Spatial accessibility and mobility have become increasingly important concepts in understanding the functioning of societies. In the era of big data, the wealth of temporally sensitive spatial data and novel analytical tools have made it possible to reveal how people can access places, how they actually move, and how they use space. In this thesis, I aim to develop novel approaches and methods to study the spatio-temporal realities of accessibility and mobility. I take advantage of open data such as time schedules of public transport or social media data, and develop further geospatial analysis techniques to extract knowledge from them. The methods developed and the understanding provided by this thesis may be used to support sustainable spatial planning. In addition, the tools and data created in this thesis are openly available online.

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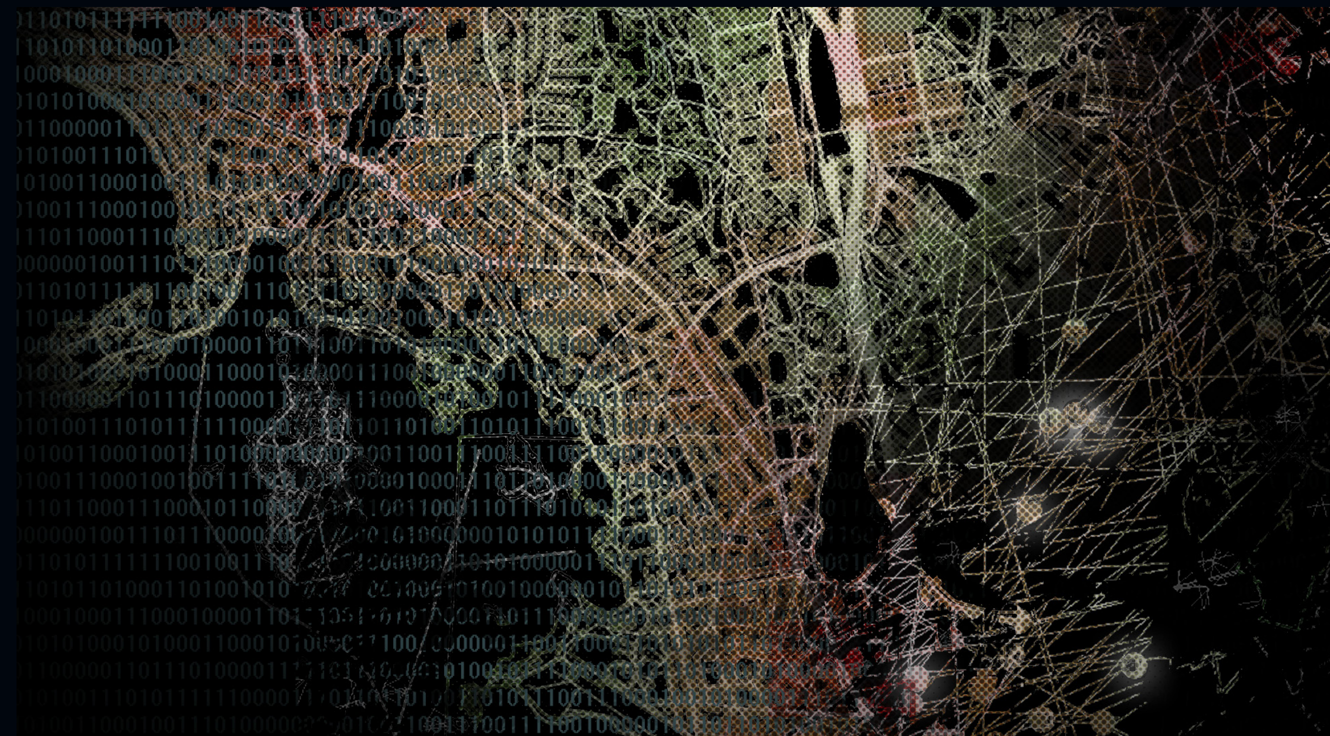

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Capturing time in space: Dynamic analysis of accessibility and mobility to support spatial planning with open data and tools

HENRIKKI TENKANEN

UNIVERSITY OF HELSINKI
FACULTY OF SCIENCE

Capturing time in space:
Dynamic analysis of accessibility and mobility to support spatial planning with open data and tools

HENRIKKI TENKANEN

ACADEMIC DISSERTATION
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ABSTRACT

Understanding the spatial patterns of accessibility and mobility are a key (factor) to comprehend the functioning of our societies. Hence, their analysis has become increasingly important for both scientific research and spatial planning. Spatial accessibility and mobility are closely related concepts, as accessibility describes the potential to move by modeling, whereas spatial mobility describes the realized movements of individuals. While both spatial accessibility and mobility have been widely studied, the understanding of how time and temporal change affects accessibility and mobility has been rather limited this far. In the era of 'big data', the wealth of temporally sensitive spatial data has made it possible, better than ever, to capture and understand the temporal realities of spatial accessibility and mobility, and hence start to understand better the dynamics of our societies and complex living environment.

In this thesis, I aim to develop novel approaches and methods to study the spatio-temporal realities of our living environments via concepts of accessibility and mobility: How people can access places, how they actually move, and how they use space. I inspect these dynamics on several temporal granularities, covering hourly, daily, monthly, and yearly observations and analyses. With novel big data sources, the methodological development and careful assessment of the information extracted from them is extremely important as they are increasingly used to guide decision-making. Hence, I investigate the opportunities and pitfalls of different data sources and methodological approaches in this work. Contextually, I aim to reveal the role of time and the mode of transportation in relation to spatial accessibility and mobility, in both urban and rural environments, and discuss their role in spatial planning.

I base my findings on five scientific articles on studies carried out in: Peruvian Amazonia; national parks of South Africa and Finland; Tallinn, Estonia; and Helsinki metropolitan area, Finland. I use and combine data from various sources to extract knowledge from them, including GPS devices; transportation schedules; mobile phones; social media; statistics; land-use data; and surveys.

My results demonstrate that spatial accessibility and mobility are highly dependent on time, having clear diurnal and seasonal changes. Hence, it is important to consider temporality when analyzing accessibility, as people, transport and activities all fluctuate as a function of time that affects e.g. the spatial equality of reaching services. In addition, different transport modes should be considered as there are clear differences between them. Furthermore, I show that, in addition to the observed spatial population dynamics, also nature's own dynamism affects accessibility and mobility on a regional level due to the seasonal variation in river-levels. Also, the visitation patterns in national parks vary significantly over time, as can be observed from social media. Methodologically, this work demonstrates that with a sophisticated fusion of methods and data, it is possible to assess; enrich; harmonize; and increase the spatial and temporal accuracy of data that can be used to better inform spatial planning and decision-making.

Finally, I wish to emphasize the importance of bringing scientific knowledge and tools into practice. Hence, all the tools, analytical workflows, and data are openly available for everyone whenever possible. This approach has helped to bring the knowledge and tools into practice with relevant stakeholders in relation to spatial planning.

Keywords: Accessibility; Spatial mobility; Spatio-temporal; Multimodal; Travel time; Open data; Social media; GIS; Data science; Data mining; Spatial planning; National parks; Finland; South Africa; Peruvian Amazonia; Helsinki Region; Tallinn;

TIIVISTELMÄ

Alueellisen saavutettavuuden ja ihmisten liikkumisen rakenteiden hahmottaminen on tärkeää yhteiskunnan toiminnan ymmärtämisessä. Saavutettavuusanalyyseistä on tullut yksi keskeisistä työkaluista alueellisen suunnittelun ja päätöksenteon tueksi. Käsitteinä saavutettavuus ja liikkuminen ovat lähellä toisiaan. Saavutettavuudella tarkoitetaan tyypillisesti ihmisten mahdollisuutta saavuttaa eri paikkoja liikkumalla, kun ihmisten liikkumisen tutkimus keskittyy toteutuneeseen liikkumiseen. Saavutettavuuden ja todellisen liikkumisen alueellisia rakenteita on tutkittu melko paljon eri ympäristöissä. Rakenteiden ajallisten muutosten huomioiminen saavutettavuus- ja liikkumistutkimuksessa on ollut paljon vähäisempää. Nykyiset massiiviset digitaaliset tietoaineistot ovat mahdollistaneet yhteiskunnan eri toimintojen tarkastelun ennennäkemättömällä tarkkuudella niin ajallisesti kuin alueellisestikin.

Väitöskirjassani pyrin kehittämään ja soveltamaan uusia lähestymistapoja sekä analyyttisia työkaluja alueellisen saavutettavuuden sekä ihmisten liikkumisen tutkimuksessa. Lisäksi pyrin ymmärtämään kuinka saavutettavuusrakenteet sekä ihmisten liikkumisen rakenteet vaihtelevat ajassa ja tilassa eri aikaperspektiiveillä ulottuen tunneista ja päivistä aina kuukausittaisiin ja vuosienvälisiin tarkasteluihin. Työni anti tieteelliseen keskusteluun on menetelmäpainotteinen, mutta tarjoan myös kontekstisidonnaisia havaintoja tutkimusalueiltani. Uusien tietolähteiden sekä menetelmien suhteen on tärkeää ymmärtää toisaalta niiden tarjoamat mahdollisuudet, mutta myös heikkoudet. Yksi väitöskirjani tavoite onkin tarkastella näitä tekijöitä eri aineistojen ja menetelmien suhteen.

Väitöskirjani koostuu johdanto-osasta sekä viidestä tieteellisestä artikkelista. Artikkelit on toteutettu erilaisissa maantieteellisissä ympäristöissä: Perun Amazoniassa, Suomen ja Etelä-Afrikan kansallispuistoissa, Tallinnassa sekä Helsingin metropolialueella.

Tulokseni osoittavat, että alueelliset saavutettavuuden ja liikkumisen rakenteet vaihtelevat merkittävästi eri ajankohtina ja niissä on selkeitä päivittäisiä ja kausittaisia vaihteluja. Ajallinen vaihtelu kohdistuu kaikkiin saavutettavuuden komponentteihin, sillä niin liikennejärjestelmä, palveluverkko, kuin ihmisten sijainnitkin vaihtelevat merkittävästi ajassa. Näiden yhteisvaikutuksesta saavutettavuus saattaa samalla alueellakin näyttäytyä eri ajankohtina hyvin erilaisena. Saavuttavuuden ajallinen vaihtelu olisikin tärkeää huomioida entistä paremmin esimerkiksi suunnittelussa. Lisäksi saavutettavuuden alueelliset rakenteet näyttäytyvät hyvin erilaisina riippuen siitä, millä kulkutavalla saavutettavuutta mallinnetaan. Autoilijan saavutettavuustodellisuus on toisenlainen kuin joukkoliikenteen käyttäjän. Tulokseni osoittavat, että myös luonnon dynamiikalla voi olla suuri merkitys saavutettavuuteen. Esimerkiksi Amazonian jokien vedenkorkeuden vuodenaikainen vaihtelu vaikuttaa suuresti navigoimiseen ja saavutettavuusrakenteisiin alueellisella tasolla. Liikenneverkon dynaamisuuden lisäksi myös ihmisten liike, ja ihmisten sijainnin dynaamisuus, tulisi ottaa huomioon saavutettavuusmallinnuksessa. Ihmisten vaihtelevien sijaintien tutkimus on perinteisesti vaikeaa, mutta uusilla aineistolähteillä, kuten sosiaalisella medialla, voidaan tuottaa tästä uutta tietoa. Toisaalta dynaaminen saavutettavuus on pitkälti riippuvainen kohdepisteiden, kuten palveluiden alueellisista rakenteista. Alueilla joissa liikenneverkko on melko vakiintunut, palveluiden rakennemuutoksilla saattaa olla liikennehankkeita suurempi vaikutus saavutettavuuteen. Menetelmällisesti väitöskirjani osoittaa eri datalähteiden ja menetelmien yhdistelyn tärkeyden datan spatiaalisen ja ajallisen tarkkuuden parantamisessa, yhdenmukaistamisessa, laadun arvioimisessa, ja rikastamisessa.

Lopuksi haluan korostaa tieteellisen tiedon, menetelmien ja aineistojen avoimuuden tärkeyttä, sillä sen avulla tehty työ on mahdollista saada tehokkaasti osaksi käytännön suunnittelua ja päätöksentekoa. Väitöskirjassani kehittämäni työkalut ja sen aikana tuotetut datat onkin julkaistu pääsääntöisesti avoimesti. Tämän ansiosta niitä voidaan vapaasti hyödyntää ja niiden laatua voidaan arvioida kriittisesti. Avoimuuden seurauksena työssä kehitetyt menetelmät ovat jo päätyneet osaksi käytännön aluesuunnittelutyötä.

Asiasanat: Saavutettavuus; Liikkuminen; Aika-tilallisuus; Multimodaalisuus; Matka-aika; Avoin data; GIS; Sosiaalinen media; Datatiede; Tiedonlouhinta; Alueellinen suunnittelu; Kansallispuistot; Suomi; Etelä-Afrikka; Perun Amazonia; Pääkaupunkiseutu; Tallinna

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In Helsinki, October 16th, 2017

Henrikki Tenkanen

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

Chapter I: Tenkanen, H., M. Salonen, M. Lattu & T. Toivonen (2015). Seasonal fluctuation of riverine navigation and accessibility in Western Amazonia: An analysis combining a cost-efficient GPS-based observation system and interviews. *Applied Geography* 63, 273-282.

Chapter II: Järv, O., H. Tenkanen & T. Toivonen (2017). Enhancing spatial accuracy of mobile phone data using multi-temporal dasymetric interpolation. *International Journal of Geographical Information Science* DOI: 10.1080/13658816.2017.1287369

Chapter III: Tenkanen, H., E. Di Minin, V. Heikinheimo, A. Hausmann, M. Herbst, L. Kajala & T. Toivonen (2017). Instagram, Twitter or Flickr? Assessing the usability of social media data for visitor monitoring in protected areas. *Scientific Reports (minor review).*

Chapter IV: Tenkanen, H., P. Saarsalmi, O. Järv, M. Salonen & T. Toivonen (2016). Health research needs more comprehensive accessibility measures: integrating time and transport modes from open data. *International Journal of Health Geographics* 15: 1, 23 p.

