are the fundamental patterns of service accessibility scores in relation to population points in the study region urban spaces?

Hypothesis 2: Higher service accessibility scores are likely to be concentrated towards higher population density areas due to the service supply conforming to the population demand. Furthermore, higher accessibility scores will be concentrated in inner city areas due to higher concentration of service points.

RQ 3: How can the supply capacity of service points be estimated in absence of empirical data?

Hypothesis 3: The total number of individual services in a region within a free society is governed by market and spatial logic. Hence, we will assume that the mean population per service is an adequate substitute for empirical data in a given study region because service capacity is concentrated within inner city areas, as opposed to the urban fringe.

RQ 4: Which input parameters of the spatio-temporal accessibility analysis influence results the most?

Hypothesis 5: Total time budgets influence the results the most through extending or contracting spatial reach. Furthermore, network travel impedance modifies time budget expenditure hence has the second highest influence on results.

Chapter 3: Research methodology

3.1. Chosen approach – Spatio-temporal E2SFCA

The two-step floating catchment area (2SFCA) by Luo & Wang (2003), and its evolution, the enhanced two-step floating catchment area (E2SFCA) by Luo & Qi (2009) have demonstrated encouraging results in modelling spatially logical accessibility to services (Luo & Wang 2003; Guagliardo 2004; Luo & Qi 2009; Mao & Nekorchuk 2013). Furthermore, the E2SFCA method offers great possibility for adjusting the method input parameters according to the need and considerations of the research. For example, it is possible to modify distance decay weights to model variable willingness of a population to seek services according to the service in question (e.g. it is reasonable to assume one would be prepared to venture farther and longer to access healthcare, than to access a shop). Furthermore, the distance decay weights allows for modelling of constant, yet unequal decrease of service utilization probability based on distance, which is in line with Toblers First Law (1970). Furthermore, the E2SFCA requires four input parameters: a network dataset, distance decay scheme, population point data, and service point data (Luo & Wang 2003; Luo & Qi 2009). Thus, it is possible to reliably apply the E2SFCA method in many different settings to calculate potential accessibility. Furthermore, the E2SFCA method benefits from higher data density and granularity. A region which is better saturated with points of interests will reveal more intra-regional variation through the accessibility analysis. Hence, it is simpler to perceive spatial logic and understand the systems being analysed, be it healthcare or socialization potential. An added benefit of input parameter granularity is that the derived interpolated geovisualizations are more congruous with actual accessibility situation in the region. This possibility guided not only the methodology choice, but also the study region choice which will be defined in the second section of this chapter. The Swiss demographic data is georeferenced within a fishnet polygon dataset of 100x100 meter cells (hectare cells) continuously spread within a region (for locations where there is population registered). Thus, the accessibility scores calculated for such population points is immediately suitable for geovisualization as well as more in line with the spatial logic of continuous geographic space as opposed to irregularly placed points of interest (Guagliardo 2004). Furthermore, the four mandatory input parameters make the method very flexible in terms of influencing the final outcome through modifying inputs. This input flexibility makes it possible to conduct varied sensitivity analysis and properly evaluate the method, its strengths and weaknesses. The network dataset is the input which offers the most variability in terms of parameter options, as well as the most significant influence on the expected outcomes of potential service accessibility analysis. The network input parameters articulate the network travel impedance which modifies reach, and accessibility. Furthermore, it is possible to modify service availability by closing or opening network links and thus mechanically changing the accessibility catchments. The service and population point input parameters can be used to adjust the regional service supply and demand. Thus, the same number of service points might provide lesser accessibility scores to a population if service supply is lowered (e.g. during the night). Likewise, by adjusting the demographic cohorts which constitute the demand for certain services, we also adjust overall regional demand. Further adding or removing service/population points from the study region will have an impact on availability and accessibility results. Finally, the distance gravity decay parameter applied to both steps of the E2SFCA allows us to model service functional centrality. Thus, for services of higher centrality (e.g. healthcare), it is possible to assign lower distance decay. The accessibility to such a service would consequently be higher, and spread farther in the study region, thus increasing overall accessibility. These four input parameters (fig. 13); population, services, network, and gravity decay, will be explained in the section on methodology implementation.

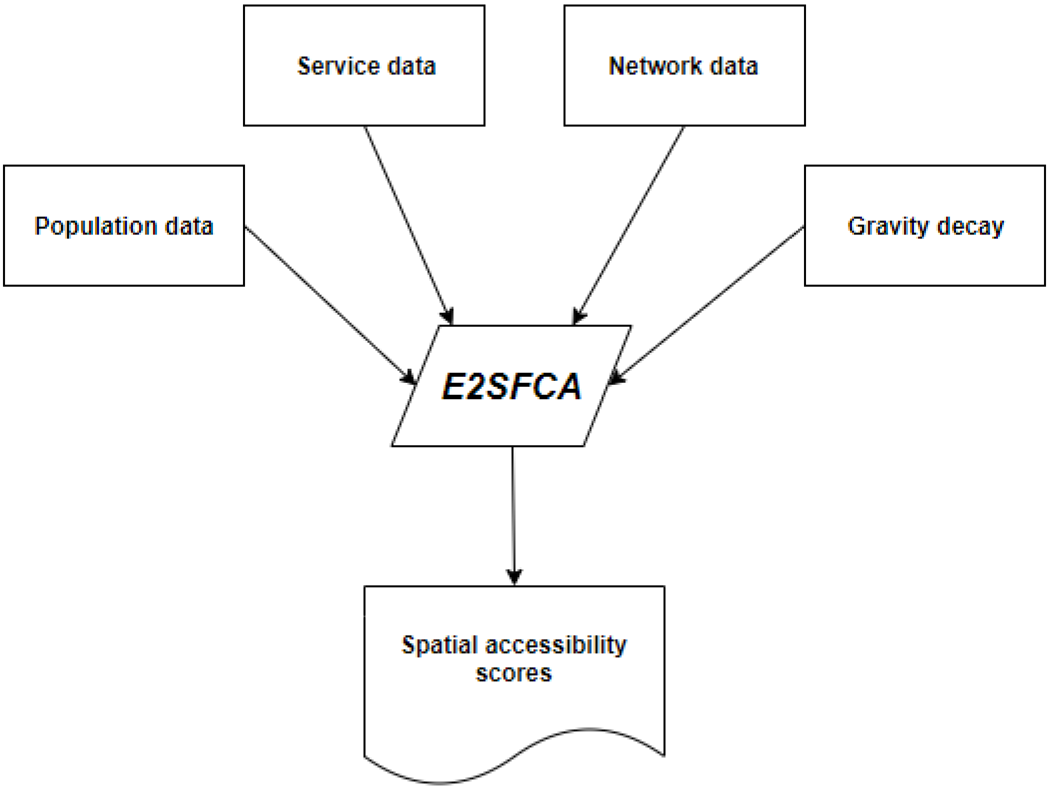

Figure 13. Conceptualisation of the baseline E2SFCA inputs and expected results.

However, it is exactly this substantial flexibility offered by the four input parameters are at the same time the main weakness of the E2SFCA method (Luo & Qi 2009). The input parameters have no defined framework on the manner they should be represented as, nor are there definite values for gravity decay (Joseph & Bantock 1982; Guagliardo 2004), nor network travel impedances (Mao & Nekorchuk 2013). While there is consensus on several topics, such as healthcare accessibility supply and demand (Joseph & Bantock 1982; Guagliardo 2004; Mao & Nekorchuk 2013), for most other service categories there is little to no research, let alone guidelines on input parameters. This has been defined as one the research gaps which during this research. Essentially, the E2SFCA method is a spatial accessibility methodology suited for calculating accessibility potentials for individual points within place-based accessibility research. However, it is possible to implement various temporal accessibility features (fig. 14) within the E2SFCA (e.g. Mao & Nekorchuk 2013). These include the variations in daily and weekly accessibility scores (Tenkanen 2017), differences in accessibility scores per travel mode (Mao & Nekorchuk 2013; Tenkanen et al. 2016; Tenkanen 2017), differences in accessibility scores between work hours and night time (Tenkanen 2017) etc. These and similar temporal parameters introduce a temporal accessibility concept within accessibility research, as outlined in the first chapter. The example of temporal accessibility implementation within the E2SFCA (Mao & Nekorchuk 2013) is more akin to a case scenario analysis of variation in accessibility given different travel speeds within the same network. However, if the temporal accessibility features would be implemented as one of the initial inputs, then the E2SFCA would be brought closer to the time-geography foundations of spatio-temporal accessibility research. Therefore, the chosen methodology for this research is based on the E2SFCA, with additional spatio-temporal input parameters (fig. 15).

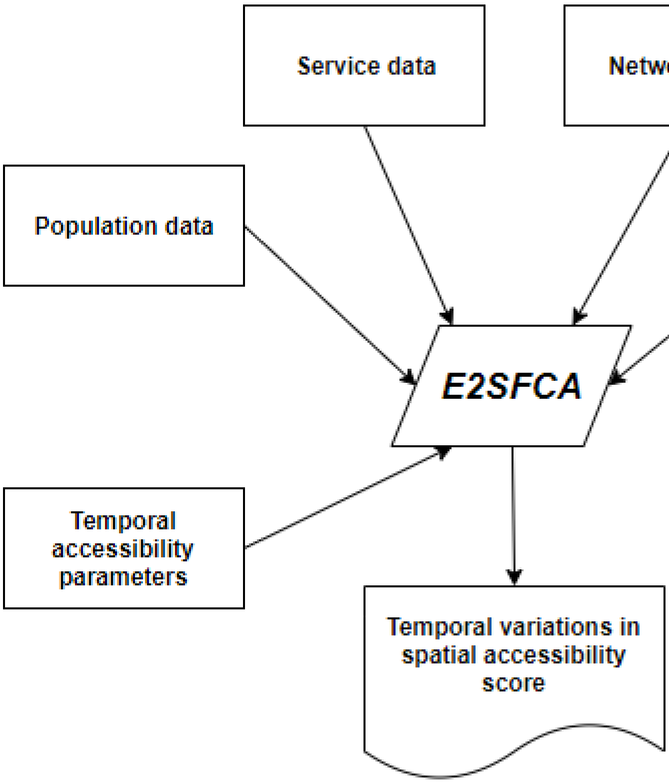

Figure 14. Conceptualisation of temporal parameter implementation within the E2SFCA methodology.

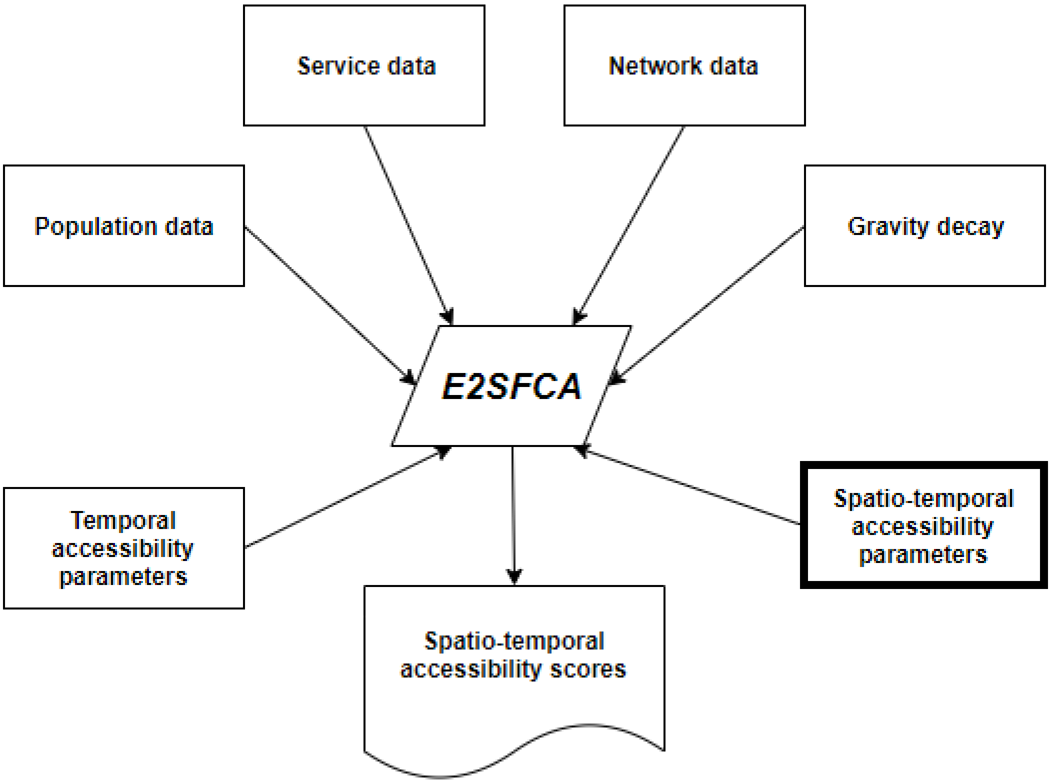

Figure 15. Conceptualisation of spatio-temporal E2SFCA inputs and expected results.

The spatio-temporal E2SFCA methodology is implemented in ArcGIS 10.6 (ESRI, California) with backwards compatibility for 10.1 when it comes to the Network analyst suite, which is one of the fundamental tools of accessibility research. The service data pre-processing is done in R Studio, while demographic and network data was pre-processed in ArcMap. The E2SFCA accessibility analysis is automated through an extension (Langford et al. 2015). Service data was sourced from authoritative data sources pertaining to each service class (e.g. the websites of banks/government), and was geocoded in R using the "ggmap" package (Kahle & Wickham 2013).

The following section will present the chosen study region, focus areas, and the data available for the research. These considerations were an important factor in deciding how to implement spatio-temporal accessibility within the E2SFCA. Hence, the study region and data section is followed by the methodology implementation section. Afterwards, when the baseline data is known and prepared, services will be chosen accordingly.

3.2. Study region

The study region used in this thesis encompasses parts of the Canton of Zurich, Switzerland. Accessibility to all services is modelled for the City of Zurich and the City of Winterthur, while healthcare is additionally modelled for the entire Canton of Zurich. This research is conducted within this study region in order to test the application of spatio-temporal accessibility analysis and also to calculate the potential accessibility situation within the two largest cities of the Canton. Finally, the application of healthcare accessibility for the entirety of the Canton is done in order to test the methodology on a larger geographic scope than an urban region. The Canton of Zurich was chosen as the setting for the research due to the author's familiarity with the space, availability of authoritative data for methodological inputs, and the possibility of using the highly granular Swiss demographic data which is well suited for calculating and visualising spatial variations in accessibility scores. Furthermore, there is ongoing debate in the local community on the closure of post office branches. Hence the results of this research can provide new insight into the potential accessibility to services and inform the debate. However, the focus of this research is on the service provision within Zurich and within Winterthur, which were chosen as examples of highly developed urban spaces. Also, Zurich being the largest and Winterthur the second largest city in the Canton of Zurich, allows for an interesting comparison of service provision and an insight into the spatial logic of the Canton. Furthermore, Zurich may be considered a city of global functional importance due to a concentration of business and academic institutions of world renown, which is contrasted by Winterthur which is a city of regional importance at most. Hence, it is intuitively expected that service provision would be better in Zurich. However, this might not be true due to differences in population, service point positions, or transport network structure.

3.2.1. Geographic position and location

The Canton of Zurich is located within the Swiss plateau, the Mittelland (fig. 16). The Mittelland is the heartland of the Swiss state. It is a geographic region of lowlands and valleys between the Jura Mountains and the Alps. Significant geological and geomorphological features include longitudinal lakes and valleys formed by glacial processes during the Riss and Wűrm glaciations (Schweizer Weltatlas 2017). Major rivers include the Aare and the Rheine. The most significant river in the chosen study region is the Limmat which flows from Lake Zurich and dissects the city in two, while Lake Zurich distorts the continuity of the landmass in the south of the Canton. The majority of the Swiss population resides within the Mittelland (Strukturalatlas der Schweiz 1997). Furthermore, the Zurich Metropolitan region (socioeconomic urban region) is the centerpoint of the Swiss economy and population. The Zurich Metropolitan region (Zürcher Wirtschaftsraum) incorporates most of North-eastern Switzerland, including the Cantons of Zurich, Thurgau, Schaffhausen, Aargau, and Zug (Strukturalatlas der Schweiz 1997). Hence, the study region of this thesis is focused on the main economic and demographic gravity point of Switzerland, the City of Zurich.

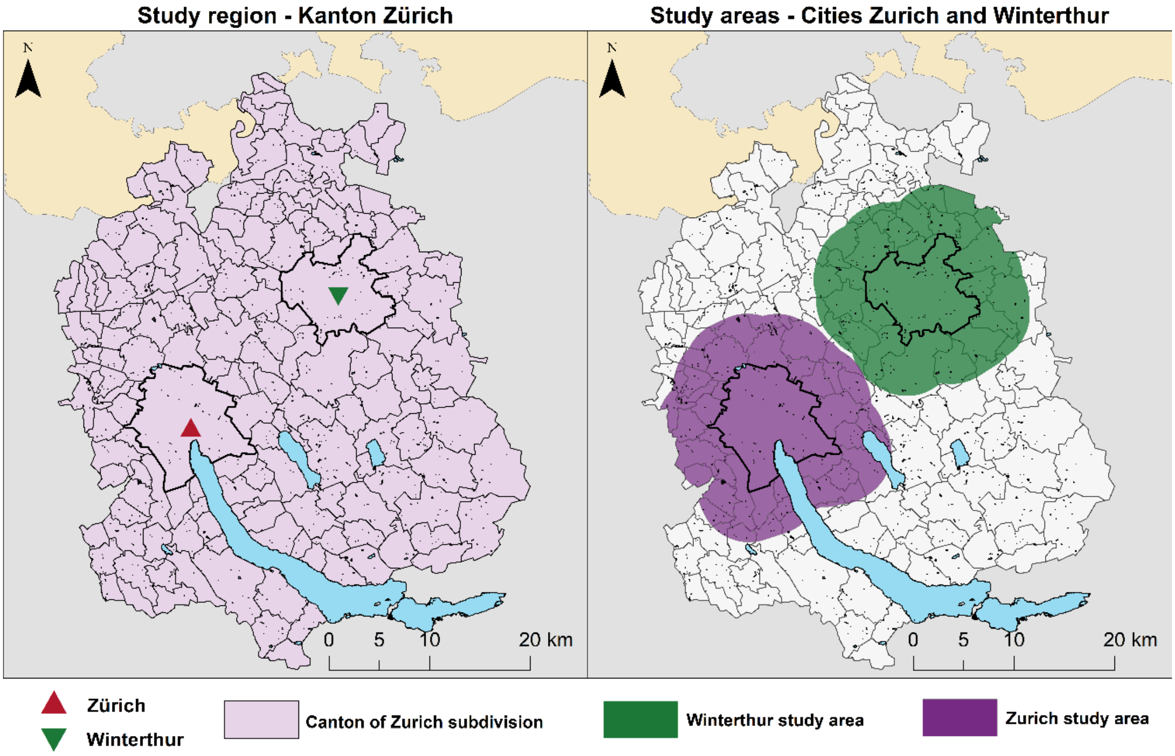

Figure 16. The Canton of Zurich municipal subdivisions (*gemeinde*) left, chosen scope of accessibility analysis for the cities Winterthur and Zurich right. (Administrative division data source: SwissTLM3D, Swisstopo 2018)

The Canton is the regional level of governance in Switzerland second in tier to the top Federal level. The Canton of Zurich is subdivided into *bezirke* (mezzo-regional level) which includes one or more *gemeinde* (municipality). Figure 16 maps the municipal subdivision of the Canton and the municipalities of Winterthur (downwards triangle) and the municipality, and bezirke, of Zurich (upwards triangle). While the bezirke are statistically derived administrative units, the municipalities conform to the morphological or historical division of the land. Thus, the municipalities of Zurich and Winterthur are used as the baseline geographic unit of analysis in this research. This notion is important because it will have ramifications when dealing with edge effects. In order to lessen edge effects the actual scope of analysis is expanded to a 5km buffer based on the municipalities of Zurich and Winterthur (fig. 16). This will include population and services adjacent to the municipalities and factor in the possibility of trans-boundary accessibility in both directions. The two study areas intersect slightly (fig. 16). However, this intersection is overlaid on an uninhabited, forested part of the Canton. Thus, there is no duplication of data. The decision to use 5km buffers was not informed through the literature because there is no definite framework for such a choice. It is based on the fact that the only way to completely remove edge effects is to analyse the entirety of contiguous landmass (Šterc 2015). However, this was restricted by data availability and limits on processing power and time. The shape of the municipalities is beneficial since it is circular with few salient protrusions, thus the shape minimizes border lengths and by extension, edge effects. Therefore, the 5km distance for the buffers was informed by the fact that the average distance from the centroid of the Zurich municipality can be rounded to 5km, as it can also be approximated for the West-East section of the Winterthur municipality. The underlying spatial logic is formulated based on the population points on the municipal boundary. If we model accessibility just using the municipality as the study area as has often been done in the literature (e.g. Joseph & Bantock 1982; Peng 1997), then we assume that the liminal population would attempt to utilize services within the municipality centres. Therefore, if we are ready to assume that a population would seek access to services 5km away in the municipality centres, then they would logically be likely to seek services 5km away in the opposite direction. Thus, the edge effects problem is shifted to the boundary of the projected 5km buffer, while the results for the Zurich and Winterthur municipalities are made less uncertain by minimizing edge effects. Therefore, when interpreting the results, the focus will be on the results for the population points within the municipalities, not necessarily within the entire study area. The only exception to this will be the case example of healthcare accessibility for the entirety of the Canton.

3.2.2. Resident population demographics

The shapes of the study areas (fig. 16 right) encompass 694 square kilometres of the Canton (total 1666 km^2), of which the Zurich areas is 20 km^2 bigger. The accessibility analysis within this thesis will cover approximately 41.6% of the study region. Conversely, the Cantonal resident population (tab. 1) numbers 1432854 per the 2013 demographic data by the Federal Statistics Bureau (Statpop 2013). Although Swiss demographics have upgraded from decennially census based to an annual register based statistics, the derived hectare GIS datasets available for the writing of this thesis were from 2013. Conversely, the 2017 Cantonal population numbered 1498641 (Statistisches Amt Kanton Zurich 2018[1]).

Population	Total	%	Male	Female	≥65	≤20	20-65
Canton	1432854	100 %	49.63%	50.37%	16.75%	19.74%	63.51%
Winterthur area	199582	13.92%	49.9%	50.1%	12.3%	23.7%	64%
Zurich area	734641	51.27%	49.75%	50.25%	11.76%	24.64%	67.2%

Table 1. Demographic statistics of the Canton and the study areas. (BFS 2013)

The study areas include approximately 65.19% of the Cantonal population, i.e. 934223 registered residents. This population will partake in the accessibility research methodology by representing the demand for services in the study region and areas. Together, Zurich and Winterthur constitute almost two thirds of the Canton, hence the accessibility score derived for this population may be inferred as the cantonal average. However, this population is probably almost exclusively urban population, unlike the rest of the canton which most likely includes the majority of the rural population in the study region. One of the topic and aims of this research was to focus on urban as space since rural space has already been exhaustively researched within accessibility research (Guagliardo 2004). Furthermore, the smaller scale of urban space means that input parameters and spatial idiosyncrasies will have a greater impact on the accessibility outcomes. Hence, applying the research on urban space allows for more variation and insight into the spatial logic of accessibility since it is possible to produce significantly different results with minor alterations to the input parameters (Delafontaine et al. 2013). Finally, applying the research on an urban population is in line with the current global trends of demographic, functional, and economic concentration within urban spaces throughout the planet. Terran reality is becoming increasingly urban for the average individual. The UN estimates for 2014 put the global urban population at 53.46%, with an unbroken trend of linear increase up to the final year used in the estimate, 2050 (United Nations 2014). Therefore, accessibility research is likely to focus more and more on urban space and small scale geographies (Luo & Qi 2009).

Figure 17 visualises the spatial distribution and density (per hectare) of the Cantonal population. Half of the cantonal population is concentrated in the Zurich urban region (tab. 1) and agglomeration (Limmattal, lake Zurich, and Glattal). The Eastern and South-Eastern (Oberland) part of the Canton is sparsely settled and rugged in terrain with few transport corridors. Conversely, the shores of Lake Zurich form a morphological continuity of settlement, albeit not densely populated. The median centre of population weighted by total population size falls within the eastern side of the municipality of Zurich. Interestingly, the location of the cantonal population centroid coincides with the location of the Zurich zoo on Zurichberg.

[1] statistik.zh.ch/internet/justiz_inneres/statistik/de/daten/daten_bevoelkerung_soziales/bevoelkerung.html

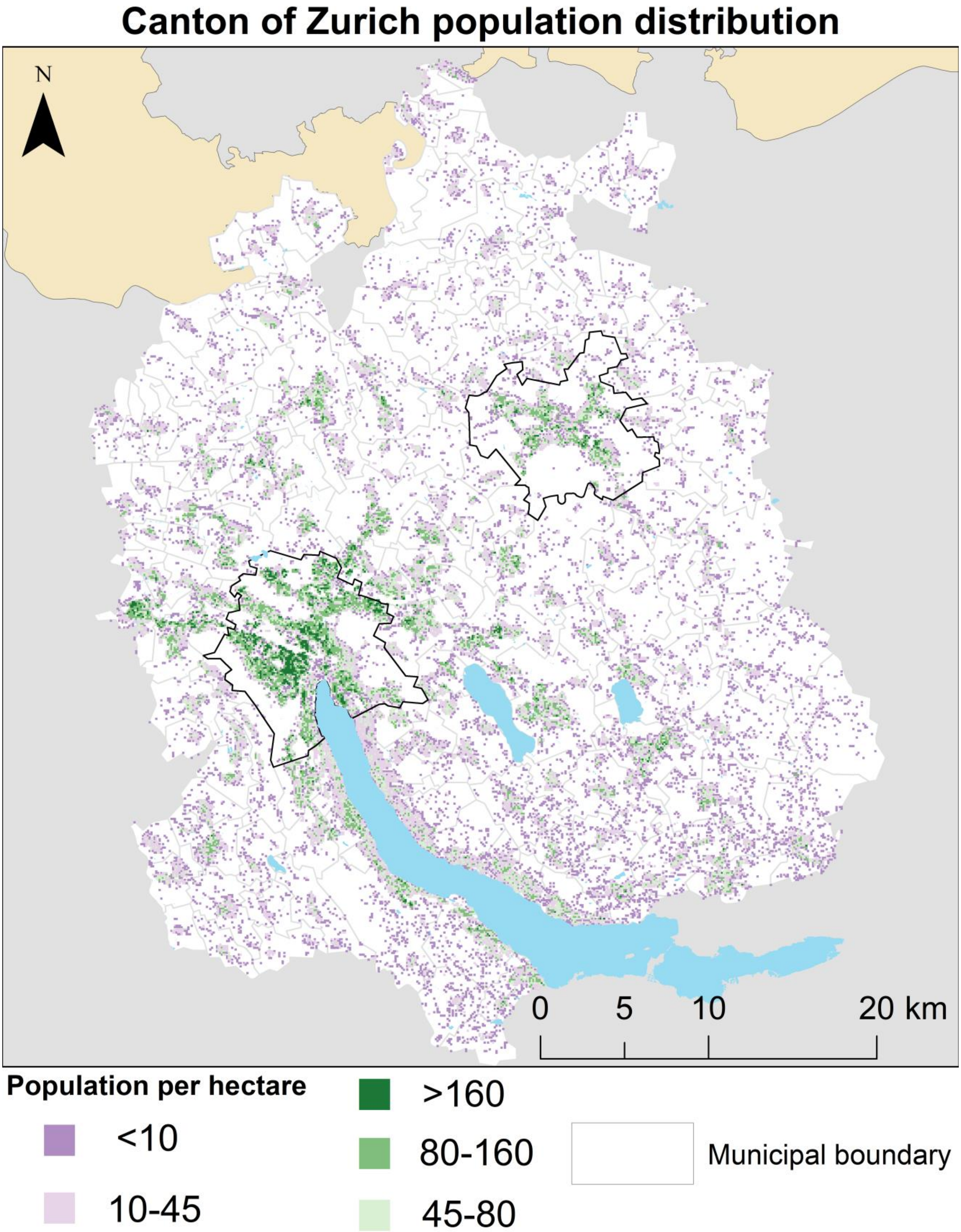

Figure 17. Population density map of the Canton of Zurich. (Data source: Statpop 2013, BFS)

3.2.3. Transport network challenges and data

Finally, the Cantonal transport network is central to spatio-temporal accessibility analysis. Based on the network used the accessibility scores are computed. One of the pre-processing step towards accessibility analysis involves creating the transport network which has to include multimodal travel options, parameters which can be modified per need, and sufficient edge density and granularity so that pedestrian and motor vehicle travel can be modelled (Mao & Nekorchuk 2013). Afterwards, service and population points have to be assigned network locations so that they may be accessed from it and have access to the network. It is important to design the snapping algorithm so that population or service points are not snapped to inaccessible network edges, or edges with special case connectivity. For example, point to network snapping in this thesis is restricted to roads between 3 and 10 metres wide to avoid inaccessibility for pedestrian or motor transport. Furthermore, this avoids the unrealistic assignment of points to highways or railways, which has the added malus of requiring access to crossover points (stations) before the proper transport network is access, and thus time budgets are wasted and accessibility is deflated. Using the Network Analyst suite of ArcGIS snapping the service points to the network is done through either network edges, vertices, or junctions. Also, turn restrictions can be modelled with the appropriate data supplements or turn restrictions can be internally allowed or restricted to end points or U-turns at junctions. Finally, network (inter-segment) connectivity can be constrained to special cases in order to model multimodal transport. Network connectivity pertains to the topology of the network dataset and defines which network edges form topological relations upon intersection (Kemp 2008). If topological relations are restricted between two edges, they do not form a junction through which accessibility can propagate in the network. For example, this models the utility of public transport station accessibility since the crossover between pedestrian/motor networks can be allowed only at points of special connectivity clauses; stations. Also, the z level (height) connectivity of network segments is import, especially for Switzerland where tunnels are prolific. This can also be a clause of connectivity constraints which should be included when possible in order to improve network dataset quality. The network used in this research dataset provides attributes of type (objektart), and elevation (stufe) for each segment. Thus, variable connectivity will be implemented. For example, access to railroad tracks (which have the highest movement speeds) is only possible through interacting with a railroad station which is accessible by road or pedestrian network, while accessing a highway (autobahn) is only possible through an highway entry or exit segment (einfahrt, ausfahrt).

The transport network used for this research is based on the line and point feature data of the Swiss topological land measure (TLM) by Swisstopo (Swiss Federal office of Topography 2016). The data ranges from 2013 to 2018 by date of input or revision and includes all network segments in Switzerland, as well as auxiliary data on transport network assets (stations, street information such as direction or names which is separates to lessen data bloat). The street network is divided by width; from 1 meter to 10 meter, and special cases for motorways and highways (fig. 19). The rail based network is divided into the categories of kleinbahn, normalspur, smalspur, and seilbahn. Of these, the kleinbahn pertains to special cases such as amusement parks or industrial implements, while the seilbahn corresponds to cable cars or gondolas; of which there is only one in the Canton. Therefore, the smalspur is deduced to be tramway rails based on the spatial distribution (only the city of Zurich has a tramway network in the Canton), while the normalspur corresponds to proper railways (fig 18.). The rail based public transport network will be implemented in the accessibility analysis as one of the multimodal travel options. This will be done by modelling special connectivity rules limiting the topology between rails and other transport network segments. This is important because the rail based transport is assigned the highest movement speeds and if it were accessible from each intersection with other segments, it would inflate accessibility scores. The usual topological interaction between two network segments upon intersection is to create a point junction and split the network into four new segments, divided by the junction point (Kemp 2008; Longley et al. 2010). However, this is unrealistic with multimodal transport, especially rail based transport. Public transport travels along set corridors form which there is little no deviation. Furthermore, the only place to access public transport are public transport stations. Hence, the logical connectivity between other network segments and the public transport would be through public transport station points. Thus, the public transport stations are a service representing public transport accessibility. Similar connectivity rules are applicable to highways which are usually only accessible from entry and exit ramps/platforms, or tunnels as is sometimes the case in Switzerland.