Chapter V: Järv, O., H. Tenkanen, M. Salonen, R. Ahas & T. Toivonen (2017). Dynamic cities: Spatial accessibility as a function of time. *Applied Geography (under review).*

Author's contribution

	I	II	III	IV	V
Original idea	HT, TT, MS	OJ	HT, TT, EDM	HT, PS, TT, MS	HT, TT, OJ, MS
Study design	HT, MS, TT	OJ, HT, TT	HT, EDM, TT	HT, PS, MS, TT	OJ, HT, TT, MS
Data collection	ML, HT, MS, TT	OJ, HT	HT, VH, MH, LK	PS, HT	OJ, HT, RA
Analysis	HT	OJ, HT	HT	HT, PS	HT, OJ
Visualization	HT	OJ, HT	HT, TT	HT, PS	HT, OJ, MS
Manuscript preparation	HT, MS, TT	OJ, HT, TT	HT, EDM, AH, VH, TT	HT, PS, OJ, MS, TT	OJ, HT, MS, RA, TT

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EDM: Enrico Di Minin
HT: Henrikki Tenkanen
LK: Liisa Kajala
MH: Marna Herbst
ML: Matti Lattu
MS: Maria Salonen
OJ: Olle Järv
PS: Perttu Saarsalmi
RA: Rein Ahas
TT: Tuuli Toivonen
VH: Vuokko Heikinheimo

ABBREVIATIONS

ACF	Autocorrelation Function
AIS	Automatic Identification System
API	Application Programming Interface
AROS	Amazonian Riverboat Observation System
CDR	Call Detail Record
DA	Dynamic Accessibility
ENTD	The Estonian National Topographic Database
GC	Gini Coefficient
GDP	Gross Domestic Product
GIS	Geographic Information System
GIScience	Geographic Information Science
GLM	Generalized Linear Model
GLS	Generalized Least Squares
GPS	Global Positioning System
GTFS	General Transit Feed Specification
HMA	Helsinki Metropolitan Area
IUCN	International Union for Conservation of Nature
ICT	Information and Communication Technology
LBE	Land Board of Estonia
LIDAR	Light Detection and Ranging
MFD	Multi-temporal Function-based Dasymetric (interpolation)
OSM	OpenStreetMap
PACF	Partial Autocorrelation Function
PT	Public Transport
SUD	Social media User Day
TMCZ	Transport Mode Competetiveness Zone

LIST OF FIGURES AND TABLES

1. INTRODUCTION

Our daily living environment is an inherently dynamic and complex system where everything is in a constant flux. People move, services open and close, and the ease of travel from one place to another varies according to the time of the day, season and year (Sheller and Urry 2006). Understanding how people can access places, how they actually move, and how they use space is necessary for understanding how human societies function, and for planning a good and lovable living environment. Especially in cities – the dynamic urban 'organisms' of the world (Batty 2012) – decision-makers and planners face difficult, complex and intertwined issues about urban sprawl, climate change, sustainability, equity, and efficiency, to name just a few examples (Behan et al. 2008; Bertolini et al. 2005; European Environment Agency 2006; Ewing and Cervero 2010; Lucas et al. 2016). Although the ability to tackle these questions affects billions of people living in urban areas, they remain equally relevant in more natural environments, outside the urban settlements. These areas are important not only for providing food and other resources for humanity, but also for preserving the biodiversity on our planet (Butchart et al. 2012; Laurance et al. 2012; Di Minin et al. 2013; Montesino Pouzols et al. 2014; Rodrigues et al. 2004).

One of the most important conceptual and analytical tools that can help understand the wealth of issues related to developing our urban-rural environments is the concept of ***spatial accessibility.*** Accessibility binds together issues of land-use, transportation and socio-economic aspects which all constitute factors that can either enable or hamper (planning of) a good and sustainable future (Banister and Hickman 2006; Campbell 1996; Farrington 2007; Hickman et al. 2013; Neutens 2017; Næss 2001). Accessibility can be defined in various ways (Geurs and van Wee 2004), but the first definition of accessibility, the *"potential of opportunities for interaction"* (Hansen 1959), captures the essence of how accessibility is conceptualized in this thesis. Accessibility, as a measure of opportunity, plays a key role in assessing how equitable our urban or rural environments are for different groups of people (Lucas 2012; Lucas et al. 2016; Pereira et al. 2017; Van Wee and Geurs 2011). Hence, it has long been an important conceptual tool for planning (Metzger 1996), as equity and social justice are considered as basic human rights (The United Nations 1948). Although accessibility can be analyzed with different measures, one of the most widely used, intuitive and well-functioning measures is time (Frank et al. 2008; MacEachren 1980; Neutens, Delafontaine, Scott, et al. 2012; Widener and Shannon 2014).

When combining a series of time and space units together, we reach a concept of movement (Andrienko, Andrienko, Pelekis, et al. 2008). Everything in our world seems to be on the move, as flows of people, goods, ideas, information, money, and so on, move from one place to another (Sheller and Urry 2006). ***Spatial mobility*** of individuals has, in fact, continuously increased and diversified (Banister 2011a; Bertolini et al. 2008; Hubers et al. 2008; Schwanen et al. 2008), partially due to the latest developments in communication technology (Kwan et al. 2007; Wee et al. 2013). In addition, societal developments such as urban sprawl and centralization of services to specific locations tend to increase the need to travel (Banister 1997; Behan et al. 2008; Næss 2005). Thus, we have entered into a 'mobilities paradigm' that touches and relates to various fields of research including, among others, social, technological, and natural sciences (Sheller and Urry 2006). Spatial mobility is closely linked to transportation, as moving between locations usually requires using different modes of travel such as a car, public transport or cycling. For this reason, spatial mobility is closely related to sustainability and climate change, as transportation is one of the main sources of carbon emissions and the use of natural resources and non-renewable energy (Bertolini et al. 2005, 2008; Bertolini and le Clercq 2003; Lahtinen et al. 2013; Määttä-Juntunen et al. 2011).

Spatial accessibility and mobility are closely related concepts as accessibility aims to describe the *potential for movement* (with modeling), whereas spatial mobility is *realized movement* (Hodge 1997) that can be observed, and which is inherently influenced by accessibility. Furthermore, accessibility has a considerable influence on mobilities, because good accessibility (shorter travel time / distance) tends to increase the interaction between places (due to the first law of geography; Tobler, 1970). In turn, understanding the spatial mobility of people may also affect the accessibility. For instance, new public transport connections may be added to routes that are widely used by people, and the demand (need to travel) is higher than the supply, i.e. the level of service of public transport (Bresson et al. 2003; Rahman and Balijepalli 2016).

Time has a profound role not only in nature, but also in how societies function. Furthermore, it has a significant impact on spatial accessibility and mobility. The dynamics of nature have a profound effect on when and where people conduct activities and how transportation operates (the effect of seasonality; summer, winter, etc.). For instance, the seasonal dynamics of rivers have a direct effect on the navigation and spatial movement patterns in fluvial riverine systems of Amazonia (Salonen et al. 2012). Cities are also highly dynamic and complex systems that have a 'pulse' (Batty 2010; Vaccari et al. 2010): The functionalities and rhythm of the city, including accessibility and mobility, are fundamentally affected and constrained by time as the locations of people, the transportation system and services change constantly (Hägerstrand 1970; Neutens et al. 2007). The dynamics of our contemporary world have increased and become more flexible as we have moved towards 24-hour societies (Glorieux et al. 2008; Hubers et al. 2008), in which people work in shifts, and services are open also during the night. Being able to understand and describe these complex and dynamic realities of our living environment requires a vast amount of data from various sources.

Knowledge-based planning and decision-making are requirements for developing environments that are good both for the humans and for the environment (Geertman and Stillwell 2004; Knight 1995; Krizek et al. 2009; Wilkins and desJardins 2001). Spatial accessibility and mobility analyses have become increasingly important conceptual and computational tools for providing relevant information and knowledge for planners and decision-makers about urban structures and spatial interactions (Geurs et al. 2010; Martín and van Wee 2011; van Wee 2011). Achieving such planning and decisions that would be driven by knowledge requires appropriate and sophisticated data, tools and information that are openly accessible, and easy enough to use and understand in practice (Bertolini et al. 2005; Curtis and Scheurer 2010). A prerequisite for producing such tools and knowledge is to have high-quality and up-to-date data that can realistically describe the environment (Goodchild 2013; Lazer et al. 2014). Hence, it is of paramount importance that data and tools are carefully validated, and that they are as transparent as possible.

The latest revolution in measurement has brought us to the beginning of a data revolution and the fourth paradigm in science that is driven by data and is exploratory by nature (Hey et al. 2009; Kitchin 2014a). Developments in information and communication technologies (ICT) have dramatically improved our capability to analyze various social and natural phenomena as ubiquitous digital devices are continuously and in real time gathering and producing vast amounts of data. This unprecedented ‘data avalanche’ (Miller 2010), commonly referred to as ‘big data’ in academia and industry (boyd and Crawford 2011; Kitchin 2013), has played a key role in enabling researchers to study the dynamics of our living environment from various perspectives including transportation, human–environment interactions, and social dynamics and interactions (e.g. Batty 2013; González et al. 2008; Grauwin et al. 2017; Hawelka et al. 2014; Järv et al. 2015; Järv, Muurisepp, et al. 2014; Lazer et al. 2009; Li et al. 2016). These advances have also significantly affected how geographical research is conducted, leading to a more ‘data-driven geography’ (Miller and Goodchild 2015).

The most significant change from the earliest computational models developed for describing e.g. urban structures (Batty 1971; Forrester 1969) is the level of detail provided by new available data sources in both spatial and temporal terms. Whereas the early models and data allowed the analysis of the dynamics of our living environment on a yearly basis with a coarse spatial resolution, modern data sources and tools have enabled analyses in very fine detail (scales ranging from seconds to years, centimeters to global level analyses). These new data sources, which have become increasingly open (in availability), and the significant methodological advances in data science and Geographical Information Science (GIS), enable us to understand various (spatial) phenomena better than ever before, hence contributing to better decisions and plans. However, there are also various challenges, limitations, biases and ethical issues in using big data that need to be understood and considered when using such data (Frank 2007; Goodchild 2013; Lazer et al. 2014; Zook et al. 2017).

The aforementioned themes serve as the foundation of this thesis, in which I aim to contribute by bringing knowledge about the influence of time on spatial structures of accessibility and mobility. The aims of these studies, and their intertwined contribution to my thesis, are both methodological and contextual, and can be distributed into four main objectives:

Objectives:

a. Methodologically, I aim to advance the methodological frameworks and develop practical tools for incorporating time into analyses of spatio-temporal accessibility and mobility including different travel modes, and

b. to develop and apply methods for enhancing and assessing the spatio-temporal "quality" of spatial mobility data from mobile phones and social media.

c. Contextually, I aim to reveal the role of time, natural dynamics and mode of transportation in spatial accessibility and mobility patterns in urban and rural environments, and

d. to discuss how a more comprehensive understanding of spatial accessibility, mobility and people's use of space could benefit spatial planning in different domains.

I study these questions in five scientific articles, conducted in four countries on three continents, covering Peruvian Amazonia in South America; national parks of South Africa; the capital of Estonia, Tallinn; Finnish national parks, and the Helsinki metropolitan area in Finland:

Chapter I aims to understand the spatio-temporal accessibility realities in Western Amazonia, where transportation is based on navigation along dynamic rivers. We studied how the river dynamics affects the accessibility in our study area by analyzing GPS-based mobility data of river boats using a dedicated observation system and mobility data mining methods. Furthermore, we aimed to understand the perceptions of the seasonal changes in navigation and the accuracy of transportation schedules by interviewing local passengers.

Chapter II focuses on developing a methodological framework and practical tools for enhancing the spatial accuracy of mobile phone data by considering land-use patterns and the dynamics of typical movement behavior in city areas. Furthermore, we test and compare the performance of our *multi-temporal function-based dasymetric interpolation method* against the simple areal weighting interpolation commonly used in mobile phone based research.

Chapter III investigates and aims to reveal the dynamics of natural area visitation in South Africa and Finland based on observed data from social media covering three platforms, namely Instagram, Twitter and Flickr. We compare the different platforms to each other and test which one performs the best for revealing the popularity of the parks and the monthly visitation patterns when compared against official visitor statistics that serve as the ground-truth data. Furthermore, we aim to identify different factors that affect where social media data correlates better with the visitation patterns, and where not.

Chapter IV aims to understand how time and mode of transport affect the spatio-temporal accessibility to healthy food in Helsinki metropolitan area. We use comparable accessibility measures to model and analyze travel times to the closest grocery stores by public transport and private car, and reveal how time and mode of transport affect the accessibility patterns. We also identify openly available data sources and tools that can be used for spatio-temporal accessibility analyses. Furthermore, the implications of excluding temporality and focusing only on a single travel mode in accessibility analyses are discussed in relation to health research.

Chapter V introduces a comprehensive framework for dynamic accessibility modeling, in which all the components of accessibility are included and considered as a function of time, i.e. people, transport and activity locations (e.g. services). We conduct a systematic empirical case study in Tallinn, Estonia, where we reveal the effect and significance of temporality on all components by comparing them to a static accessibility model. Analyses are conducted on an hourly basis, hence revealing the temporal dynamics within a single day. The study combines modeled accessibility analyses to reveal the level of access to grocery stores, and spatial mobility analyses (applying the model presented in Chapter II) that reveal the whereabouts of people for each hour of the day based on mobile phone data.

Although all the Chapters above are related to each other, Chapters I-III are more related to analyzing the spatial mobilities and whereabouts of people, whereas Chapters IV and V are more related to dynamic accessibility modelling.

2. FRAMEWORK OF THE RESEARCH

2.1 Positioning the research

An understanding of the dynamics of our living environment cannot be achieved using a single perspective. Hence, in terms of both theory and methods, this thesis is inherently interdisciplinary and transdisciplinary. The thesis touches upon various fields of science, while also involving practitioners from different domains, as the tools and data have been evaluated and put into practical use by planners and other stakeholders. Traditionally, issues of ***accessibility*** have played a key role in studies focusing on spatial interaction, thus concerning e.g. transportation, planning, land-use modeling, and spatial economics. Different domains of geography, such as time geography and transport geography, have been central in developing concepts of accessibility, whereas Geographical Information Science (GIScience) has been instrumental for developing the methodological frameworks and tools for analyzing accessibility. Various subfields of geography, including urban geography, planning geography, health geography, economic geography, and fields such as sustainability science, and (spatial) conservation science (and planning) make active use of tools and concepts related to accessibility.

Understanding the ***spatial mobility*** of people is closely related to accessibility, and for this reason, the issue relates closely to the fields listed above. However, as the analysis of travel behavior requires advanced techniques, and the data is often owned by telecommunication companies, studies of spatial mobility have also been conducted by researchers from fields such as engineering, data / computer science, and physics, who have conducted large-scale analyses and developed theories about human mobilities and interactions based on big data sources, such as mobile phone data or social media data.

My thesis touches upon questions and approaches of several fields of science considering the interdisciplinary nature of accessibility and mobility studies (Figure 1). As the broad aim of the thesis is to develop and apply dynamic and multimodal accessibility and mobility tools, it requires the use of a fusion of various methodological approaches and data, in order to improve our knowledge and capability to support spatial planning and decision-making. Therefore, the thesis touches upon different domains from a technological perspective (covering GIScience / data science techniques), while the methods applied in this thesis draw on spatial planning, covering domains of health geography, conservation science and urban planning.

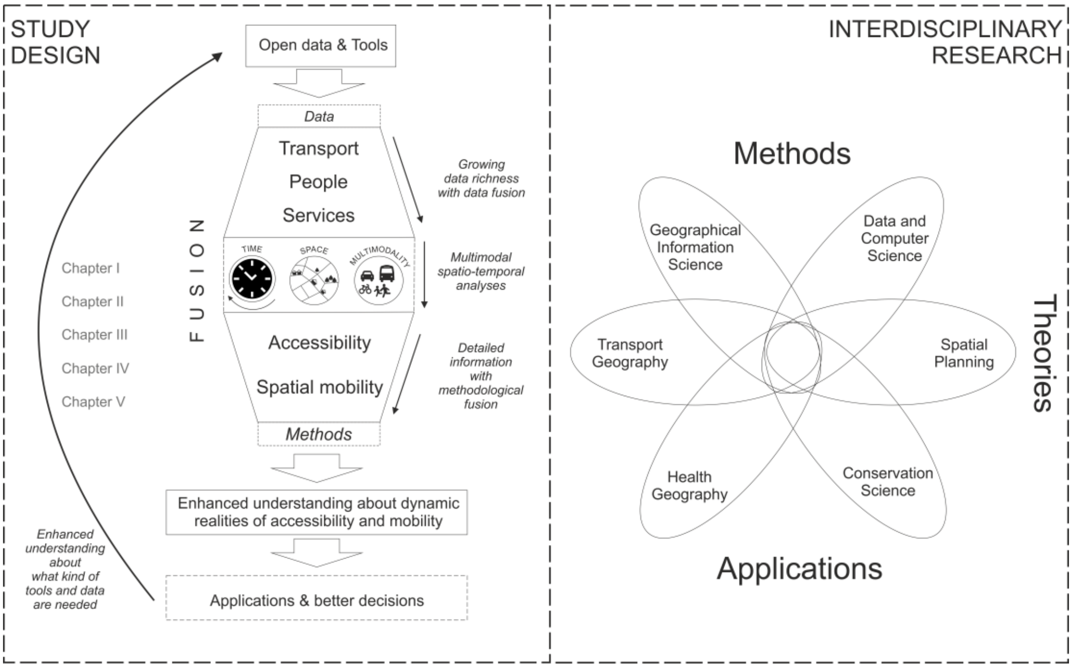

Figure 1. Study design and the fields of research that are touched upon in this thesis. Increased understanding about the dynamic realities of accessibility and mobility can be achieved with data and methodological fusion that can feed to better decisions and practical applications.

2.2 Diverse ways to comprehend accessibility

Accessibility, or the ease of accessing places, is a fundamental concept that influences people's everyday life and decisions (Hägerstrand 1970; Kwan 2013; Kwan and Weber 2003; Miller 1999). Accessibility can even be considered as a universal human right, as the needs and rights to access e.g. health care, education, work and social interaction belong to everyone (Farrington 2007). In more practical terms, accessibility is widely recognized as a highly useful and important conceptual and methodological tool for understanding and describing the spatio-temporal structures of our living environment (Batty 2009; Geurs and van Wee 2004; Martín and van Wee 2011; Scheurer and Curtis 2007; Silva et al. 2017).

Definitions: As a concept, accessibility is rather confusing due to its many definitions, and its precise meaning depends on the perspective adopted by the study in question. Hence, researchers define accessibility in various ways, but the definitions most relevant to the current study are: *"the potential of opportunities for interaction"* (Hansen 1959); *"the degree to which two places (or points) on the same surface are connected"* (Ingram 1971); *"the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)"* (Geurs and van Wee 2004); and *"the amount and the diversity of places of activity that can be reached within a given travel time and/or cost"* (Bertolini et al. 2005).

Components: Theoretically, accessibility can be conceptualized and operationalized in various ways, as the meaning of the concept depends on the perspective. Geurs and van Wee (2004) identify four components that construct accessibility: i) land-use, ii) transportation, iii) temporal, and iv) individual components. In this thesis, I consider the land-use component reflecting the number and distribution of services; the transportation component reflecting the transportation system considering time and transport mode; and temporal component reflecting the temporal constraints that restrict the access to services, such as the opening hours of businesses. Although the individual component (reflecting the individual's needs, abilities, and opportunities) is not included in the analyses, it is also discussed in the chapters.

Measures: Accessibility can be measured in many ways: earlier studies have often measured accessibility using a metric Euclidian distance between locations, whereas nowadays the majority of studies consider distance as a function of time. Time is considered a more intuitive and comprehensible measure (Frank et al. 2008; MacEachren 1980; Olsson 1965), and for this reason, it is used as a measure of distance throughout this thesis. Furthermore, accessibility can be classified into i) place-based, ii) person-based, iii) infrastructure-based, and iv) utility-based measures (Geurs and van Wee 2004). This thesis focuses mainly on place-based measures, in which accessibility is evaluated from the perspective of a location (describing, for instance, how many people can reach a given location within 30 minutes). However, also person-based measures, describing an individual's movements or how s/he is able to access locations (originating from time geography; Hägerstrand 1970), are considered, when accessibility is derived from spatial movements. Furthermore, infrastructure-based measures (reflecting e.g. the level of congestion) are considered from a methodological perspective. Accessibility can be further categorized into three broad classes of indicators (Páez et al. 2012): cumulative opportunities, gravity-based (e.g. Huff's model, 1963), and utility-based. From these categories, I only consider cumulative opportunities by exploring the amount of population that can reach specific services within a certain time-limit (place-based approach).

Interplay with mobility: Spatial mobility, traditionally referring to a geographic displacement of entities along a trajectory that can be described in terms of space and time (Andrienko, Andrienko, Pelekis, et al. 2008; Kaufmann et al. 2004) is an inherent part of all societies. 'Being mobile' has turned into an ideology in the contemporary world, in which the ability to move in spatial, temporal and social dimensions can be considered as a new form of capital (Kaufmann et al. 2004; Kellerman 2012; Urry 2007). It is important to note that the movements of an individual and the ability to move (person-based accessibility), and place-based accessibility are, in fact, highly interrelated concepts, as accessibility is as much about people as it is about places (Farrington 2007; Moseley 1979). Hence, spatial mobility (as a measure of behavior) may be conceptualized as a realization of accessibility (fundamentally a measure of potential; Hodge 1997), which defines how I approach the concept of spatial mobility in this thesis. However, I recognize a broad spectrum of research conducted in relation to mobilities from social and spatial perspectives, ranging from mobility data mining to theories of human interaction and segregation studies (e.g. Ahas et al. 2010; Cass et al. 2005; Dodge et al. 2012; González et al. 2008; Grauwin et al. 2017; Hawelka et al. 2014; Järv, Ahas, et al. 2014; Järv, Muurisepp, et al. 2014; Sheller and Urry 2006; Urry 2007).

2.3 Accessibility as an instrument to understand the spatial dynamics of society

Early attempts to systematically describe and model the structures of our environment and how our societies function date to more than 50 years ago (Crecine 1968; Forrester 1969; Lowry 1964), in which accessibility already played an important role. Lowry's model of the metropolis (Lowry 1964) was probably the first model that aimed to understand the spatial organization of human activities within the city of Pittsburgh, which also accounted for accessibility. Lowry's model was developed to help decision-makers to assess the impacts of their decisions on the transport system and the employment and growth of population, in which (static) accessibility was still measured as Euclidian distance between home and destinations. Acknowledging the limitations of a static model, the first dynamic models were introduced shortly afterwards (Batty 1971; Crecine 1968; Forrester 1969), arguing about the importance of incorporating time into mathematical models describing urban structures (Figure 2). However, the difficulty of collecting spatially and temporally sensitive data to feed the dynamic urban models presented a considerable obstacle, hampering the ability to assess the models and results (Batty 1971).

In recent years, the improved availability of high-quality data and sophisticated analytical tools has enabled us to move from simple metric accessibility measures to time-based measures (Salonen et al. 2012), while also affording an increased level of spatial and temporal detail. For this reason, the number of studies incorporating temporality into place-based accessibility analyses has increased steadily. Spatio-temporal accessibility patterns have been studied, for example, in relation to food (e.g. Farber et al. 2014; Horner and Wood 2014; Luan et al. 2015; Widener et al. 2013, 2015, 2017; Widener and Shannon 2014); health (e.g. Jamtsho et al. 2015; Schuurman et al. 2015); spatial equity or efficiency of the transport system (e.g. Kawabata 2009; Stępniak and Goliszek 2017; Tribby and Zandbergen 2012); and sustainability (e.g. Salonen et al. 2016; Zahabi et al. 2015). In addition, the availability and creative fusion of data from multiple sources have increased the number of studies incorporating multimodality in accessibility analyses, covering similar themes to those listed above (e.g. Dewulf et al. 2015; Jäppinen et al. 2013; Lubamba et al. 2013; Salonen et al. 2014, 2016; Salonen and Toivonen 2013). These examples demonstrate our enhanced capability to capture and systematically analyze the dynamics of urban and rural environments better than ever before. My thesis contributes, and provides a step forward in these contemporary trends in accessibility research.

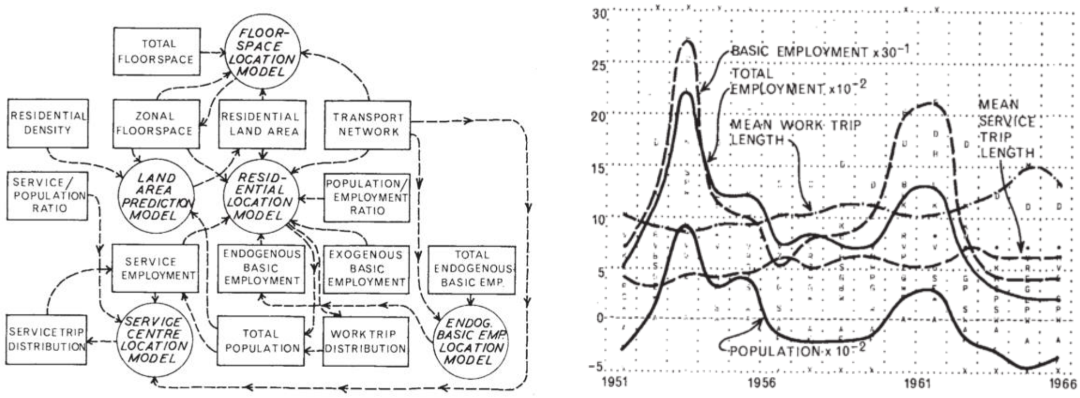

Figure 2. Components of the simulation model (left), and the temporal changes in accessibility and socio-economic factors (right) aimed at describing the dynamic realities of a city, introduced by Michael Batty in his article “Modelling cities as dynamic systems” (1971). These graphs include various similar aspects that we have included and considered in our methodological frameworks concerning dynamic accessibility modeling (Chapter V) and when enhancing the abilities to understand the mobilities of people in urban areas based on mobile phone data (Chapter II). Figures were adopted from Batty (1971).

2.4 Extracting knowledge from (big) spatial data with GIS and data science methods

Our improved capability to analyze the dynamics of our living environment is closely linked to the methodological developments in different fields such as Geographical Information Science (first coined by Goodchild 1992), (geo)statistics, and computer / data science, which have been driven forward by the emergence of detailed, up-to-date, and content-rich data sources. By being a methodologically-oriented thesis, this work touches upon various problems, techniques, data, and modeling approaches in Geographic Information System (GIS) and data science. Although including rather technical aspects, I would say that this thesis represents “data-driven geography”, a term which was recently coined by Miller and Goodchild (2015). Hence, this thesis emerges from applied and problem-based science that attempts to find answers and develop solutions to understand topical geographical questions that are rooted in different theories and concepts (such as the ones presented earlier), applying both inductive and deductive reasoning (Hempel 1966).

Big data: Geographical research, as any other field of science, has evolved in relation to the societal, environmental and technological trends that shape the thinking of people, and enable us to conduct science in a way that was impossible or more difficult earlier. One such trend in past years has been the data revolution (Kitchin 2014a, 2014b), and the emergence of vast quantities of ubiquitous data (Hotho et al. 2010), commonly referred to as 'big data'. Similar to the concept of accessibility, big data is also a rather confusing construct having multiple different definitions. Most common definitions refer to the 3Vs: it is i) huge in volume (tera-, or petabytes of data), ii) high in velocity (created in, or near real time) and iii) diverse in variety, including different types, and structures of data, which are often spatially and temporally referenced. However, recent literature recognizes a number of other key characteristics, with big data being exhaustive in scope; fine-grained in resolution; relational in nature; and flexible and scalable in nature (Kitchin 2014a).

Semantic and linked web: The rapid growth of big data is closely linked to the emergence of Web 2.0 and the semantic web (Berners-Lee 1999; Decker et al. 2000; Kitchin 2014b; O'Reilly 2005) that made two important changes to how the World Wide Web has functioned since the early 2000s. First, it allowed people to not only read and receive data from the web, but also to actively produce content themselves (followed by the emergence of social media). Secondly, it made the web machine-readable by encoding and structuring the wealth of data on the web using unique identifiers and a mark-up language, such as XML or a data-interchange format such as JavaScript Object Notation (JSON), which made it easy for computers to read and generate automatically. These developments have been a prerequisite for the rapid spread of Application Programming Interfaces (APIs) that have a central role in relation to the opening of data (i.e. open data), and how modern web and mobile software applications function. APIs enable different systems to communicate with each other, which allows the harvesting, merging and mixing of data from various sources together. These technological developments have had a considerable role e.g. in the emergence of social media research, and data science in general, as scientists are able to collect data using the APIs, which can be further processed into knowledge with various state-of-the-art techniques of modern (geo)data science. These technological developments have had a considerable role e.g. in the emergence of research using novel data sources (such as social media data), as scientists are able to collect data using the APIs, which can be further processed into knowledge.