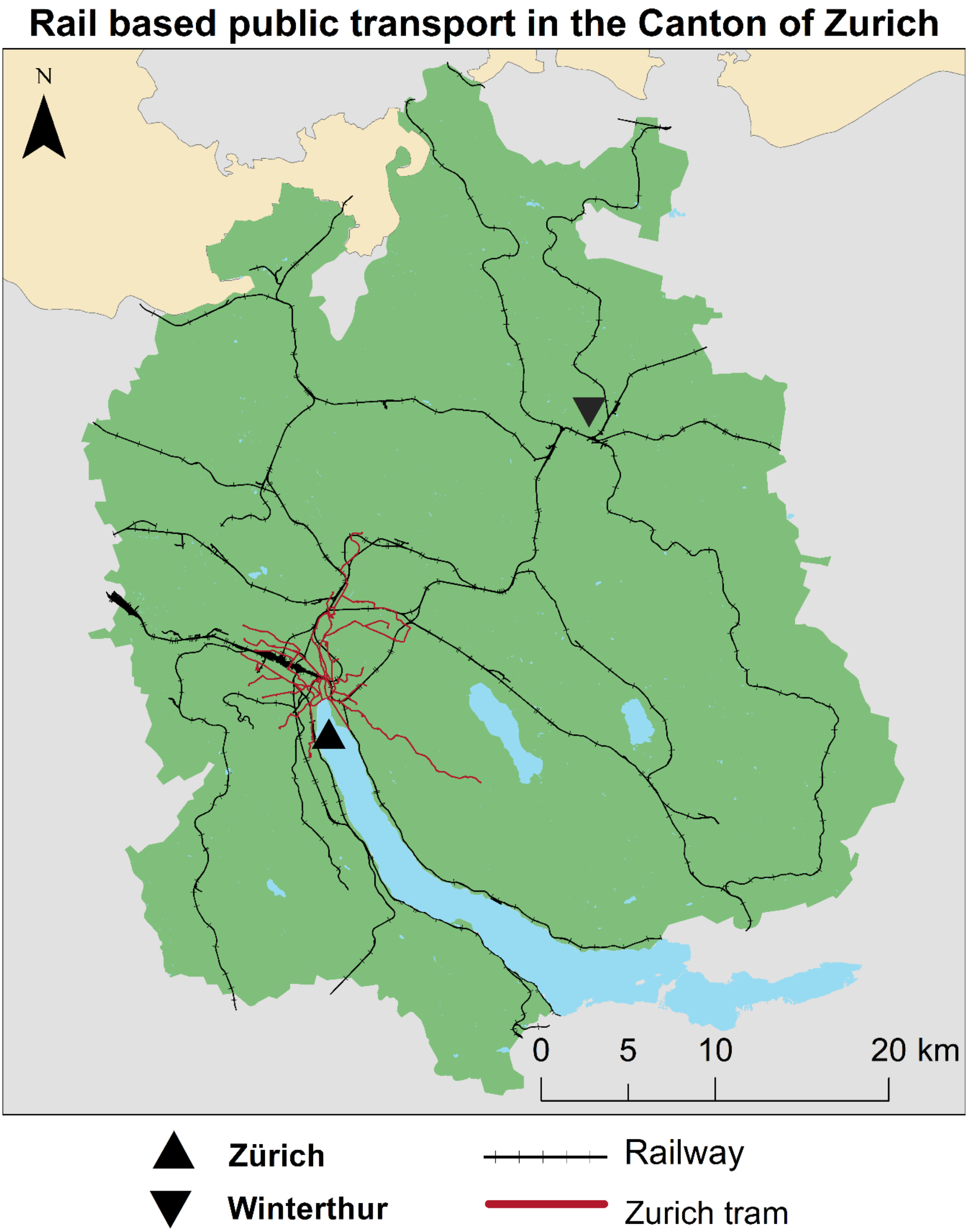

Figure 18. Rail based public transport network in the Canton of Zurich for the year 2016. (Data source: TLM3D, Swisstopo 2016)

Figure 19 visualizes the location of the motor transport network segments within the study region. The axis of the regional motor network is the A4 highway between Zurich and Winterthur (Altdorf-Zug-Zurich-Winterthur-Schaffhausen-Germany). AS demonstrated in the subsections on demographic data, the majority of the Cantonal population (65.19%) resides within the study areas which the A4 motorway dissects. Also, almost all the employed cantonal population (91.4%) resides within the study areas which the A4 connects. Apart from the highways, regular road network density is also concentrated within the study regions, which will improve potential accessibility to services since the least cost path from population to service points is more likely to better optimized the more detailed the more dense the transport network is.

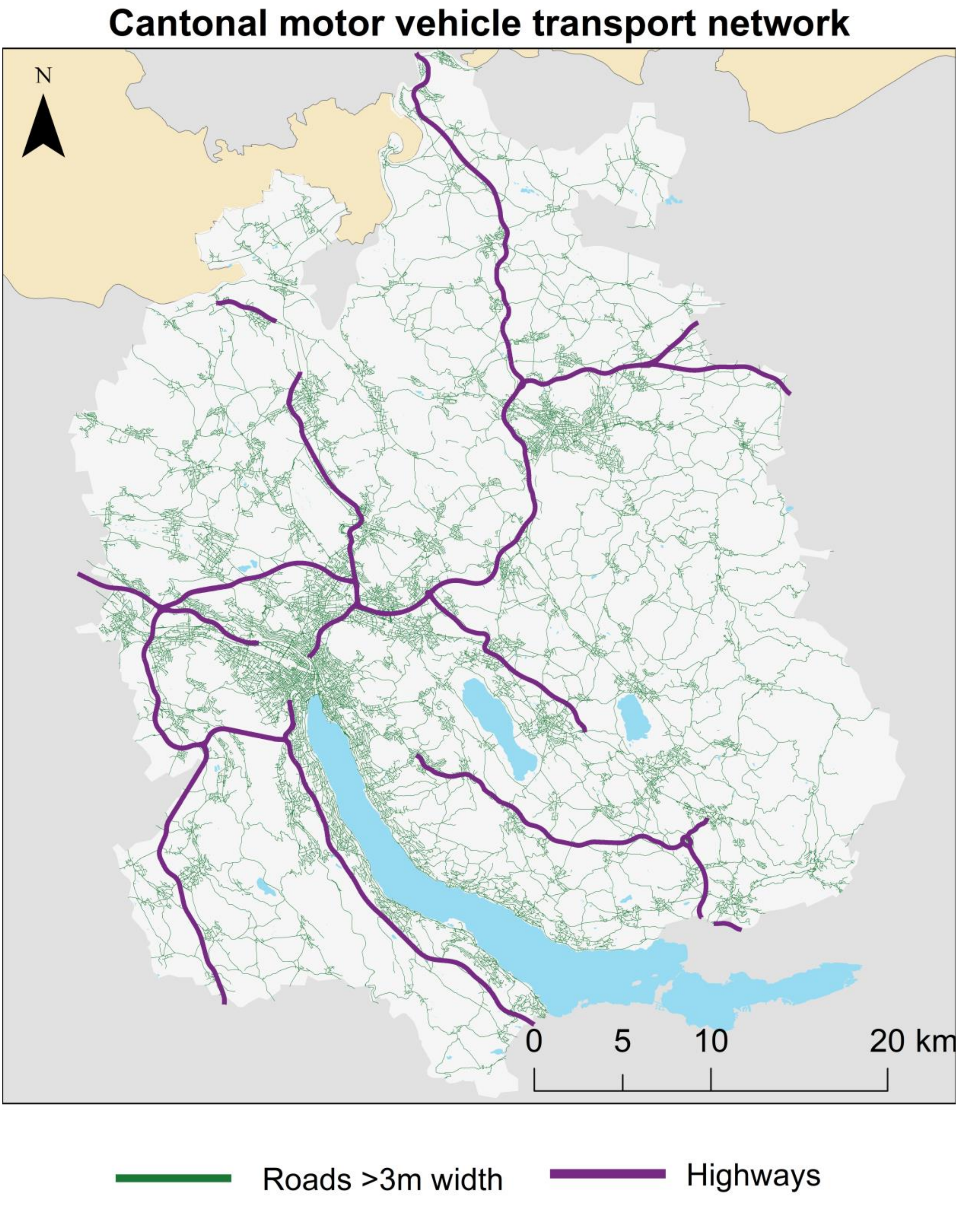

Figure 19. Motor vehicle eligible roads (>3 metre wide) in the Canton of Zurich. (Data source: TLM3D, Swisstopo 2016)

Figure 20 visualizes the line density of network segments within the study region. This map was created using a line density kernel function weighted by speed limits. The line density function projects a fishnet of equally spaces raster cells (kernels) over the specified map extend (Longley et al. 2010). Thereupon, a circle is drawn around each kernel using the input search radius. Finally, the length of the portion of each line that falls within the circle is multiplied the weight input (speed limit). These values are summed, and the total is divided by the circle's area (ESRI 2018[2]).

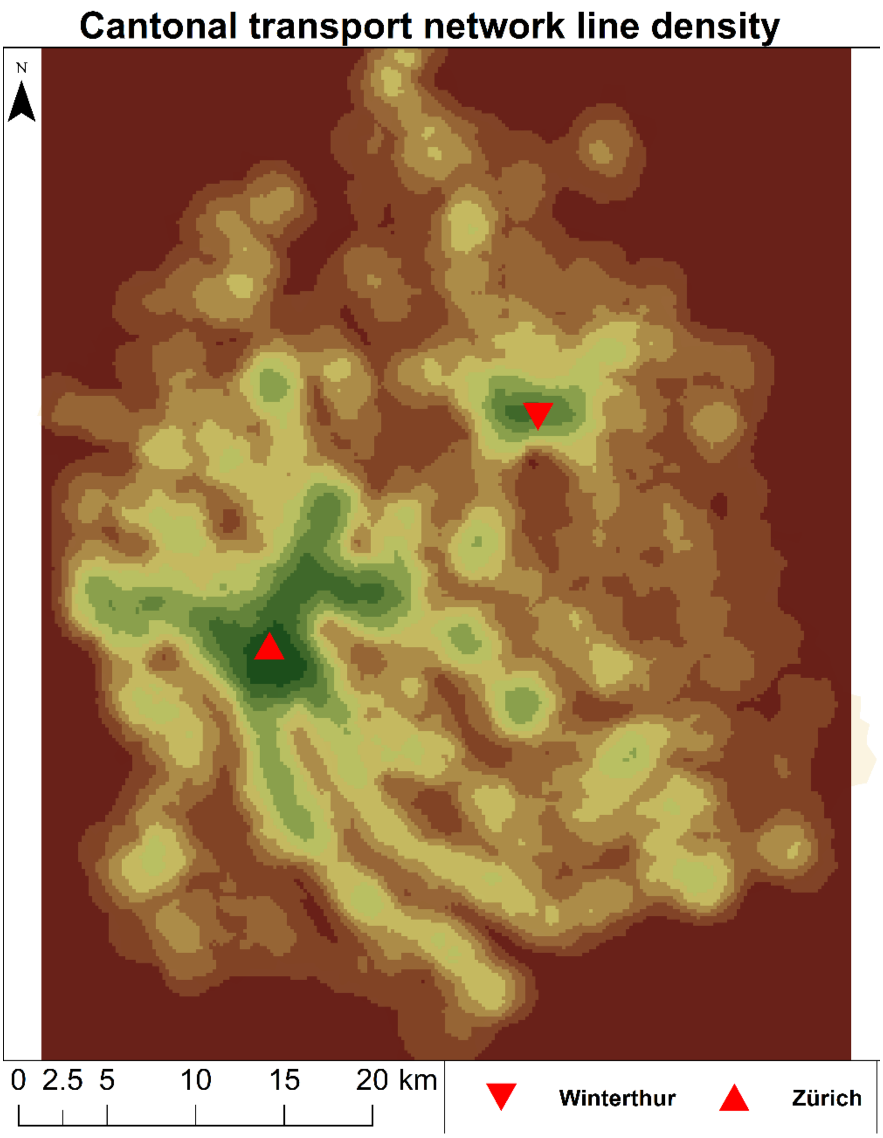

Figure 20. Line density map of the Cantonal motor network calculated with Kernel line density function. Green areas indicate higher line density, brown areas indicate lower line density. (Data source: TLM3D, Swisstopo 2016)

Auxiliary data for the TLM includes the locations of public transport stops for trains (Bahnen), buses, ships, and trams. Therefore, accessibility to transportations services will be a measured by availability and spatio-temporal accessibility of public transport stops within a certain distance/timeframe (Tenkanen 2017). This is further corroborated by existing official estimations of public transport accessibility within the Canton by the Cantonal traffic department (2017). The Cantonal authorities defined public transport accessibility and availability as a Güteklasse; zones of goodness or benefit. These zones are catchments of variable temporal and spatial accessibility (timetable based) to public transport. Six classes were defined (A-F) (fig. 21) and they were based

[2] http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-line-density-works.htm

on a buffer analysis to estimate linear distance (Luftlinie) to transport stops, and temporally weighted by frequency and mode of public transport present. The public transport stops were aggregated if multiple modes intersected in a location, and assigned a station category (I to VII) based on the frequency of passing public transport in minutes; weighted by transport mode.

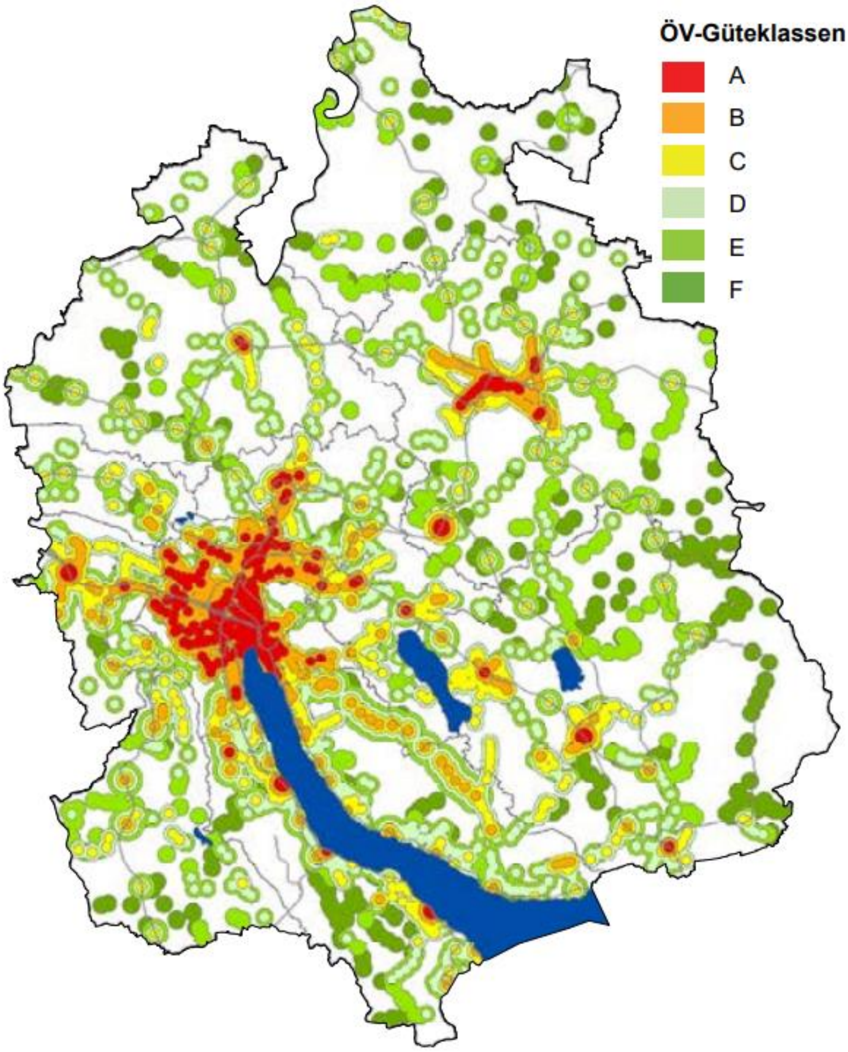

Figure 21. Public transport goodness classes for spaces in the Canton of Zurich per linear distance from and transport capacity of public transport stations. A is the best and F is the worst class. (ÖV-Güteklassen, Amt für Verkehr 2017)

Thus, the top class of accessibility, A, was estimated for locations which were under 300 metres distance to stations of the 1st or 2nd category; or 300-500 metre distance of 1st category stations. The lowest class, F, was estimated only for locations within 500 metre of category VII stations. Hence, it was deemed inaccessible everything farther than 500 metre from category VII and VI stations, or farther that 750 metres from category V, IV, and III stations. Evidently, the results in figure 21 are based on a weighted buffer analysis based on public transport stop availability. Therefore, this is not strictly an accessibility analysis, but more of a weighted availability analysis. The demand for transportation (the population, or the space?) was expected to be willing to travel further to access services of higher quality (i.e. higher functional centrality in terms of transportation services). This principle of estimating public transport accessibility will be applied in this research as well, albeit with a different methodology.

3.2.3.1. Motor vehicle and pedestrian networks

The segment type (objektart) attribute field allows for classification of streets per possible travel mode, e.g. motor vehicle transport cannot be conducted on edges with a width below 3 metres. This restriction is based on the information that the average car width is between 1.6 metres and 2.0 metres[3], hence traffic cannot be reliably conducted on 2 metre or 1 metre wide segments. Furthermore, the 1 metre, 2 metre, and 3 metre segments are primarily located in rugged terrain; hill, forests, or pedestrian areas; parks, plazas, University campus etc. Hence, the road network is divided into two iterations; a motor network, and a pedestrian network. The pedestrian network (fig. 22) contains all road edges except highways, motorways, and associated elements (rest areas, connections, exits etc.). Likewise, the motor network (fig. 23) contains all edges apart from the 1 metre, 2 metre and associated elements (wegfragments). Furthermore, figure 23 demonstrates the manner in which network speeds are assigned in this research. Conversely, foot networks have a continuous movement speed of 3 kilometres per hour (Mao & Nekorchuk 2013; Neutens et al. 2013), which amount to circa 0.83 metres per second. However, motor network speeds are assigned according to federal speed limit guidelines (FEDRO 2013) for roads of various widths. The fastest being the highways with 120 kilometres per hour. Likewise, the public transport speeds are also adjusted according to the official standards. The Zurich Public Transport company (ZVV) limits the driving speeds of trams and buses to a maximum of 50 kilometres per hour (Stadt Zurich 2013). Hence, this speed was assumed for all bus and tram transport in the study region. On the other hand, railway transport was assigned the movement speed of 160 kilometres per hour in line with the maximum reported speeds of the Zurich S-Bahn regional railway system (per SBB 2018[4]). In summary, the main difference between motor vehicle and pedestrian networks are the edges available for network traversal, and the movement speeds assigned to each edge. The pedestrian networks have a greater density of network edges to calculate better least-cost paths than the motor networks. However, the slow movement speed of 3 km/h will limit actual network reach. Likewise, the increased the network speeds are likely to condition motor network based accessibility score to conform to transport corridors. Hence, a radial spread of accessibility scores is expected from motor networks. Conversely, the accessibility score spread for foot networks is expected to be more concentric, albeit with greater spatial variation due to less available services within walking speed catchments. The network input parameters mentioned within this section will be analysed in the following section on the chosen methodology, along with several others which are instrumental within the intended methodological approach.

[3] https://www.automobiledimension.com/

[4] https://company.sbb.ch/en/sbb-as-business-partner/federal-government-cantons/regional-traffic/zurich/s-bahn-trains-and-buses/zurich-s-bahn.html

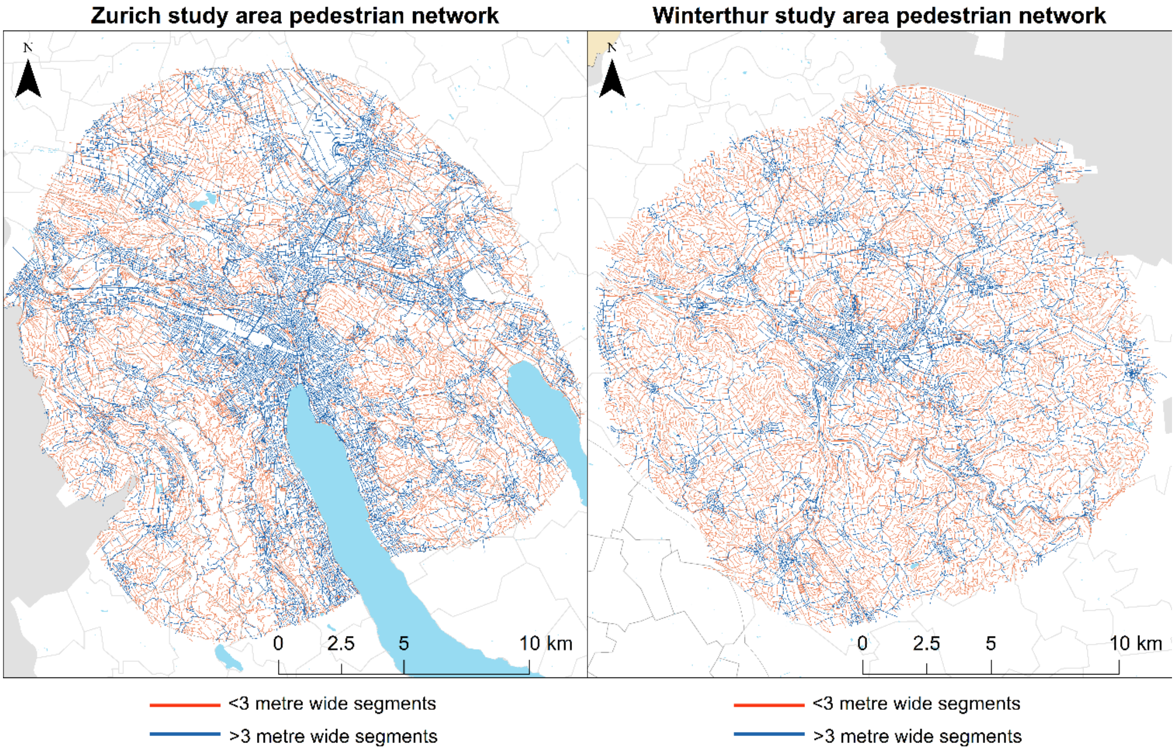

Figure 22. Pedestrian networks in the study areas (Zurich left, Winterthur right) for 2016. (Data source: TLM3D, Swisstopo 2016)

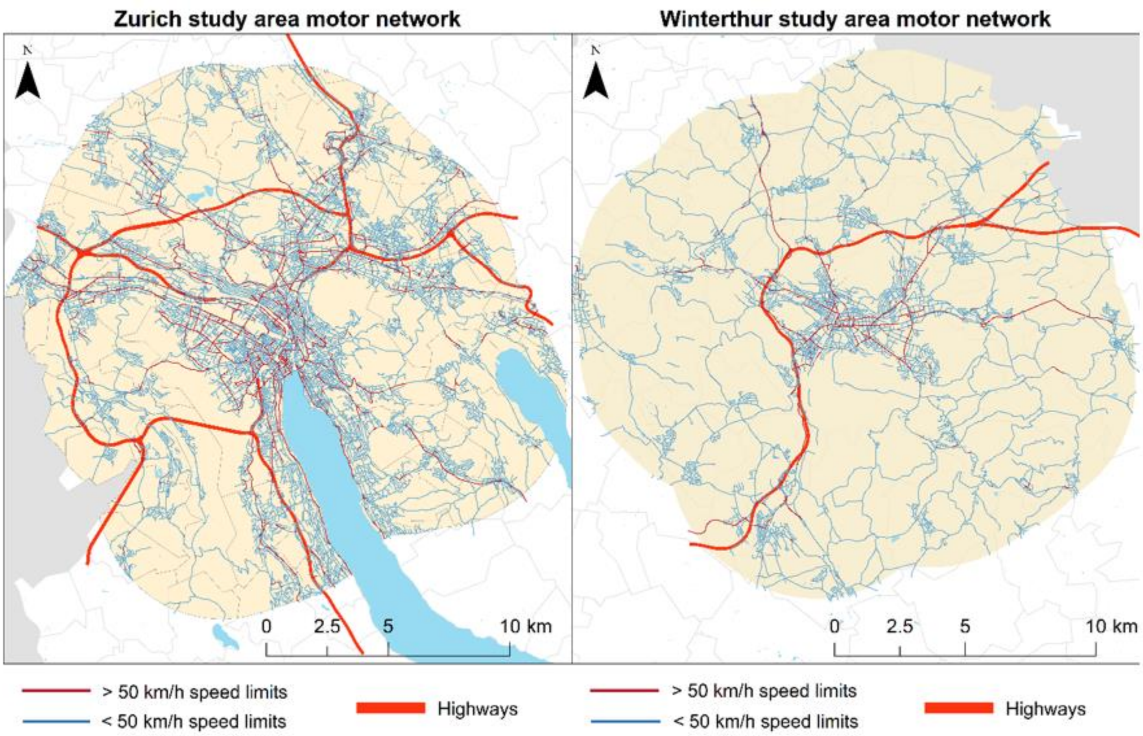

Figure 23. Motor vehicle networks in the study areas (Zurich left, Winterthur right) for 2016. Background colour fill added for contrast. (Data source: TLM3D, Swisstopo 2016)

3.2.3.2. Transport network parameters

The transport network used within this research is built from line and point data of the Swiss road and rail network (TLM3D, Swisstopo 2016). The dataset is split into transport networks by type; roads, rails, and footpaths. To model multimodal accessibility we have compiled three network datasets from the available data. The pedestrian network which will be used to model accessibility to services on foot, a motor (vehicle) network which is used to model car and public transport accessibility, and a modified foot network which includes public transport stops through which it will be possible to access increased movement speeds. The main difference between these three network dataset is in the edge segments used to build it, and the movement speeds assigned to them. Thus, the most important network parameters are the network segments used and the movement speeds assigned. The movement speed for network segments is based on cantonal and federal speed limits (Peng 1997; Mao & Nekorchuk 2013), while the foot network dataset is modelled with a walking speed of 3km per hour. Accessibility analysis uses network time to generate catchments (Peng 1997; Radke & Mu 2000; Luo & Wang 2003; Guagliardo 2004; Luo & Qi 2009; Neutens et al 2010a, 2010b, 2011, 2012a, 2012b, 2013; Delafontaine et al. 2012; Tenkanen et al. 2016; Tenkanen 2017). The network time is derived from movement speeds and geometry. Thus, the simple formula for length travelled; s = v*t, is used to calculate the time (in seconds) it takes it traverse an individual network segment. Afterwards, the methodology time budget (in seconds also) is expended to traverse individual network segments. Therefore, increased travel speeds have an inverse proportional relationship with the time cost (travel impedance) associated with each network segment. Consequently, varying the network speeds would have significant impact on the accessibility scores. It is possible to use length as the travel impedance, in which case it is necessary to calculate the geometry of each network segment. This a simple matter in ArcMap. Another important network parameter is connectivity. As explained in the previous subsections, connectivity allows us to model the topology of the network dataset. To determine which segments may intersect with which segments and thus model things such as public transport stops as crossover points between network types. This group of network parameters pertains to the internal division and interaction of network segments. Conversely, there are indirect network parameters which are modelled through assigning service and population points their respective network locations necessary to generate catchments. It is possible to define to which parts of the network a population or a service point is snapped, whether it is snapped to a vertex, junction, or edge etc. These transport network parameters will be analysed within a sensitivity analysis to ascertain their influence on the final results.

3.3. Spatio-temporal Enhanced two-step floating catchment area (S-T E2SFCA)

"Spatio-temporal accessibility is the measure of temporally constrained spatial accessibility."

This definition sets the approach when implementing the E2SFCA, spatio-temporal accessibility parameters have to be included somewhere (fig. 15). Hence, spatio-temporal constraints will be introduced into the baseline methodology of the E2SFCA which was chosen as the methodological framework for this research. These constraints are modelled according to the time geography theories of Hägerstrand (1970) which represent the theoretical framework within this research. Individuals are temporally constrained in their spatial mobility (and accessibility). Therefore, we will modify the enhanced two-step floating catchment area (E2SFCA) by Luo & Qi (2009) through the introduction of temporal constraints on individual mobility which would be modelled in the methodology during the second step of the E2SFCA. The temporal constraints are defined by Neutens et al. (2012a, 2013) into three categories; personal constraints which represent the time budget an individual has available when seeking access to a service; the network constraints which represent the time it takes to reach the service from place of habitation or work; and the utilization constraints which represent the time it takes to properly utilize a service. We will combine the E2SFCA with the temporal constraints as defined by Neutens et al. (2012b). Furthermore, the temporal accessibility methods of multi-modal transport (Mao & Nekorchuk 2013, Tenkanen 2017) and variable service working hours (Neutens et al. 2012b) will be applied to model variability in temporal accessibility in order to provide a full spectrum insight into service provision of the study region. Multi-modal transport assumes the possibility of individuals seeking services by using different mobility options, such as personal automobiles, public transport, and bicycles or on foot. This is represented in the model through variable network travel speeds (not temporal constraints). For example, the same network link may be assigned a travel speed of 80 km/h to model accessibility with personal automobiles, or a travel speed of 3 km/h to model walking speed. Likewise, certain network links may be assigned travel speeds of 0 km/h to model inaccessibility to certain transport modes. Variable service working hours introduces opening and closing times to service points, thus to utilize a service, an individual would have to be able to reach it and utilize it before closing time. A simpler aspect of the working hour variability is modelling the difference in accessibility to services between workdays and weekends, or during the day and night. Unfortunately, we are unable to implement complex traffic models which would include congestion, and the subsequent accessibility variability between rush hours and off hours (Tenkanen 2017). This is due to a lack of data on this issue.

Therefore, we will include network time constraints, service utilization time constraints, and model network time budgets as total time budgets for service access. In the original E2SFCA the time budget participates only in the process of reaching a service points from a population point. However, in our research the total time budget will also have to be expended in order to utilize a service upon reaching it. These temporal and spatio-temporal constraints will vary from service to service based on reasonable assumptions and where possible, literature examples (e.g. for healthcare, government services, shops).

The E2SFCA differs from the baseline 2SFCA (Luo & Wang 2003) in the introduction of variable distance decay to both the supply and demand aspect of spatial accessibility (Luo & Qi 2009). It consists of two steps:

- 1. Estimate service capacity-to-population demand ratio for service points by dividing supply capacity of the service point with the population demand of all population points within the network catchment of the service point (Luo & Wang 2003).
    - 1.1. Apply gravity weights to the population demand according to distance between the supply and population point in order to model closer population demand having a greater impact than farther demand and address uniform regional accessibility (Luo & Qi 2009).
    - 1.2. “Float“ the calculated supply-demand ratio over the study region within the service point temporary attributes.
- 2. Create network catchments for all population points. Extract all supply-demand ratios of available service points (outcome of step 1.).
    - 2.1. Weight the extracted supply-demand ratios by distance to the service points from which the value is extracted.
    - 2.2. Sum up the extracted ratios after weighting. The final result is the E2SFCA spatial accessibility score.

The mathematical representation of these two steps is presented by Luo & Qi (2009) as follows.

Step 1: For each service point $\boldsymbol{j}$, search all population points ($\boldsymbol{k}$) that are within a threshold travel time ($\boldsymbol{d_0}$) from service point $\boldsymbol{j}$ (intersect $\boldsymbol{j}$ catchment), and compute the service capacity-to-population demand ratio $\boldsymbol{R_j}$ within the catchment area for service points $\boldsymbol{j}$.

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

Where P_k is the population demand in population point $\boldsymbol{k}$ whose centroid intersects with the catchment of service point $\boldsymbol{j}$, i.e. the travel time $\boldsymbol{d_{kj}}$ is less than the threshold travel time D_r ($\boldsymbol{d_{kj}} \leq D_r$). $\boldsymbol{S_j}$ is the service capacity in service point $\boldsymbol{j}$, and $\boldsymbol{d_{kj}}$ is the travel time between $\boldsymbol{k}$ and $\boldsymbol{j}$.

W_r represents the distance gravity decay weight applied within the E2SFCA, calculated from the standard Gaussian decay function (Luo & Qi 2009). Hence, each individual population point within service catchment of $\boldsymbol{j}$ has its population demand value weighted according to distance.

Step 2: For each population point $\boldsymbol{k}$, search all service points ($\boldsymbol{j}$) that are within the threshold travel time (D_r) from location $\boldsymbol{k}$ (that is, within network catchment area of population point $\boldsymbol{k}$), and sum up the supply/demand rations, $\boldsymbol{R_j}$, at these locations.

$$A_k^F = \sum_{j \in \{d_{kj} \leq D_r\}} R_j \; W_r$$

Where A_i^F represents the potential E2SFCA accessibility score at population point k. R_j is the service capacity-to-population demand ratio at service point ***j*** whose centroid intersects the catchment of k, that is ($d_{kj} \leq D_r$), and $d_{kj}$is the travel time between k and ***j***. A larger A_k^F indicates a better accessibility at population point k. W_r represents the distance gravity decay weight applied within the second step of the E2SFCA. Alike the 1st step, the W_r distance decay is applied to the R_j values within the network catchments of population points k. The distance decay in Luo & Qi (2009) take form of fixed time-zone thresholds per the theoretical work by Joseph & Bantock (1982). However, the Gaussian decay can also be implemented as a relative value derived from mean distances between all points ***j*** and ***k*** which partake in the accessibility analysis during step 1 or 2 (Langford et al. 2014).

3.3.1. Integration of spatio-temporal constraints

The aspect of the space-time pyramid representation of reality which is most suitable for implementation within the E2SFCA are service utilization costs. Upon reaching a service, the individual has to use a part of his or her time budget to utilize it, hence less time is left for network traversal. The current methodologies invest the entire time budget for network traversal which is unrealistic and omits a significant spatio-temporal constraint within accessibility research. The service utilization cost is regarded as a spatio-temporal constraint because it forms a capability constraint (Hägerstrand 1970) for individual mobility. While expressed as a temporal value (n seconds), the utilization cost is primarily spatial in reality. It immobilizes the individual and enforces a coupling constraint when attempting to utilize a service. Thus, it makes most sense to implement the utilization cost as part of the network time budget. In this way, we transform the network time budget into a total time budget (Hägerstrand 1970; Neutens et al. 2012a, 2012b; Delafontaine et al. 2013). However, the E2SFCA methodology workflow does not foresee input of additional parameters within the methodology itself (fig. 24). Instead, the utilization cost parameter is implemented within the network dataset and partakes in the method process by proxy through the catchment generation.