Developments in GIScience: It is argued that 60-80 % of the data in the world is geographically referenced (Hahmann and Burghardt 2013). Being able to understand and draw conclusions from such big (geo)data, and to assess the quality of it (Goodchild 2013; Li et al. 2016) requires sophisticated, scalable and flexible approaches (Li et al. 2016) that have been in an active development in geoinformatics, including spatial data mining and geographic knowledge discovery (e.g. Giannotti and Pedreschi 2008; Mennis and Guo 2009; Miller and Han 2009; Shekhar et al. 2011); spatial statistics (e.g. Anselin and Getis 1992; Fortin et al. 2012; Griffith 2012; Rey and Anselin 2009); (geo)visualization (e.g. Andrienko et al. 2007; Dodge et al. 2008; Keim et al. 2008; Tsou and Leitner 2013; Vaccari et al. 2010); and Geographic Information Systems (see an overview from De Smith et al. 2007). Furthermore, developments in computer and data science, considering especially the advances in parallel and distributed computing (e.g. Assuncao et al. 2015; Leskovec et al. 2014) have had a key role in enabling large-scale analyses with big data. This is due to the fact that large-scale computational jobs can be distributed to hundreds or thousands of cores/nodes using e.g. cluster-computing frameworks such as Apache Hadoop or Spark; high performance computing (HPC) clusters with SLURM (work-load manager/scheduler); GPU-accelerated geocomputing e.g. with MapD; or cloud computing environments such as OpenStack.

Accessibility modeling: Spatio-temporal accessibility modeling and (mobility) data mining are in the core of this thesis from the methodological perspective. Accessibility modeling is closely linked to transportation research utilizing techniques and principles of GIS, and is hence sometimes referred to as Geographic Information Systems for Transportation (GIS-T; Miller and Shaw 2015). The most relevant GIS-T technique incorporated in this work is network analysis (especially shortest path estimation; Dijkstra 1959) that originates from graph theory, which was problematized as early as 1736 by Leonhard Euler (Baraba´si 2002; Biggs et al. 1986). In transportation modeling, one track of research is to use activity-based analysis incorporating microsimulation, such as agent-based models, to estimate e.g. traffic demand and conduct traffic forecasts at specific parts of the street network (e.g. Balmer et al. 2006). In this thesis, however, I exclude such detailed-level modeling approaches, as the objective here is to understand and reveal the spatio-temporal accessibility patterns from a more regional perspective. Accessibility modeling can be divided into person-based (or individual-based) and place-based models, in which the former utilizes ideas from time geography, such as the space-time prism (Delafontaine et al. 2011; Hägerstrand 1970; Kwan 1998; Miller 1991; Miller and Wu 2000; Neutens et al. 2007; Wang and Cheng 2001; Wu and Miller 2002), whereas the latter typically incorporates a more spatial approach to examine larger-scale patterns. In this thesis, I use place-based accessibility models, although Chapters I and III touch upon principles of person-based analysis from a methodological perspective (incorporating e.g. the space-time cube for data quality assessment; see Tenkanen et al. 2014). There exist a wide array of accessibility tools and instruments that have been developed during the last decade (see Bro¨mmelstroet et al. 2014 and Papa et al. 2015 for an overview), in which ours are focused on comparable multimodal spatio-temporal time-based accessibility models considering the whole travel-chain using the so-called door-to-door approach (see 4.2).

Mobility analysis: Web 2.0 has dramatically increased the amount of person-based data as individuals have got a significant new role in the data production. Goodchild (2007) considers individuals as 'citizen sensors', referring to people who actively observe their environment, and voluntarily share their experiences and observations e.g. via social media. To extract knowledge from a wealth of spatial data generated with different devices or platforms such as GPS, mobile phones, or social media, it is required to incorporate different data mining methods combined with spatial analytics. This knowledge extraction process is sometimes referred to as geographic knowledge discovery (Laube et al. 2005; Mennis and Guo 2009; Miller and Han 2009; Tenkanen et al. 2014) or mobility data mining (Giannotti and Pedreschi 2008) when extracting knowledge from moving point objects (Dodge et al. 2009; Laube et al. 2005; Laube and Imfeld 2002). A variety of techniques and principles exist to extract knowledge based on mobile phone data, such as Call Detail Records (see e.g. Ahas et al. 2010, 2012; González et al. 2008; Grauwin et al. 2017; Järv, Ahas, et al. 2014), GPS-data (see e.g. Bar-Gera 2007; Demšar et al. 2015; Laube et al. 2005; Tenkanen et al. 2014; Zheng 2015), and social media data (see Steiger, de Albuquerque, et al. 2015 for a review). These approaches are extensively exploited throughout this thesis, and developed further.

2.5 Geographical and temporal scope

This thesis covers a wide range of study settings in terms of both spatial scale and temporal granularity. They range from spatially detailed and hourly-based analyses in the urban capital regions of Helsinki and Tallinn, to yearly, seasonal, and monthly-based analyses with coarser spatial scales in rural areas of Peruvian Amazonia, South Africa and Finland. Furthermore, the study regions differ significantly in their cultural, socio-economic, and natural characteristics, as well as in their transportation and the adopted level of information and communication technology. These versatile study areas provide an exciting setting for conducting spatio-temporal and multimodal accessibility and mobility analyses (Figure 3) from the methodological perspective.

Urban context: Chapters II and V are conducted in Tallinn, which is the capital and largest city in Estonia, with approximately half a million inhabitants living in the metropolitan area. Tallinn has developed rapidly since Estonia regained its independence in 1991. The city is experiencing considerable changes in its socio-economic and urban structure, which date from the Soviet period (Kährik et al. 2011; Kährik and Tammaru 2008; Tammaru 2005; Tammaru et al. 2009). Tallinn was chosen as a case study region due to the availability of appropriate data for dynamic hourly-based accessibility modeling in Paper V (most importantly, the public transport schedules in GTFS format) and mobile phone data, which was required for developing the interpolation model in Paper II and for studying the spatial population dynamics as a part of the dynamic accessibility model in Paper V.

The capital region of Finland, Helsinki Metropolitan Area (HMA), is the study area for Chapter IV. This region provides an interesting setting for multimodal spatio-temporal accessibility analyses, because it has one of the world's best public transport systems (Curtis and Scheurer 2015), but the dominant daily travel mode in the area remains the private car (HRT 2013). HMA was chosen as a site for research because the methodological development of the GIS tools for analyzing accessibility by public transport and private car in a comparable manner was conducted at the same location. For HMA, we also had access to high-quality open data sources that were instrumental to the aforementioned development. Furthermore, we have a good contextual knowledge of the study region, which provided significant benefits for understanding our results and the accuracy and quality of the developed tools.

Rural context: The Loreto and Ucayali regions in northeastern Peru (Western Amazonia) and the South African and Finnish national parks constitute a more rural spatial setting (i.e. outside urban areas) for the case studies in Chapters I and III. Peruvian Amazonia was chosen as a study area in Chapter I because this location provides an exciting setting for accessibility analysis, as transportation is mainly based on riverine transportation due to the lack of a road infrastructure. The area is characterized by an extensive and dynamic fluvial system where the seasonal variation in water level can exceed 10 meters, hence influencing significantly the dynamisms of natural habitats and human livelihood (Abizaid 2005; Puhakka et al. 1992; Salo et al. 1986). The study focuses on studying access to the city of Iquitos, an important center of commerce, which holds the dubious distinction of being the world's biggest city without a road connection to the rest of the world (Gill 2015).

Chapter III studies visitation patterns in South African and Finnish national parks. Nature-based tourism in protected areas attracts both national and international tourists in both countries, which is significant for producing financial, political and social support for protected area management and conservation. These countries were chosen because (i) they differ substantially as nature-based tourism destinations and attract a variety of tourist markets, and (ii) we had access to official visitor statistics of all national parks in both countries via the park authorities (SANParks in South Africa and Metsähallitus in Finland). Additionally, we had a good background knowledge of the various environmental and societal aspects in both countries due to our personal knowledge and that of our collaborators, which helped to understand the results of the extensive research, which covered altogether 56 national parks.

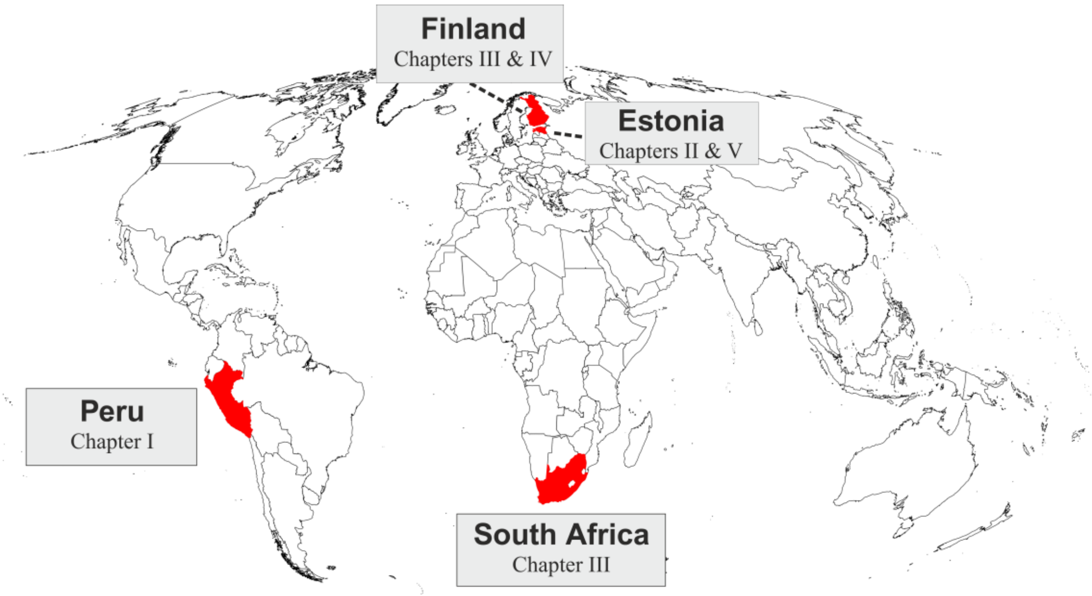

Figure 3. Study areas of the thesis in Europe, South America and Africa.

3. DATA

In this thesis, I utilize a wide array of spatial data from a variety of sources that are either static or dynamic, and which can be further classified into observed and modeled data. Observed data includes datasets that have been generated by different sensors or mobile devices, whereas modelled data considers datasets that have been in one way or another created via modeling, aggregation, or by combining observed and modeled data together.

3.1 Accessibility data

I use several transport-related data sources: most importantly, I utilize public transport schedules and network data, and GPS data (see 3.1) to analyze spatial accessibility patterns in different regions (Table 1).

In Chapters IV and V, we used openly available public transport data in two different data formats, namely Kalkati XML (in Helsinki Metropolitan Area) and General Transit Feed Specification (GTFS) in Tallinn, Estonia. Kalkati and GTFS are data standards providing information about public transport timetables, routes, and stops that were used to estimate travel times between origin and destination locations using the modified Dijkstra's (1959) algorithm. Dijkstra's routing algorithm was used to find the optimal (fastest) travel routes between departure and destination locations considering different (public) transport modes (see 4.2). Furthermore, we used OpenStreetMap (OSM) data (a global road network dataset) to estimate the walking parts in public transport routing.

In Chapter IV, we utilized high-quality national road network data (Digiroad) for routing with a private car which was modified to consider the decelerating effect of traffic at different times of the day. This modified and enriched road network, called *MetropAccess-Digiroad*, includes drive-through times (impedance values) for each road segment during the rush-hour and midday in Helsinki Metropolitan Area (HMA). Impedance values were calculated according to speed limits that were adjusted according to GPS observations from floating car measurements (capturing the decelerating effect of traffic) to give more realistic driving times (Salonen and Toivonen 2013; Tenkanen et al. 2016; Toivonen et al. 2014).

Table 1. Data sources that were used for spatio-temporal multimodal accessibility analyses.

Dataset	Purpose	Open	Coverage	Resolution	Applied in	Source
MetropAccess-Digiroad	Modified road network for car routing considering congestion levels.	Yes	Helsinki metropolitan area	Rush-hour / midday	IV	Accessibility Research Group / Finnish Transport Agency [(a)]
Open-Street-Map	Street network for routing by walking.	Yes	Global	Static	IV; V	OpenStreetMap [(b)]
Kalkati XML	Public transport schedules, routes and stops	Yes	Finland	Minute based schedules in 30-day chunks	IV	Helsinki Region Transport [(c)]
General Transit Feed Specification (GTFS)	Public transport schedules, routes and stops	Yes	Global	Minute based schedules in 30-day chunks	V	Transitland [(d)]

[a] blogs.helsinki.fi/accessibility/data/metropaccess-digiroad; [b] www.geofabrik.de [c] developer.reittiopas.fi/; [d] transit.land

3.1 Mobility data

To study the spatial mobility, I considered data from three sources: GPS devices, mobile phones and social media, which are rather different in their temporal (granularity) and spatial characteristics (level of detail); see Table 2.

In Chapter I, we incorporated GPS-based observations about the movements of river boats in Peruvian Amazonia. The data was collected with GPS-based satellite messengers (see Figure 4) that constructed a dedicated riverboat observation system that was developed for our study. Our observation system covered five to seven different vessels navigating along the Amazonian rivers (to/from the city of Iquitos) that were owned by three different transportation companies operating in the area. The GPS observations were analyzed with dedicated mobility data-mining methods to understand the variation in travel speeds during different seasons, which were further generalized into spatio-temporal movement patterns.

In Chapters II and V, we incorporated Call Detail Record (CDR) data collected from mobile phones to reveal the whereabouts of people (in space and time) in the city of Tallinn, Estonia. CDR data is passively collected (Ahas et al. 2010): only such mobile phone activities that can be billed by an operator are captured (such as text-messages, calls, internet usage). The spatial accuracy of CDR data was on the level of base station (n=290). Since the spatial distribution of mobile network base stations is not equally distributed in space (cell size varies in different parts of the city), it was required to enhance and harmonize the spatial accuracy of the CDR data (Chapter II) with ancillary data sources (such as travel surveys, land-use data, and information about buildings) to use it as a proxy for human presence (population density), which varies in space and time (Chapter V).

Table 2. Data sources that were used for spatio-temporal mobility analyses to understand the whereabouts of people and professional vessels.

Dataset	Purpose	Open	Coverage	Resolution	Applied in	Source
Mobile phone data (Call detail records)	Analyzing the spatial mobility of people in Tallinn.	No	Tallinn	Hourly at base-station level	II; V	Positium Ltd. [(a)]
GPS-data	Analyzing the spatial mobility of professional vessels in Peru	No	Peruvian Amazonia	10-min interval at accuracy of GPS	I	SPOT Satellite Messenger System [(b)]
Instagram	Analyzing the visitation patterns in Finland and South Africa	Yes*	Global	Real time at place-tag accuracy	III	Instagram API (REST) [(c)]
Twitter	Same as above	Yes	Global	Real time at GPS level or place-tag accuracy	III	Twitter API [(d)] (Streaming)
Flickr	Same as above	Yes	Global	Real time at GPS level or place-tag accuracy	III	Flickr API [(e)] (REST)

* Open access to Instagram API was restricted in June 2016;
[a] www.positium.com; [b] www.findmespot.eu/en/; [c] www.instagram.com/developer/; [d] dev.twitter.com/;
[e] www.flickr.com/api

In Chapter III, we incorporated social media data from three platforms, namely Instagram, Twitter and Flickr. Social media data were collected using the Application Programming Interface (API) provided by the platforms. The data was used as a proxy for human presence in the national parks of Finland and South Africa. Social media data can be used to estimate the presence and movements of individual users since it includes meta-data about the location (coordinates) where the post was taken (or uploaded from) and the timestamp showing when the post was created.

3.2 Origin–destination data

In Chapters IV and V, we analyzed travel times between selected origin and destination locations. As origin locations, we applied surrogates representing people's locations at different times of the day: in Chapter IV we used a static night-time population of HMA based on statistical grid cells at 250×250 meter spatial resolution provided by Statistics Finland, whereas in Chapter V, we incorporated spatially and temporally varying population densities in Tallinn at 500×500 meter spatial resolution based on mobile phone data (see 3.1). As destination locations, we considered open grocery stores at specific times of the day in both Chapters IV and V. Opening hours and locations of the grocery stores were retrieved from the websites of the stores. However, only stores that provide a full selection of food products were considered (excluding gas-stations, kiosks etc.).

3.3 Validation and ancillary data

In addition to data which is directly linked to accessibility or mobility analyses, I used various supportive datasets in Chapters I–III to (i) assess the quality of the data (or analysis), or to (ii) enrich the data or analyses to better understand the studied phenomena.

In Chapter I, we incorporated daily water level statistics (SEHINAV 2014) from four measurement points including the most important rivers for navigation in our study area, Peruvian Amazonia. Furthermore, we included a travel survey (n=76) that was conducted on board our collaborative riverboats, to enrich our analysis by asking how local people perceive the realities of traveling in our study area.

In Chapter II, we incorporated various ancillary data sources to enhance the spatial accuracy of the mobile phone data, and to assess the quality of our methodological approach (see Table 3). We included different land-cover, building and human activity data to create and implement an advanced interpolation method that takes mobility data (such as mobile phone or social media data) representing a surrogate for human activities / presence as input data, which is interpolated (see 4.3) into predefined statistical target zones (such as 100 m or 500 m grid cells). In addition, we used population registry data to assess the representativeness of our interpolation method (see 4.4).

In Chapter III, we used statistical information from national park authorities in Finland (data from Metsähallitus) and South Africa (data from SANParks) to assess the performance of social media data for estimating the monthly visitor numbers in 56 parks during the year 2014. In addition, we conducted semi-structured group discussions with the national park authorities in both countries, which were held during three separate workshops (one organized in Finland, and two in South Africa).

Table 3. Ancillary datasets used to enhance and harmonize the spatio-temporal population distribution layer used in Chapter V. Adapted from Chapter II.

Dataset	Attributes	Source	Date
Land-cover data	Land-cover parcels with classification (polygon)	Estonian National Topographic Database (ENTD), Land Board of Estonia (LBE)	2015
Building data	1. Building footprints (polygon) with binary usage classification (residential and public; other)	ENTD, LBE	2015
	2. Building heights based on LIDAR measurements with 1m accuracy (raster)	nDSM data, LBE	2013
	3. Building functionality based on crowdsourcing input on building usage (point) for refining building usage classification	OpenStreetMap Database (OSM)	2015
Human activity data	The average hourly distribution of people by activity type based on cross-sectional time use survey study	Estonian Time Use Survey, Statistics Estonia	2010
Population register data	Residential population data at building level which is aggregated to both target zones (100 m & 500 m grid cells)	Population registry data, Tallinn municipality	2015

4. METHODS

In this thesis, multiple dedicated tools were developed and applied in each step of the (typical) analysis process including automatized (i) collection, (ii) management, (iii) cleaning, (iv) analysis, and (v) visualization of the data (Miller and Han 2009). The development of these tools is one of the major outcomes of this thesis, including significant contributions from my personal programming and system architectural design work.

4.1 Data collection and management

In Chapters I and III, we developed and applied data collection and management tools that were used to collect GPS and social media data to study spatio-temporal accessibility and mobility in Peruvian Amazonia, and the visitation patterns in national parks of Finland and South Africa.

GPS-data collection: For Chapter I, we developed and applied a data collection and management system called Amazonian Riverboat Observation System (AROS). Its basic components and data-flow are illustrated in Figure 4. The movements of the riverboats were first collected with low-cost SPOT Satellite Messengers [1] that sent the coordinates of the vessels (every 10 minutes) into the service provider's database via communication satellites. Because the data was stored only temporarily (7 days) in SPOT's database, we retrieved the data via their API to our own MySQL database for permanent storage. From there the data was further exported as csv-files and analyzed in R.

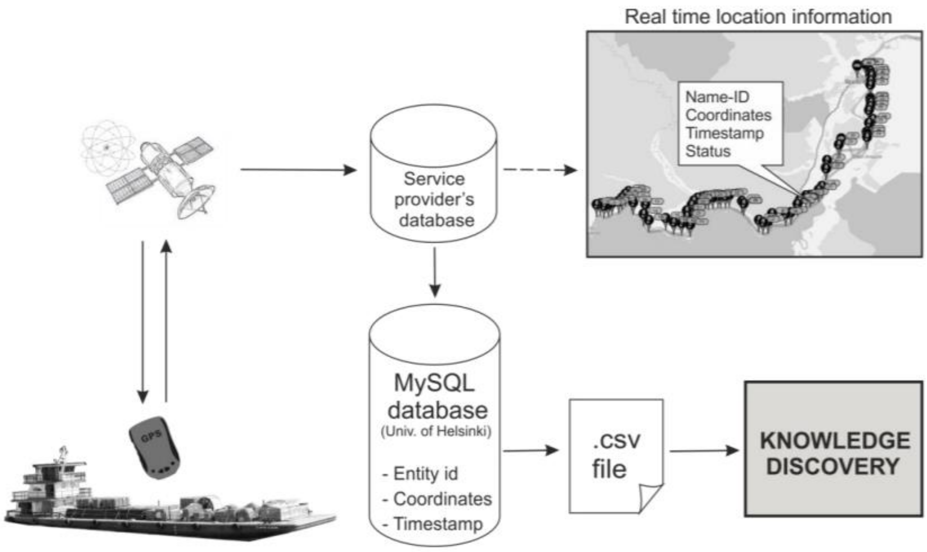

Figure 4. Illustration of Amazonian riverboat observation system (AROS) used in Chapter I to collect the spatial movement data of river boats navigating along the rivers in Peruvian Amazonia. Adapted from Tenkanen et al. (2014).

[1] https://www.findmespot.com/en/

Social media data collection: In Chapter III, we applied a dedicated data collection, storage, and management system which I developed for harvesting and managing data from various social media platforms including Instagram, Twitter and Flickr. The basic components of this geosocial observation system are illustrated in Figure 5, including a relational database (Postgres / PostGIS) for (i) storing and managing the collected data, and (ii) controlling and monitoring the data collection procedures. Data collection is conducted with separate data-collector servers that execute dedicated Python scripts to (iii) retrieve the data (in JSON format) via APIs of the social media platforms, and (iv) upload the data into the PostGIS database in the data-server.

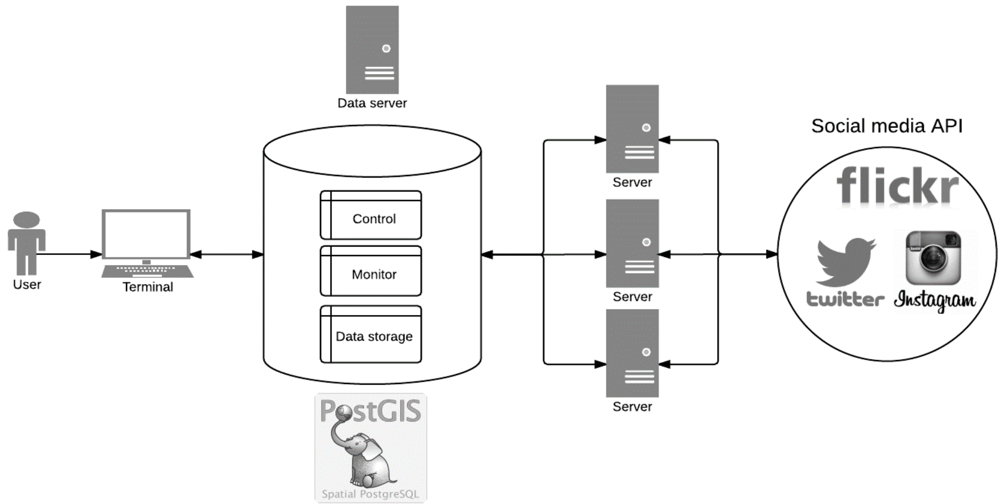

Figure 5. System architecture of the geosocial observation system used in Chapter III. The data from various social media platforms was collected and managed using dedicated scripts written (primarily) in Python programming language. The data is stored into a PostgreSQL / PostGIS database.

Data is managed, cleaned and filtered in the data-server using SQL queries that can be used to select data with specific criteria and conduct basic spatial queries by utilizing the GIS functionalities of the PostGIS extension (such as point in polygon, buffer, or nearest functions). Furthermore, the performance of the queries in the database is enhanced by indexing: the Generalized Search Trees (GiST) index [2] is used for efficient spatial lookups and the self-balancing B-Tree index (Comer 1979) is used to conduct efficient numerical queries (numbers, timestamps, etc.). In addition, our database includes Full Text Search functionality [3] provided by PostgreSQL, which makes it possible to filter documents efficiently based on queries using natural language, where documents are tokenized and converted into lexemes that are stored in specific *tsvector* format, which allows fast text-searches. These tsvectors are further

[2] https://www.postgresql.org/docs/9.5/static/gist-intro.html
[3] https://www.postgresql.org/docs/9.5/static/textsearch-intro.html

indexed with the Generalized Inverted Index (GIN) [4], which makes it possible to find relevant data efficiently, even from hundreds of millions of rows in the data table. While inserting the collected data into the database, we exploit *triggers* [5] that continuously create and update the aforementioned indices and convert text documents into tsvectors. Using the Full Text Search functionalities efficiently requires that the language of the text is identified. Twitter provides the language identification information as a part of the tweet. However, for Instagram and Flickr data we applied a separate language detection tool [6] written in Java to identify the language of the post simultaneously while collecting the data. Accurate language detection is also a prerequisite for doing more advanced natural language processing using e.g. deep recursive neural networks (İrsoy and Cardie 2014).

4.2 Multimodal spatio-temporal accessibility modeling

We have developed two separate openly available tools for accessibility modeling. MetropAccess-Reititin [7] was developed in collaboration with BusFaster Ltd. for transport routing based on public transport or walking (Järvi et al. 2014), whereas MetropAccess-Digiroad tool [8] was developed for transport routing based on private cars (Toivonen et al. 2014). Both of these tools are based on Dijkstra's (1959) algorithm to find the optimal single source shortest paths. However, the algorithm used in MetropAccess-Reititin was modified to track the time of the day in addition to the optimized cost. MetropAccess-Reititin is a stand-alone software written in JavaScript (runs in a browser, and on desktop with Node.js [9]), whereas MetropAccess-Digiroad tool was developed as an extension for ArcGIS Desktop [10] by ESRI Inc. In addition to these tools, we utilized an openly available tool called localroute.js [11] for public transport routing with GTFS data, which has partially the same codebase as MetropAccess-Reititin.

Door-to-door approach: Our accessibility tools are developed to estimate travel times between origin and destination locations using a so-called *door-to-door* approach (see Figure 6), where every step of the journey is taken into account (Salonen and Toivonen 2013). When modeling with private car, our model considers not only the actual driving time (considering traffic conditions), but also the time that it takes to find a parking place, and the walking time from “home-door” to a parking place, and the time that it takes to walk from the parking place to the actual destination. Similarly, with public

[4] https://www.postgresql.org/docs/9.5/static/gin-intro.html
[5] https://www.postgresql.org/docs/9.5/static/plpgsql-trigger.html
[6] https://github.com/shuyo/language-detection/blob/wiki/ProjectHome.md
[7] http://blogs.helsinki.fi/accessibility/reititin/
[8] http://blogs.helsinki.fi/accessibility/digiroad-tool/
[9] https://nodejs.org/en/
[10] http://desktop.arcgis.com/en/
[11] https://github.com/HSLdevcom/localroute

transport, our model considers walking time to the nearest stop, the time that one needs to wait for the public transport vehicle to arrive, the actual time traveled with the vehicle(s) (including transit times), and the walking time that it takes to reach the destination. This approach makes it possible to compare different travel modes to each other realistically, which is demonstrated in Chapter IV.

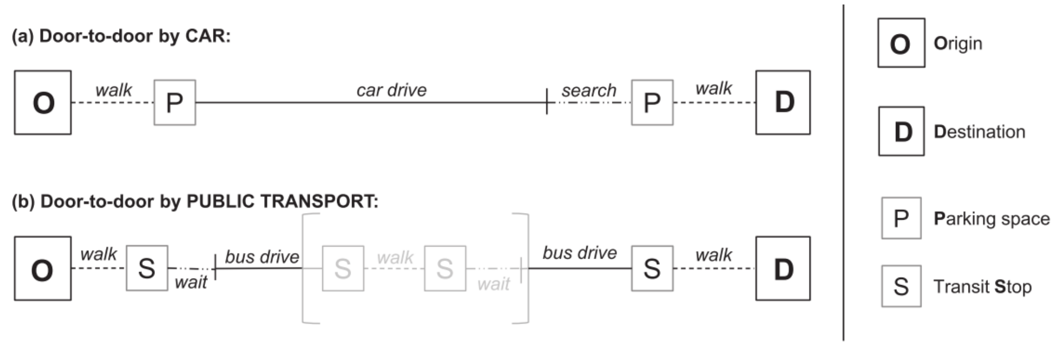

Figure 6. Accessibility models incorporated in this thesis use the door-to-door approach, in which every step in the travel chain is considered. Figure adapted from Salonen and Toivonen (2013).