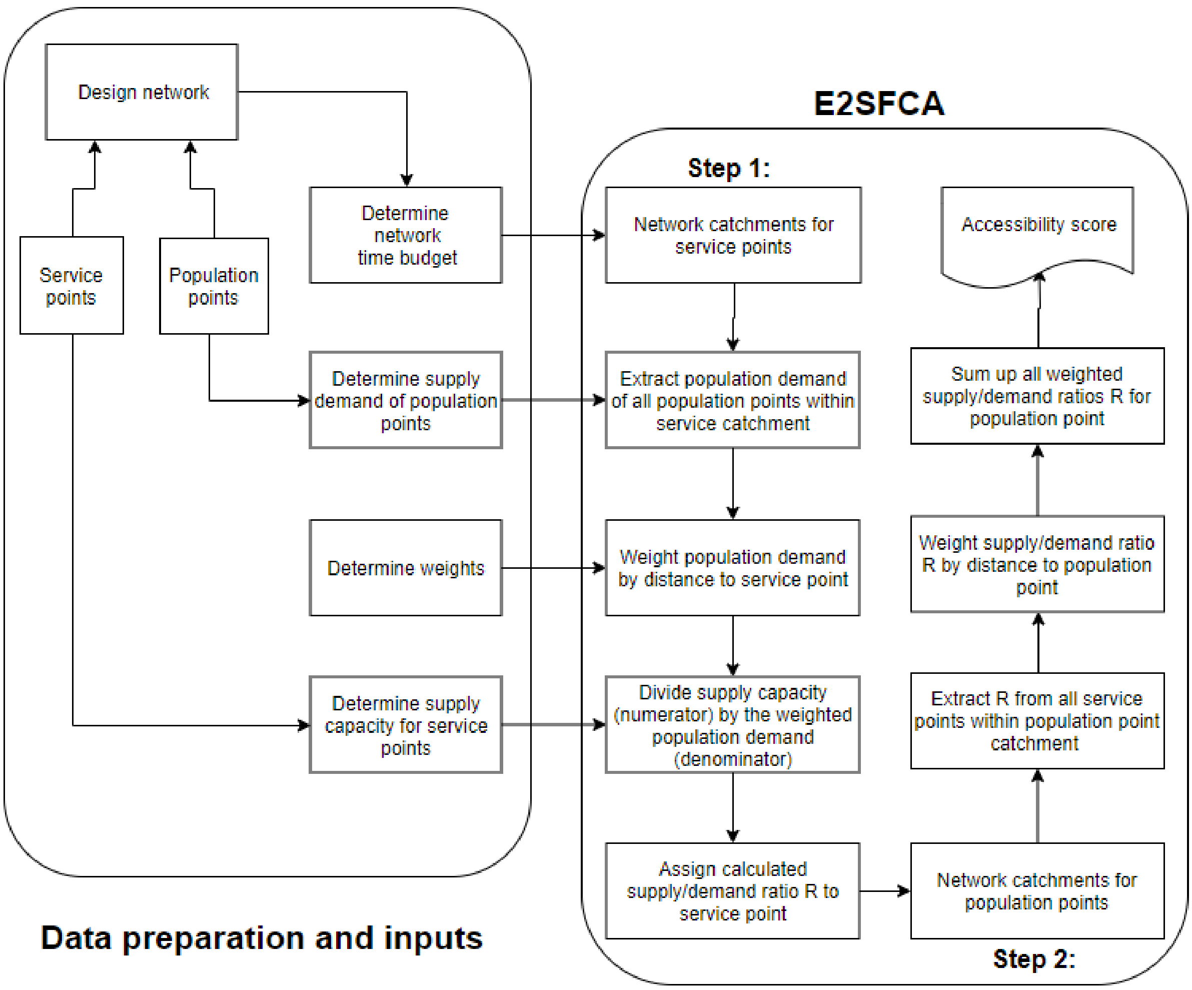

Figure 24. Workflow diagram of the Enhanced Two-Step Floating Catchment area method (E2SFCA).

The service utilization time spatio-temporal constraint will be represented as an artificial network segment which connects supply points within the study region to the network dataset. The network dataset preparation involves snapping service and population points to network segments. This step will be modified for service points (but not for population points). Instead of snapping the service point to the network, a new network segment will be created (fig. 25) between the supply point and the nearest network segment (only roads between 3m and 10m are taken into consideration so the supply points do not get stranded for a particular travel mode). The generated network segments are then manually assigned a custom time cost. This value represent the utilization cost of the service connected through the generated network segment. The utilization cost network segments are then calculated for each service individually and then merged with the network datasets used in the accessibility analysis. This way the spatio-temporal constraint of utilization cost is implemented indirectly in the E2SFCA methodology. However, it is important to note that the E2SFCA methodology makes use of the utilization cost segment twice; first when calculating service point catchments during the first step and when calculating population point catchments during the second step (fig. 26 right). Therefore, the utilization cost specific to each service category is assigned only half the utilization cost. By accessing the same segment twice, the E2SFCA models the full utilization cost.

The utilization cost network segment is created through three steps using various tools available in ArcMap. First, we calculate the point on the network dataset closest to the service point by linear distance proximity. Then we generate a new line feature using the point coordinates of the service point and the near point as the end points of the line. The result often exhibits dirty topology and have to be validated for overshoots and undershoots. After these issues are addressed, a utilization cost time value in seconds is manually assigned to service utilization cost segments. Finally, the segments are merged with the existing network dataset and service point network locations are calculated. Since the generated utilization cost segments share geometry with service points, they are always assigned to the utilization cost segment. Thus, the utilization cos segment represent a spatio-temporal bottleneck which serves to constrain mobility and accessibility.

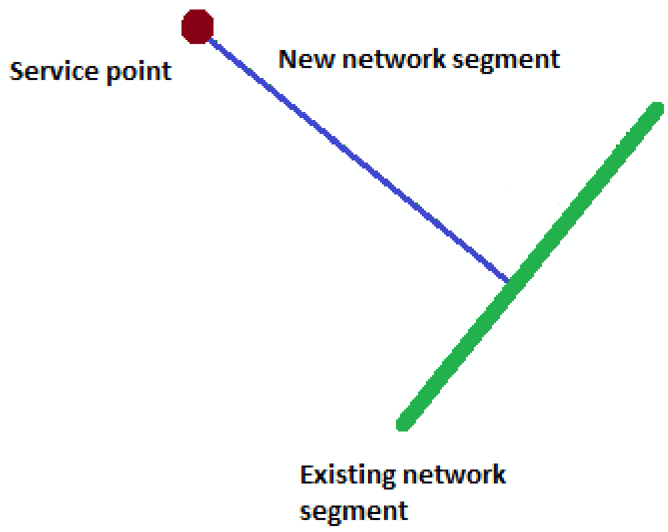

Figure 25. Illustration of utilization cost implementation as network segments.

First, we used the GENERATE A NEAR TABLE tool to compute coordinates for a line feature between the service point and network location (Analysis tools – proximity – generate near table). The NEAR TABLE function offers a checkbox for “select only closest (1) feature” which guarantees the results will be as expected every iteration and that the nearest point to the input feature is found. It is also necessary to select the option to write the location of the near feature. The NEAR TABLE contains the coordinate data for the service point input and the feature class used for the near input as; FROM_X, FROM_Y (service point lon/lat), and NEAR_X, NEAR_Y (closest network point lon/lat). Plus some additional data, e.g. NEAR_ANGLE (the angle between the service point input and the near feature input), and NEAR_DIST (the distance between the service point and the nearest network feature (near input)), which can be used to generate line features of the following step proves unsuccessful. The near feature for the service point can either be the edge of the network or a junction in the network. While the distance to the edge is most often shorter (fig. 25), the length of this segment is not important. Therefore, when connecting to junctions, one can avoid having to implement new topology and geometry in the edge features. Thus, it is advisable to generate cost segments to junctions, rather than network edges. The disadvantage is that this can either reduce or increase time friction necessary to reach the service point. However, the expected positive and negative influence cancels out the overall impact on the regional accessibility.

We generated the utilization cost segments with the FROM X/Y and the NEAR X/Y attributes in the NEAR table by using the XY to Line tool (Data Management – Features – XY to Line). The generated lines did not all properly extend to the network dataset. Hence they had to be extended or snapped. The initial gap was minimal, but this would preclude proper topology needed to adjoin the network dataset. Therefore, we used the EXTEND LINES tool (Editing – Extend Lines). The input features are the utilization cost segments created with the XY to Line tool, while the input parameters are max length of extension and whether lines can extend to other extensions. The latter was left unchecked and the former undefined, hence the lines would extend indefinitely until they intersected a network dataset edge. Since the angle of the line arcs faced the nearest network segments, no lines extended indefinitely. Once this was done there were several overshoots from the extend line which were fixed with the TRIM LINE tool (Editing – Trim Line). Once the results were validated and inspected for errors, they were merged with a network dataset by the MERGE tool (Data Management – General – Merge).

Figure 26 illustrates the position and logic of our addition of utilization cost segments into the E2SFCA methodology. Within the pre-processing step the utilization cost segments are created and service points are connected through them to the wider network. The travel impedance of these segments corresponds to the utilization time of the adjoined service points.

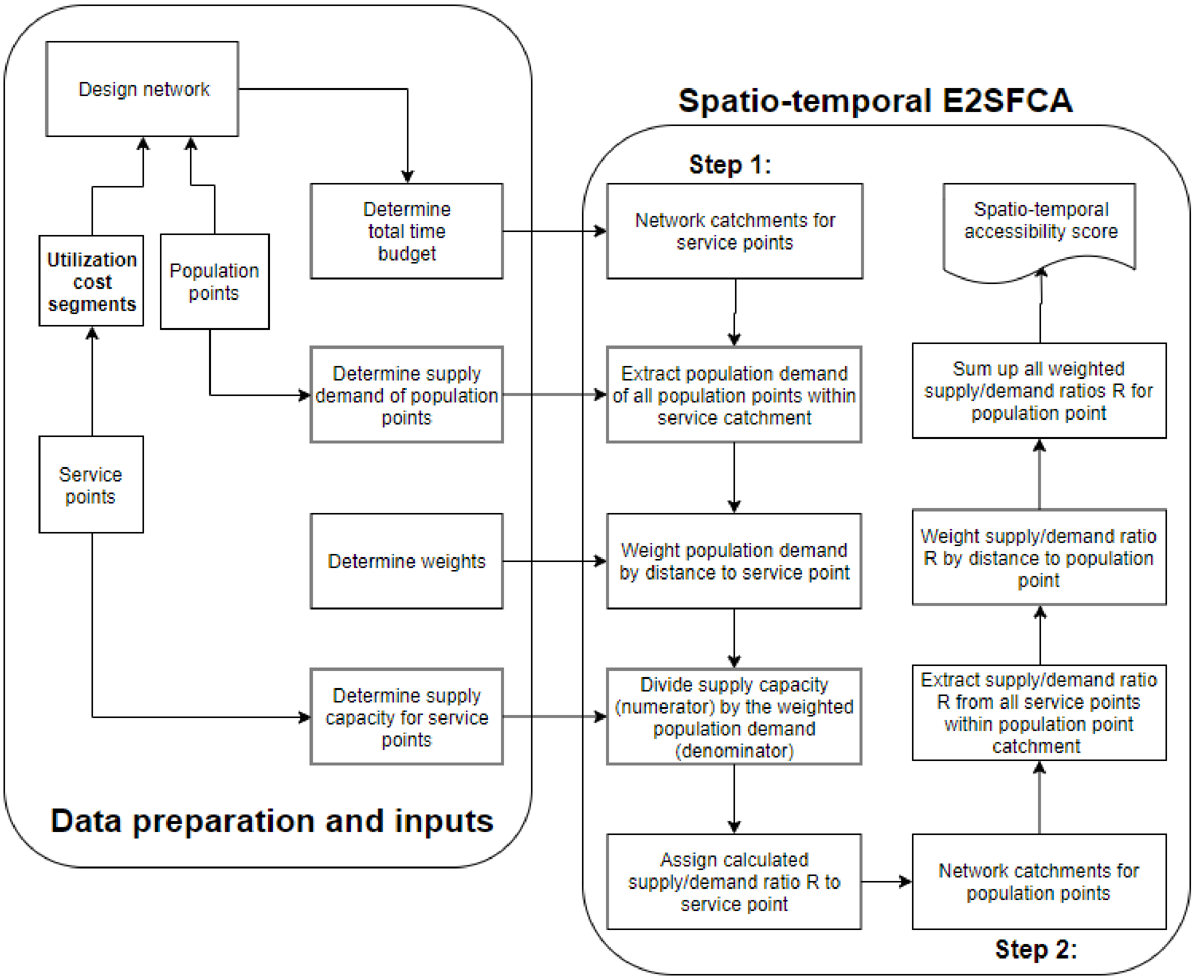

Figure 26. Workflow diagram of the methodology used for spatio-temporal E2SFCA accessibility analysis within the Master thesis.

Therefore, our addition to the E2SFCA is represented as an additional time constraints $\boldsymbol{d_j}$, which models the service utilization cost network segment.

$$\boldsymbol{R_j} = \frac{\boldsymbol{S_j}}{\sum_{k\in\left\{\left(\frac{1}{2}d_j+d_{kj}\right)\leq D_r\right\}} \boldsymbol{P_k W_r}}$$

Where P_k is the population demand in population point $\boldsymbol{k}$ whose centroid intersects with the catchment of service point $\boldsymbol{j}$, i.e. the combined temporal cost of the travel time $\boldsymbol{d_{kj}}$ and half the service utilization cost $\boldsymbol{d_j}$ is less than the total time budget $\boldsymbol{D_r}$ ($(\frac{1}{2}\boldsymbol{d} + \boldsymbol{d_{kj}}) \leq \boldsymbol{D_r}$). $\boldsymbol{S_j}$ is the service capacity in service point $\boldsymbol{j}$, and $\boldsymbol{d_{kj}}$ is the travel time between $\boldsymbol{k}$ and $\boldsymbol{j}$. Only half the service utilization cost ($\frac{1}{2}\boldsymbol{d}$) is included in each step since the utilization cost segment is accessed during both steps.

Step 2: For each population point $\boldsymbol{k}$, search all service points (*j*) that are within the total time budget (D_r) from population point $\boldsymbol{k}$ (that is, within network catchment area of population point $\boldsymbol{k}$), and sum up the supply/demand rations, $\boldsymbol{R_j}$, at these locations.

$$A_k^F = \sum_{j \in \left\{ (\frac{1}{2}d_j + d_{kj}) \leq D_r \right\}} R_j \; W_r$$

We expect that the increased temporal cost of accessibility, and by this directly decreased spatial reach, will significantly lower accessibility results for population points in the study region compared to the outcome of the unmodified E2SFCA method. However, we argue that our concept is more realistic and in accordance with everyday life since it models service utilization time. This modification to the E2SFCA method transforms it from a spatial accessibility method to a spatio-temporal accessibility method by introducing constraints in accordance with time geography theories (Hägerstrand 1970). Hence, the definition of spatio-temporal accessibility posited in the introductory section is fulfilled. The results of our method will model temporally constrained spatial accessibility to service points for population points in our study region. For that reason, the challenges of this method are setting reasonable time budgets $\boldsymbol{D_r}$ to account for the higher temporal resource investments for traversing the network due to the utilization cost segments $\boldsymbol{d_j}$. Furthermore, service utilization time constraints $\boldsymbol{d_j}$ are undefined in the literature save for a few select services (Delafontaine et al. 2012; Neutens et al. 2012b; Mao & Nekorchuk 2013), and constitute a research gap. Therefore, our method increases the uncertainty (Longley et al. 2011) involved about the generated outcomes compared to the unmodified method. However, if proper temporal constraints might be determined, the modifications introduced would improve the flexibility and spatial logic of the outcomes. To address the inevitable drop in potential spatial accessibility, one may either increase total time budgets $\boldsymbol{D_r}$, or modify the temporal accessibility parameters in the research. Increasing travel speeds (e.g. car vs pedestrian) decrease temporal investment into traversing networks and thus allow for more time to utilize service**,** which will increase the spatial reach and service accessibility for population points. Conversely, decreasing the travel speed will increase temporal resource expenditure on travel impedance, and thus leave less time for utilizing services**.** This results will likely be most noticeable with pedestrian network accessibility analysis, due to lower travel speeds and generally small total time budgets since services accessed by foot often are of lower functional centrality (e.g. stores for provision, or parks for leisure). This is logical, transportation modes significantly influence individual spatial mobility (Hägerstrand 1970). In fact, transportation is exemplified by multiple authors as a mobility multiplier (Luo & Wang 2003; Guagliardo 2004; Luo & Qi 2009; Wang et al. 2009; Mao & Nekorchuk 2009, Tenkanen 2017) and an essential factor of quality of life (Townsend 1987; Neutens et al. 2012a, 2012b, 2012c, 2013). Hence, pedestrian accessibility might prove uncompetitive (Tenkanen 2017).

3.3.2. S-T E2SFCA implementation in ArcMap

The E2SFCA accessibility method technical implementation in ArcMap is done through several stages reiterated for each service accessibility modelled. The required inputs are population points which include some form of demography based demand; service points which can but do not have to have supply capacity parameters (capacity can default to 1, although it is advisable to include proper capacity estimation); and a network dataset through which the accessibility is projected; and a gravity decay function which weights scores by distance or time. Figure 24 illustrates this process for the baseline E2SFCA and figure 26 illustrates the process for the modified spatio-temporal E2SFCA used in this thesis. Therefore, for each service it is necessary to assign network locations, generate spatio-temporal catchments based on the network, and create a full origin-destination matrix of distances between all service and population points so that the gravity function could be calculated. This constitutes the first, pre-processing part of the method (step 0). The most important part of the pre-processing is to pay attention to the sequence in which the network dataset is built. Depending on given topology, it may be needed to create artificial connector segments to connect public transport stations with the regular road network. In the case this is necessary, it has to be done before the Network dataset is built otherwise the process has to be repeated. Furthermore, before the network is built, time friction costs have to be calculated for each feature participating (including the artificial edges created). Finally, the topology has to be validated by creating a topology feature and addressing issues, otherwise service facilities are inaccessible. Only then can the processing part of the method (step 1) be start. The processing part of the E2SFCA implementation in ArcMap begins by assigning composite population demand to service point catchments. The population demand encompassed by the receiving supply point is weighted based on distance or time in accordance with Toblers First Law. Each population demand value extracted from overlaid population points is divided by the supply capacity of the point to derive the weighted supply and demand ratio R. Afterwards, the same procedure is applied to the service supply/demand ratio which is extracted to population point catchments from overlaid service points (step 2). By summing up the gravity decay weighted supply/demand ratios R, we calculate the accessibility score for the population point. Essentially, the E2SFCA method has 3 steps; step 0, step 1, and step 2. These three steps have to be implemented in the same order for each service. Therefore, it is imperative to automate the process through an ArcGIS model or python script.

Langford et al. (2014) have developed an ArcMap extension which helps automate and implement the E2SFCA. The extension is programmed to accept necessary inputs chosen from map features within the ArcMap workspace, and gravity decay values chosen from several inbuilt options. Figures 27 through 30 demonstrate the utilization of the extension through its four stages on the example of healthcare provision within the Canton of Zurich.

3.3.2.1. E2SFCA extension stage 1

The first stage (fig 27.) of the E2SFCA extension involves the network dataset used in the accessibility analysis. We need to choose between the network datasets loaded in the ArcMap workspace. Nota bene, the network dataset has to have calculated locations for the service and population points used within the same accessibility analysis. The travel impedance parameter is chosen from among the network dataset cost parameters, which are in turn based on attribute fields (e.g. length or time cost).

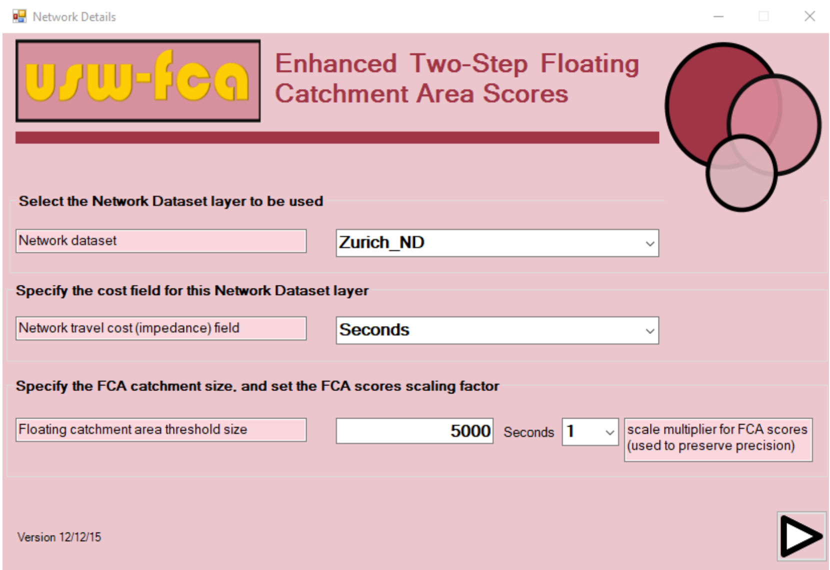

Figure 27. E2SFCA extension (Langford et al. 2014) first stage; network input parameters and time (or distance) budget.

3.3.2.2. E2SFCA extension stage 2

The second stage (fig. 28) of the extension involves the service and population points used to model spatial distribution of supply and demand. For the service point we can designate the attribute field which holds the supply value for the individual point. Otherwise, this can be left empty and supply will be estimated at 1 which will provide suboptimal results compared to including supply estimations. In practice, not setting the supply capacity underestimates accessibility in more populated areas. When choosing the population points we are required to designate a demand field. In the figure 28 example, the amount of population above 65 years old is designated as the demand volume. Also, primary key for population points (ORIG_FID in this example) is necessary to enable joining the accessibility scores to population points in stage four.

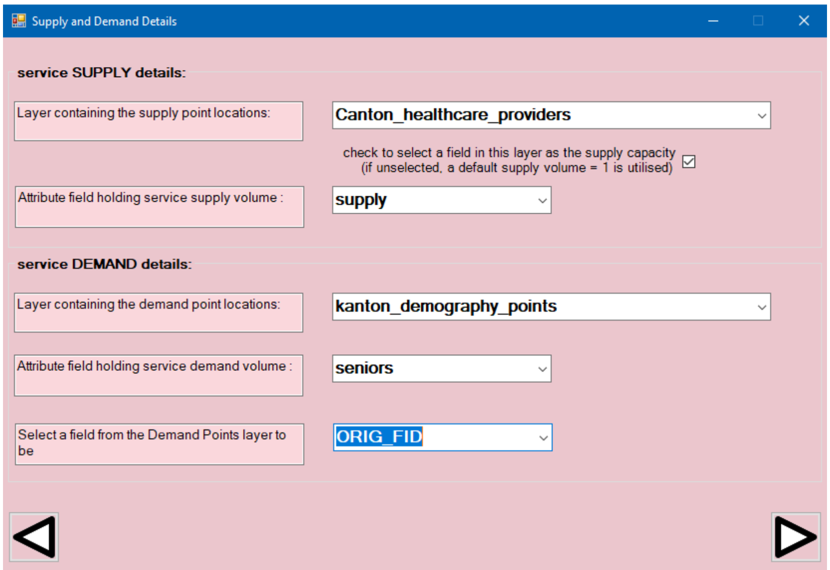

Figure 28. E2SFCA extension (Langford et al. 2014) second stage; service point inputs and supply capacity designation, and population point inputs and demand designation.

3.3.2.3. E2SFCA extension stage 3

In the third stage (fig. 29) we define the gravity decay function and values used in the E2SFCA (or no decay for 2SFCA). The extension offers four options; no decay, linear decay, Gaussian decay, and Butterworth decay. In this thesis the Gaussian decay Function was used in combination with a Decay bandwidth of 50, the default Gaussian decay value (Langford et al. 2014). The Cartesian graph on the left side of figure 29 visualizes the effect of the decay function on the data. The X axis (horizontal) of the graph represents distance from the supply or population point (0). The distance is the temporal or spatial measure of travel impedance between two points in the generated accessibility network catchment. In the graph, the 0 value represents the point of origin, i.e. the population or service point. Conversely, the value 1 on the X axis represents the boundary of the catchment which based on the point at value 0. That is, the value 1 of the X axis represents the isolines which connect points at which the time budget is expended.

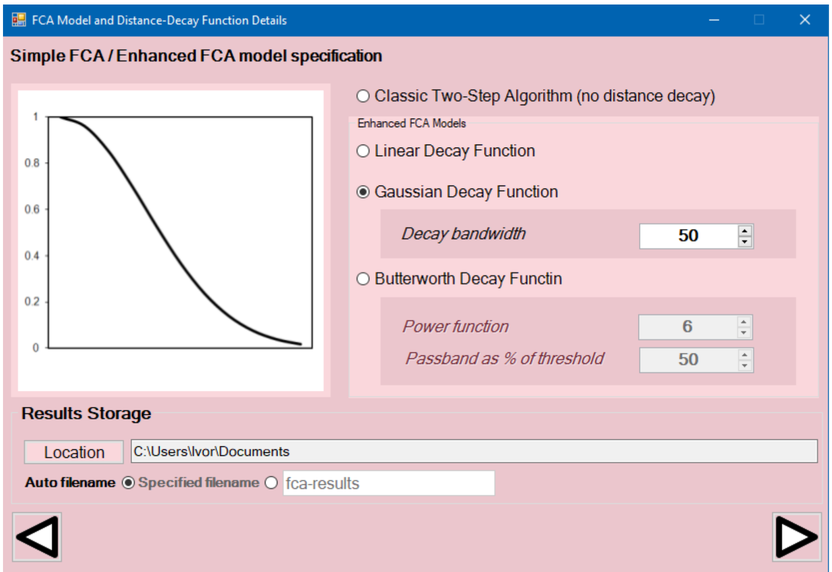

Figure 29. E2SFCA extension (Langford et al. 2014) third stage; gravity decay function designation. The Gaussian Decay function is applied in this research with the default bandwidth of 50.

The Y axis (vertical) of the graph represents the intensity of the weight applied to the value of the attribute which is being weighted (fig. 30). The intensity of the weighting increases per distance travelled as argued for by Luo & Wang (2003), Guagliardo (2004), and Luo & Qi (2009). However, the Y axis values between 0 and 1 in figure

30 conceptualise the post-weighting value of the attribute which was weighted. Hence, only the points which share network location are allocated the full original value, while all other locations are weighted according to travel distance (time or length depending on chosen impedance); with the intensity determined by the gravity decay function.

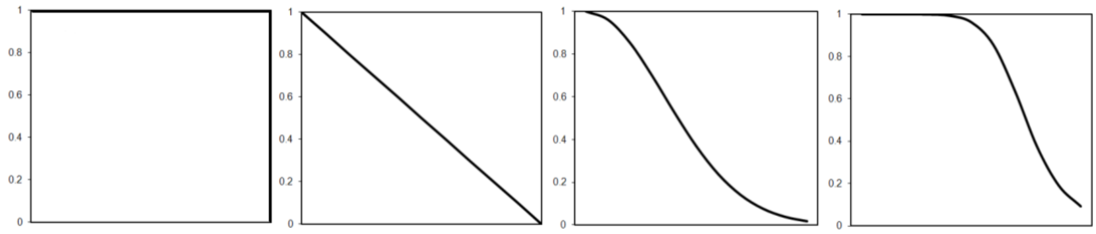

Figure 30. Graphs used within the E2SFCA extension (Langford et al. 2014) to visualize the gravity decay function for, from left to right; no decay, linear decay, Gaussian decay (50 bandwidth), and Butterworth decay (power function6, passband 50).

Langford et al. (2014) argue that the Gaussian decay function with the bandwidth of 50 is common, hence set as the default. They further explain that higher Gaussian decay bandwidths cause a steeper rate of decline, while lower bandwidths cause gentler curves closer to the linear model. It is therefore inferred that the decay bandwidths determine the kurtosis of the weight intensity distribution. While not explicitly stated within the E2SFCA extension documentation, we can deduce from the graphs and the provided description that the Gaussian decay bandwidth of 50 represents the Normal, mesokurtic distribution. Thus, with the default bandwidth of 50, points within the first tertile of the distribution preserve at least 75% of their original attribute values. Points between the first and the second tertile preserve between 75% and 25% of their original value, while points in the third tertile by distance from point of origin preserve under 25% of their original value. Unfortunately, the authors did not elaborate on the manner in which the bandwidth value is translated into distribution kurtosis hence the gravity decay implementation represents a black box of the E2SFCA extension. The normal Gaussian gravity decay distribution was originally considered as the most logical option for the gravity decay function. After a sensitivity analysis of the bandwidth effect on results (Chapter 4), the default Gaussian decay bandwidth of 50 was chosen for the universal distance decay used in this research. While it is suggested in the literature that gentler distance decay functions can be used to model the increased willingness to utilize certain services (Luo & Wang 2003; Guagliardo 2004; Luo & Qi 2009), it was decided to utilize the same values across all services. Since in this research we are analysing a wide variety of services, not just healthcare, we do not have the theoretical or empirical literature examples or information to base our bandwidth on. Above all is the fact that the Gaussian decay bandwidth of 50 is the only one elaborated on by Langford et al. (2014) in sufficient detail to deduce the underlying logic. Hence, when using other bandwidths the interpretation of the results would be uncertain. Finally, the Butterworth decay function was not considered because the gravity decay weight distribution presented by it is not logical in terms of our theoretical premises (Hägerstrand 1970; Tobler 1970; Šterc 2015), nor literature on healthcare service point choice (Guagliardo 2004). Likewise, the linear gravity decay function is overly geodeterministic based on our considerations of service utilization (Hägerstrand 1970).

3.3.2.4. E2SFCA extension stage 4

The final stage of the E2SFCA extension involves the recording of the calculated accessibility scores within a text document exported into a folder designated during the third stage. This text document contains the list of all population points involved in the accessibility analysis. The primary key designated during the second stage is used as the primary key in the list and the other attribute fields contains all data pertaining to the E2SFCA accessibility analysis process. Figure 31 is the screenshot of one such list generated during this research; whereas the m1_fca field holds the final accessibility score. The m1_SupID fields holds the unique id of the closest service point (-1 if none available within time budget), and the m1_Dist represents the distance to the closest service point. The distance is in this case temporal since time was chosen as the travel impedance attribute. The value of the m1_Choice field represents the number of service points available within the time budget. The m1_AveD represents the average distance to all available supply points for a population point.

OID	OBJECTID *	DemandID	m1_SupID	m1_Dist	m1_Choice	m1_ChoiceW	m1_AveD	m1_AveDW	m1_fca
0	1	1	-1	-1	0	0	0	0	0
1	2	2	-1	-1	0	0	0	0	0
2	3	3	-1	-1	0	0	0	0	0
3	4	4	-1	-1	0	0	0	0	0
4	5	5	176	924.529	9	225	2319.82	2319.82	0.009348
5	6	6	176	958.479	9	225	2330.37	2330.37	0.009378
6	7	7	176	957.162	9	225	2326.05	2326.05	0.009433
7	8	8	177	1074.71	9	225	2441.29	2441.29	0.008812
8	9	9	166	1285.37	9	225	2715.19	2715.19	0.005476
9	10	10	-1	-1	0	0	0	0	0
10	11	11	-1	-1	0	0	0	0	0
11	12	12	176	853.313	9	225	2248.6	2248.6	0.009846
12	13	13	176	886.952	9	225	2262.04	2262.04	0.009825
13	14	14	176	922.216	9	225	2283.29	2283.29	0.009791
14	15	15	118	3013.89	9	225	3129.85	3129.85	0.000564
15	16	16	118	3001.25	9	225	3117.21	3117.21	0.000578
16	17	17	166	1547.79	11	275	2849.13	2849.13	0.004062
17	18	18	166	1380.55	10	250	2798.4	2798.4	0.004858

Figure 31. E2SFCA extension (Langford et al. 2014) fourth stage; the output of the extension is a table containing accessibility scores (m1_fca) for each population point by primary key (OBJECTID*), alongside other information.

This table is joined to the population points feature used in the analysis by primary key. Thereupon it is possible to geovisualize the accessibility scores through layer symbology settings.