Travel time calculations: In Chapters IV and V, we calculated travel times between origin points (centroids of the statistical grid cells) and destination points (locations of the grocery stores). We calculated the travel times for different hours of the day, considering the operative public transport timetables at a given hour. We used multiple different departure times within an hour to find the fastest travel route and time between the origin and destination points. Departure times were selected based on a Golomb ruler, which can be used to find the optimal positions for departure times within a single hour (Babcock 1953; Bloom and Golomb 1977). Travel times by private car were calculated using separate impedance values (cost) for rush-hour and midday. Our analyses were conducted only to such destinations that were open at a specific time of the day (according to the opening hours of the stores). As the number of potential connections between origin (n=13231 and n=628 in Chapters IV and V, accordingly) and destination locations (n=396; n=131, accordingly) is high, considering multiple departure times within an hour for all 24 hours (see Chapter V), the travel time calculations were conducted using parallel computing. Calculations were distributed into ~250 CPU cores using the high-performance computing resources of CSC – Finnish IT Center for Science [12].

4.3 Analysis of spatial mobility and whereabouts of people

Mobility data mining: To reveal the spatio-temporal accessibility patterns in Peruvian Amazonia, we tracked the movements of operating riverboats in the area using a dedicated observation system (see 4.1). Transforming the

[12] https://www.csc.fi/en

mobility data into generalized accessibility information required the development of dedicated mobility data mining methods that were used to (i) clean the data of outliers (due to inaccurate GPS points); (ii) identify individual journeys from the GPS observations (trajectory reconstruction) and assess the quality of trajectories with geovisual analytics utilizing the space-time cube (Figure 7a); (iii) calculate the travel speed of the vessel utilizing a linear referencing method (Figure 7b); and (iv) smooth the data with moving averages to reveal the movement profiles of the vessels. After extracting the spatial mobility profiles from the GPS data (including travel speed at different parts of the river), it was possible to generalize the movements into isochrone maps showing the seasonal differences of accessibility in the study area (see Chapter I).

Revealing the locations of people: Understanding where people were located at specific times of the day or year (Chapters II, III and V) required specific analytical techniques to transform the data into an appropriate format and/or resolution. To understand the monthly visitation rates in national parks based on social media data (Chapter III) required us to (i) extract relevant data posted from the park by point in a polygon query; (ii) clean and filter the resulting person-based data; (iii) aggregate these into the number of days a single user had been active in the park (social media user-days); and (iv) aggregate the social media user-days into monthly level statistics. This approach ensured that a single user was counted only once per day, which corresponds to how visitors are officially counted in parks using counters.

In Chapters II and V, hourly population distribution patterns (derived from mobile phone data) were interpolated into 100×100 m and 500×500 m grid cells using an advanced multi-temporal function-based dasymetric interpolation method (and tool; Järv et al. 2017). Our interpolation method merges information from various ancillary data sources: the physical surface layer is used to target/restrict observed activities to/from certain areas; time-sensitive human activity data (travel survey) transforms the physical surface layer into a probability surface; and these are used to interpolate the mobile phone data into predefined target zones such as statistical grid cells (see Figure 8).

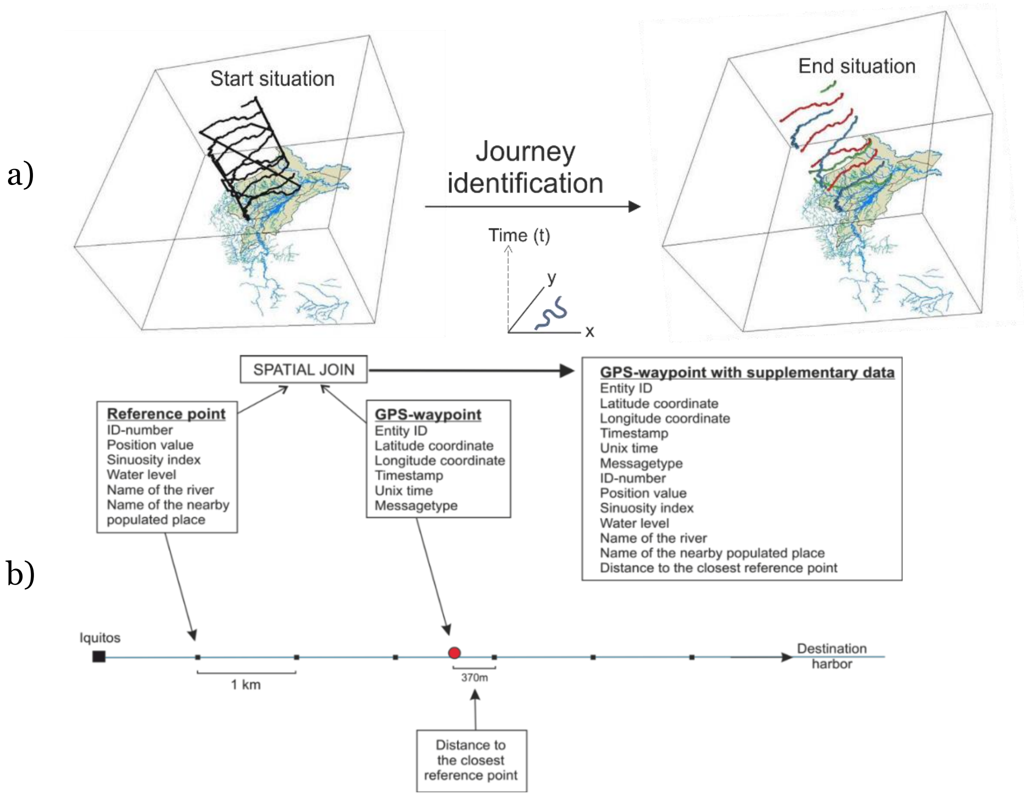

Figure 7. a) In Chapter I, the individual journeys of navigating vessels were identified from the GPS observations based on a dedicated algorithm and assessed using geovisual analytics. Adapted from Tenkanen (2013); b) calculating the travel speed of moving riverboats required that the position of the vessel along the meandering river was known. Determining the location of the vessel was conducted by utilizing a linear referencing method where the location was determined by joining the GPS waypoint to the closest known reference point. Adapted from Tenkanen et al. (2014).

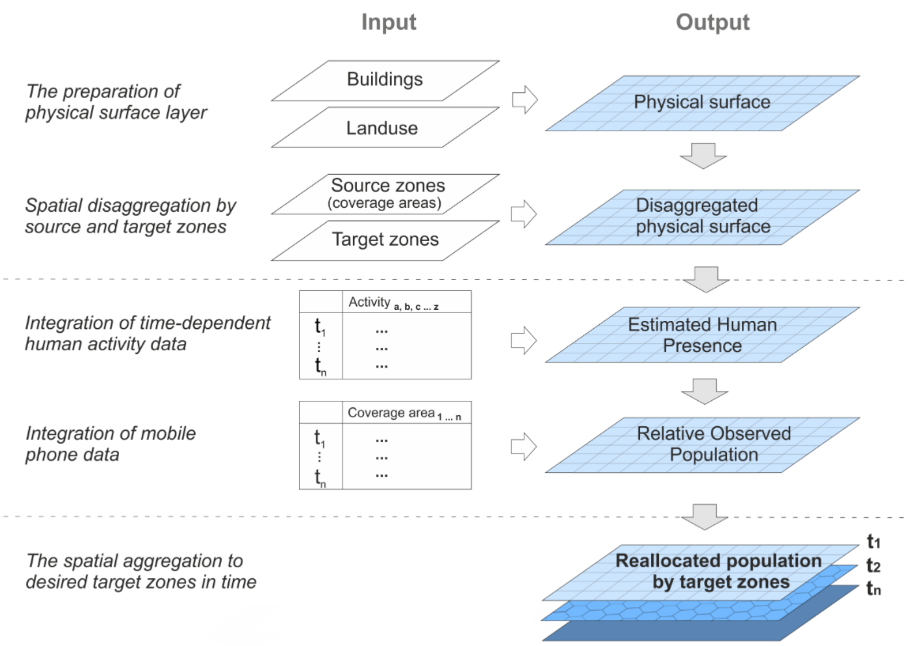

Figure 8. Enhancing the accuracy of mobile phone based data is done in five steps where information from various data sources is merged to reallocate the population to desired target zones at specific times of the day. Modified from Chapter II.

4.4 Data validation methods

This thesis includes two chapters in which the main target is to validate the developed methods (see Chapter II) and data (see Chapter III) against other data sources. In Chapter II, we systematically estimated the accuracy of the interpolation method that we developed for enhancing the spatial accuracy of mobile phone data. We compared the night-time population distribution based on our temporally and spatially sensitive interpolation method, and the areal weighting method (typically applied in mobile phone-based research) to official population registry data representing the night-time population (i.e. locations where people sleep). Furthermore, we estimated the differences with three statistical analyses: (i) linear regression for comparing the correlation coefficients and standard error of the estimate; (ii) the mean absolute error; and (iii) the coefficient of variation based on the root mean square error of each target zone normalized by the baseline target zone value.

In Chapter III, we systematically assessed how well social media data can be used to estimate temporal visitation patterns in national parks. Comparisons between social media data and official statistics were conducted by creating visualizations that allowed us to easily compare the temporal patterns, and using simple statistical measures such as the Pearson correlation coefficient and Spearman rank correlation to estimate the strength of the relationship between the data sets.

4.5 Sharing practices for data and tools

In this thesis, I produced various datasets, tools and data analysis workflows that were all shared openly following the contemporary principles of open science, source and data. The shared tools and data were licensed using open source licenses such as Creative Commons BY-SA 4.0 [13], or GPLv3 [14] that are widely used by scientists and developers supporting open science. Datasets and tools were shared and documented in GitHub [15] which is currently the largest online storage space of collaborative works that exists in the world. All the codes and documentation about the analysis workflows related to this thesis are shared openly in www.github.com/HTenkanen/PhD-thesis.

[13] https://creativecommons.org/licenses/by-sa/4.0/
[14] https://www.gnu.org/licenses/quick-guide-gplv3.html
[15] https://www.github.com

5. RESULTS AND DISCUSSION

In this chapter, I summarize the key contextual and methodological results of my thesis. In addition, I aim to offer certain practical recommendations on the basis of my findings.

5.1 People, transport and activities constitute accessibility - as a function of time

All chapters (I-V) in this thesis demonstrate the significant role of temporality for the realities of accessibility and mobility. Chapters I, IV and V highlight the impacts of temporality in the transport network, Chapters IV and V demonstrate the consequences of temporal changes in the service network and II, III and V touch upon the temporal dynamics of an increasingly mobile population. The interplay of all these components is discussed in the conceptual presentation of the dynamic accessibility modeling, and its empirical evaluation in Chapter V.

Both urban and rural environments are shaped by the dynamism of everyday life, in which everything is constantly on the move (Sheller and Urry 2006). Capturing how people can reach places to pursue various activities (work, shopping, hobbies, etc.) requires taking various factors into account, such as the time spent on traveling, the destinations (e.g. services) and their characteristics, and the mode of transport (Handy and Niemeier 1997). These factors, however, are not sufficient for a fully dynamic model of accessibility. The final component in a dynamic accessibility model is the dynamic population, which should be incorporated into models of dynamic accessibility (preferably also including socio-economic factors). After all, the individuals are the ones who conduct the activities and create the dynamism of our societies. This thesis provides a conceptually comprehensive framework (Figure 9), and empirically shows that considering the different components (people, transport and activities) as a function of time, including different modes of travel, makes it possible to better understand the dynamics of society in both urban and rural environments.

From the methodological perspective, there has long existed an interest in describing the spatial structures of our living environment (e.g. von Thünen 1826) and understanding the dynamism of urban environments using computational methods (Batty 1971; Crecine 1968; Forrester 1969; Lowry 1964). What has changed during the last few decades, however, is the availability of detailed data sources (Miller and Goodchild 2015). These data sources, as demonstrated in Chapters I–V, provide us with an unprecedented view into the dynamics of our environment, not only on a yearly basis (as the earlier models did), but by considering various temporal granularities ranging from hourly-based analyses (diurnal patterns) to comparative time-series analyses including data from multiple decades or even centuries.

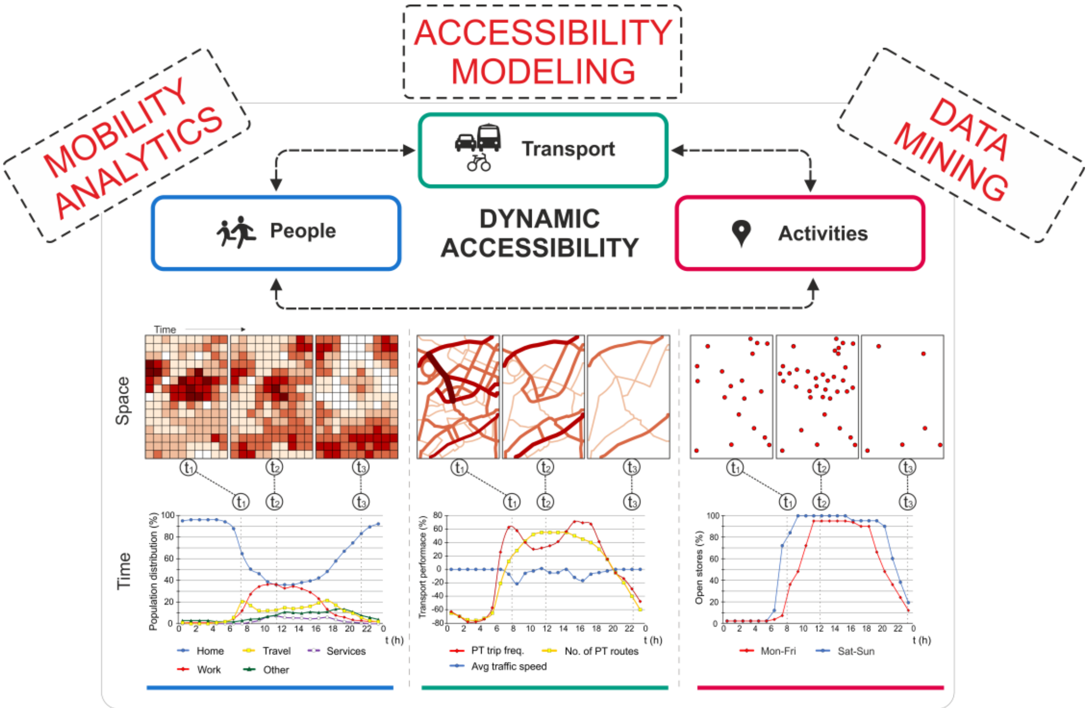

Figure 9. Our framework of dynamic accessibility modeling is constructed by three components which all have distinct spatial characteristics that change in time. Analyzing the effect of temporality in the dynamic accessibility model requires various methodological approaches including multimodal accessibility modeling, mobility analytics and data mining. Adapted and modified from Chapter V.

Needless to say, revealing the dynamic realities of spatial accessibility and mobility on a detailed level is not an easy task. This thesis shows that when applying a fully dynamic accessibility model, a diverse set of data and methodological approaches (including modeling and data mining) are needed to capture the dynamics of spatial accessibility in order to understand the fluctuations in accessibility, activities, and spatial mobility.

Conclusions: Time influences the realities of spatial accessibility and mobility. Understanding the true patterns of accessibility and mobility requires diverse information about (i) how people can access specific services from (ii) the locations they depart from (iii) at specific times of the day (iv) using a given mode of transport.

5.2 Dynamic accessibility is driven by the characteristics of the transport system

The results of this thesis show that in urban environments, spatial accessibility is heavily influenced by changing schedules of public transport and traffic conditions on the roads (see Chapters IV and V). During rush hours, when most people commute, public transport is typically more efficient as it has more extensive and frequent service levels compared to other times, which typically leads to shorter travel times and better accessibility. Hence, there is an expected dependence between the demand and supply. At the same time, roads are more congested due to increased traffic, and finding a parking place for a car can be more difficult, which tends to increase travel times. As revealed in Chapter IV, the temporal characteristics of the transport system have the effect that, against typical assumptions, public transport or walking can, in fact, be faster than using a private car to reach the services. This happens especially when travel distances are short. However, during the evening and night-time the private car becomes faster compared to public transport due to the sparser service network, which leads to longer travel times and distances. Chapter I demonstrates that, in rural environments such as Peruvian Amazonia, the role of the transport network remains significant, although completely different. In fluvial environments of Amazonia, the river network lays the foundation for transportation. Hence, nature determines the impedance levels for transport (either accelerating or decelerating movement according to the water level), in a similar manner to the level of congestion in urban environments.

Furthermore, this thesis shows that the mode of transport plays a key role in spatial accessibility (see Chapter IV). Thus, understanding the accessibility realities in different regions (urban or rural) requires an understanding of which transport modes and their combinations are relevant for the study area. For example, in Peruvian Amazonia where the majority of people and cargo are transported by riverboats due to the lack of road infrastructure (Chapter I), understanding the effect of accessibility for local societies and environments should be conducted by studying the riverine navigation (Abizaid et al. 2017; Salonen et al. 2012, 2013). Similarly, in urban environments, a combination of appropriate travel modes (see Chapter IV) needs to be considered as people use different transport modes for traveling. If focusing only on a single travel mode, such as the private car, all other transport modes are excluded. Therefore, also conclusions drawn from the results would be biased towards the selected transport mode, as is argued in Chapter IV. Hence, if possible, including the modal share in the actual accessibility analysis (see e.g. Salonen et al. 2016) can provide a more realistic and comprehensive understanding of the studied phenomenon.

Conclusions: When conducting spatio-temporal accessibility analyses, one should not only take into account the temporal variation of the transport system (with appropriate temporal granularity), but also consider appropriate travel modes for the study area (naturally according to the research question at hand). For many urban areas in Europe at least, planning has been made with private cars in mind, while the true accessibility realities are much more diverse. Hence, when drawing conclusions from the results, one should consider the modal share in the studied region, in order to identify who (and how many) are actually affected by the studied phenomenon.

5.3 People's spatial mobility is an inherent part of accessibility

The lack of understanding about the spatial dynamics of the population within urban areas has long been a major limitation in dynamic accessibility modeling, leading to studies in which the population has always been treated as static (however, see Moya-Gómez et al. 2017). Typically, place-based accessibility models have incorporated simplified assumptions about the locations of people, using e.g. residential locations or workplaces as proxies for their whereabouts. However, the spatial behavior of people (i.e. their presence in space) changes continuously.

This thesis shows that there exists significant short- and long-term spatio-temporal variation in the locations of the population and how people use space throughout the day, month, season and year (see Chapters II, III and V). Our findings from mobile phone data reveal evident short-term variation in spatial patterns of population throughout the day as the locations of population densities vary considerably (see Chapters II and V). Furthermore, our empirical findings in Chapters I and III reveal the long(er)-term temporal variation in spatial mobility and population dynamics: Chapter I demonstrates how the varying river levels (due to nature's seasonal dynamics) affect heavily the accessibility patterns in Peruvian Amazonia, whereas Chapter III demonstrates how visitation to natural areas is strongly influenced by time.

Hence, to understand the spatio-temporal realities of accessibility more realistically, it is important to know where people are at specific times, and as a result, those areas should be considered as the departure locations of people in accessibility analyses (Widener et al. 2015). Excluding the dynamics in the locations of people might lead to unrealistic, inaccurate or even contradictory results in accessibility analyses, which may lead to decisions or plans having unwanted consequences.

Conclusions: People's daily activity locations have long been neglected in dynamic accessibility models, which is problematic as the assumption of a static population is conceptually wrong and a simplification of the reality. Understanding how people move and where they are located at specific times of the day, month or season should be incorporated into place-based accessibility analyses to achieve more realistic results. Having realistic information about the locations of people (fluctuating in time) is extremely useful and important e.g. for planners, or for rescue services when doing risk analyses.

5.4 Geography of points of interests significantly influences dynamic accessibility

In Chapter V, we reveal that the geography of points of interests (i.e. their distribution and coverage) such as services has the most considerable influence on dynamic accessibility (Figure 10D). The opening hours of services constrain the access to them (with a service being either open or closed) (Hägerstrand 1970; Neutens, Delafontaine, Schwanen, et al. 2012; Weber and Kwan 2002), which typically has a considerable effect on the level of spatial accessibility in their proximity as the travel times/distances to the next available service get longer, as confirmed by our empirical results (see Chapters IV and V). Furthermore, hourly-based analyses in Chapter V show that travel times by public transport in our study area remain rather stable during the night-time (i.e. equally poor accessibility) when the service network is rather sparse, but also during the day when all stores are open (i.e. equally good accessibility). For this reason, the most significant changes in spatial accessibility [16] tend to occur at times when the number of open stores changes (typically at 7-10 am, 17-18 pm, 22-23 pm in Estonia and Finland), and when the efficiency of the public transport system changes (more/fewer routes and departures), which is in line with the recent findings in the literature (Widener et al. 2017).

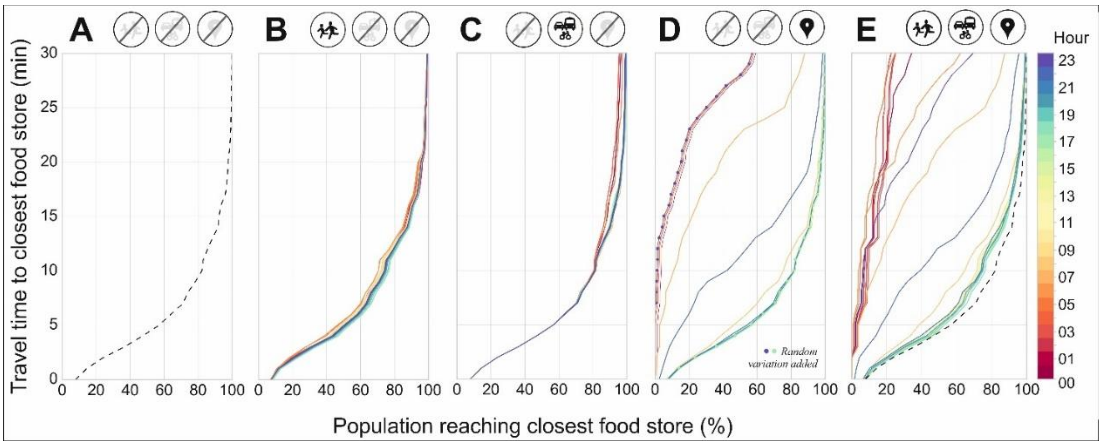

Figure 10. Our systematic analysis shows how accessibility components are influenced by temporality. Temporal variation in the service network (D) causes the most significant changes to spatio-temporal accessibility and how people can reach the services. A: static accessibility model; B: only population is dynamic; C: only transportation is dynamic; D: only services are dynamic; E: all components are dynamic. Adapted from Chapter V.

Overall, when comparing static and dynamic models to each other, our results reveal that the static models tend to overestimate the level of accessibility at every hour of the day (Figure 10E). The difference is especially striking when comparing accessibility levels during the evening and night- time. However,

[16] An animation of the spatio-temporal changes in accessibility patterns on an hourly basis is available at: www.github.com/AccessibilityRG/DYNAMO/

the discrepancy between static and dynamic models depends on the characteristics of the service network, and furthermore it is place-specific. When looking at single locations (see supplement in Chapter V), our results show that in certain places the static version tends to underestimate the level of accessibility, whereas in some areas it shows a similar level of accessibility compared to dynamic models.

Conclusions: Although all components of a dynamic accessibility model exhibit temporal variation, the geography of destinations is the most influential one. The changes in the service availability tend to be more significant than the changes in the transport network and population, both in the day and at night as well as over longer periods of time. For this reason, if one cannot consider temporality in all the components of accessibility due to limitations in access to appropriate data or methods, it is highly recommended to at least consider time in relation to the service network (including opening hours). Furthermore, when the objective is to improve accessibility in a region, the focus should be broadened from the transport network to the spatial and temporal pattern of the services.

5.5 Creative fusion of data and methods makes it possible to capture the dynamic realities of accessibility and mobility

Sophisticated spatio-temporal accessibility and mobility analyses require us to incorporate various methodological approaches and data from multiple sources (see Chapters I–V). Furthermore, as demonstrated in Chapters I and III, by incorporating both quantitative and qualitative data sources, it is possible to enrich the pool of information, which makes it possible to better understand the research findings. Hence, a creative fusion of data can lead to more valuable insights and enables more realistic analyses, and useful applications that can be highly beneficial for science and society at large (Fosso Wamba et al. 2015).

In accessibility modeling, data and methodological fusion is typically a necessary step when conducting the analyses as the services, transport network and people are in a constant flux (as demonstrated in Chapters I–V). Luckily, current data sources have considerably improved our abilities to conduct data-intensive studies as vast quantities of data e.g. from GPS devices, mobile phones, social media and crowd-sourced platforms have become available for analysis (Cheng et al. 2014; Li et al. 2016; Miller and Goodchild 2015). Combined with advanced GIS techniques, these data have made it possible to analyze spatial accessibility and mobility more accurately than ever before, covering different spatial and temporal scales, while also considering both place- and person-based approaches (Geurs and van Wee 2004; Steiger, Westerholt, et al. 2015). Furthermore, combining spatial and temporal data from various sources makes it possible to enhance the spatial and temporal accuracy of data. In Chapter III, we demonstrated that combining (primary) data from multiple social media platforms produces the most robust results. In Chapter II, the spatial accuracy of mobile phone data was significantly improved when combined with ancillary data sources: land-use data (i) to weight and restrict human whereabouts to/from certain areas; travel survey data (ii) to understand the typical time-use of people at specific land-use and transportation areas; and laser scanning data (iii) to extract information about building heights and numbers of floors to weight the mobile phone activities to higher and bigger buildings, which are likely to have more people inside. With this approach, the spatial accuracy of spatio-temporal population densities derived from mobile phone data is better, and the data can be fitted with other relevant spatial data sources.

In this study, a combination of different GIS, data science and modeling approaches were applied. When conducting multimodal and spatio-temporal accessibility analyses considering the whole travel chain (Salonen and Toivonen 2013), advanced routing algorithms are required (Järvi et al. 2014) since the algorithms need to consider all steps of the journey with public transport, including walking, transit and the actual travel parts by different modes of travel (bus, metro, tram, ferry, train, etc.). Similarly, when analyzing the travel times by private car, the walking times to the car, the actual driving time considering traffic conditions (congestion) at different times of the day, and the time it takes to find a parking place must be accounted for. Only by considering the entire travel chain does it become possible to conduct comparable and more realistic analyses, which take the different transport modes (public transport, private car, cycling, walking) into account, as was done in Chapter IV.

This thesis demonstrates that understanding how traffic conditions affect travel times at different times of the day and in different parts of the city requires methodological fusion. First, it must be understood how much different road network elements (roundabouts, ramps, crossings etc.) decelerate the travel speeds (drive-through times for different road segments), which can be accomplished with mobility data mining based on GPS data (floating car measurements). Secondly, a model that binds the impedance values extracted from GPS data to the road network data must be created to allow more realistic routing (network analysis) considering varying traffic conditions, for instance during rush-hour or at midday (Salonen and Toivonen 2013; Toivonen et al. 2014).

Chapter V, which introduces the fully dynamic accessibility model, includes the most versatile fusion of different methodological approaches (and data), as we combine spatio-temporal accessibility analyses (by public transport) with spatial mobility analysis based on mobile phone data, which has been enhanced and harmonized by increasing its spatial accuracy by using the model presented in Chapter II. Furthermore, all analyses were compiled and run according to the temporal constraints of the service network based on the opening hours of the stores.

Conclusions: Methodologically, understanding the dynamic realities of accessibility and mobility is a complicated analytical task that has inspired researchers for decades. Achieving an in-depth understanding of the prevailing accessibility realities - crucial for knowledge-based decision-making - generally requires a fusion of various data sources and different methodological approaches. The spatial and temporal scale of the study question determines which methods should be applied (e.g. individual- vs. place-based analyses).

5.6 Novel data sources are exciting but they should be used with caution

Novel, easily available big data sources, such as the social media data addressed in Chapter III, can provide numerous opportunities for understanding various aspects of our world, including discovered information about social interactions, what people are talking about, or how they experience specific places at specific times. For this reason, their use has been increasingly popular in different fields of study ranging from social sciences to conservation biology (Andrienko et al. 2013; Hausmann, Toivonen, Heikinheimo, et al. 2017; Hausmann, Toivonen, Slotow, et al. 2017; Heikinheimo et al. 2017; Steiger, de Albuquerque, et al. 2015; Williams et al. 2013). Furthermore, novel spatial data, such as crowd-sourced OpenStreetMap (OSM) data that has global coverage (Jokar Arsanjani et al. 2015), enables us to conduct even continental-scale routing [17] that can give directions on how to drive from one place to another. Similarly, standardized public transport data, such as schedules, routes and stops derived from General Transit Feed Specification data [18] (GTFS) (see e.g. Wong 2013), makes it possible to conduct spatio-temporal accessibility analyses in more than a thousand urban regions worldwide [19].