3.4. Services modelled

The challenge with applying the E2SFCA method on a wide range of services is that the first step of the E2SFCA requires supply capacity values for service points. This is not an issue for healthcare research where the supply capacity of service points is reliably quantifiable based on empirical research through the years (Joseph & Bantock 1982; Lee 1997; Guagliardo 2004; Mao & Nekorchuk 2013). Indeed, it is possible to intuitively assume a supply capacity for a healthcare facility based on number of beds, or number of physicians. However, supply capacity for other services is not so straightforward nor extensively researched (Townsend 1987; Smoyer-Tomic et al. 2004; Zenk et al. 2005; Apparicio & Seguin 2006; Smith et al. 2009; Salze et al. 2011; Zhang et al. 2011; Järv et al. 2016). How would one approximate the supply capacity of a bank? By number of counters? By number of employees? By floor space? By financial flows? Even if these parameters were appropriate, the necessary data is unlikely to be available. Hence, for the purpose of this research, the supply capacity will have to be estimated based on reasonable assumptions, and where possible, on examples in literature. There are numerous auxiliary services which the population of an average region would have access to. While this is in most cases a beneficial thing for society, it poses a problem in research. The total number and variety of individual services which are suitable for an accessibility research is unrestricted. Therefore, we have to classify services into archetypes and assign these archetypes into broader categories according to their function (e.g. Neutens et al. 2012a with public services). For example, a LIDL branch is a retail store and is classified as such alongside other similar stores like Migros or Spar. All retail stores fulfil the function of provisioning the population with consumer goods and other life necessities. Thus, the service class of retail stores is part of the service category fulfilling the function of provision. In order to posit reasonable estimates for service supply, it is first necessary to generalize them into classes of equal quality/goods provided so that we may assume a baseline level of service quality/quantity provided by a service class. This will facilitate research implementation and provide results which are simpler to comprehend and interpret. Conversely, modelling all available individual iterations of services in a study region without classifying them will leave us with a deluge of information, which might make it difficult to recognize or understand spatial logic. However, delineating between two different services is not straightforward. Since objective indicators or data might not be available, differentiation between services cannot always be based on quantitative considerations. Classification would optimally be based on such quantitative data. For example, how would one determine what constitutes a small department store versus a large department store if data such as total shop area, money or customer flow, etc. is not available? On the other hand, a department store with a smaller floor area might have a greater customer flow due to a better network position, which further complicates the notion of a completely objective classification. The variety of services to be modelled at the same time complicate and necessitate classification. Therefore, we will classify services into archetypes. The reasoning and cognitive process operate thusly; both a small and a large department store are department stores, and our research is not focused on variations in accessibility scores between large or small department stores. Furthermore, a department store is essentially a store. Just like a park with a playground and a park without a playground are both parks. The point is that the spatial resource (service) fulfils the same function (provision for stores, leisure for parks) in an identical way, albeit with different levels of quality (which is also beyond the scope of this research). Both parks have the same baseline features, spaces of tranquillity and balance, while the specifics may differ. Two stores also share the common feature of providing spaces for exchanging resources for necessary consumer goods and we can thus infer that there is an expected baseline of products which can be found in all stores, no matter the size. Classifying services allows us to generalize service point data and expand the scope of our research.

Alike the service classification process, categorization will also be based on intuitive considerations pertaining to the nature of the service (Apparicio & Seguin 2006). The nature of the service draws on the introductory considerations of this thesis; services are spatial resources which a population utilizes for their benefit while fulfilling a function of life (e.g. provision, communication, healthcare etc.). If the population creates such a spatial resource and utilizes it, then it is most likely based on the fulfilment of some innate need. The utilization of such a service fulfils a functional need of the population. Building on the notion of work and habitation being essential functions, every other service fulfils an auxiliary function. Therefore, we will categorize services according to the auxiliary function they fulfil. The functional categorization will determine multiple service categories, which include intuitive categories such as healthcare or provision.

The process of choosing the individual services to model is open-ended due to the large amount of available data for most urban spaces. There are often both authoritative and open-source data available which expands the choice both quantitatively and qualitatively. However, we have decided to define our service categories before considering individual services which would constitute the categories. The main advantage of this approach is that it helps better shape the service choice according to the broad topic of interest we decided upon; spatio-temporal accessibility of service provision. Had the research topic been more specific, e.g. the spatio-temporal accessibility analysis of parks, the logical research flow would be to extract all possible data on parks in the study area, and then classify them according to a logic characteristic to parks. With each additional service one seeks to model, the topic of interest expands, as does the amount of resources needed to extract service information and the subsequent classification into service categories. Since we are interested in the totality of service provision, setting the categories beforehand is both a parsimonious investment of resources and the logical research flow. Considering the service categories beforehand also helps determine which services to outright reject according to the geographic scale of our study region. The spatial scope of some services might be either too great or too small to properly model in a given study region. For example, the catchment area of a major airport extends well beyond the boundaries of the administrative unit it is based in, perhaps even the regional administrative unit. Therefore, accessibility analysis of an airport would have to expand the geographic scope until the research region included another airport, ideally of similar significance, so that the space in-between might be divided according to a gravity model. Conversely, the accessibility analysis of neighbourhood cafés might significantly vary in its outcomes from spatial reality due to the micro-geographic scale and the resulting neighbourhood effects (Kemp 2008). A further problem with smaller scale services is that they are less durable in terms of operational lifespan than services operating on a larger scale, which is even more relevant for private sector services. It is more probable that a small private clinic will close down due to demographic or market shifts, than it is probable a large public hospital would. Another problem with modelling micro-scale services such as cafés is that demand for those services might be infrequent or conditioned by factors which we cannot properly model without empirical person-based or realized accessibility research, e.g. the social interaction models (Neutens et al. 2012).

Finally, service choice, classification, and categorization was also influenced by data availability for the study region. Where possible, we used authoritative data sources instead of open sources data. In this case, authoritative data pertained to any data which could be sourced to or built from the service provider itself. For example, modelling retail stores from authoritative data means we retrieve the location and characteristics of every retail store from the website of the company which operates it. Conversely, the same data could be sourced from volunteered geographic information (Goodchild 2007), such as Open Street Map, through custom queries. The obvious advantage for using authoritative data is that it is most likely up-to-date and exact in its geographic information, thus the uncertainty involved is decreased (Duckham 2015). However, open source data is not necessarily unusable, the sites and platforms which compile and provide volunteered geographic information (VGI) set certain guidelines for content creation and thus improve data quality (Goodchild et al. 2012). Furthermore, not all authoritative data is by default of a higher quality. Since such data is usually gathered in intervals and can thus omit recent changes in spatial distribution. However, the "authority" behind authoritative data is based on the clear and universal methodologies used or gathering official geographic information (Goodchild 2007). Unfortunately, this often sets a price tag on authoritative data, potentially leaving it outside reach for most of its intended users. In this research, the data on services was sourced from authoritative data in all cases. Most often, this involved the website of the service provider, or a compilation of service points from second-hand compilations (e.g. list of theatres from the regional tourism office) which were verified by checking google maps or the website of the particular service point. The data gathering process was primarily concerned with geographic locations so that the service points could be mapped. Where applicable, additional data was acquired. For example, where working hours were listed they were also recorded. In all cases, the geographic location of the service data was in the form of street addresses. These addresses were afterwards geocoded in R using R Studio and the google maps package "ggmap"[5] by Kahle & Wickham (2013). The ggmap package allows for an API to access google maps queries for the address and assigns the longitude and latitude corresponding to the address queried.

The most comprehensive, in terms of services modelled, accessibility analysis uncovered during the literature analysis is the research by Apparicio & Seguin (2006). The authors analysed accessibility to eight service categories containing 38 service classes. The topic was accessibility to service facilities for public-housing residents in Montreal, with a focus on spatial equity and underprivileged populations. Despite thoroughly analysing the implications and theory of accessibility locational benefits, the methodology developed and applied by Apparicio & Seguin (2006) is essentially an availability analysis using distance weighted availability scores. Hence, there were no considerations of service supply which are a limitation in this research. However, the research by Apparicio & Seguin (2006) inspired service choice as well as the approach to service categorisation and classification used in this research, albeit from different theoretical perspectives (time geography vs social geography).

3.4.1. Service categories

Based on our research topic, geographic scope, and data available for the study region, we have decided on five service categories:

- 1. Provision services
- 2. Healthcare services
- 3. Public transport services
- 4. Leisure services
- 5. Communication services

The data sources for the services modelled in this research are provided in the final, supplementary chapter.

3.4.1.1. Provision

Provision concerns the functional need to secure regular sustenance (Hägerstrand 1970) and access to other consumer goods. Hence, the primary service class fulfilling the function of provision are retail stores. In order to generalize the manner in which stores are modelled, we have chosen to limit the retail stores in the research to branches of larger retail chains. The retail chains modelled in this research are: Aldi, Lidl, Coop, Migros, Spar, and Denner. Such chain stores are structured on a pre-determined standard of content and quality (e.g. all LIDL

[5] https://cran.r-project.org/web/packages/ggmap/ggmap.pdf

stores are almost the same in both layout and products). Furthermore, all retail chains operate on a grand scale economy where it is important to remain competitive in regards to the competition through keeping up with quality, price, and range of goods offered (Zenk et al. 2011). This is contrasted by local stores operated by families or chains of ethnic retail stores (e.g. Turkish stores in Zurich). Such local stores are likely to vary significantly in both the quality and range of goods offered, while at the same time relying more on neighbourhood consumer logic rather than true economic trends and markets. Therefore, local and ethnic stores would have to be classified into a different class than chain stores. Even then there would likely be a large intra-class variance. It is for that reason that provision is modelled solely by chain stores in this research. Assuming all chain stores offer the same quality and range of goods due to market competition, we can ascribe the same supply capacity to all chain stores. Furthermore, we can assume that chain stores, being market driven commercial enterprises, adjust their supply according to the demand in a region. Since demand for provision is universal, the regional provision supply is logically determined by regional provision demand. Hence, in a study region there is likely to be as many chain stores as competition and demand allows. Based on these assumptions, the supply capacity of each individual chain store is determined by the arithmetic of regional supply and demand (n service points/ n service demand). The average supply per chain store is hence approximated at 2000. We apply a utilization time of 300 seconds (5 minutes) to the utilization cost segments of provision service points, and a total spatio-temporal accessibility time budget of 900 seconds (15 minutes).

3.4.1.2. Healthcare

Healthcare concerns the functional need for maintaining health, preventing diseases, and security in case of medical emergencies. Healthcare is the staple of accessibility research and it is rightly regarded as one of the most important services available to a population of an area (Joseph & Bantock 1982; Townsend 1987; Guagliardo 2004; Yang et al. 2005). Healthcare is most often provided in centralised locations; clinics or hospitals. However, private doctor practices are also a valid and rather ubiquitous (in urban spaces) method of healthcare provision. However, the function of healthcare can be subdivided by the range of service offered. This is clear from the manner in which healthcare professionals are subdivided by specialisation. For the general population, the most important healthcare professional is the general practitioner (GP) (Townsend 1987); the lynchpin of primary healthcare provision (Joseph & Bantock 1982; Guagliardo 2004; Mao & Nekorchuk 2013). GPs can either be private or work in hospitals or other care centres. Retirement homes were considered as a candidate for the accessibility analysis. However, accessibility to retirement homes from population points is a redundant metric since utilization of retirement home services involves settling down in the retirement home.

The supply capacity framework of healthcare provision is well developed. Examples of healthcare service supply capacity are based on numbers of beds, numbers of doctors, hospital funding, or floor area (Joseph & Bantock 1982; Guagliardo 2004; Mao & Nekorchuk 2013). More importantly, there exists empirical research on the individual daily capacity of a general practitioner (Murray et al. 2007). The patient capacity per doctor is called a panel size, and can be approximated for any timeframe, e.g. daily panel or yearly panel etc. Murray et al. (2007) defined the ideal daily panel size per doctor to be 25, based on equations of supply and demand and surveys among doctors. Hence, healthcare supply capacity will be derived from this estimate and the number of doctors per supply point. Data on the hospital system of the Kanton Zürich includes employment data per qualification (Gesundheitsdirektion Kanton Zürich 2012). However, it is unrealistic to assume that each Dr. Med. working in a hospital would count as a general practitioner. Therefore, only one third of hospital doctors count towards supply capacity. Data on private doctors was sourced from the doctor.ch website on which doctors create individual profiles and define the focus of their practices. Hence, the supply capacity for private doctors is not altered. Therefore, we estimate total healthcare supply capacity by multiplying with 25 the number of doctors and physicians in hospitals or general practitioners in private practices. The 25 daily patients' panel size would correspond to approximately 20 minutes per patient in an 8 hour workday, whereas 30 minute per patient would lower the expected daily panel to 16. However, it is not clear whether the chosen panel size based capacity is an overestimation or underestimation of service supply. The same dilemma is present in all services since supply capacity estimation is a veritable research gap within accessibility research. We apply a utilization time of 1200 seconds (20 minutes) to the utilization cost segments of healthcare service points for primary health providers (Nekorchuk et al. 2013). Total time budgets assigned to healthcare accessibility are 3600 seconds for primary healthcare (Joseph & Bantock 1982; Mao & Nekorchuk 2013).

3.4.1.3. Leisure

Leisure concerns the functional need of self-investment through recreation and socialization (Hägerstrand 1970). Free time activities are possible during approximately a third of the average employed individual's day (given an 8 hour workday, and 8 hours of sleep, not counting commute). Most free time activities are likely to be related to leisure either through social activities or through recreation outdoors and indoors. The ability to utilize free time is an important aspect of quality of life (Hägerstrand 1970; Neutens et al. 2011). Therefore, a network of service points within which the function of leisure can be fulfilled is an important spatial resource. We have determined four leisure service classes which are suitable for accessibility analysis: parks, sports facilities, museums, and theatres. They are regarded as sufficiently static in their spatial distribution, range and quality of service provision, and their spatial catchment scope (as opposed to e.g. restaurants). The leisure services functional category can be divided into two subdivisions: parks and recreation, and social and cultural activities. This division is chosen to represent the likely population demand for each. Parks and recreation are a recurring theme in accessibility research (Nichols 2001M Smoyer-Tomic et al. 2004; Apparicio & Seguin 2006; Smith et al. 2010; Salze et al. 2011; Zhang et al. 2011). This is most likely tied to the rising levels of unhealthy lifestyle and obesity in the West (Smith et al. 2010; Salze et al. 2011; Zhang et al. 2011). However, parks are a primarily urban resource since there is ample free space and preserved nature in rural areas. Parks and recreation are assigned universal population demand (total population contributes), while museums, and theatres are assigned population demand equivalent to the adult population of the study area. This is primarily motivated by the fact that the latter group of services almost always entail an entry fee (per the data gathered). Conversely, the former group of leisure service classes has open access in most cases. Parks are a special case since they are an urban feature. Therefore, accessibility to parks will take into account only the municipality population of each study area. The supply capacity for the service classes of theatres and museums is informed by the data on annual visitors in the Canton of Zurich for museums (2014 n = 1126641) and theatres (2015 n = 444785) from the BFS annual report (2015). Therefore, the supply capacity of museums and theatres is estimated at 5000. Sport facilities containing a pitch or a court (e.g. for basketball or football), or indoor sport halls and gyms, or swimming areas are assigned a service capacity of 250. Conversely, all other sport facilities are assigned a capacity of 50 (e.g. shooting ranges, golf courses, equestrian sport sites etc.). As for parks, the estimation of service capacity could not be bound to any objective category since the data available contained no metadata. Hence, the supply capacity of parks is estimated based on spatial and market logic. Thus, based on the number of parks and the municipal population within the study areas, the supply capacity for parks is estimated at 4000. The total time budget for museums and theatres is 1200 seconds (20 minutes), for sports facilities it is 900 seconds (15 minutes), and for parks it is 600 seconds (10 minutes). We use a utilization cost of 300 seconds (5 minutes) for cinemas and theatres. Conversely, no utilization time is assigned for parks and recreation.

3.4.1.4. Public transport

Public transport concerns the practical need for large scale mobility in space in the absence of personal automobilism. Accessibility to public transport can significantly improve individual mobility which in turn improves quality of life (Hägerstrand 1970; Joseph & Bantock 1982; Townsend 1987; Peng 1997; Radke & Mu 2000; Luo & Wang 2003; Guagliardo 2004; Apparicio & Seguin 2006; Luo & Qi 2009; Neutens et al. 2011, 2012a, 2012b, 2013; Delafontaine et al. 2012; Tenkanen et al. 2016; Tenkanen 2017). Furthermore, public transport is a public interest due to integrating state and municipal territory into a functional whole. This facilitates regional economy, the exchange of goods, information, and services (Jefferson 1928; Bertolini et al. 2005). It improves possibilities for rural and underprivileged populations (Kolars & Malin 1970; Domanski 1979; Townsend 1987), and public transport also facilitates tourism (Kraft 2016). Evidently, there is great functional utility in public transport accessibility. Therefore, the public transport network accessibility will be analyses for the study areas based on the spatio-temporal accessibility to public transport stations. Public transport stations differ to all other service points modelled in that they have no utilization time nor supply capacity. Unfortunately, integrating travel schedules for public transport was not feasible in the scope of this research, despite literature examples proving the utility of including timetables (Neutens et al. 2012b; Tenkanen et al. 2016; Tenkanen 2017; Järv et al. 2018). Consequently, public transport stations are not assigned supply capacities which would logically be derived from the frequency of public transport passage at a particular station (e.g. ÖV-Güteklassen, Amt für Verkehr 2017). However, the dendritic nature of public transportation networks means that it is possible to reach any part of a connected network from another part, given enough time. The accessibility scores calculated within the upcoming accessibility analysis will therefore corresponds to the accessibility to the public transport network, not necessarily individual stations. Hence, population points which can access multiple public transport stations are assigned greater accessibility scores. Nevertheless, the inclusion of timetables and public transport network frequency is a valid point of interest for future research.

3.4.1.5. Communication

Communication concerns the functional need of access to information, free contact with other individuals, and reliable delivery options such as postal services. For the purpose of this research, only postal services were included as the service representing communication. The post office is a multifunctional service point within which many services can be utilized. For example, the post accepts classic postal services of sending and delivering mail, packages, correspondence, long distance telephone calls etc. The post further accepts financial transactions, most often when paying bills or withdrawing cash, salaries, or pensions. The post office sells consumer goods such as paper, Belletristik, birotics, mobile phones, telecommunication subscriptions etc. In that regard, the post office is a great value to the local population, especially the older cohorts which are less tech savvy and accustomed to the post office role in their activity spaces. This is contrasted by the growing drive to decrease the amount of post offices in order to rationalize operational costs as well as acknowledge the waning role of the traditional post office in the 21st century (Swiss Post 2016). Swiss Post, the federal post company, plans to rationalize business by 2020 by closing down up to 600 traditional brick and mortar post office branches from 1400 in 2016. However, the closed branches will be substituted by automated post machines akin to self-checkout counters in retail stores. Consequently, there is an ongoing debate in Switzerland on this issue and how will it affect different parts of the country and different demographic groups.

The service capacity of post office branches is estimated at 1000, based on the relatively uniform distribution of branches which follows the population. Hence, we divide the total number of post office branches in the study areas with the population of the study areas. We apply a utilization time of 600 seconds (10 minutes) to the utilization cost segments of post office service points. The total time budget for spatio-temporal accessibility is 1800 seconds (30 minutes).

Chapter 4: Results

4.1. Overview of results per service category

The results of the accessibility analysis are presented within this chapter per service category with a comparison of Zurich and Winterthur. The primary parameters which are presented as the default inputs for this research are a Gaussian decay function bandwidth of 50, multimodal network datasets (foot travel speed 3 km/h), population demand is determined by population size, and service supply and utilization costs vary from service to service per the values defined in the previous chapter (tab. 2).

Service category	Service class	Total time budget	Utilization time	Demand	Supply
		seconds	seconds		
Provision	Chain stores	900	300	total population	2000
Communication	Post offices	1800	600	adult population	1000
Healthcare	GP private practices	3600	1200	total population	25 per doctor
	Hospitals	3600	1200	total population	25 per doctor / 3
Transport	Public transport stations	600	x	total population	x
Leisure	Parks	600	x	total population	4000
	Sports facilities	900	x	total population	250-50
	Theatres	1200	300	adult population	5000
	Museums	1200	300	adult population	5000

Table 2. Overview of services modelled and parameters used during the accessibility analysis.

The classification and colour scheme used to geovisualize the results of the accessibility research is based on the topic and aims of this research. We are interested in the relative distribution of scores within the study areas and between the study areas more than we are interested in absolute values of accessibility scores. Our goal is to understand the spatial logic of service provision and test our initial hypothesis. However, it is hard to compare between two maps if no absolute metric of accessibility is used (Slocum et al. 2009). Conversely using a diverging colour ramp centred on the median value allows us to visualize intra-regional differences clearly. Therefore, we use a combination of a relative colour ramp and absolute accessibility values by not classifying the results. Instead, each accessibility score is assigned a discrete colour shade from the colour ramp ranging from 0 (purple) to the maximum value (green). The colour ramp is algorithmically generated within ArcMap based on the maximum and minimum values retrieved from the ColorBrewer[6] diverging purple to green scheme. This way, it is possible to understand the intra-regional accessibility score distribution and at the same time compare between different maps since the accessibility score is derived from the same method (albeit with different inputs). The accessibility scores range from 0 upwards of several thousand depending on the iteration. However, most often the spatio-temporal accessibility score is a value between 0 and 1. For each iteration of the accessibility analysis, the scores are colour ramped around the mean value.

The primary set of results are presented in the following subsections per service category. The chosen examples were based of pedestrian accessibility research with the other parameters given as outlined in table 2. The pedestrian accessibility analysis produced the most striking intra-regional differences whereas automobile accessibility produces relatively evenly distributed (concentric) zones of accessibility gradation. Therefore, for each service class there are two figures, one for the Winterthur study area (first) and one for the Zurich study area (second). Both these study areas are almost equal in spatial extent thanks to the similarity of shapes of theirs municipalities around which the study areas are projected. This way, edge effects were dealt with, without inducing significant MAUP issues (Kemp 2008). However, the study areas differ significantly. The Winterthur study area is much more centralized in terms of population distribution and service concentration. Conversely, the Zurich study area is polycentric in its urban fabric. For these reasons the absolute accessibility scores tend

[6] http://colorbrewer2.org/?type=diverging&scheme=PRGn&n=6

to be higher in the Winterthur area, especially for pedestrian accessibility. Therefore, the following figures will demonstrate keen spatial variation in accessibility to services. Pedestrian accessibility employs multimodal transport in all of these examples. However, the impact of multimodal transport is again greater for the Winterthur study area since the local public transport network is less developed than in Zurich. The automobile accessibility scores tend to produce spatially similar outcomes for both study areas. These, and other parameter variation outcomes, will be presented in the section on sensitivity analysis.

4.1.1. Provision services

Figure 32a and 32b visualize results of the spatio-temporal accessibility analysis of chain store service provision in the study areas (a) Winterthur, b) Zurich). The input parameters of both figures are the same, except the geography of the area. However, dissimilar trends of accessibility score propagation are present in the two study areas. Whereas the Winterthur study are zone of higher provision accessibility is on an West to East axis, the equivalent zone of higher accessibility in Zurich is concentrated in the inner city area and in the Oerlikon area of northern Zurich. Furthermore, the accessibility distribution of both study areas follows the means of public transport; busses and railways in Winterthur, and trams, busses, and railways in Zurich. Interestingly, the residential neighbourhoods of both study areas exhibit lower accessibility scores compared to the city centres. This is due to not including workplace demographics with the resident demographics during the accessibility research. Unfortunately, the open source data available for workplace demographies proved to be of inadequate quality or granularity for the standards of this research. This remains an outlook for the research. It was expected that higher accessibility scores would follow zones of higher population density (H 2). Conversely, the spatial patterns of higher accessibility conform to the expectation that they would follow transport corridors and inner city areas (H 1).

The maximum accessibility scores of both study area are dependent on the supply and demand calculations within the E2SFCA method. All chain stores are assigned equal service capacities, while not all areas have the same demand. Hence, the much higher maximum score for the Winterthur study area is due to the existence of a high supply capacity in the city centre, which is not within the network reach of higher demands outside of the city centre. Conversely, the area of highest population density in Zurich is directly west of the city centre. Here we observe higher accessibility scores along public transport corridors, yet the spaces in between these exhibit a significantly lower accessibility. It is spatially logical that access to main traffic corridors would facilitate spatio-temporal reach (H 1).

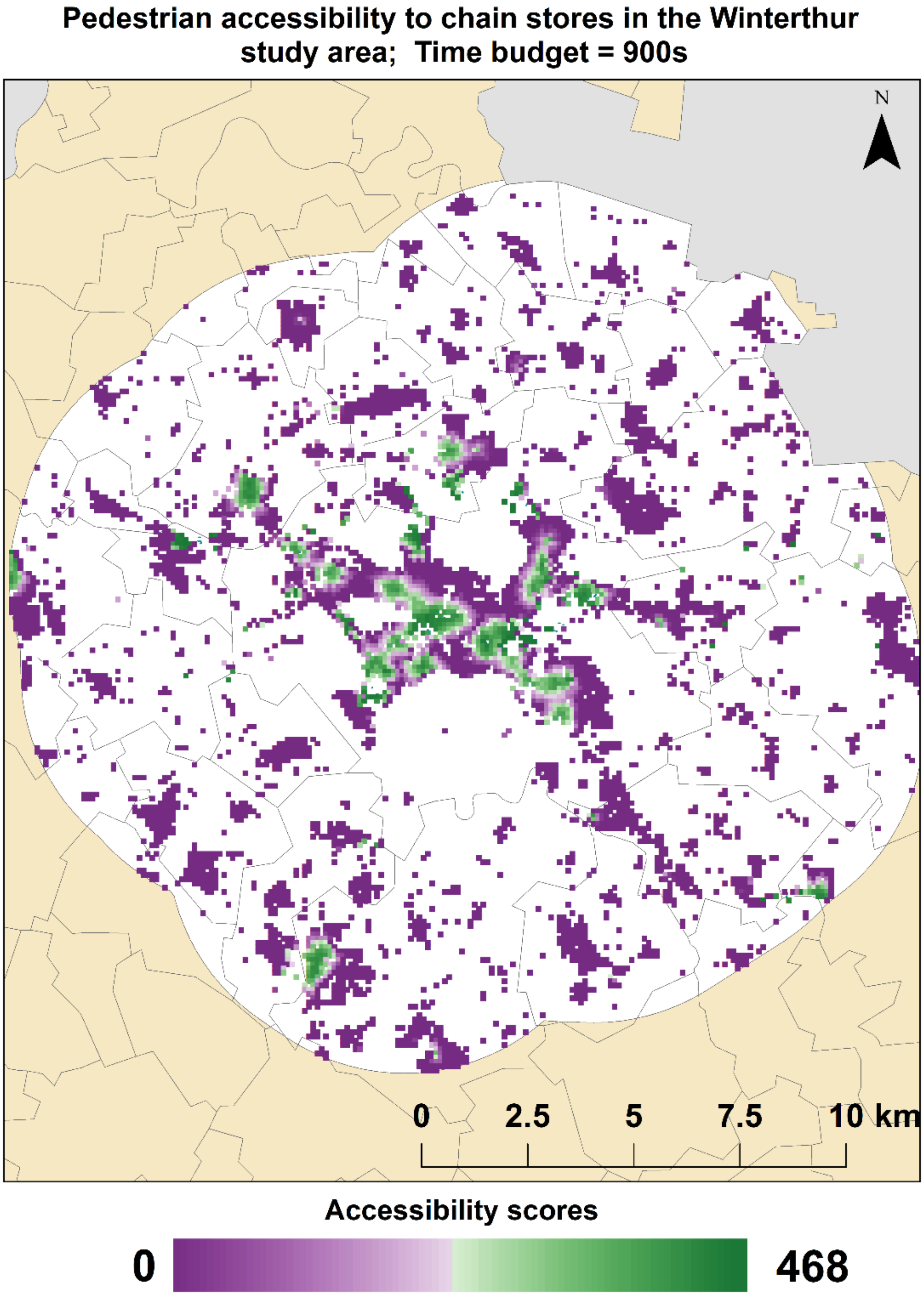

Figure 32a. Accessibility to provision services (chain stores) in the study area of Winterthur.

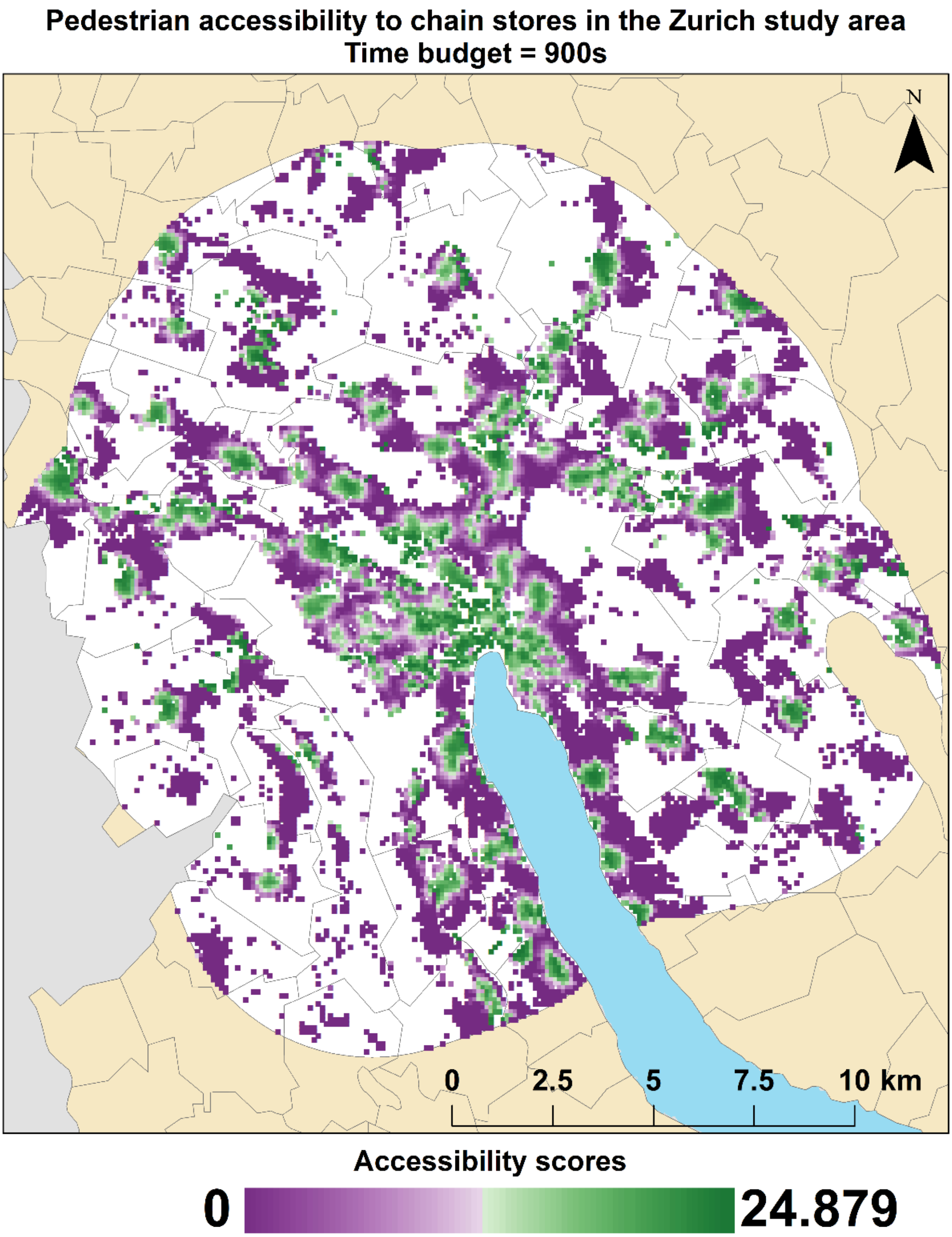

Figure 32b. Accessibility to provision services (chain stores) in the study area of Zurich.

4.1.2. Communication services

The accessibility to communication services (post offices) is an interesting topic due to the ongoing debate on the future of the Swiss postal service. Figures 33a and 33b visualize the results of the spatio-temporal accessibility analysis for post office branches in the study areas. The same parameters applying, we can observe a similar spatial trend in both study areas: The accessibility scores for post offices are equitably distributed across the study region. Evidently, the distribution of post office branches is sufficient to adequately cover bigger settlement. Conversely, this equitable distribution brings about lower accessibility scores in the spaces which have the highest population density. The residential zones of both Winterthur and Zurich have some of the lower scores in continuity. In Zurich it is especially glaring the disparity between the city centre and the adjacent residential zone to the west (fig. 33b). The inclusion of workplace demographies would likely change this situation, but it is clear that the placement of post office branches was oriented towards servicing each administrative unit from a central position within the unit. This does not correspond to the population distribution and any future evaluation or changes of the post service system has to set its priorities clear. Should the post service the business or the population in greater quality? The rationalization of business is the drive behind the Swiss post reform, and this is mainly achieved by introducing automatic post systems (akin to self-checkout). Therefore, more of these system should be assigned to spaces with higher population densities instead of servicing administrative units from central positions.