However, it is extremely important to understand and recognize the limitations, errors and biases in the data. For instance, there might be errors such as missing routes or times in GTFS data, or invalid roads in OSM (Barron et al. 2014; Graser et al. 2014). Hence, different automatic techniques and manual work are required to estimate the validity of the data, as was done in Chapters II and III. Thus, more traditional data sources must not be forgotten, because they can provide a deeper understanding of the studied phenomena

[17] See e.g. https://openrouteservice.org for European-wide routing.
[18] https://developers.google.com/transit/gtfs/
[19] See e.g. https://transit.land/ or http://transitfeeds.com/ providing global coverage of GTFS feeds.

and valuable information e.g. about the representativeness and quality of big data. In short, it must be clearly understood which data source(s) to use and which are most relevant for the research questions at hand.

This thesis demonstrates that the spatial and temporal characteristics of the data determine the level of detail that can be drawn from the data, thus spatial and temporal scale matters (Kwan and Weber 2008; Schwanen and Kwan 2008; Widener and Shannon 2014). For instance, the varying spatial scale (modifiable areal unit problem; Openshaw 1984) makes it challenging to compare mobile phone data (base station level accuracy) to statistical data sources (100 or 500 meter grid) without appropriate spatial interpolation methods (see Chapter II). In addition, our findings reveal that the usage of mobile phones tends to be biased towards the city center where mobile phone activities are overrepresented. Furthermore, the level of detail that can be drawn from the data is tied to the quantity of observed data within the area of interest. Our results show that the temporal granularity observable from social media data varies according to the social media platform used, as was revealed in Chapter III. For instance, if Flickr is used to estimate the number of visitors in national parks, it is necessary to combine data from multiple years (Sessions et al. 2016) to enhance the representativeness of the data against official statistics, whereas Instagram (with a higher quantity of data) performs well without the need to aggregate data.

In addition, it is important to understand that “novel” and “traditional” sources are not necessarily fully comparable since they might catch different population groups, therefore telling a slightly different story. For example, Heikinheimo et al. (2017) found that respondents who answer surveys in national parks tend to be older, whereas younger persons tend to be more active on social media. For this reason, mining data from social media can provide a better and a more complete picture about how young people visit national parks and what kinds of activities they undertake in the parks. Overall, big data sources can be thought of as being complementary rather than a substitute for other more “traditional” data sources.

Finally, it is extremely important to critically evaluate and consider the ethical issues related to the use of big data, and especially if big data is used to study human spatial behavior, as in Chapters II, III and V of this thesis (Elwood and Leszczynski 2011; De Montjoye et al. 2013). For example, people do not necessarily understand that their public posts on social media might be used for research purposes (or any other purposes for that matter). Furthermore, social media research is usually conducted without informed consent (i.e. asking permission from social media users) due to the difficulty in acquiring permission from (possibly) millions of users whose content belongs to the data used for analysis. Even though their data is public, it does not mean that there are no ethical problems in using the data (Zimmer 2010). Hence, it is extremely important to follow the ethical guidelines and a code of conduct (Zook et al. 2017) that ensures that the privacy of individuals is not in danger or violated (e.g. with rigorous data anonymization).

Conclusions: Big data can bring new insights about human activities, behavior and environment on an unprecedented level of detail, in both spatial and temporal terms. However, researchers face many challenges when using big data, ranging from data quality and representativeness issues to ethical and privacy concerns, as big data sources often reveal much about people and their activities. To overcome these issues, it is necessary to combine data from multiple sources including both quantitative and qualitative data, and to conduct responsible big data research following a code of conduct that minimizes the risks and harm for individuals, while maximizing the benefits for research.

5.7 Multi-dimensional analyses require advanced computational approaches

Incorporating large quantities of data from different sources and conducting multi-dimensional analyses, both spatially and temporally at various scales and granularities, requires the automation of data collection, data management procedures (in databases), and analytical process flows. Databases, such as MySQL or PostgreSQL used in this thesis, are required to store, handle and analyze the voluminous data e.g. from GPS devices (Chapter I), mobile phones (Chapters II and V) and social media (Chapter III). In addition, large-scale spatial queries covering hundreds of millions of social media records require the use of software (such as PostgreSQL) that can handle and query massive datasets efficiently (applied in Chapter III). Furthermore, distributed (parallel) high-performance computing and cloud computing utilizing specific computing frameworks such as MapReduce (Dean and Ghemawat 2004; Maitrey and Jha 2015) are typically required to run the (big data) analyses within a reasonable timeframe (Assuncao et al. 2015).

In this thesis, I made extensive use of distributed computing resources, to run the spatio-temporal accessibility analyses (Chapters IV and V) with a fine spatial resolution and temporal granularity that required millions of shortest path routings (Dijkstra 1959) with different travel modes. In addition, preparing the data for exploratory spatial data analysis (ESDA, see e.g. Anselin 1999; Anselin and Getis 1992; Bivand 2010; Miller and Han 2009) and (geo)visualization (Andrienko et al. 2007; Andrienko, Andrienko, Dykes, et al. 2008) required automatization. Most of the data analyses and preparation of the figures for the Chapters were automated using Python programming language and its numerous libraries for data science, GIS, and data visualization. For example, Chapter III included 56 study areas under investigation and data from three social media platforms and two statistical data sources, which would present a challenging combination without programming and automated analytical workflows.

Conclusions: Handling and analyzing large volumes of diverse data requires advanced and automated computational approaches that make it possible to cope with process flows that are often complex, extensive, and time-consuming. Traditional GIS approaches and tools might not be the most usable for analytical purposes in relation to spatio-temporal accessibility and mobility analyses, so the role of computer and data science is increasingly important, especially as the data has become increasingly voluminous.

5.8 Spatially and temporally sensitive multimodal analyses can improve spatial planning, equity and sustainability

Spatial accessibility and mobility analyses are often incorporated into planning processes in different domains (Batty 2009; Dalvi and Martin 1976; Ewing and Cervero 2010; Handy and Niemeier 1997; Hickman et al. 2013; Neutens 2017). However, their quality and spatial accuracy may vary. To be able to make (spatial) plans, the current spatial structures and dynamics in the area must first be understood (Barredo et al. 2003; Batty et al. 1999). This thesis demonstrates that accessibility and mobility analyses can provide answers and useful information for planning, as they allow us to understand how easily a given area can be reached by an individual or the underlying population. Furthermore, combined with novel data sources, they can provide answers to questions about who are actually using the areas and for which purposes (Lansley and Longley 2016; Longley et al. 2015). These questions have become increasingly important for planners, and for the first time, it is possible to give more comprehensive insights about those themes. One of the topical themes in science, planning and policy is the aim of developing ‘smart cities’ (Batty 2013; Batty et al. 2012) with the help of novel computational tools and planning support systems (Geertman and Stillwell 2004). The concept of a smart city, which is nevertheless much criticized (see e.g. Hollands 2008; Shelton et al. 2015), has arisen from the availability of novel digital (big) data sources and state-of-the-art data analytics and sensor systems that can produce more detailed control over the city systems in both temporal and spatial terms (Paroutis et al. 2014). Accessibility and spatial mobility analyses have a key role in the developing smart cities, as understanding the movements of people allows resources to be targeted more efficiently even in real time. For example, allocating transportation resources into areas only when they are needed (more demand), or having lights on in the streets only when there are people or vehicles passing by could save resources, money and energy (see e.g. Pentland 2014).

From the perspective of equity, spatial accessibility can provide information about the equality of our urban city structures (e.g. spatial equity, social and/or environmental justice), which accounts for the underlying transportation system, service network (destinations) and socio-economic factors (Geurs and van Wee 2004; Laatikainen et al. 2015; Lucas et al. 2016; Stępniak and Goliszek 2017; Talen and Anselin 1998; Van Wee and Geurs 2011). To study the equality (or inequality) of accessibility, one needs to embrace diversity. This involves considering personal characteristics of the individuals (age, gender, socio-economics etc.); multimodality, i.e. the available transport modes; and temporality, as people have different daily rhythms. In Chapter IV, we argue that including these factors e.g. into decisions and plans concerning health is of paramount importance (Neutens 2015), which should be considered when optimizing the locations for the healthcare system (Kotavaara et al. 2015, 2017; Páez et al. 2010) or when trying to understand the relationship of the food environment (proximity to unhealthy food) to obesity (Burns and Inglis 2007). Overall, understanding spatial accessibility may promote equality by enabling more informed and equal decisions. However, our findings reveal that temporality should also be considered, as spatial equality (measured with the Gini coefficient) is time-dependent (see Chapter V).

Spatial accessibility and mobility are inherently connected to sustainability, as they can be directly linked to carbon emissions from transportation (Banister 2008, 2011b; Bertolini et al. 2008; Hickman et al. 2013). For this reason, sophisticated accessibility analyses can be used to spatially evaluate e.g. how CO_2 emissions are produced and if specific destinations in the city produce more carbon emissions than others (Lahtinen et al. 2013; Salonen et al. 2016). Understanding how and where people move can furthermore contribute to sustainable tourism and conservation of natural areas by understanding how people use those areas (see Chapter III), which can directly support e.g. park or protected area management (Balmford et al. 2015; Buckley 2009; Heikinheimo et al. 2017; Di Minin et al. 2015; Sessions et al. 2016; Wood et al. 2013).

Conclusions: In order to understand the realities and structures that enable people to access places, it is necessary to incorporate time and multimodality into the analyses. Understanding these realities in relation to time is highly relevant in terms of spatial (and temporal) equality and sustainability. Spatial planning and decision-making in urban and rural areas that exclude the temporal aspects cover only a fraction of the underlying realities of how our dynamic cities and societies function. By excluding time and the diversity of travel modes, there is a risk of ending up with unwanted planning and decision outcomes that might discriminate against certain subpopulations.

5.9 Open data and tools transfer new developments into practice and endorse transparency

Scientific knowledge and tools must be brought into practice in such a way that planners and different stakeholders can understand and use them (Bertolini et al. 2005; Curtis and Scheurer 2010), thus promoting transdisciplinarity that converges science with practice. All the tools, data and analytical workflows developed in this thesis (Chapters I–-V) are shared openly on GitHub [20] whenever possible. Promoting and applying principles of open science, sources and data enables other researchers, stakeholders and basically anyone with an interest, to evaluate the conducted work and tools, which makes the work transparent. We have found this extremely valuable, as it makes finding and fixing undesired errors and bugs easier. Open data promotes fast development, not only in science and technology, but also in society at large, as better tools and improved understanding about different phenomena spread faster among different parties. One of the policy developments that have emerged recently concerns the principles of how our personal data can be used. These new policies have the potential to dramatically change how data science is conducted in the future, as individuals have more power to say who can use their personal data and for what purposes (e.g. MyData movement). These policies aim to bring increased privacy while offering even better opportunities to study various phenomena.

The principles of openness (science/data/source) followed during this research have helped to bring the tools and data into practice. They are used e.g. by the city planning departments, private sector (retail chains), and individuals in Helsinki metropolitan area. We have regularly published openly available data, which can be used to understand the spatio-temporal realities of accessibility [21] or estimated carbon emissions from traveling in the Helsinki region [22], which have been actively used by different actors. One of the tools developed during this research is an online analytical accessibility tool called "Mapple – My Accessibility Planner" [23]. The tool enables anyone to analyze accessibility by different modes at different times of the day in Helsinki metropolitan area without any skills in GIS, or having one's own computer, because the whole data analysis is conducted in the cloud. Hence, it can be considered as a geospatial cyberinfrastructure (Li et al. 2013). Such easy-to-use web interfaces and analytical tools have the potential of bridging the gap between science and society, as they are easy to use for practical purposes e.g. when searching for a new apartment or when finding the optimal location for

[20] www.github.com/HTenkanen/PhD-thesis
[21] Helsinki Region Travel Time Matrix 2013 & 2015
[22] Helsinki Region Travel CO2 Matrix 2015
[23] http://mapple.fi

a new business. Furthermore, publicly available tools have been published that can be used to improve the spatial accuracy of mobile phone data [24] (Chapter II). Finally, all the accessibility tools developed earlier are also publicly available: MetropAccess-Reititin is a tool for public transport and walking routing, whereas MetropAccess-Digiroad is a tool dedicated for routing based on the private car, which also considers congestion and the time required to find a parking space in the Helsinki metropolitan area.

To conclude: Sharing the developed tools, data and knowledge openly helps to bring these into practice with relevant stakeholders, who can use them in practice for spatial planning purposes, for instance in relation to city planning, business, and conservation. Furthermore, openness can foster quicker methodological advances while promoting transparency.

5.10 The world is unfinished – Prospects and challenges for research

There are numerous possibilities, and challenges in relation to dynamic accessibility modeling, even though significant progress has been made in recent years. Hence, as a last point, I would like to raise a few interesting opportunities that could advance the conceptual and methodological approaches presented in this thesis.

Considering the current availability of various spatially and temporally fine-scaled and content-rich data sources with extensive spatial coverage (from local to global), there are exciting new possibilities to conduct large-scale comparative studies. For example, it is possible to compare the realities of accessibility in different areas of the world (see e.g. Curtis and Scheurer 2017), considering both temporality and multimodality. Such information could be used to map the modal equality of accessibility in different metropolitan areas considering people's possibilities to use different transport modes (e.g. car, public transport, or bike). Implementing a fully dynamic accessibility model in relation to international comparisons could further increase our understanding of the functioning of cities in the world. However, obtaining appropriate data to consider the dynamism in the distribution of people in cities is challenging (and biased towards the 'global north'). Getting access to appropriate data (such as mobile phone data) can be rather difficult due to privacy concerns and the varying interests of the stakeholders (e.g. economic ones). Openly accessible social media data could provide an alternative for mobile phone data in this respect. However, more research is needed to understand if (and how) social media data could be used reliably as a surrogate for people.

[24] MFD-interpolation-tool: https://doi.org/10.5281/zenodo.252612

Furthermore, multimodal spatio-temporal accessibility and mobility analyses could be enriched even further by incorporating the social context into the analyses from user-generated data. For instance, mining data from social media could make it possible to better incorporate the social dimension into mobility studies by investigating how people use space by leveraging the contents of the posts and the sentiments associated with places (and times). Furthermore, by incorporating social network analyses into the accessibility and mobility analyses, it could be possible to understand e.g. the role of social networks (see e.g. Pentland 2014) in motivating movements and the choice of travel mode (incorporating social pressure, attitudes and norms etc.). In addition, new data sources could bring an enhanced understanding of how space is used in cities (considering temporality) that could contribute to spatial planning in different domains: For instance, urban planners could benefit from understanding how different areas of the city are used: On the one hand, they could discover if certain areas are avoided by people and the reasons for this behavior. On the other hand, they could better understand and know how to create spaces for people at all times of the day.

Finally, when open data and tools are applied creatively and responsibly, they can dramatically increase our capabilities to find groundbreaking insights about the interplay between people, societies and environment – considering temporality.

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