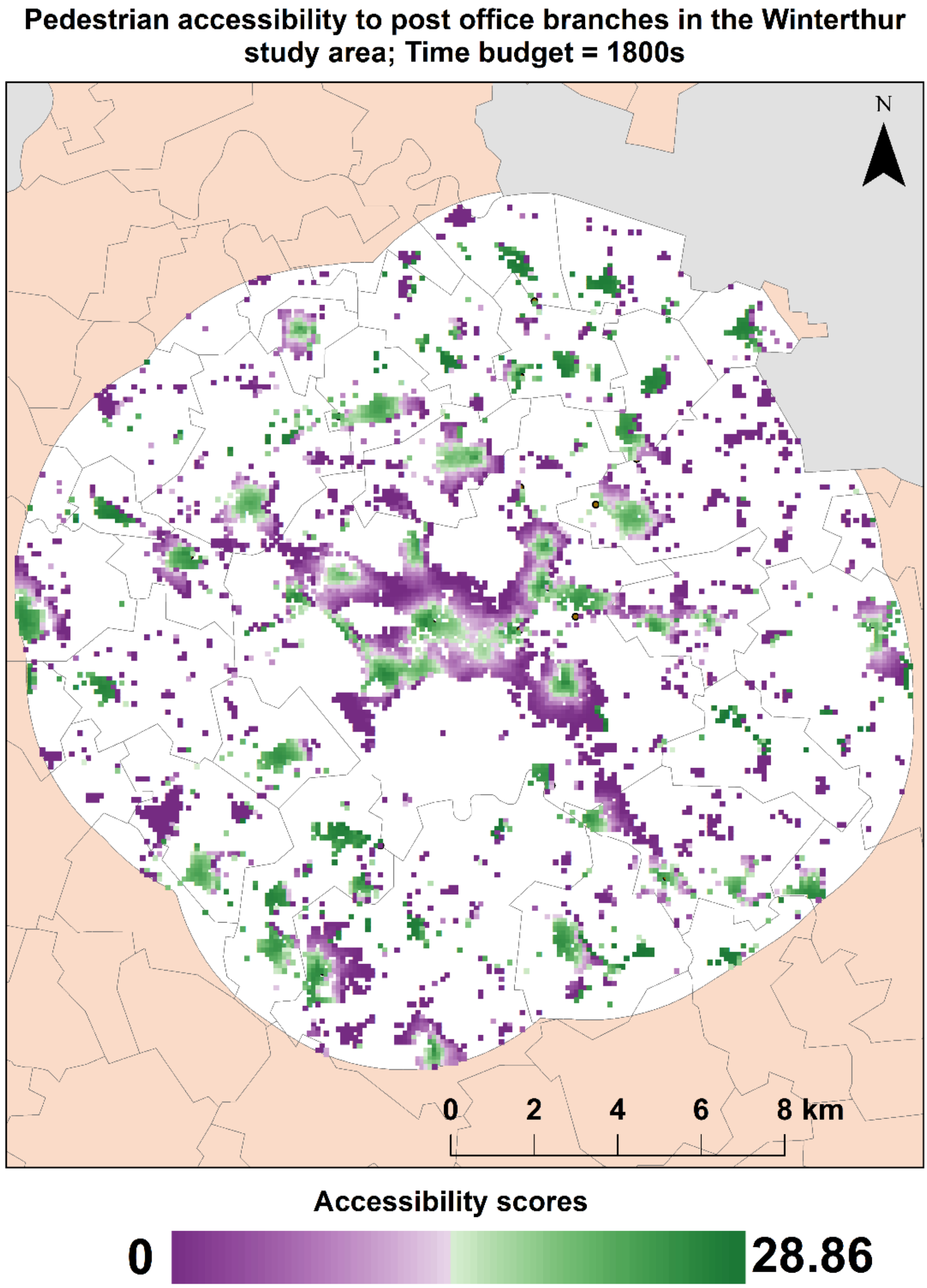

Figure 33a. Accessibility to communication services (post offices) in the study area of Winterthur.

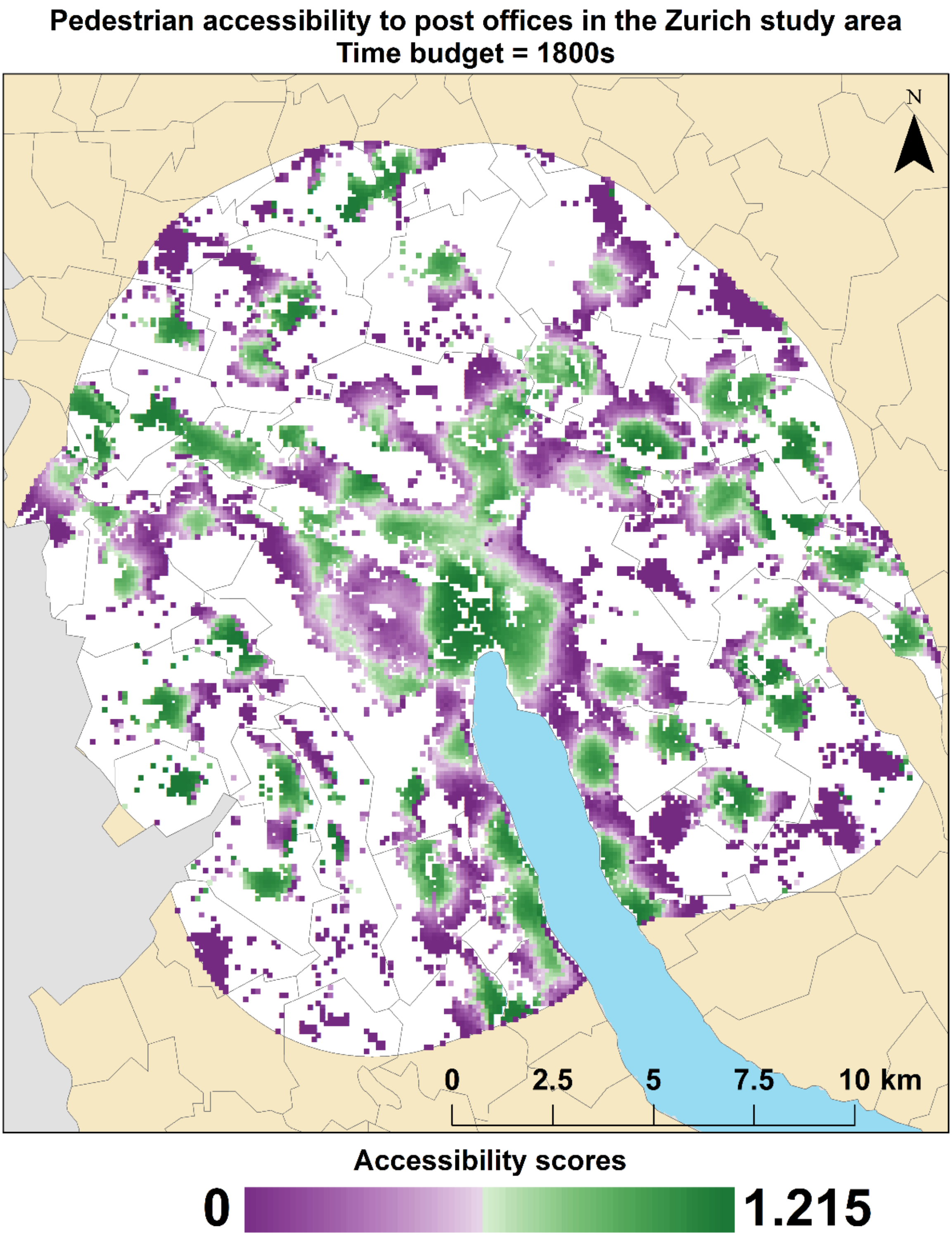

Figure 33b. Accessibility to communication services (post offices) in the study area of Zurich.

4.1.3. Healthcare

Healthcare is a recurring topic in accessibility research and it was the most logical addition to the research within this thesis. Since healthcare is a well-researched topic, the input parameters for accessibility research are well defined in the literature. These included the supply capacity of healthcare service points, population demand estimates, total time budgets and utilization costs. Figures 34a and 34b visualize the results of the conducted accessibility analysis for the two study areas. Additionally, figures 48 and 49 visualize the cantonal healthcare provision system and accessibility scores. The total time budget for healthcare accessibility was the highest (1 hour), out of this 20 minutes were assigned for service utilization. The resulting 40 minutes of network time demonstrated the great utility of public transport systems, as well as the limitations of its implementation in accessibility research. Firstly to compare the two study areas. The supply capacities within the study area of Zurich are much higher than in Winterthur. Winterthur has one (albeit a large one) hospital. Conversely, Zurich has multiple hospitals of the same size as the Kantonalspital Winterthur. Therefore, the overall accessibility situation to healthcare in Zurich is better distributed throughout the study area by the E2SFCA function. However, the position of the hospital in Winterthur is better suited for servicing the residential neighbourhoods which consequently have some of the highest scores. In Zurich, the highest scores correspond to the city centre where workplace demographies are, if not prevalent, then at the very least as numerous as residential demographies. However, this is logical because of the presence of the Zurich University hospital, the highest capacity healthcare service point in the whole Canton (fig. 49). Consequently, the maximum accessibility score in Zurich is much higher than the maximum score in Winterthur since the high capacity of the hospital system in Zurich accentuated local maxima, and regional medians. The trend of higher accessibility propagation in the Zurich study area follows the lakeshore due to the presence of multiple healthcare institutions on it. There is a disparity with the northern zones of Zurich as well as the communities south and west of the Uetliberg hill which forms the natural barrier between the Limmat valley and the areas southwest. In Winterthur, the zones of highest accessibility are spread throughout the municipality of Winterthur. However, there is a radial spread of accessibility scores along rail lines. Municipalities which might not have any native healthcare service point are nevertheless some of the better serviced. This is due to the presence of railway stations. The railway station in Winterthur is in close proximity to the Kantonalspital, hence the supply capacity is transported directly to the municipalities through railway stations. The large time budget allows for this effect which is otherwise absent with other services which have lower time budgets. In order to properly model multimodal accessibility, it has to be assigned adequate temporal resources to demonstrate its competitiveness (Tenkanen 2017). The effect of public transport is likewise observable in the Zurich study area, but to a lesser degree.

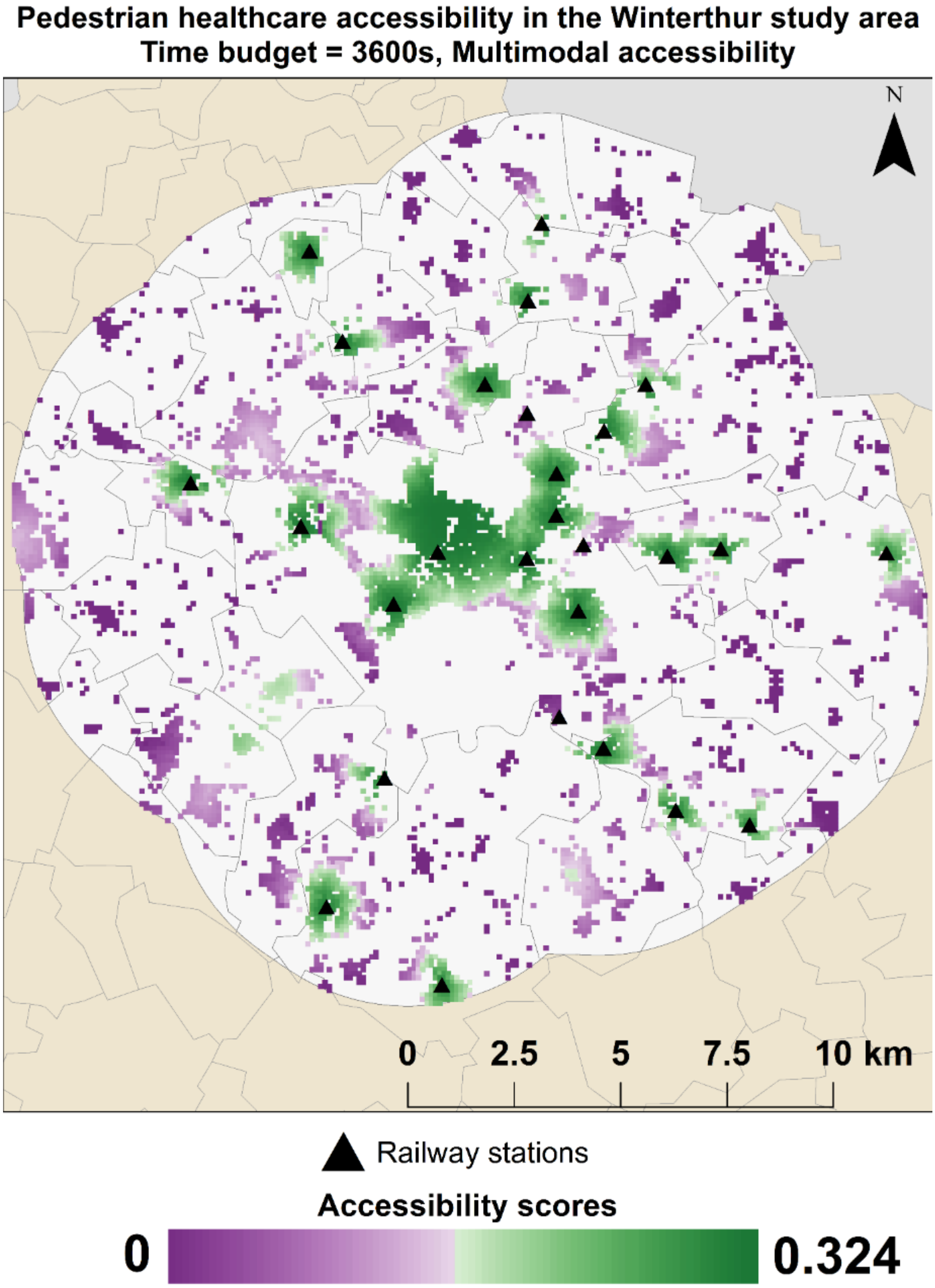

Figure 34a. Healthcare accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

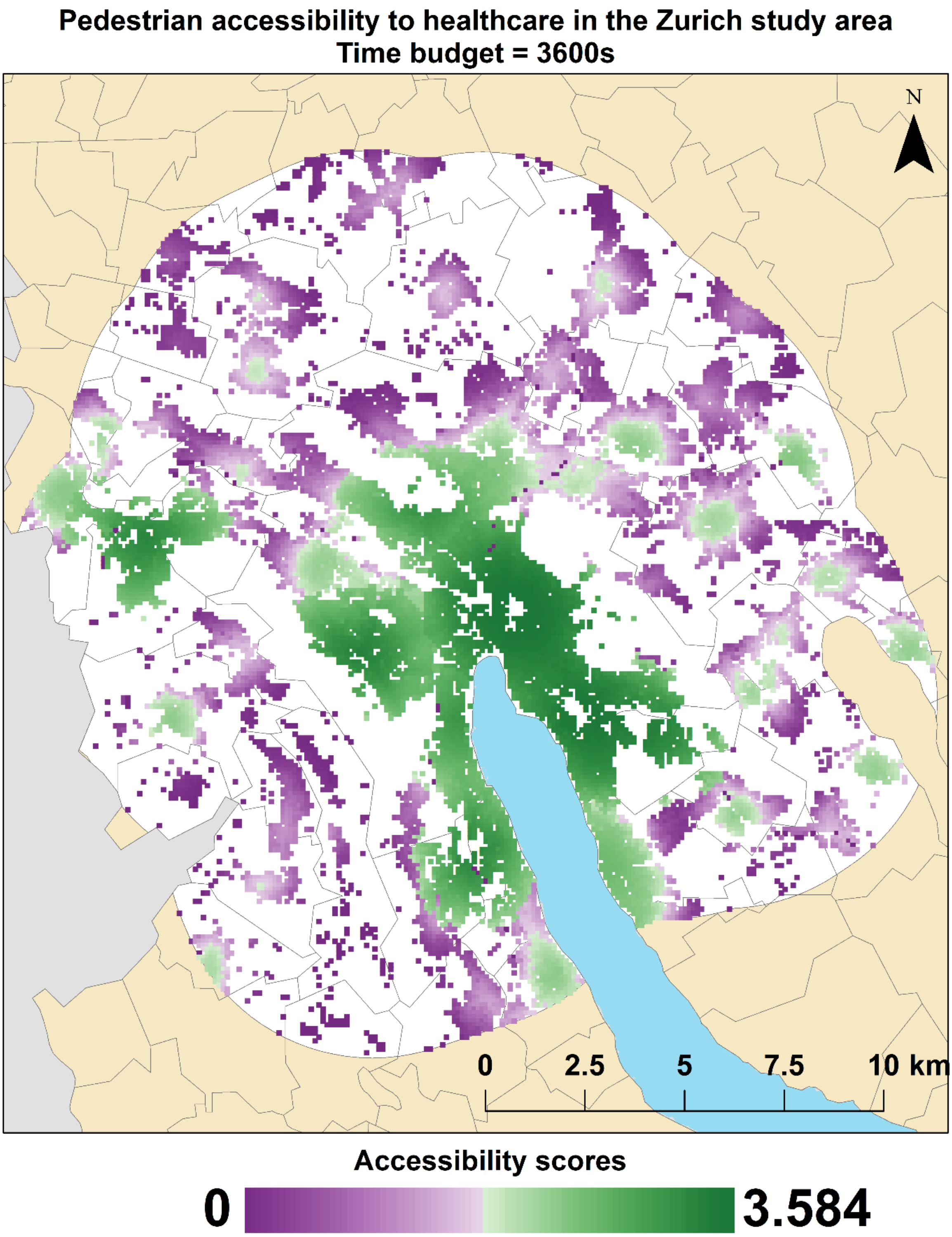

Figure 34b. Healthcare accessibility scores derived by the S-T E2SFCA for the Zurich study area.

4.1.4. Transport

As demonstrated with healthcare accessibility scores, the regional and local public transport system can significantly alter local accessibility patterns. Therefore, accessibility to the transport system itself is a logical concern and research topic. Since the public transport system has the purpose of facilitating individual mobility, it makes sense that it would be accessed primarily on foot, and that utilization costs would not be logical given that it is possible to time ones arrival with the frequency of public transport. Likewise, timing the arrival of public transport means that it is likely to be assigned the minimum of network travel budgets. We have modelled public transport accessibility at 10 minutes, which is also in accordance with the Cantonal public transport availability evaluation (fig. 36) parameters (Amt fur Verkehr 2017). Therefore, the figures 35a and 35b visualize the accessibility scores for public transport in our study areas using the spatio-temporal E2SFCA method, while figure 36 is a comparison with the Cantonal methodology results. What is clear at a glance from the S-T E2SFCA method is that there is a high degree of spatial variation in accessibility patterns. This is due to a large number of service points. It is important to note that the public transport service points do not have a supply capacity. Thus, the local concentration of service points is the primary means of achieving higher accessibility scores. Whereas the official classification divides space by linear equidistance into more or less concentric zones, the S-T E2SFCA divided space into more radial and pronounced gradations. The latter is more in line with expected spatial logic. Furthermore, we recognized areas of great disparity between the two sets of results for multiple spaces. The most noticeable is the disparity for the Zurich inner city quarters of Wiedikon and Albisrieden, and for the lakeshores south of Zurich. Nevertheless, we can observe a dendritic structure of public transport accessibility trends within these areas, as well as in the Winterhtur municipality (H 1).

The disparities between the official classification of goodness and the one calculated in this research are present due to including supply (albeit supply = 1) and demand ratios for service accessibility (and network catchments/distance decay). The official OEV Güteklasse availability assessment does not take into account population density (fig. 17, page 41 for density map). Due to a high number of resident in the above mentioned Zurich quarters, the supply and demand ratio is disfavourable, hence lower accessibility scores are derived. Similarly, the Winterthur study area rural spaces have a lower population density than the municipalities of Winterthur and Effretikon (the class A in the south of the study region on the left side of figure 36). While the results from figure 50 and 51 are derived from a fundamentally different methodological approach, they are both a form of accessibility analysis. Hence, it can be inquired, which of the two results would the residents of an area find more useful or informative?

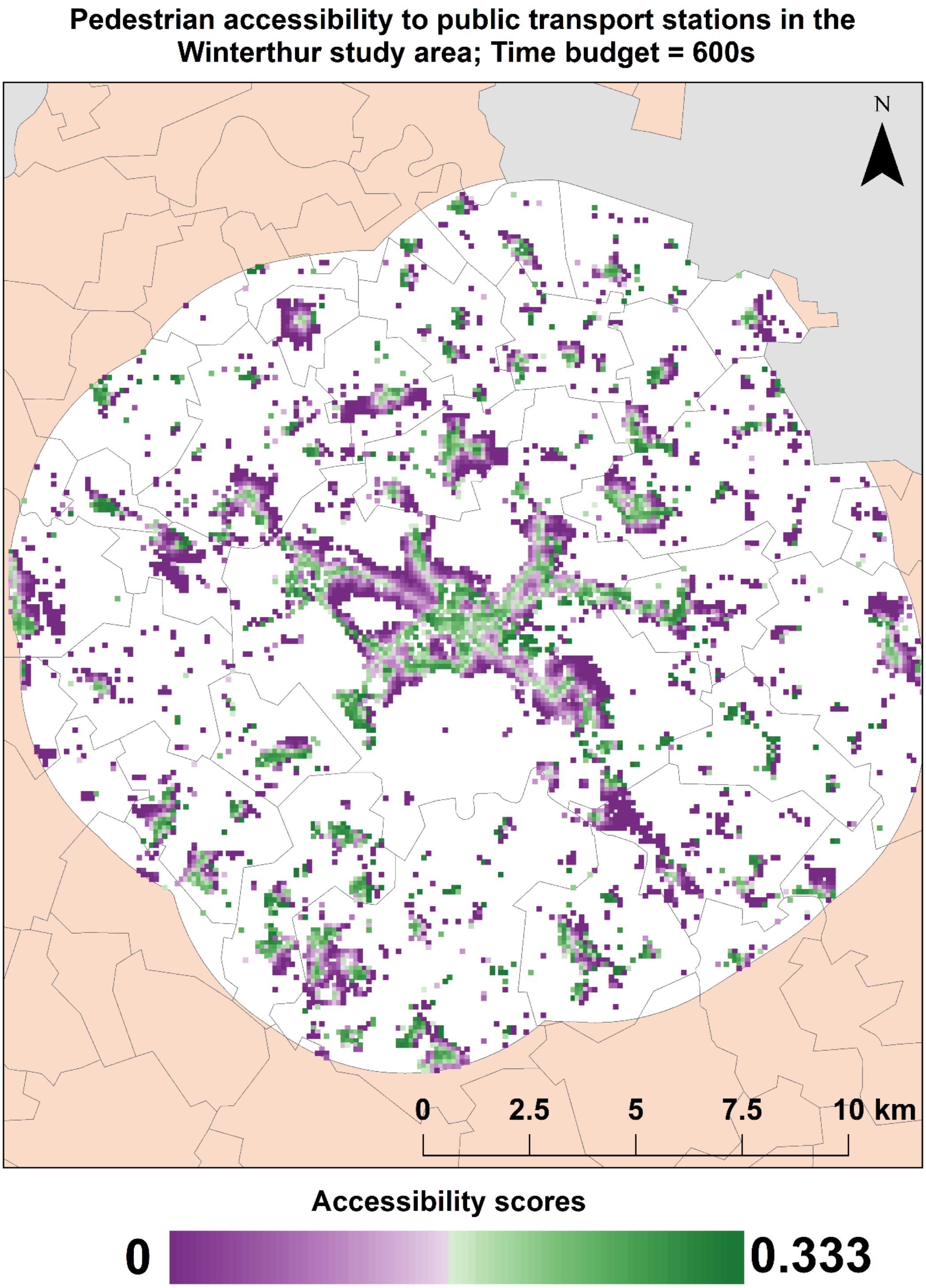

Figure 35a. Public transport station accessibility scores derived by the S-T E2SFCA for the Winterthur study area

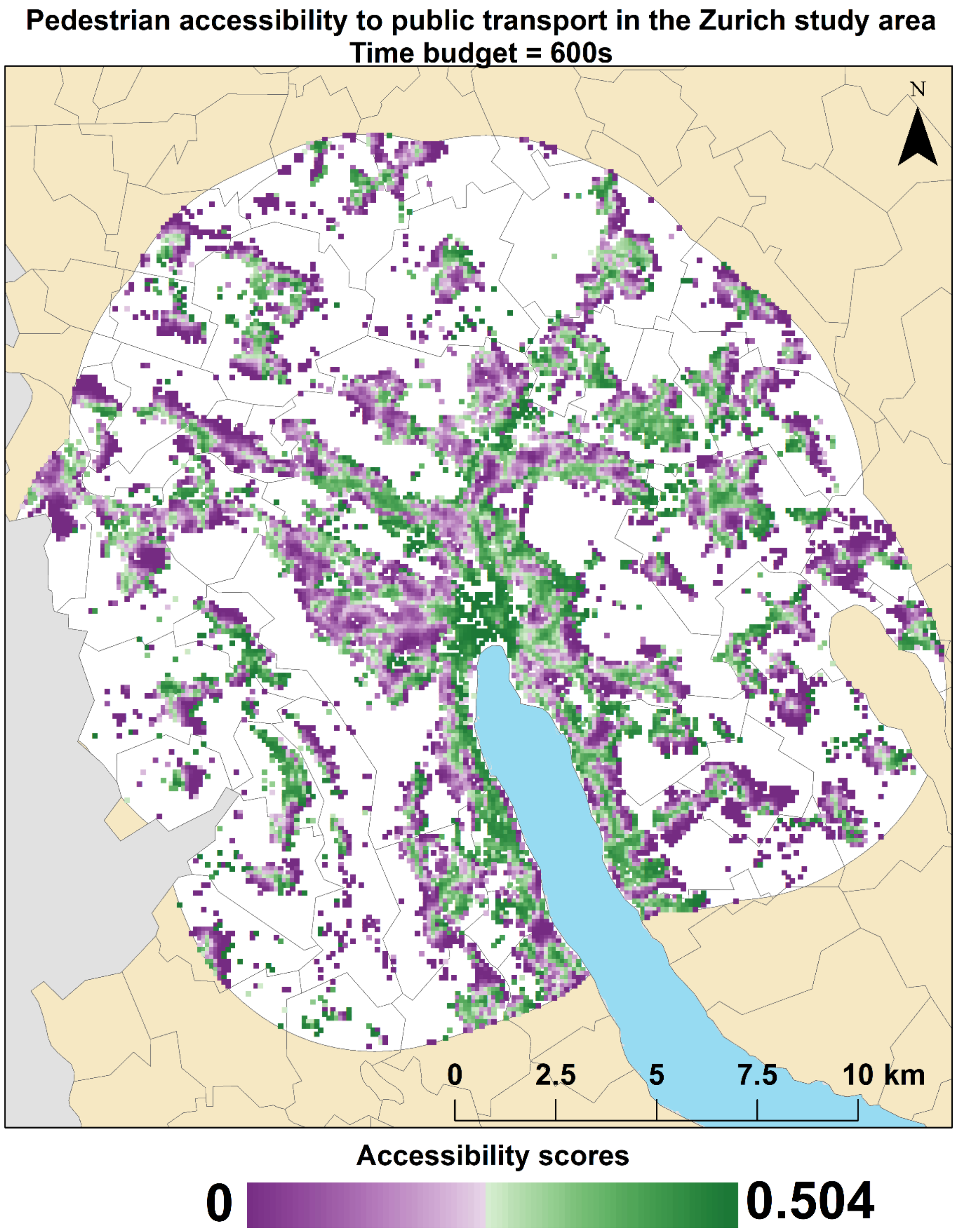

Figure 35b. Public transport station accessibility scores derived by the S-T E2SFCA for the Zurich study area.

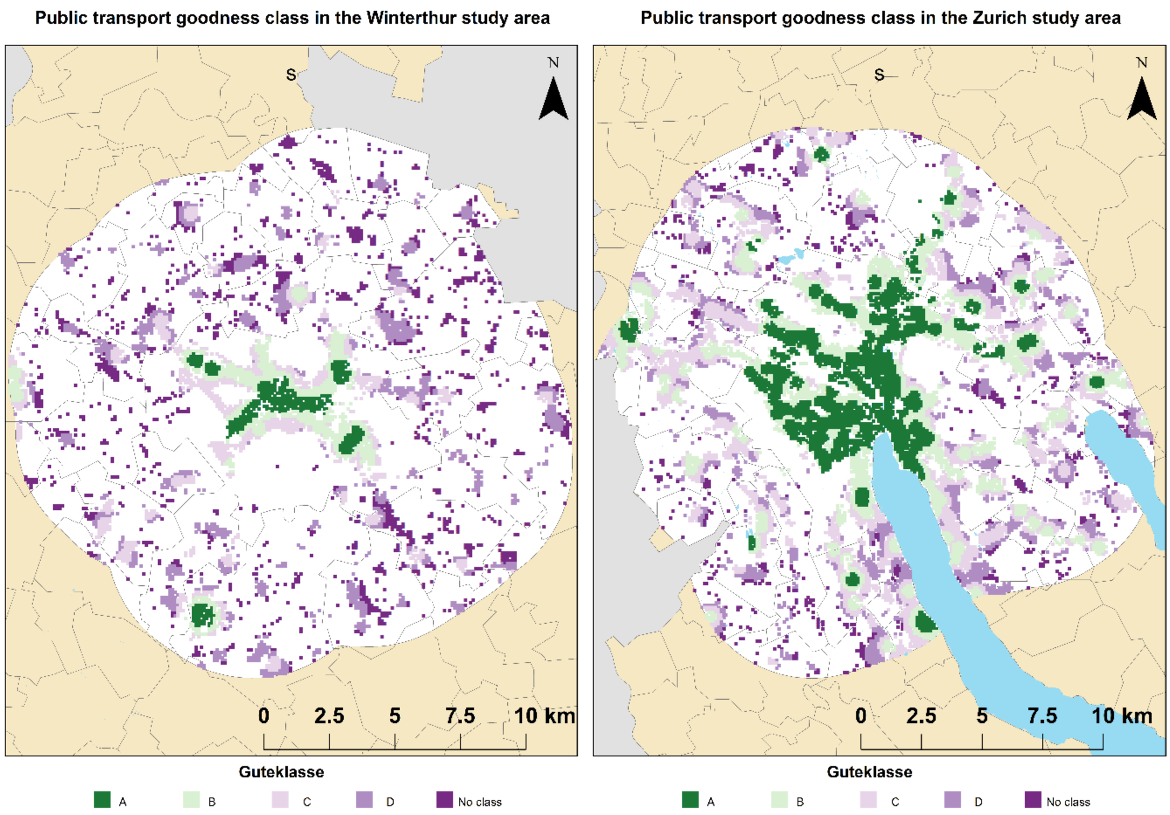

Figure 36. OEV Güteklasse 2017. A is the best, D is the worst. (Data source: Canton of Zurich 2017)

4.1.5. Leisure

The leisure service category includes two sub-categories; recreation, which is utilized through sports facilities and parks, and socialisation which is utilized through museums and theatres in this thesis. Firstly, the recreation services are a common good which helps maintain public health (Apparicio & Seguin 2006; Salze et al. 2011). Be it public or private, the sports facilities within which the recreational part of leisure is utilized vary in their type and capacity. The data lacked the metadata on supply capacity but it did include attribute fields of content and type. We classified all sports facilities in the study areas into two groups: large facilities and small facilities, akin to the healthcare provision system. The large sports facilities were defined to be stadiums, swimming areas on the lakes or rivers, fields and pitches, sport halls, gyms, swimming pools, and racing tracks. All other sports facilities were defined as small (e.g. shooting ranges, basketball courts etc.). The main difference between the two study areas is that the service provision of sports facilities is much better (fig. 37a and 37b). Sports facility accessibility within the Winterthur study area is concentrated solely in the municipality of Winterthur. While it is equitably distributed within the city of Winterthur, the outlying rural spaces are completely bereft of comparable accessibility scores. Conversely, the situation in Zurich is much more equitable. There is a concentration of accessibility to sports facilities in the city centre, most likely overestimated due to not including workplace demographics. However, there is no clear spatial gap in sports facility accessibility coverage. Even the most populous parts of the Zurich study area do not exhibit a gap in supply due to high demand. However, a noticeable gap in accessibility is present in the northern part of the study region. This gap corresponds to the industrial part of Oerlikon and the Glattpark. The effect of public transport on service accessibility is limited due to a limited network mobility time budget.

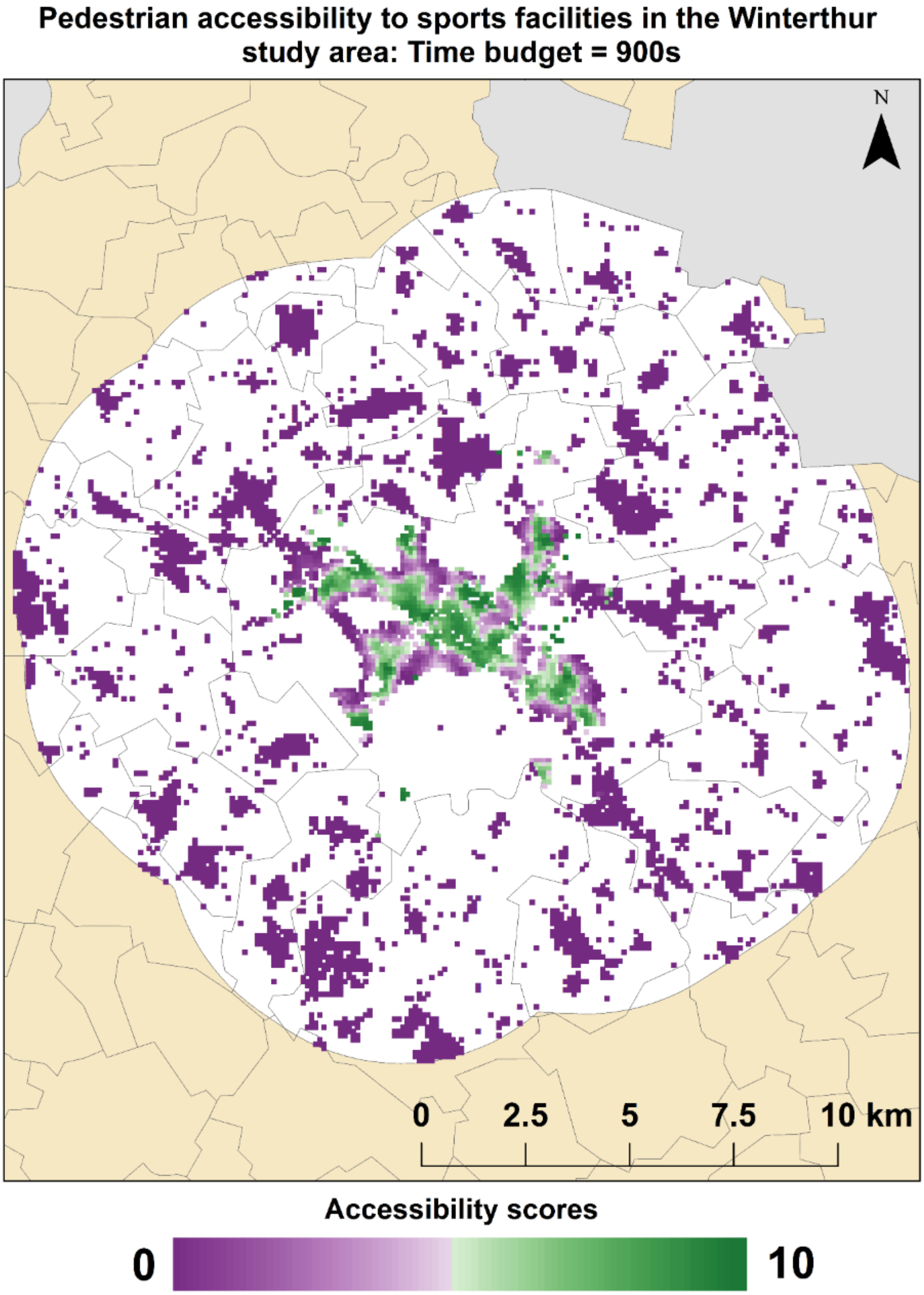

Figure 37a. Sports facilities leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

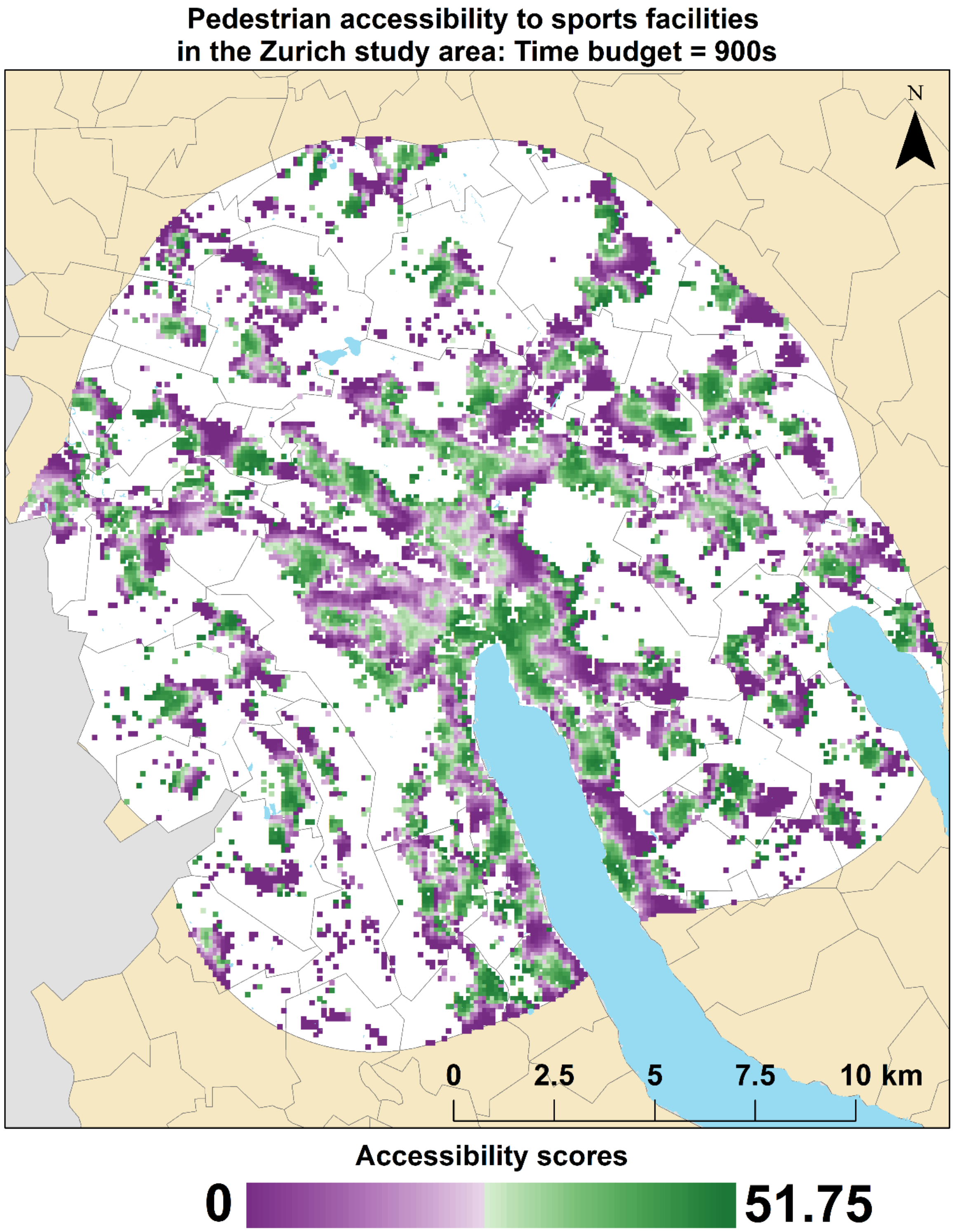

Figure 37b. Sports facilities leisure service point accessibility scores derived by the S-T E2SFCA for the Zurich study area.

The accessibility scores to museums (figures 38a and 38b), and the accessibility scores for theatres (39a and 39b) are much more spatially concentrated in city centres than any other service modelled. This is due to both being functions of relatively higher functional centrality. Museums are more ubiquitous than theatres, with municipal museums being a regular occurrence in the study region. Theatres are likely more difficult to establish and maintain. Therefore, the spatio-temporal accessibility to theatres is much lower than the equivalent for museums. Despite both being assigned a relatively small utilization time of 300 seconds, the lack of service points in the region and their concentration frustrates accessibility. The situation with museums is better. There are more, and they are better spread out, especially in the Zurich study area. Therefore, we can observe the polycentrism of museum (37a and 37b) accessibility whereas theatre accessibility is exclusively monocentric (38a and 38b).

Conversely, parks are a public spatial resource which is freely open to all citizens. It does not have a set activity but rather a range of possibilities (Zhang et al. 2011) which make it suited for rest, recreation, peace, socializing; i.e. leisure. However, parks are logically a predominantly urban spatial resource since there is no need for parks in the rural spaces which have substitutes for fulfilling the functions parks offer. Therefore, accessibility to parks is modelled using only the shape and content (population and services) of the municipalities of Zurich and Winterthur, not the study areas. Figures 40a and 40b visualize the distribution of accessibility scores to parks within the municipalities. Furthermore, parks are an important part of urban spatial fabric since they are often the only natural relief in the urban morphology. Hence, great emphasis has been placed on integrating parks and greenery into cities since the advent of modern urban planning in the 19th century. This is observable in the study areas as well.

The city of Winterthur prides itself as a garden city[7]. This is reflected in the equitable distribution of accessibility scores to parks within the municipality, only the fringe parts of the city of Winterthur exhibit below average accessibility; which is due to edge effects. The urban development strategy of Winterthur has been manifested in spatial reality to the benefit of the residents, workers, and visitors. Conversely, the general state of park accessibility in Zurich is much less favourable. There are wide disparities in park accessibility within the municipality of Zurich, with the greatest concentration of park accessibility being along the lake shore (which is logical), and in the city centre (which is likely overestimated due to demography issues). Interestingly, the newer city quarters in the north and the northwest have a favourable accessibility to parks, despite being located on the edge of the municipality. The city quarter of Affoltern (northwest) is one of the newest with the majority of high capacity residential buildings being built after 2000 (BFS 2018). This quarter exhibits higher accessibility scores than older quarters, e.g. Flüntern (due east, up the hill from the city centre). This is contrasted with the socioeconomic connotation of these two quarters. Evidently, the city of Zurich transformed its most attractive and suitable parts into parks and thus the concentration is around the lake and the Limmat River. Conversely, the city of Winterthur maintained a policy of establishing and maintaining parks which resulted in a better accessibility distribution.

[7] stadt.winterthur.ch/themen/leben-in-winterthur/freizeit-und-sport/ausflugsziele-freiraeume/anlagen-garten-und-parks

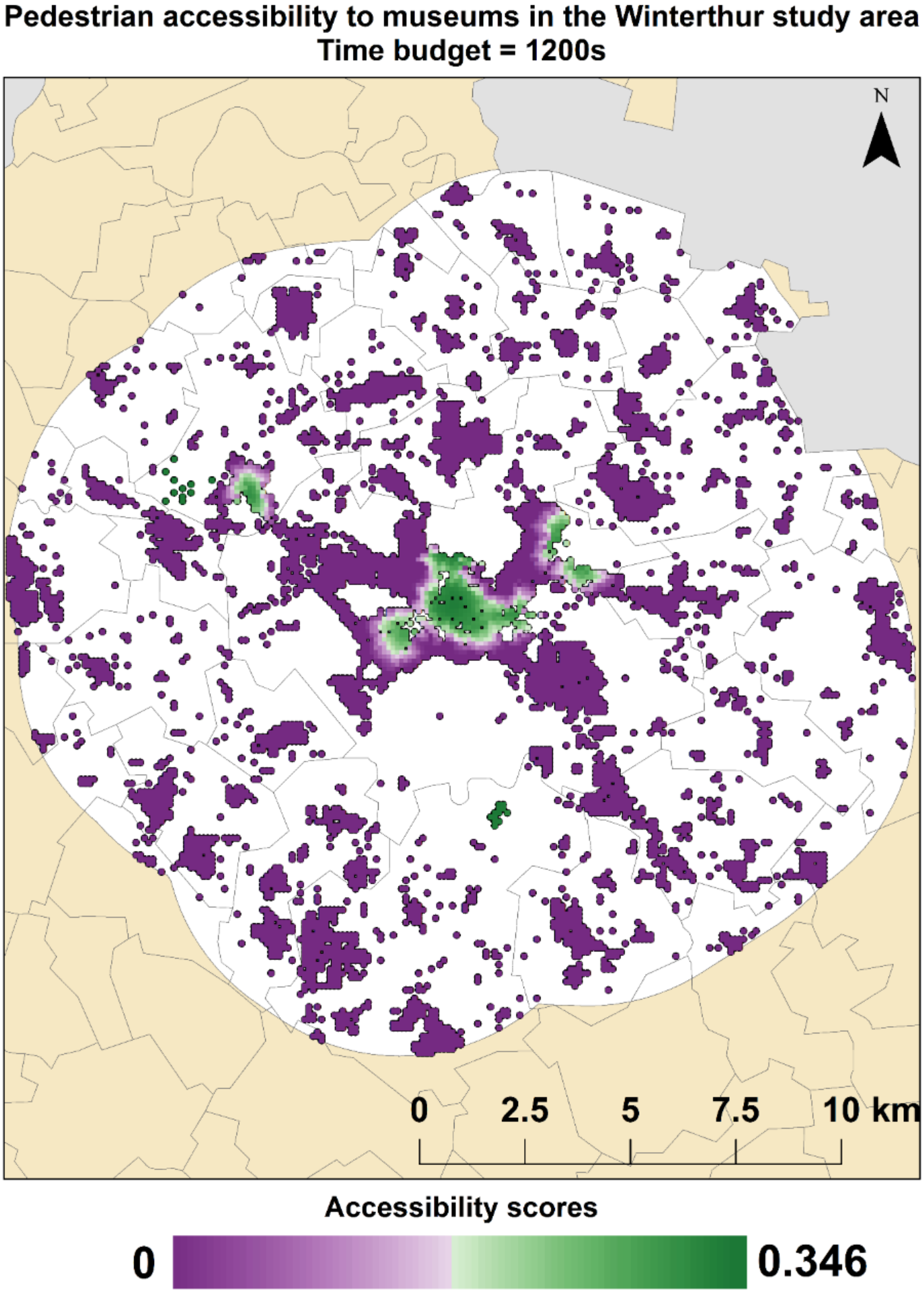

Figure 38a. Museum leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

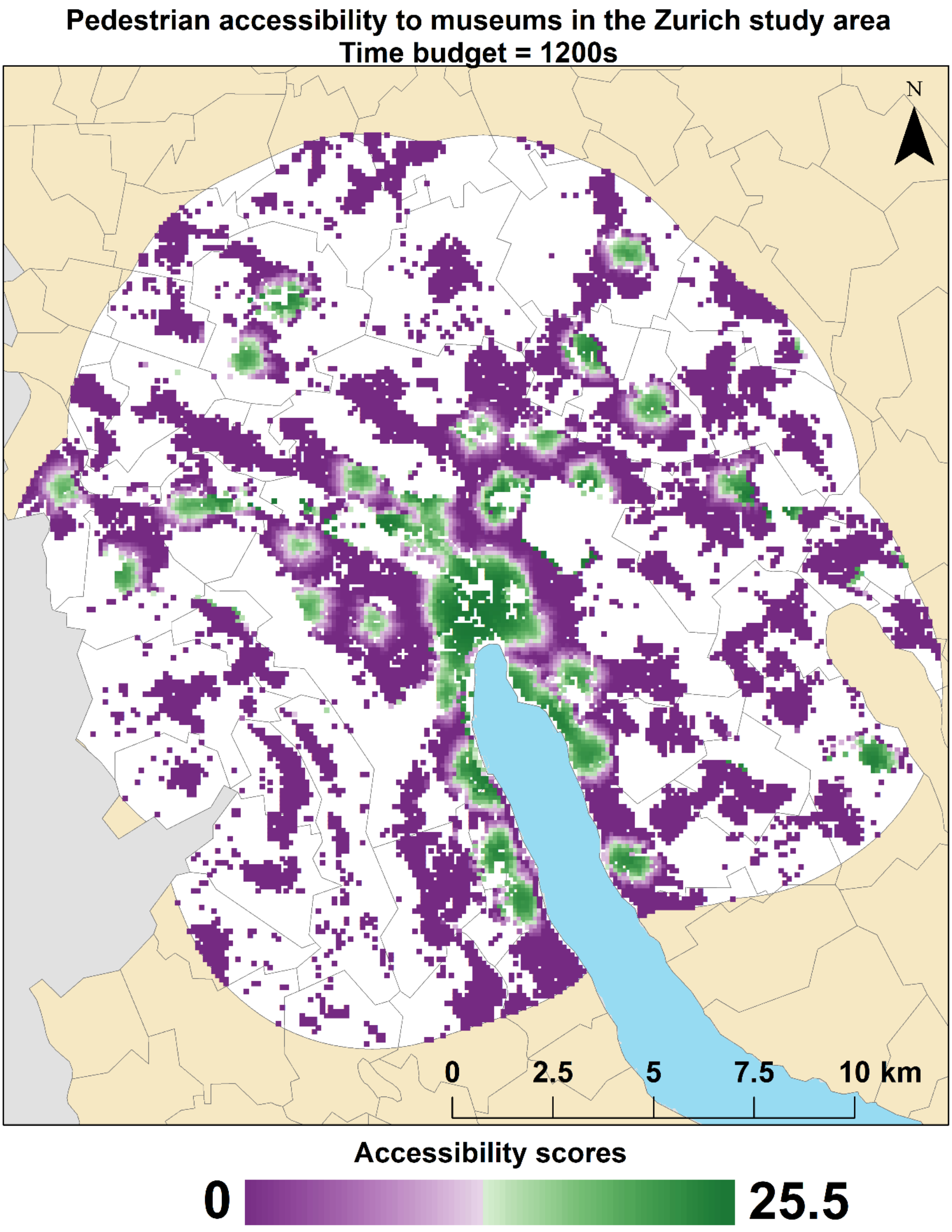

Figure 38b. Museum leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

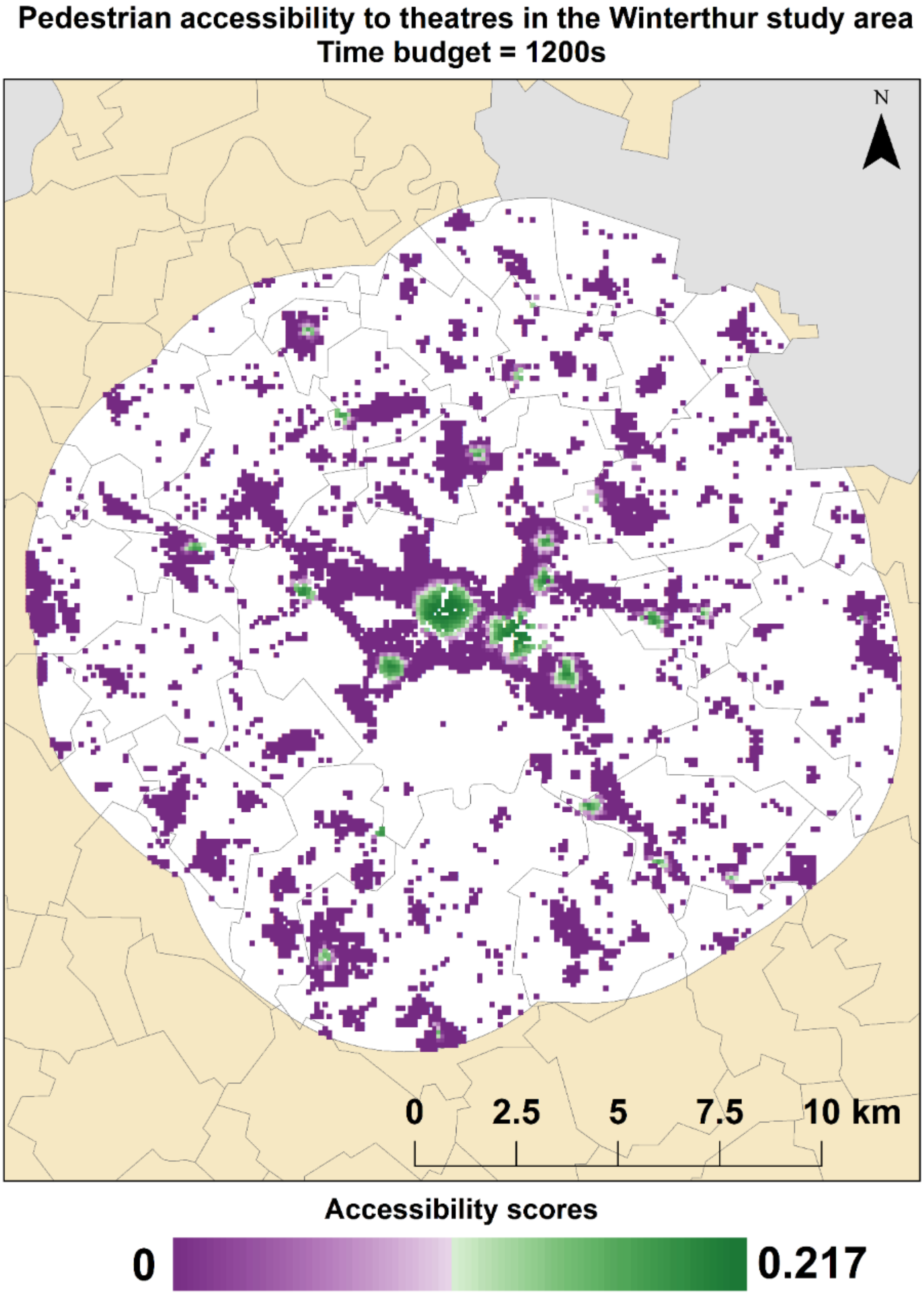

Figure 39a. Theatre leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

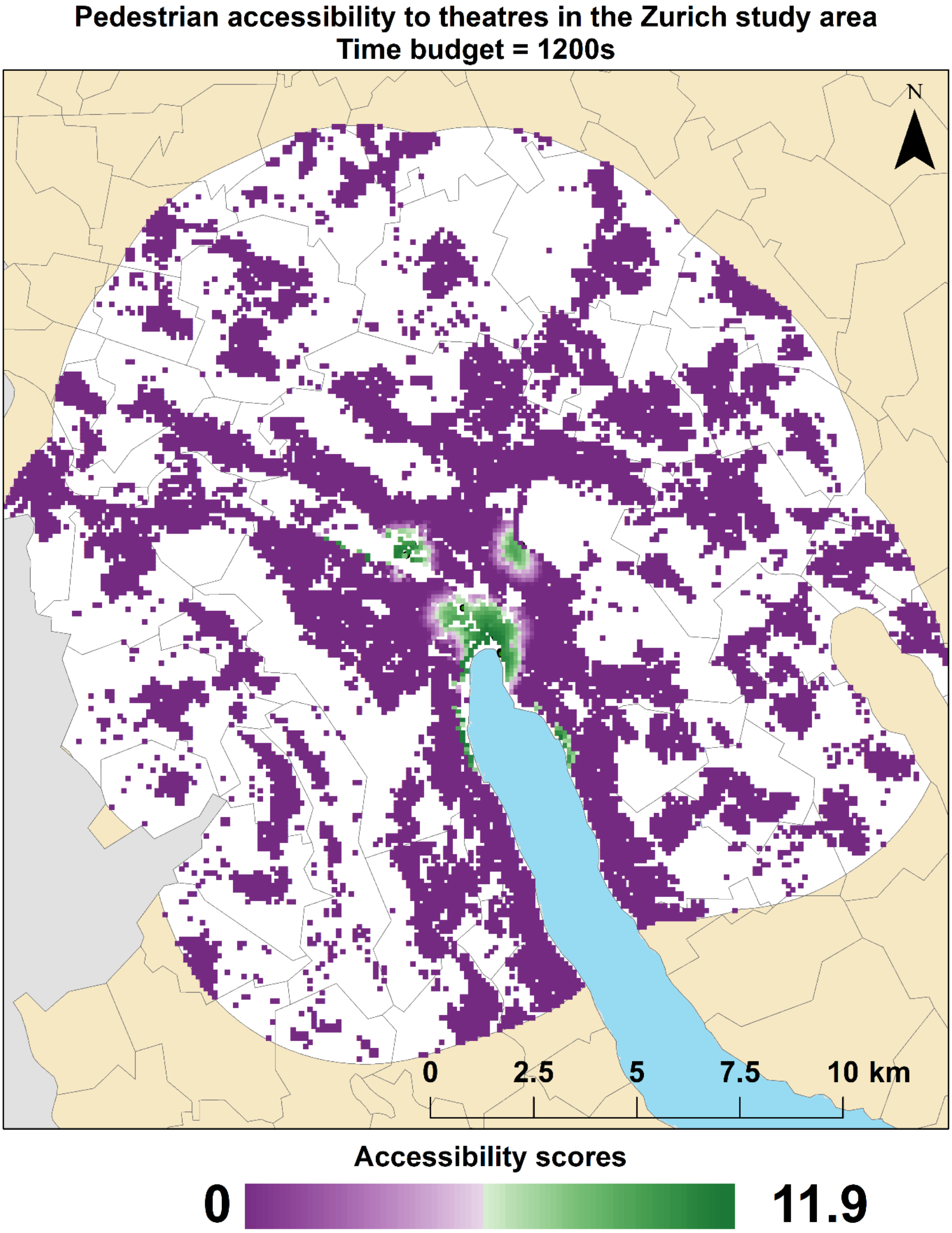

Figure 39b. Theatre leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

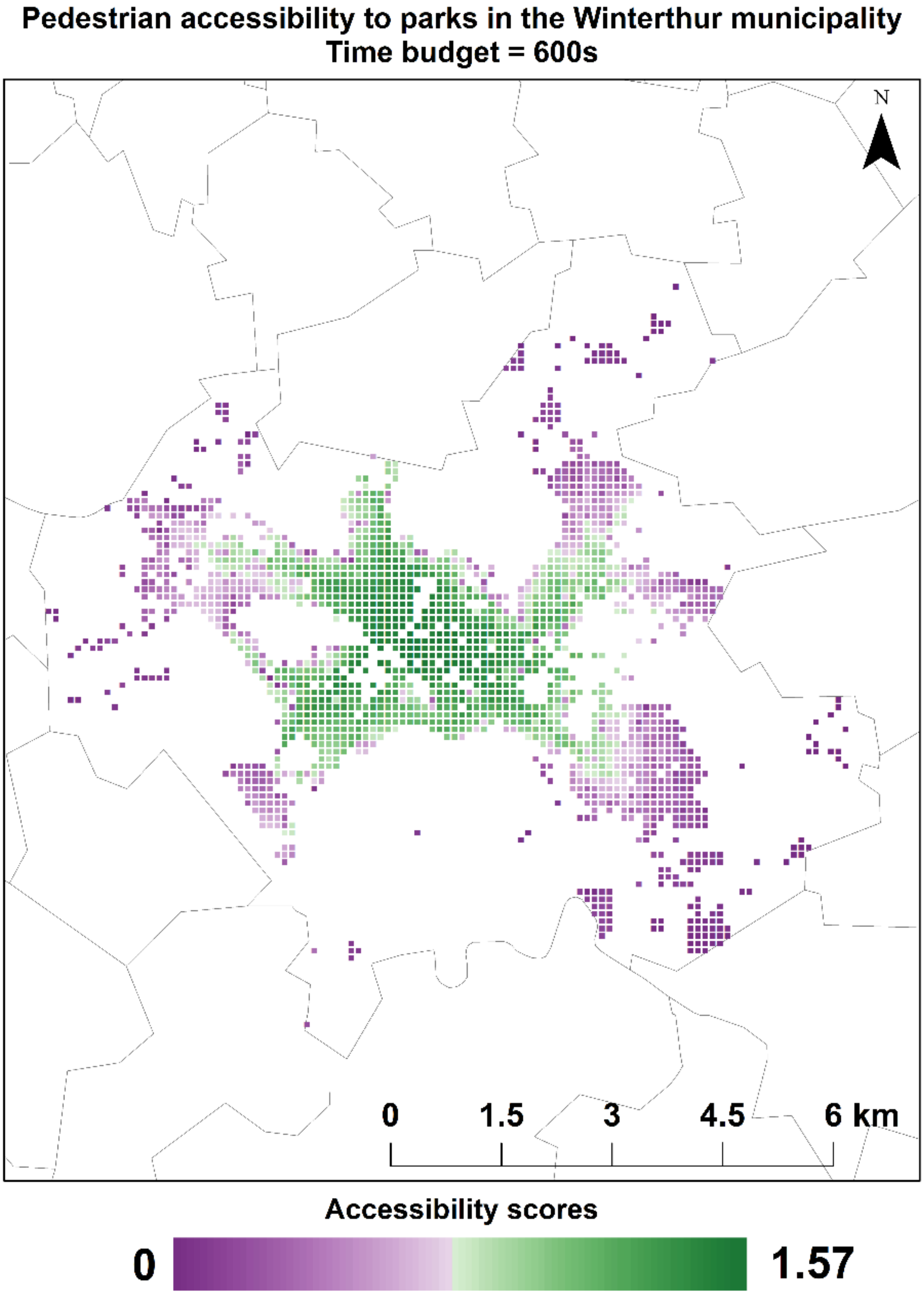

Figure 40a. Park leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

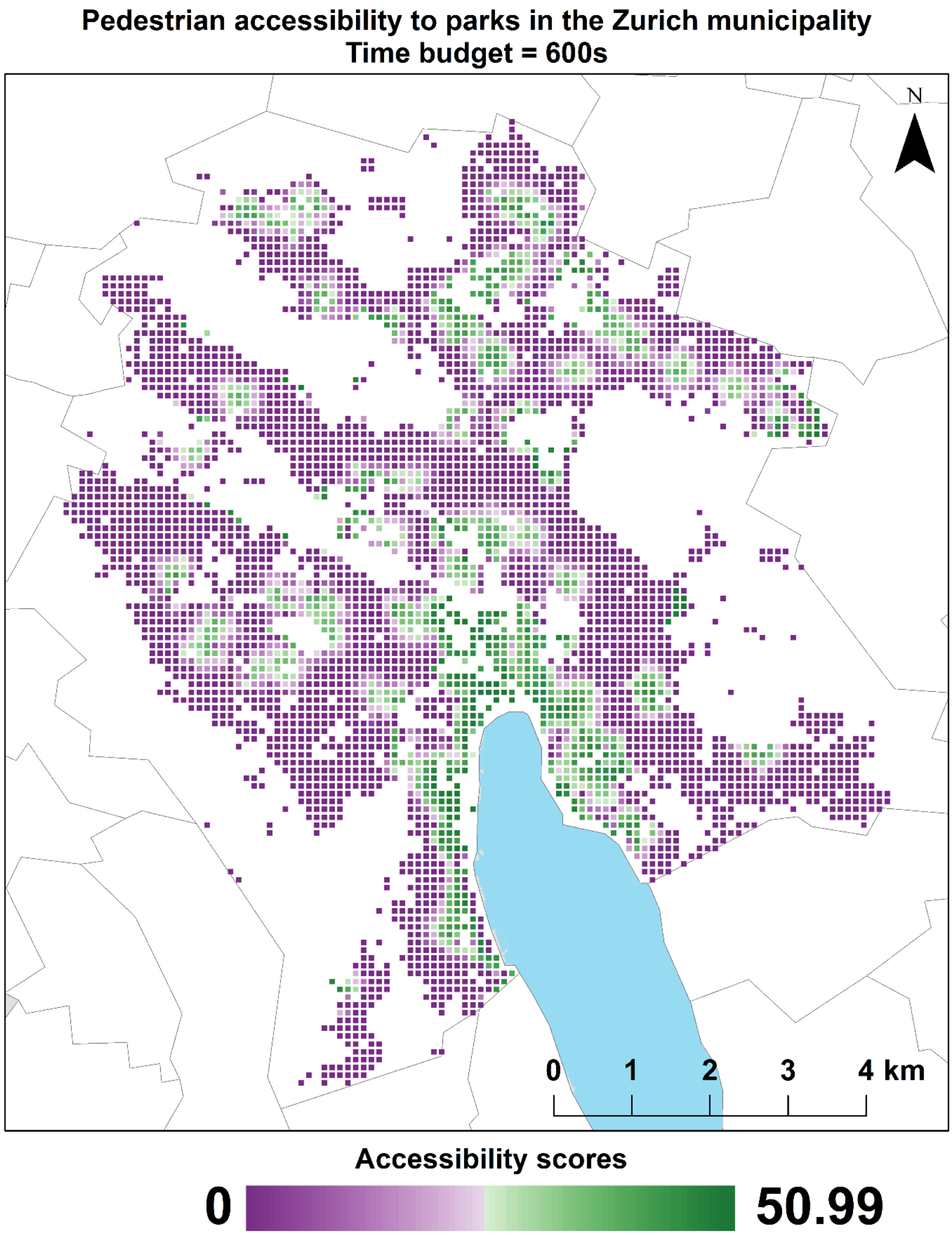

Figure 40b. Park leisure service point accessibility scores derived by the S-T E2SFCA for the Winterthur study area.

4.1.6. Cantonal healthcare accessibility

Figure 41 visualizes the cantonal accessibility to healthcare service points; hospitals and private doctor practices which provide primary healthcare. The parameter of 3600 second (1 hour) network distance was used since this is the value often used in the existing literature (Joseph & Bantock 1982; Guagliardo 2004; Mao & Nekorchuk 2013). The supply capacity was estimated according to a daily patient panel of 25 and service demand is total resident population numbers. The distance decay function is the Gaussian function (bandwidth 50).

The results grant insight into the spatial distribution of cantonal healthcare accessibility. Logically, the cities of Winterthur and Zurich (and their adjacent spaces) have the highest accessibility scores. This is due to the concentration of healthcare provision service points in these two cities, especially the private and public hospitals (fig. 42). Conversely, the region of the Oberland, the highlands and valleys in the East of the Canton, have the worst accessibility to healthcare. Similarly, the spaces in the North and the south of the Canton are also assigned below average accessibility scores. Unfortunately, we cannot know whether this inaccessibility is addressed by accessing healthcare services in neighbouring cantons. The border spaces of accessibility research are always prone to edge effects (unless uniform regional accessibility is calculated, which is itself illogical). The outlier in the south-east of the Canton is the area of the Wald municipality. The accessibility score in Wald is most likely above average due to a low population density in combination with access to the railway Hinwil and Wetzikon which have higher capacity volume healthcare providers.

The highest healthcare accessibility in the Canton is as expected the City of Zurich. However, there is intra-city disparities and on this grand scale accessibility analysis we can observe the Limmat dividing the city in two parts. North and East of the river (and lake) healthcare accessibility is higher than South and West of the river and the lake. Although not analysed in this research, the disparity inside the City of Zurich corresponds to the socio-economic stratification found within Zurich. The areas on sun-facing north lakeshore are more opulent compared to the south shore. Furthermore, there is a concentration of both hospitals and private practices in the same area. Finally, the population density of this area is much lower than the population density south and west of the Limmat and the lake.

The spaces of no accessibility within zones of highest accessibility are due to process malfunctions due to Network analyst running out of RAM available mid process. The result of this unfortunate limitation within this research is that it was unfeasible to calculate accessibility for the entirety of the Canton (or wider). The example of healthcare accessibility for the entirety of the Canton is a case study of the limits and possibilities of the developed spatio-temporal E2SFCA method. The fundamental nature of spatial reality and geographic space means that unless the entirety of contiguous space is included in the analysis, there will be edge effects (Šterc 2015). Nevertheless, the accessibility scores visualized in figure 48 are the result of several days of attempts to successfully calculate scores. The average geoprocessing attempt lasted for five hours of continuous process. The highest load on the CPU and memory is due to the development and resolving of a full Origin-Destination matrix of all service and population points which participate in the analysis iteration. Hence, there is room for optimization of the process which is one of the outlooks for this thesis.

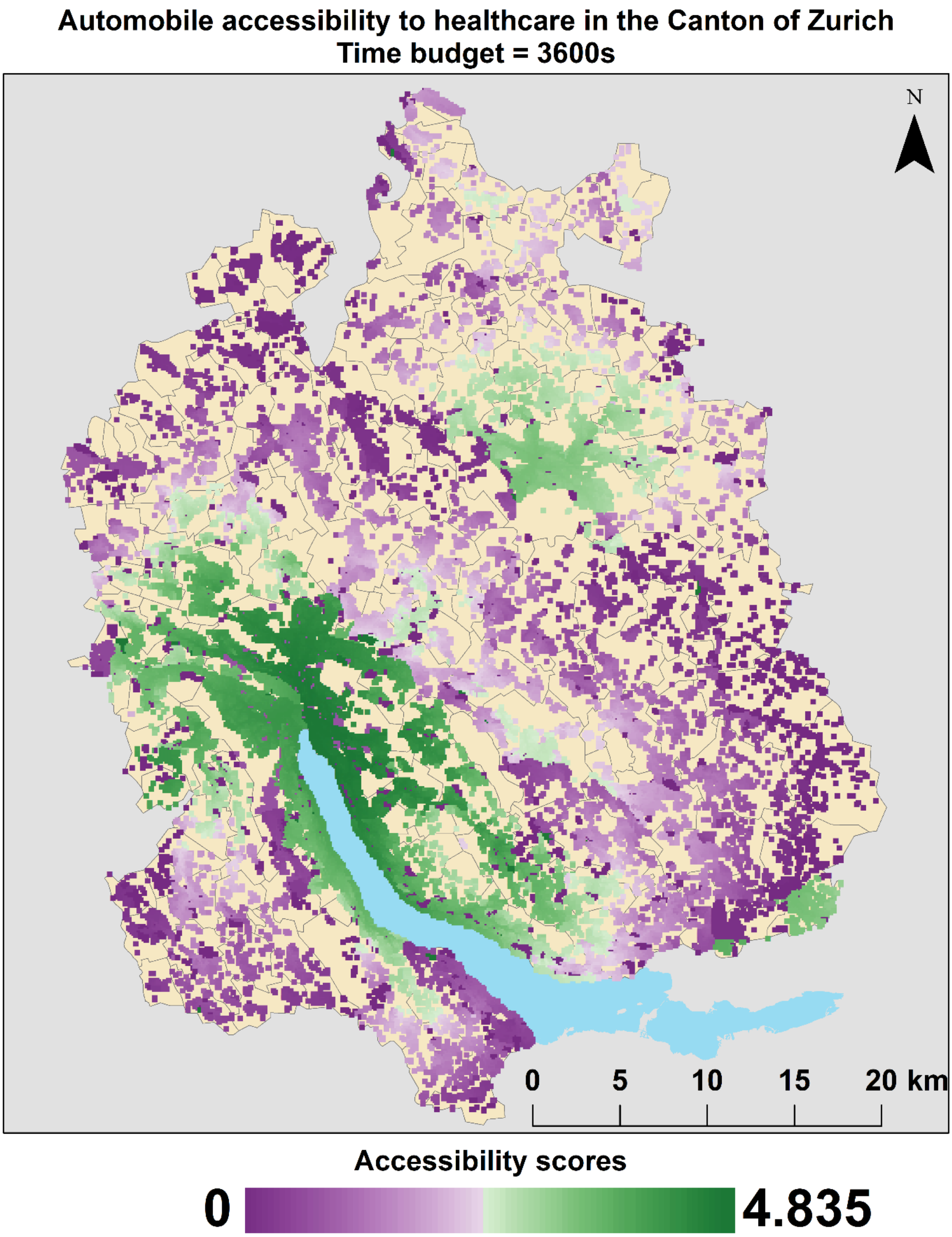

Figure 41. Cantonal distribution of healthcare accessibility scores using 3600 second automobile accessibility with Gaussian decay (Bandwidth 50), service points are hospital and private practices.

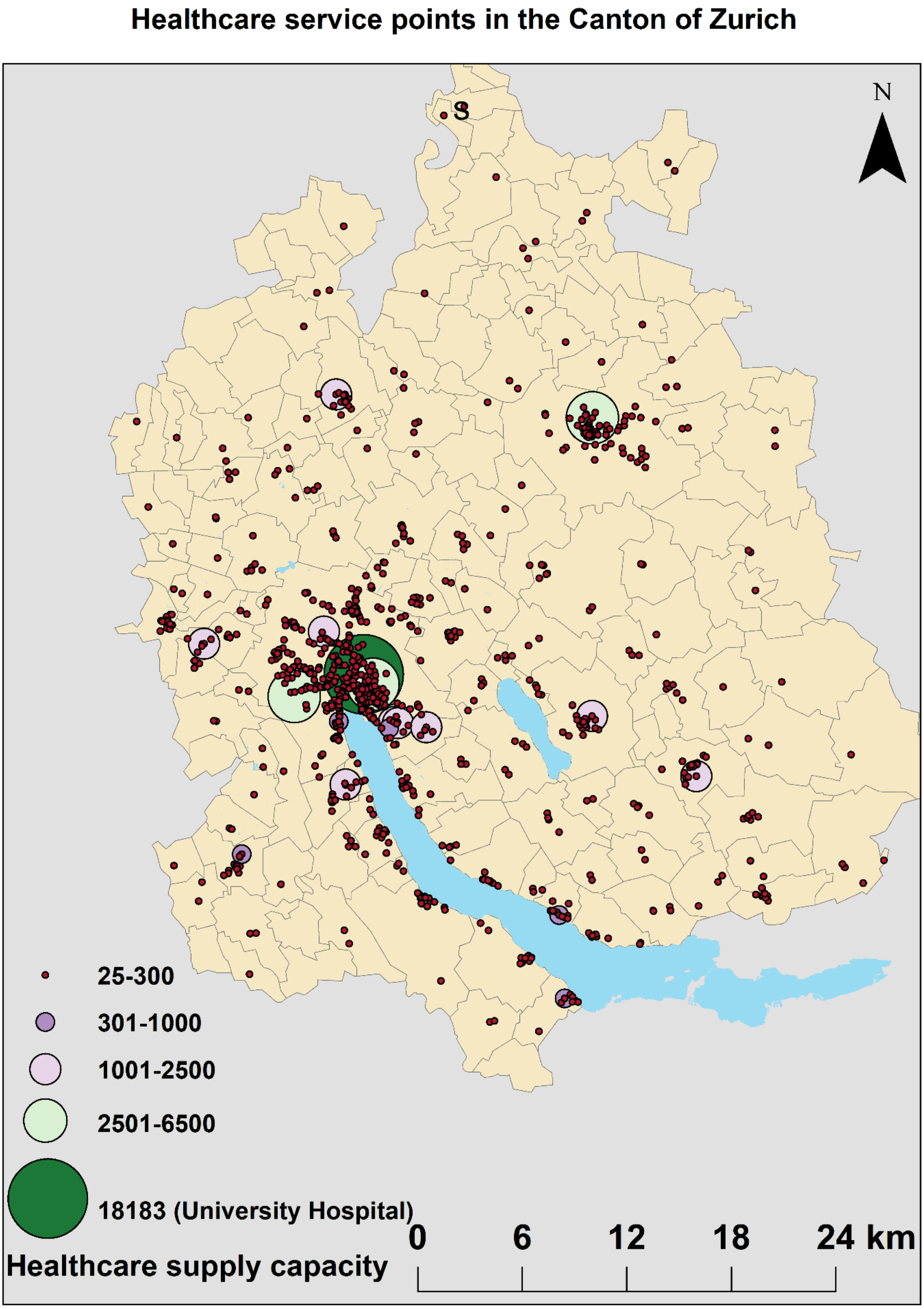

Figure 42. Cantonal healthcare provision service points; hospitals and private practices (Q2 2018).

4.2. Sensitivity analysis

In order to test the impact of various input parameters on the final accessibility scores, we conducted a sensitivity analysis on three key inputs: Total time budgets, Network speeds, and Gravity decay functions. The impact changing any of these parameters influences both absolute accessibility scores and their relative distribution. The most impactful of these is the total time budget, followed by network speed (H 4).

4.2.1. Total time budget

We hypothesised that the total time budget would have the greatest impact on the results since all other steps of the S-T (spatio-temporal) E2SFCA method rely on it. Figure 42 demonstrates the impact of total time budgets on regional accessibility scores (I would argue that this effect scales with scope).

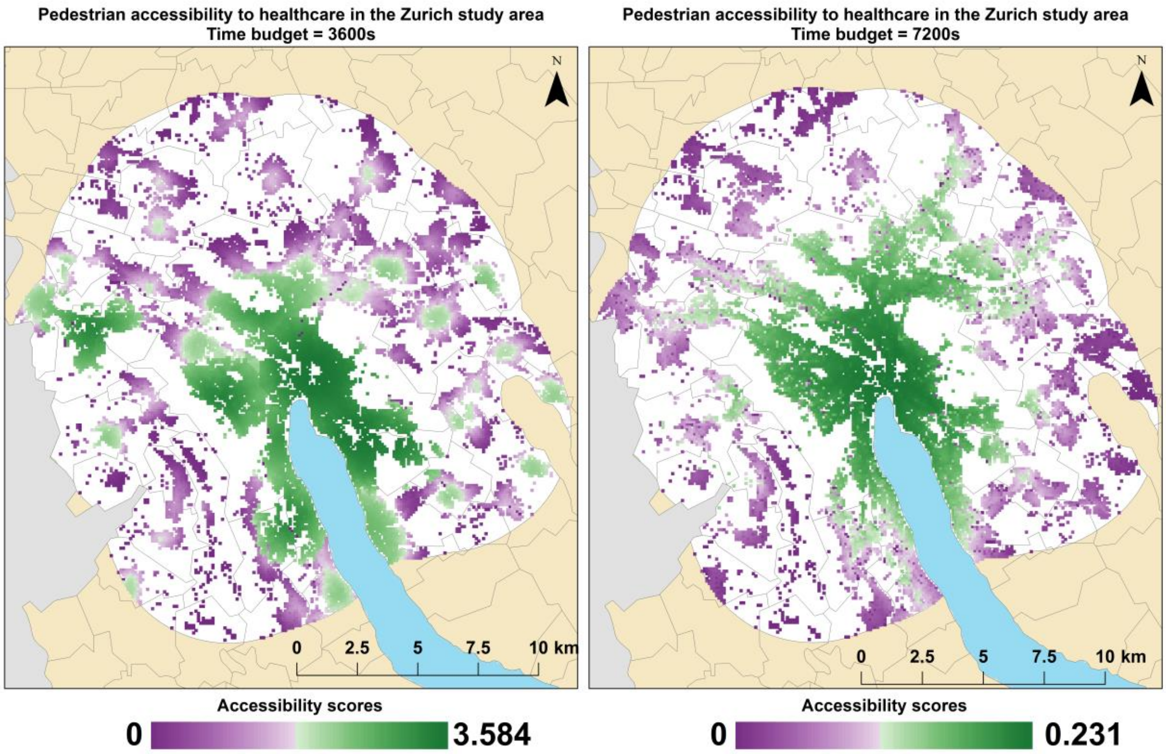

Figure 42. Example of the impact of total time budget variation on the final accessibility score maxima and relative spatial distribution.

First of all, the absolute accessibility scores are influenced thusly. Having a greater time budget means that the service point catchment is larger. A larger service point catchment means a less favourable supply/demand since the demand increases while supply is static. Therefore, the R values calculated in the method become smaller across the study region. This translates into the relative distribution of accessibility scores through the larger population point catchment in the second step of the E2SFCA. While supply/demand ratios are lower, more of them may be encompassed by individual population points. Thusly, the population points which are centrally located in the study region disproportionately "benefit" in from higher total time budgets. Lower time budgets increase local variation and differences inside the region. For example, we can observe on figure 42 (left) that the satellite settlements of Schlieren and Dietikon are ascribed above average accessibility to healthcare in the study region. This is due to the location of the Limmattal hospital which has a supply capacity of over one thousand, as well as numerous private practices (fig. 42). Despite the edge position in the study region, Dietikon and Schlieren were properly modelled above average accessibility due to spatial reality and logic. This is completely obscured when the total time budget for healthcare is doubled from 1 hour to 2 hours (fig. 42 right). With the increased time budget, the population points within the inner city areas (and those within easy reach e.g. Oerlikon) encompass more service supply points in their catchments. The edge settlements lose a portion of their catchment expansion due to the border of the study area, hence their relative standing is diminished. Observing the right side of figure 42 one can come to the wrong conclusion about the geographic reality of the study region. As demonstrated in the literature (Guagliardo 2004), humans are disproportionately inclined to choosing the more convenient (i.e. closer) option when given a choice between healthcare service providers. The increased accessibility score of inner city areas are contributed to by far away nodes of miniscule supply/demand rations. However, given enough time, a sufficient number of such points can be encompassed thus inflating relative locational benefit (Neutens et al. 2012) of the population point.

4.2.2. Network speed

Network speeds translate time budgets into spatial reach. Therefore, the second input parameter which will be critiqued in this sensitivity analysis. By increasing network speeds, the network edge cost attribute (travel impedance/friction) decreases; or conversely, it increases. Therefore, the capacity to cover increased or decreased spaces is primarily gauged by the network speed parameters. Figure 43 demonstrates the impact of network speed on accessibility results on the example of theatres in Zurich (which were n.b. one of the lease accessible services modelled). Pedestrian accessibility models network speeds limit all edge segments (except multimodal transport capable segments), to the travel speed of three kilometres per hour (circa 0.833 metres per second). To cross a network edge 100 metres long, the pedestrian has to expend approximately 120 seconds (out of a total time budget of e.g. 900 for provision services). However, of the travel speed was doubled, the spatial reach would also be doubled. The exponential effect of this is evident in figure 43. The non-existent pedestrian accessibility to theatres is transformed into a regionally equitable and favourable concentric distribution of high accessibility scores. Perhaps on the case of theatres this is indeed realistic. However, the impact is clear. The increase of relative accessibility is followed by the increase in absolute accessibility scores alike with the total time budget. Population points centrally positioned disproportionately benefit from higher network speeds since they can cover a wider scope.

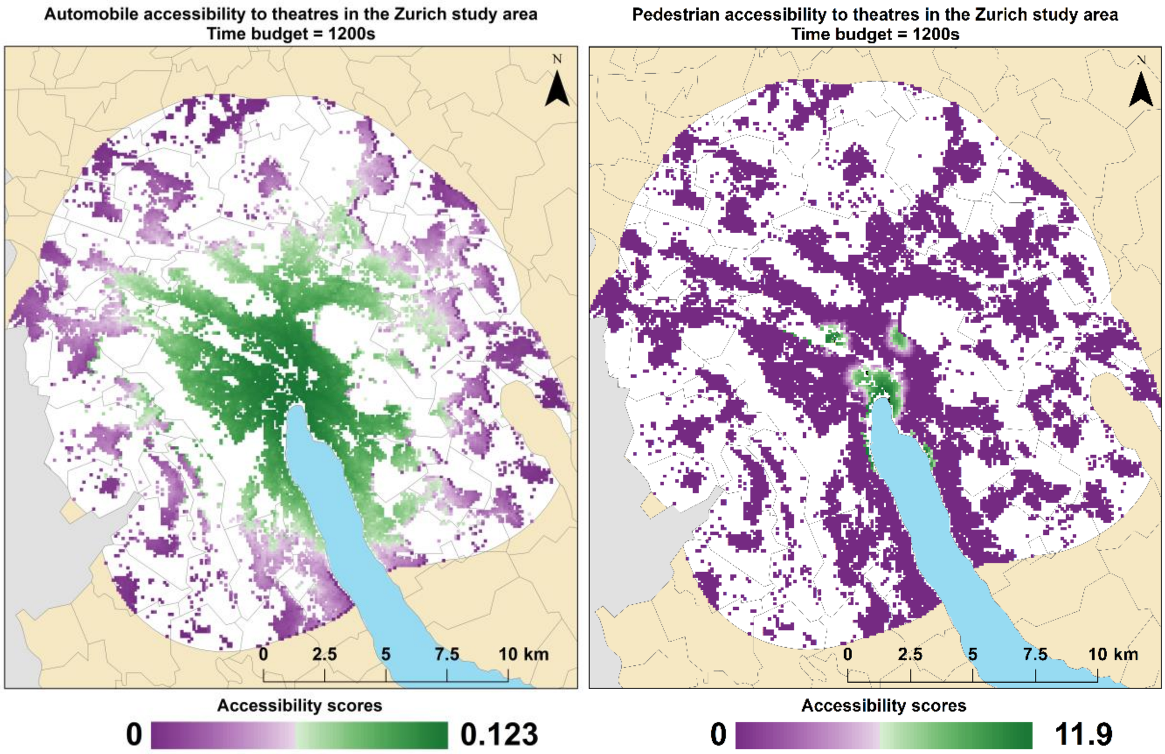

Figure 43. Eclatant example of accessibility score differences between transport modes for the same service in the same area.

Multi-modal transport options are implemented through assigning special speed attributes to certain network segments and then conditioning their connectivity to the rest of the network through public transport station points. We can see on figure 44 that the combination of pedestrian accessibility and multimodal transport methods (which is a form network speed increase) has the opposite effect of general network speed increase/decrease. Multimodal transport improves service accessibility in the fringe areas of study regions while it decreases the accessibility scores of centrally positioned areas. Again, we can observe the increase of absolute accessibility scores when the spatial scope of the analysis is restricted. However, figure 45 demonstrates the quantification of the network speed effect on healthcare accessibility in Winterthur by comparing the accessibility score difference of integrating multi-modal transport into pedestrian accessibility. This can be understood as the competitiveness of transport methods (Tenkanen 2017). Due the railways having the highest impact on speed (160km/h versus 3 km/h), the radial increase of accessibility scores is most significant. We can conclude that it is possible to produce fundamentally different accessibility patterns by altering network speeds. However, this is in some cases beneficial if modelled appropriately. Furthermore, some network speeds are unrealistic for larger geographic scales. The principal reason pedestrian accessibility is central in this thesis is that the modelled study areas are urban spaces, compact in extent and exhibiting a concentration of services. Hence, it would be possible to achieve access to most services on foot within a reasonable timeframe. However, applying automobile accessibility within a city would produce results which could make the entirety of the city accessible within the same timeframe for which pedestrians cover modest distance (e.g. for Zurich 30 minutes covers almost the entire study area from the source of the Limmat). In the case study of cantonal healthcare accessibility, using automobile (3600s) time budget and network speeds managed to recognize regional accessibility patterns (fig. 41). However, if we compare the accessibility scores for the Zurich study area on figure 41 and on figure 46, we can see that lots of insight into the local variance of accessibility was lost.

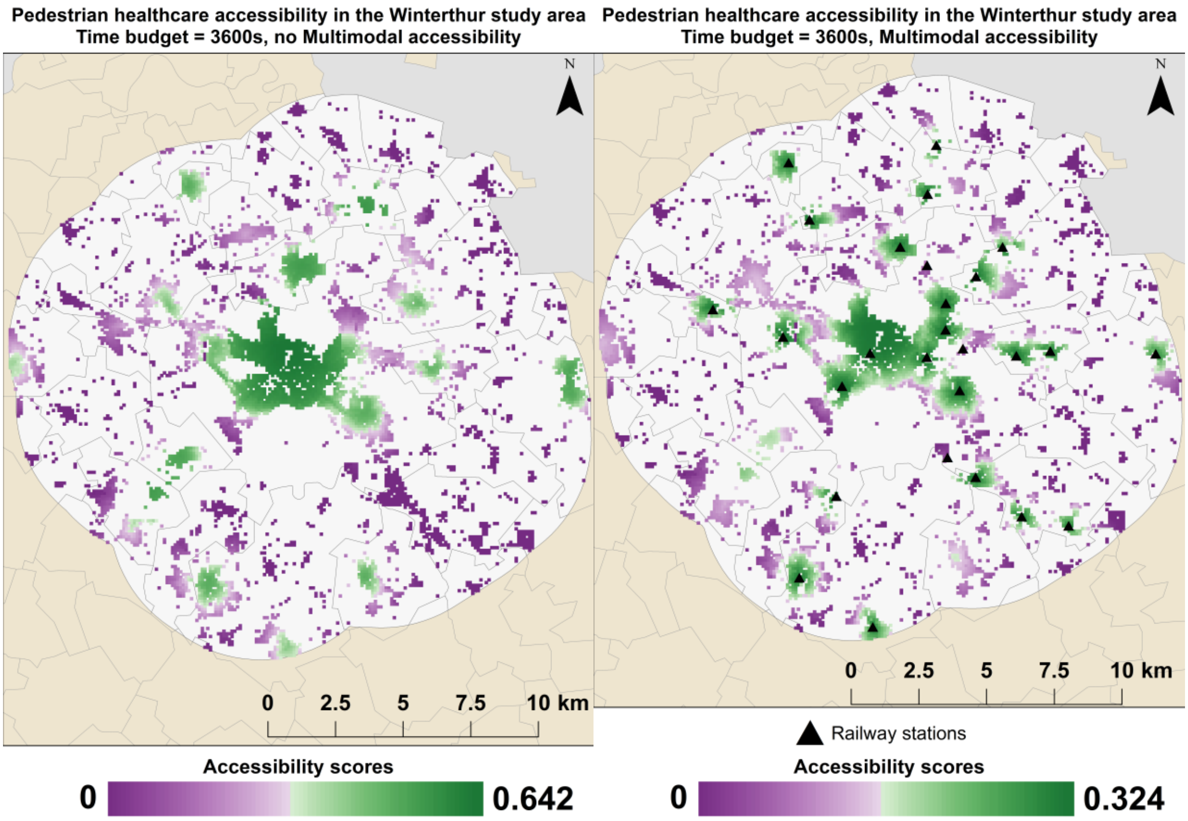

Figure 44. Comparison of healthcare accessibility with multi-modal transport options disabled (left) and enabled (right).

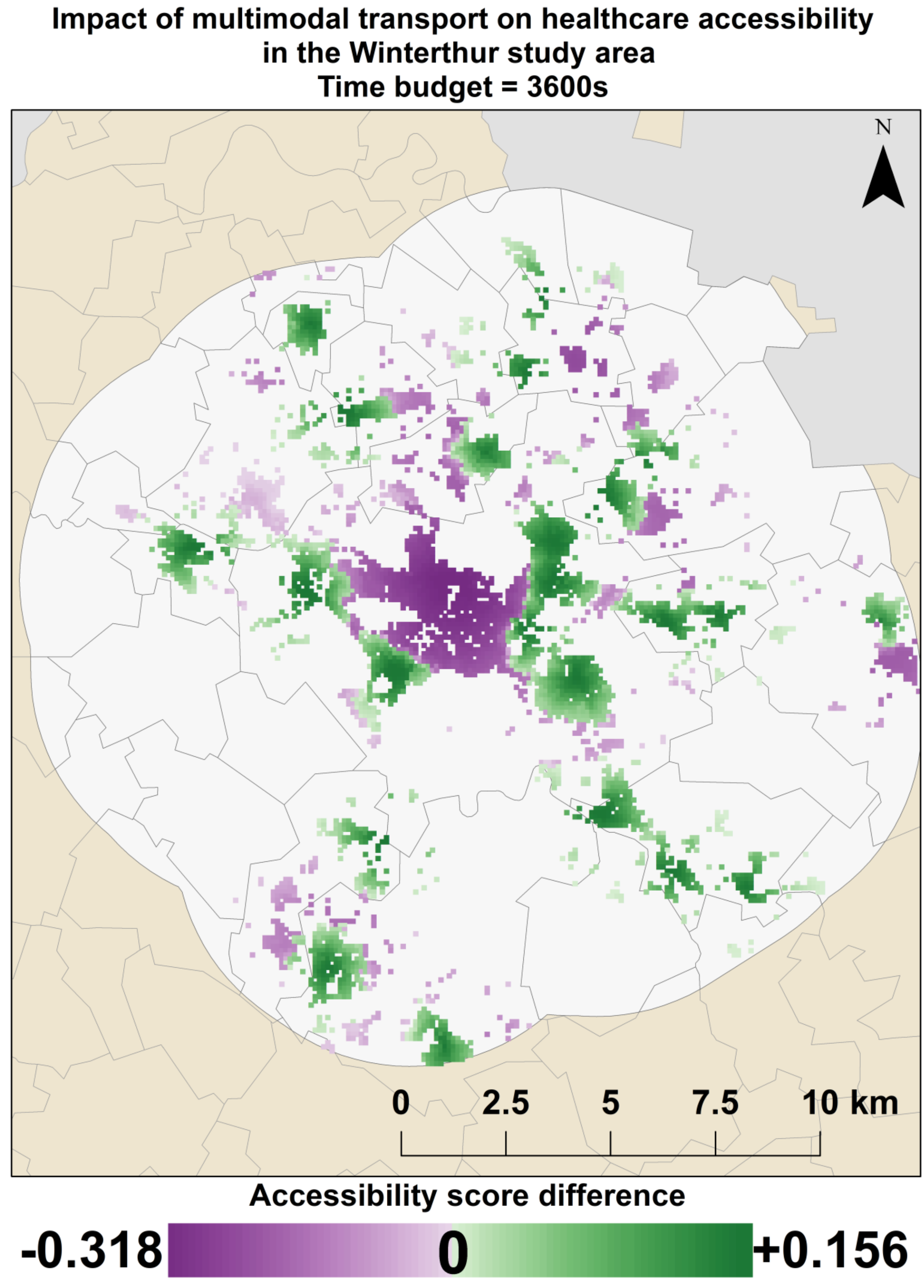

Figure 45. Quantification of the accessibility score difference between the two maps on figure 44. Points with no difference omitted.

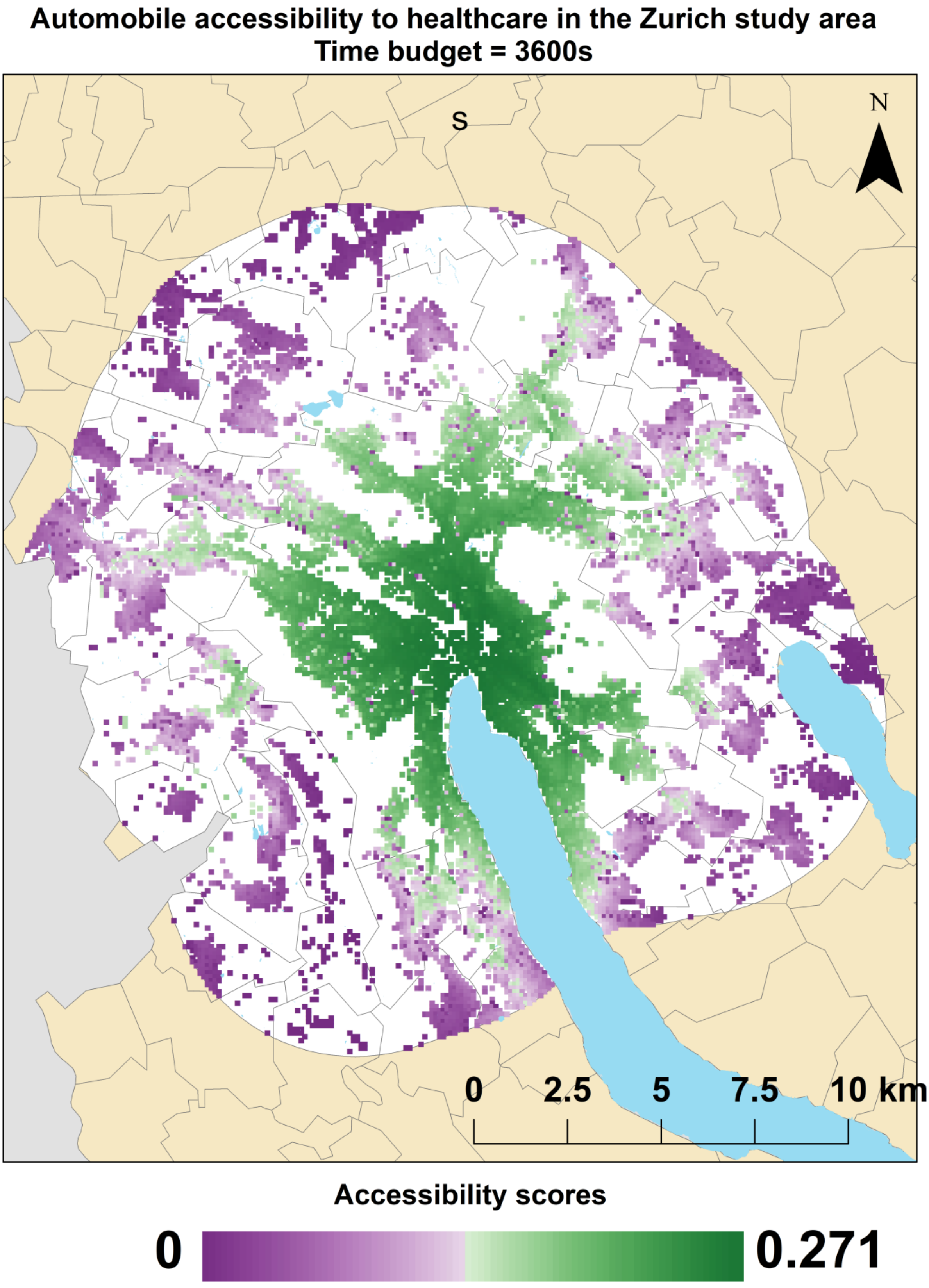

Figure 46. Healthcare service point automobile accessibility in the Zurich study area.

4.2.3. Gravity decay functions

Finally, the gravity decay function structure the manner in which supply and demand distance attrition is modelled. The E2SFCA methodology offers multiple gravity decay functions (Chapter 3, Section 3.3.). The Gaussian decay was chosen for this research. However, it is possible to assign a bandwidth to the Gaussian decay which determines the kurtosis of the normal distribution. The bandwidth of 50 is presented as default and as such used in this research. The Gaussian decay bandwidth of 50 corresponds to the Normal, mesokurtic distribution; only the values within one tertile of total time budget derived distance retain over 75% of their initial supply or demand value. Consequently, by increasing the bandwidth we make the distribution more platykurtic with an increase in value retention by distance. Lowering the bandwidth to below 50 makes the distribution more leptokurtic and hence less value is retained over distance. Figures 47, 48, 49, and 50 demonstrate the effect of different gravity decay functions as well as Gaussian decay bandwidths on the results and the statistical distributions of spatio-temporal accessibility scores.

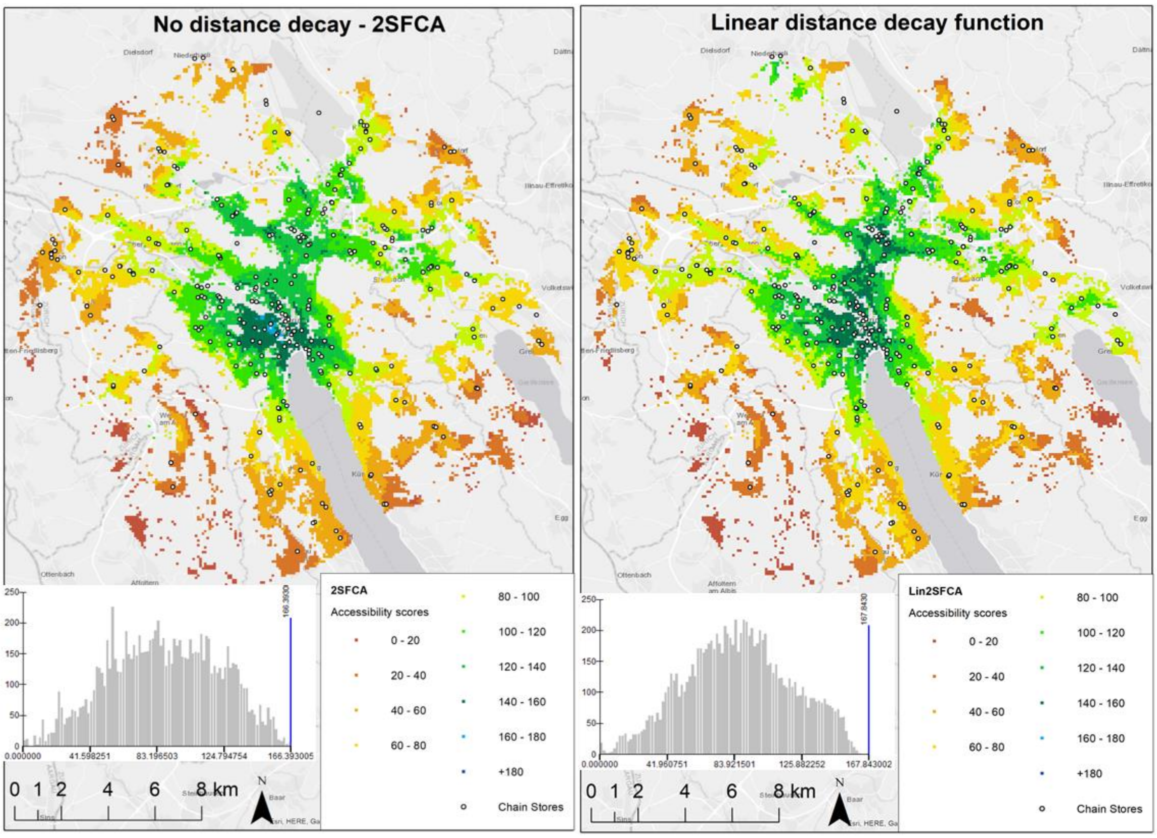

Figure 47. No distance decay and Linear distance decay function. Reflection on chain store automobile accessibility in the Zurich study region: Time budget = 900s. Blue = high, red = low.

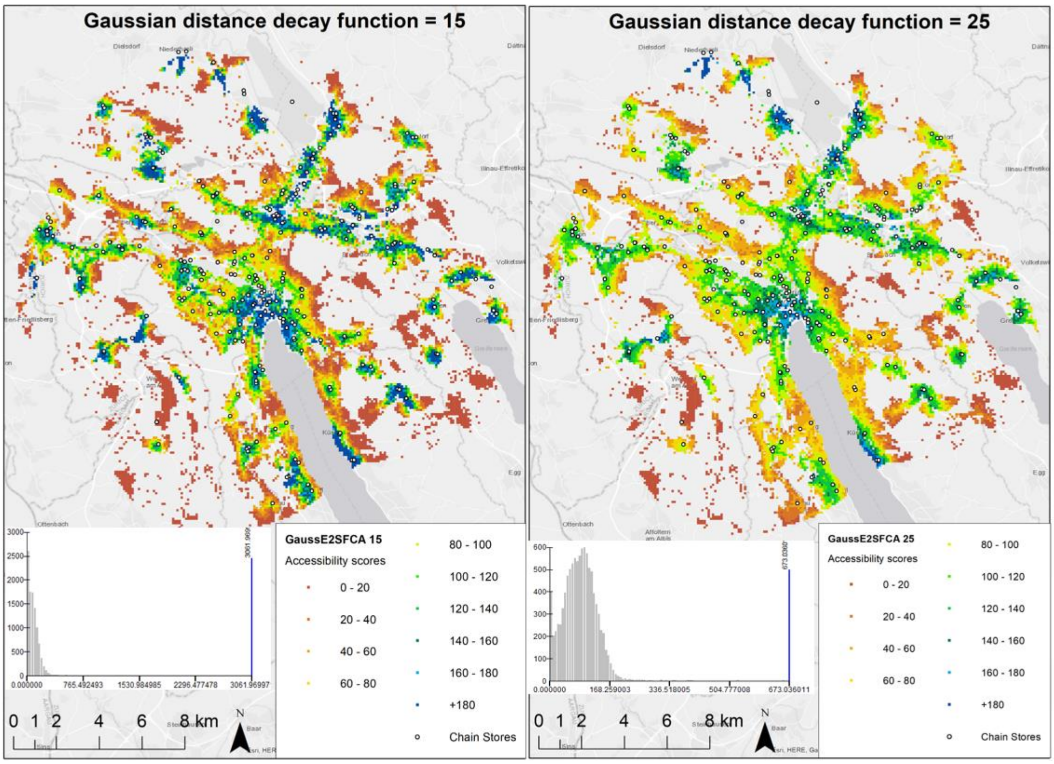

Figure 48. Gaussian distance decay functions bandwidths of 15 (left) and 25 (right). Reflection on chain store accessibility in the Zurich study region: Time budget = 900s. Blue = high, red = low.

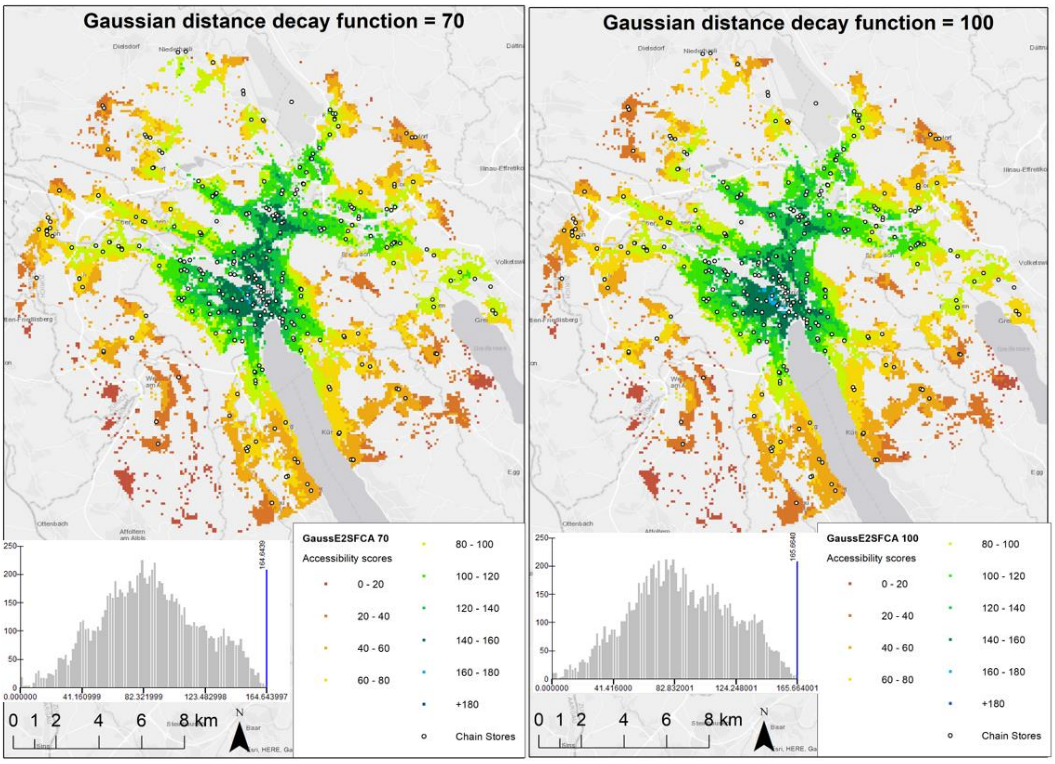

Figure 49. Gaussian distance decay functions bandwidths of 70 (left) and 100 (right). Reflection on chain store automobile accessibility in the Zurich study region: Time budget = 900s. Blue = high, red = low.

The results of the analysis using the default (50) bandwidth for the Gaussian decay produced the result most in line with the expectations and theoretical considerations (fig. 50). Distance decay has to be included per Toblers First Law. However, we want to recognize the intra-regional differences in accessibility scores. Hence, steeper value gradation helps better geovisualize spatial discord (Šterc 2015).

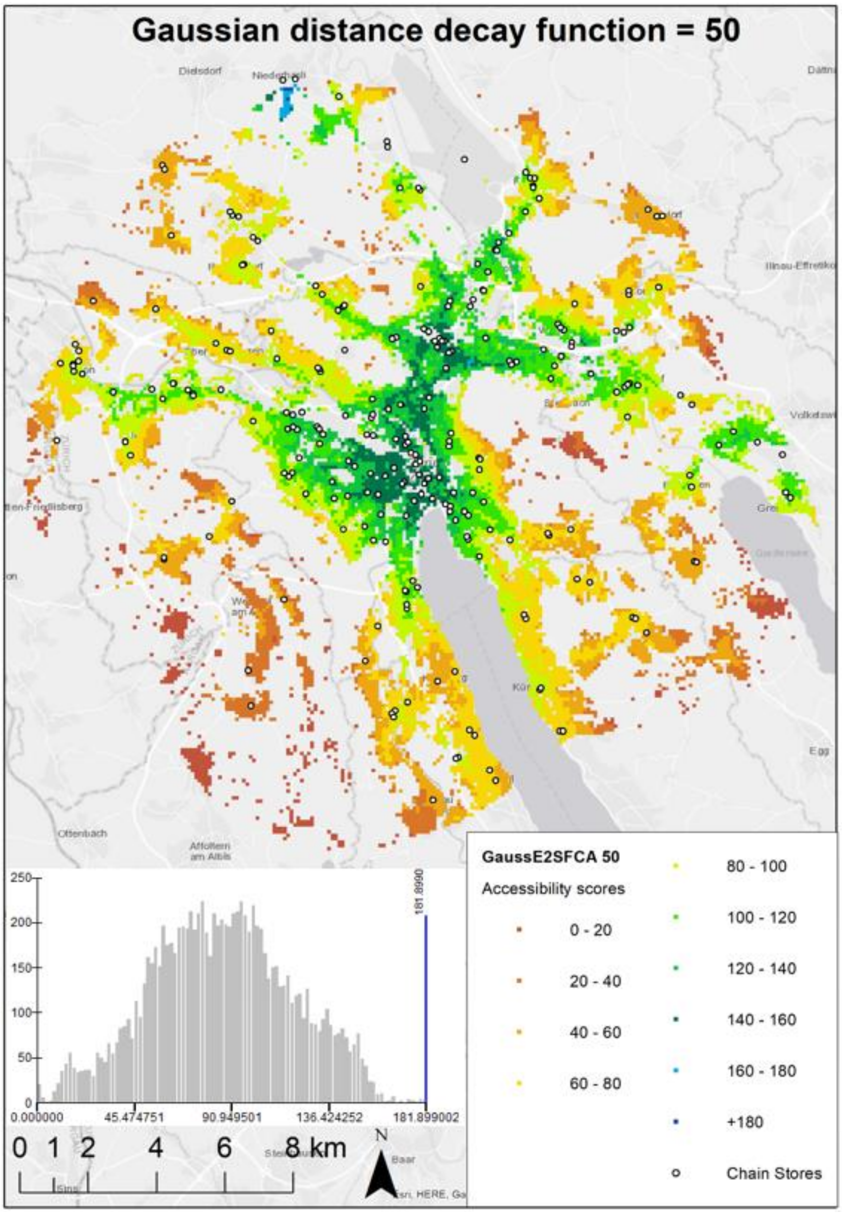

Figure 50. Gaussian distance decay function of 50 bandwidth. Reflection on chain store automobile accessibility in the Zurich study region: Time budget = 900s. Blue = high, red = low.

In conclusion, the sensitivity analysis revealed the manner in which accessibility scores vary by input (H 2) parameter (and in general). Two primary modes of score value variance; changes in the absolute accessibility scores and the relative distribution of (relatively) higher accessibility scores. Increasing any of the parameters analysed within the senstivity analysis has the effect of lowering absolute accessibility scores and thus changing the distribution of relative high acessibiltiy scores in the study region. It is possbile to completely alter the meaning and implication of the accessibility analysis if different input parameters are used. We demonstrated on the example of 1 hour and 2 hour pedestrian accessibility to healthcare within the Zurich study area that the spatial logic of service provision which is implied by a map can provide two opposite messages. Likewise, we demonstrated how multi-modal accessibility is a compromise solution which dissapates local maxima, while increasing regional minima. The input parameters with the greatest influence on accessibility scores and distribution are the total time budget and the network speeds (H 4). However, the challenge remains to ascertain the right value. If the chosen input parameter values are too small, there will be much local variation in scores but perhaps little spatial logic or patterns to spot (e.g. theatre accessibility). However, if the chosen values are too large, centrally positioned spaces will be disproportionately benefited and we wiill fail to model spatial logic and reality.

Chapter 5: Discussion and outlook

5.1. Discussion

The successful implementation of spatio-temporal parameters within the E2SFCA method yielded intriguing results based on which we can address our research questions. The spatial distribution of accessibility mostly conformed to the initially hypothesises spatial logic of urban areas (H1 and H2), whereas the inner cities have highest scores, and the urban fringe has the lowest, while transport corridors radially distribute higher accessibility scores. However, this could not be observed in every point with several services. These are the post offices, the public transport, and a special case with sports facilities and parks. Firstly, the post offices are equitably distributed throughout both study areas. However, the inner city accessibility to post offices is lower than the accessibility with the urban fringe satellite settlements. This means that the system of post office provision could be optimized in order to better service the majority of the population in the dense inner city areas, whereas the rural spaces could be substituted with automated postal systems. The public transport accessibility differed from the hypothesis in the positive aspect of being well accessible throughout the study regions. However, the modelled disparity within the Zurich city centre with the immediate residential neighbourhoods to the east demonstrates the downside of not using supply capacities for public transport (e.g. frequency of transport). By basing the accessibility score solely on the number of stations available divided by the population in reach, we overestimate areas of lower (residential) population densities and/or intersection of multiple public transport modes. The special case for sports facilities is that the spatial distribution of service points within the Zurich study area is significantly different. The spatial logic of sports facility accessibility in Winterthur conforms to the hypothesis that inner city areas have higher accessibility, which is radially distributed, while the urban fringe has lower accessibilities. However, Zurich provides a different story. Within the Zurich study area sports facilities are equitably distributed throughout the region. The zones of lower ports facility accessibility conform to zones of industry, science or commerce, while the zones of higher accessibility conform to the resident population distribution of the study area. Thus, on the example of Zurich, we can argue that the third hypothesis has been confirmed (H 3). Modelling supply capacity by demographics produced an outcome which corroborates it. However, more research is needed before we can conclusively answer the third RQ and Hypothesis. Park for example exhibit a similar trend to sports facilities, just in the opposite direction. With parks, Winterthur is the city with the superior distribution and accessibility, while Zurich has a zone of concentration along the Lake and the Limmat and other areas bereft of park services. These two examples could be ascribed to socio-economic and political factors of the two study areas. There is greater market incentive to invest in sports facilities within Zurich, hence there are more. Likewise, the Winterthur local government is committed to the expansion and maintenance of park infrastructure whereas in Zurich this is a lower priority.

As for the services which conformed to expectations. Healthcare is the most interesting, both in terms of general accessibility research trends, and in terms of observed distributions. Importantly, the healthcare accessibility analysis was expanded to the scope of the entire Canton as part of a case scenario. Despite hardware limitations, we have managed to implement the S-T E2SFCA on the regional scale which opens up further research opportunities. Also, the impact of multi-modal transport and public transport competitiveness was successfully quantified and visualized on the example of 1 hour pedestrian accessibility to Winterthur study area healthcare services. Nevertheless, Zurich has a more favourable healthcare provision due to greater supply and distribution of the supply. On the example of museums and theatres we demonstrated that time budget and network speed parameter choice simply has to be determined on a per-service level, with as much information as possible. Pedestrian accessibility to theatres revealed only that they are inaccessible to the majority of the population, whereas automobile accessibility to theatres provided a positive message of equitable accessibility. The initial idea behind this thesis was to use many more services alongside those which are present in this research. Many had to be dropped due to a lack of data or information to base parameters on. This was compounded by the inability to properly model workplace demographics. The dataset developed was eventually rejected as overly uncertain and incomplete. However, if the proper workplace demographics could be obtained, this research should be repeated with them included. The main critique of several results (as presented in chapter 4) was that city centre accessibility scores are overestimated due to not including workplace demographics. This is an important and central research outlook. In summary, the study area of Winterthur demonstrates a greater inequity in spatial distribution of accessibility scores than does the study are of Zurich. While Winterthur has access to all services Zurich has access to, they tend to be more concentrated in the city centre of Winterthur. This due to Zurich not only being much bigger, but also more functionally important which enables greater demographic and monetary resources to base the economy on. The overall service provision system in Zurich is thus evaluated as spatio-temporally accessible. However, we recognize a supply deficiency in the Kreis 3, 4, and 9 based on the potential accessibility scores. These parts of the city have the highest population densities hence the concept of maximum service coverage should be adjusted. Preferably, the service placement would be optimized based on the results of spatio-temporal individual potential accessibility. Therefore, the next stage of a research series involving this thesis would determine optimal locations for service points in order to achieve better overall accessibility for the population, or utility for the business. However, the intermediate steps to this are outlined in the following section.

5.2. Outlook

Introducing simple spatio-temporal utilization costs into the E2SFCA method expanded the possibility with the method, but also increased the uncertainty. It was evident during the course of the research that the utilization costs were formed arbitrarily, albeit as informed as possible by available data and literature. The values were derived from the given characteristics of the chosen study region. Due to this study region being in the same country, even the same historical and geographic region, it is probable that this skewed the results. Hence, the first perspective of the research outlook is the comparison of a foreign city of similar size and functional importance as Zurich. Furthermore, the results of the research could be expanded by including various scenarios in the accessibility analysis. This would generate new insights and provide differing sets of results which could be compared one to the other. Thusly, the depth of the research could be improved without expanding the geographic scope. There are several possibilities for such scenarios and they include variations in service availability (working hours/days), variations in service demand (differences by age group), or variations in the service supply. For example, the supply capacity for services could have been calculated twice. First, informed by the parameters and existing state of the Swiss study region used in this thesis. And a second version of supply capacity informed by the parameters and existing state in another study region. Albeit not as significant influence on the results as is the network dataset, the supply (and demand) inputs are core parameters of the E2SFCA. Increasing the supply capacity significantly increases local accessibility (with lessened influence inversely proportional with network distance). Thus, more local variance would be observed, especially at lower time budgets or network speeds. Furthermore, similarly expanded insight could be gained from including more temporal variation through working hours. However, the inclusion of work hours requires additional data which is not available for every service or varies based on service provider within the same category. Furthermore, generating accessibility scores for different age cohorts present within the current methodology as variable demand. However, the demographic dataset by BFS (statpop 2013) contains 5 year demographic cohorts from 0 to 90 plus. If the cohorts could be modelled to the granularity of 1 year classes, we could be more specific when assigning variable demand. Also, we would avoid generational overlap between adults and juniors, or even push the age of seniority to 67 as is the popular trend. Further possibilities lie in generating accessibility outlooks solely for certain age groups; the elderly, the young, the working aged; or accessibility scores by sex, Swiss born, foreign born etc. However, these topics were not the topic nor the scope of this thesis. They could be undertaken as part of a future research, which would preferably include different cities also.

5.2.1. Workplace demographics

Unfortunately, the cantonal workplace demographics GIS data are locked behind a paywall by their owner, the Zurich canton statistics office. However, the total number of employees per municipality is available for free for the year 2013[8] (Amt für Raumentwicklung 2013). The total number of employees in the study areas is 94993 for the Winterthur area, and 687775 for the Zurich area. Compared to the resident populations of these areas, 199582 for Winterthur and 734641 for Zurich, the workplace population constitutes a statistically and practically significant number; and a significant demand for services. The resident population of Winterthur is adequate in number to fulfil local employment opportunities with approximately 127732 residents aged 20-65 (Statpop 2013). Many likely seek job opportunities outside the Winterthur area, probably in the adjacent Zurich area. However, the daily migrations of the population and workforce are outside the scope of this research. Nevertheless, they represent a research gap. Unlike the Winterthur area, the Zurich area resident population aged 20-65 (i.e. working age) numbers 492678. Therefore, the Zurich area working age resident population is short approximately 195097 workers, despite the workforce eligible resident proportion already at almost 70%. The economic and functional position of Zurich on the regional, national, and international hierarchy enable it to be the focus of migratory workforces, as well as permanent immigration. Indeed, the foreigner percentage in Zurich has grown from 31.3% in 2013 to 32.2% in 2017 (Statistisches Amt Kanton Zurich 2018). Therefore, it is clear that employment opportunity is one of the services which Zurich offers and attracts people with. Despite employment being ranked second by functional centrality, it can be regarded as a service to which potential accessibility may be measured for population points. For that reason, employment will be one of the services for which accessibility scores will be calculated. The total amount of jobs occupied in the Canton of Zurich is 978455 (Amt für Raumentwicklung 2013). Hence, the study areas encompasses an impressive 91.24% of all employed populace within the Canton of Zurich. Figure 51 visualizes the distribution of potential employment opportunities within the study area of Zurich (right), and Winterthur (left). These values were derived through raster analysis of web-GIS rendering of the unavailable workplace demographics data. Therefore, uncertainties and errors were likely to occur. Nevertheless, through redacting the results of automated ArcGIS processes, the obtained result is spatially logical and consistent with observed trends in the source material (Amt für Raumentwicklung 2013). Since exact workplace demographics for were unavailable, we only had data for 5 classes in the offered data preview. Hence, these classes are mapped in hectare tilesets assigned a supply capacity of the upper bound value in the source material classification. The result of this is that supply capacity is overestimated. For example, the Zurich area is allocated a supply (potential jobs) capacity of 995670. This is almost 50% more than the actual number of people (n.b. not necessarily residents) employed in the Zurich study area. Despite access to a more granular workplace demographic dataset, the generated data will be sufficient to conduct an employment service potential spatio-temporal accessibility research.

Therefore, the accessibility analysis of service provision to workplace demographics is certainly an important aspect for future research. However, it has not been implemented in this thesis due to the lack of proper dataset. The example derived in figure 51 is at best a rough approximation by ArcMap of pixel brightness and saturation on the screenshot of the workplace demography example provided on the cantonal GIS web service. For that reason, it was not included in the thesis.

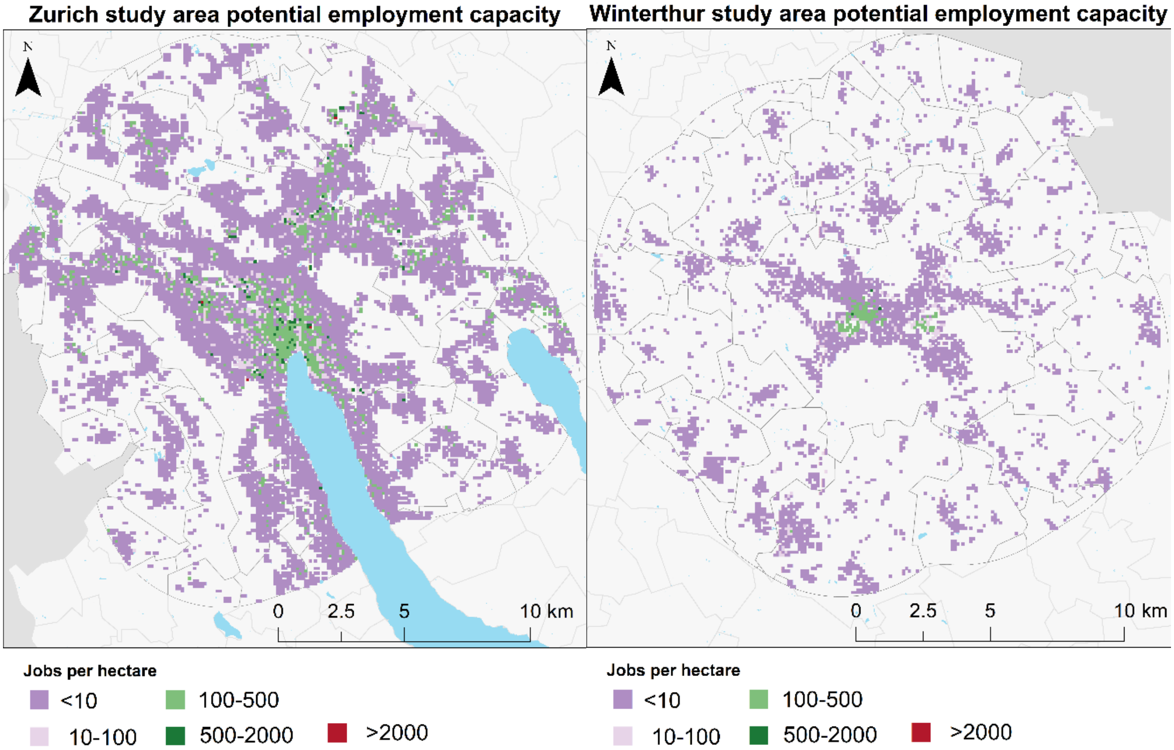

Figure 51. Potential employment capacity within the study areas. (Data source: Beschäftigtenstatistik, Amt für Raumentwicklung 2013)

5.2.2. Daily and weekly variation in accessibility

During the initial service data acquisitions we endeavoured to record the working hours of every service which provided it in the source. This includes weekday hours, Saturday hours, and Sunday hours. With this, it is possible to select by attribute and include only certain services in the accessibility analysis thus simulating differing times of day. This is already an established topic in research (see Neutens et al. 2011; Tenkanen 2017). Unfortunately, not all services had this data available hence in the case we would have undertaken this scenario analysis, not all services could partake. However, the true value in using the time of day is to model traffic density in peak and off hours, thus introducing different network costs for mobility which generates different accessibility results, which was far outside the scope of this thesis. An extension to intra-daily accessibility variation would be the inter-daily accessibility variation. However, this one is simpler since I would only require a Boolean value for each service to simulate whether it is open on a particular day. However, most services work shorter hours on Saturdays and are closed on Sundays. Some services lack data on this (e.g. primary health care practitioners) at all. Thus, the addition of accessibility variability by days in the week should be narrowed to services which are interesting in this regard; chain stores (provision), and leisure services (culture, recreation) since the citizenry has free time for these services on weekends as opposed to weekdays. As argued in the analysis of the differences between temporal and spatio-temporal accessibility within the first chapter, the accessibility variation between times of day or days in week constitutes temporal accessibility. Therefore, this has not been a priority to implement. It is however an interesting aspect which deserves a place in the research outlook.

5.2.3. Parameter analysis

The sensitivity analysis demonstrated the profound impact of the different accessibility input values for time budgets, network speeds, and gravity decay functions. However, these are only half of the total input parameters used in the S-T E2SFCA. There remains the supply and demand capacity, and the introduced utilization cost segments. They have not been included in the sensitivity analysis within this thesis because they were deemed to have a lesser impact on the results compared to the prior group. Furthermore, the supply capacity and the utilization cost were approximated for the needs of this research based on the available information, literature, and logic of the final results. Although the results are arguably consistent with expected spatial logic of service provision in urban areas, we cannot conclusively claim that they are realistic, nor that they are unrealistic. This is not such an uncertain issue as is for example network speed which can be argued by road type, or time budgets which are informed by time-geography research (Hägerstrand 1970; Neutens et al. 2011; Delafontaine et al. 2012), or even the distance decay for which it can be said that the linear or Gaussian (Normal) decay distribution is in line with Toblers First Law (Tobler 1970). Therefore, we cannot conclusively answer the third research question, nor can we confirm or reject the corresponding hypothesis (H 3). Further research is required, with the particular focus on the input parameters.

5.3. Conclusion

Accessibility analysis is an old topic of research. However, it is constantly improving with new applications and methodologies. We have contributed to this drive through finding a way to implement spatio-temporal constraints (Hägerstrand 1970) into the enhanced two step floating catchment area (E2SFCA) (Luo & Qi 2009). This is important since the E2SFCA is a powerful method of potential accessibility analysis which can be undertaken with readily available data on commercial GIS software. Hence, the application scope is wide. By introducing spatio-temporal constraints we have managed to gain deeper insight into the intra-regional variation of accessibility to services while at the same time providing an additional parameter to work with. The original E2SFCA method uses four input parameters to derive accessibility scores. It requires two sets of points of interest, e.g. population and services. A network dataset through which the points of interests interact. And finally, the measure of gravity decay to address uniform regional accessibility scores. The primary mode of increasing or decreasing accessibility scores was to adjust the network dataset parameter of speed and travel distances. This would produce a concentric increase or decrease of accessibility scores in a region. Similarly, the change would be radial if multimodal transport was modelled. However, we have introduced the utilization spatio-temporal constraint which does not interfere with the original network logic. Instead, it functions as a spatio-temporal overlay on the existing network which models the person-based aspect of accessibility. While the network reach remains the same, the spatial reality of spatio-temporal constraints is added. Whereas before a service was unavailable only if it was outside of network reach, with the spatio-temporal E2SFCA services may or may not be available even if within the network catchment of a point of interest. Therefore, the theoretical concept of the spatio-temporal pyramid was successfully introduced within the E2SFCA. This follows the trend of latest accessibility research which has not made use of the floating catchment area methods, instead developing new ones (Neutens et al. 2011, 2013; Delafontaine et al. 2012). Further development of the theoretical and conceptual framework pertaining to spatio-temporal constraints and services can help make accessibility research more competitive in terms of person-based accessibility research.

In summary, the service provision system in within the cities of Zurich and Winterthur conform to the expected spatial logic of urban areas. Although there is a trend of increased accessibility scores within the inner city areas, this is predominantly observable when using larger time budgets or network travel speed. The study area of Winterthur demonstrates a greater inequity in spatial distribution of accessibility scores than does the study area of Zurich. This is most likely due to the city of Winterthur being monocentric and lacking in satellite cities. This is contrasted with the city of Zurich which is polycentric with three axii of higher accessibility trends; the Limmattal, the Glattal, and the lakeshores towards Meilen and Horgen. Nevertheless, the majority of auxiliary function services in the Zurich study area are equitably distributed. The implementation of the modified E2SFCA on the example of service provision of Zurich and Winterthur had the goal of testing the method, which it succeeded. The next step of research is to expand on the implications of the introduced utilization cost spatio-temporal constraint. Specifically, to establish a framework for informed parameterisation, to ascertain the ground truth through a survey or a realized accessibility research, and to implement the method on a wider geographic scope using improved hardware or to compare Zurich with a foreign city. The observed trends of accessibility scores in the course of this research indicate that the most informative insight is obtained when conducting the accessibility analysis on a larger geographic region, and when modelling services which are not spatially concentrated. With the whole research progress in hindsight and the final results analysed, we can answer the guiding research question of this research set almost a year ago:

How are services accessible, spatio-temporally, to the population of the chosen study region?

We hold that the accessibility of services in any region is thus equally conditioned by time as it is by space. Conditioned, but not constrained, for the spatio-temporal aspect of reality introduces greater human agency in the logic of space. The impact of altering the spatial or temporal inputs of the original E2SFCA artificially determined and classified space. However, the potential of spatio-temporal parameters helps lessen this determinism and allows for more variation according to the given situation. We thus conclude, that space is not a geodetermined prison, but a spatio-temporally conditioned prism, within which all content interacts with logic and grace, in time and space.

Chapter 6: Supplement

6.1. Literature and references

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6.2. Services data

- Healthcare services[9].
  - Private general practitioners[10]
  - Hospitals[11]

- Leisure services.
  - Theatres [12]
  - Museums [13]
  - Parks (Zurich[14], Winterthur[15])
  - Sports facilities[16]

- Provision services
  - Chain stores
    - Spar[17]
    - Lidl[18]
    - Coop[19]
    - Aldi[20]
    - Migros[21]
    - Denner[22]

- Communication services.
  - Post offices[23] (Swiss post)

- Public transport services.
  - Tram stations (Swisstopo, TLM3D)
  - Bus stations (Swisstopo, TLM3D)
  - Train stations (Swisstopo, TLM3D)

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9 https://gd.zh.ch/internet/gesundheitsdirektion/de/themen/institutionen.html
10 www.doktor.ch
11 https://gd.zh.ch/dam/gesundheitsdirektion/direktion/themen/behoerden/spitalplanung/strukturbericht/strukturbericht_september_2011/akut_zuercher_spitalliste_gueltig_ab_1.1.2018/spitalliste_akutsomatik_version_2018_2.pdf.spooler.download.1513351447276.pdf/spitalliste_akutsomatik_version_2018_2.pdf
12 https://www.zuerich.com/en/culture-in-zurich-museums-music-plays-more
13 https://www.zuerich.com/en/culture-in-zurich-museums-music-plays-more
14 Open Data Zurich
15 Stadt Winterthur
16 http://maps.zh.ch/ Sportanlagen
17 https://www.spar.ch/spar-maerkte/#?region=LU&s=1
18 https://www.lidl.ch/de/Filialfinder-475.htm
19 http://www.coop.ch/de/services/standorte-und-oeffnungszeiten.html
20 https://www.aldi-suisse.ch/filialen/
21 https://filialen.migros.ch/de/center:47.3774861,8.536715/zoom:12
22 https://www.denner.ch/de/filialen/
23 https://places.post.ch/?shortcut=standorte

6.3. Geocode R script

```
library(ggmap)

#First geocode pass. ggmaps returns many false query limit breaches, hence it is necessary to
implement the geocoding multiple times.
```

```
for (i in 1:nrow(dataframe_name)) {

  c <- as.character(dataframe_name $address_column[i])
  t <- geocode(c)
  x <- t[2]
  y <- t[1]
  Sys.sleep(1) #lessens query limit bug
  if (is.na(t)) {
    Sys.sleep(3)
    t <- geocode(c)



    x <- t[2]
    y <- t[1]
    Sys.sleep(1)
  }

  else
    dataframe_namel$ address_column[i] <- c
  dataframe_name$lat[i] <- x
  dataframe_name$lon[i] <- y
}
```

#Additional Geocode passes. Geocodes only NA values (result of query limit bug).

```
for (i in 1:nrow(dataframe_name)) {

  c <- as.character(dataframe_name $ address_column [i])
  x <- dataframe_name$lat[i]

  if (is.na(x)){
    t <- geocode(c, override_limit = T)
    Sys.sleep(2)

    x <- t[2]
  }

  y <- dataframe_name$lon[i]

  if (is.na(y)){
    y <- t[1]

    Sys.sleep(0.2)
  }

  else
    dataframe_name$address_column [i] <- c
dataframe_name$lat[i] <- x
  dataframe_name$lon[i] <- y
}
```

6.4. List of tables and figures.

Personal Declaration

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

Zurich, 30.9.2018.

Date

Ivor Mardešić