Incorporating the four accessibility components into an interactive accessibility instrument

Master’s Thesis

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Date of submission Munich, 15 January 2020

Abstract

In order to create livable cities and shape a more sustainable mobility, it is crucial to focus on walkable environments. By providing adequate walking infrastructure and proximity to destinations, walking accessibility can be improved. Accessibility instruments as planning support systems can help to face these challenges. Ideally, all four components of accessibility (land-use component, transportation component, temporal component, individual component) are included in an accessibility instrument. This thesis examines how those four components can be incorporated into the Geo-Open Accessibility Tool (GOAT). All necessary data was mapped in OpenStreetMap for a selected study area. By adjusting the backend functions, three new routing profiles (elderly, wheelchair, safe-night) that influence the route choice, were implemented. In addition, the opening hours of the Points of Interest were included to allow for time-based accessibility analyses. These two new options represent the individual and the temporal component. Besides, the frontend was adjusted to include new layers on different walkability criteria, which visualizes the transportation component more realistically. These improvements provide valuable insights into how different groups of people are influenced in their walking accessibility and enhance GOAT to provide more holistic accessibility analyses.

Acknowledgements

First, I would like to thank my thesis supervisor M.Sc. Elias Pajares, who has always given me professional assistance and supported me in the further development of my research. I cannot appreciate enough that he was always available and even spend his weekends with me programming. I could not have imagined having a better advisor and mentor for my thesis.

Many thanks go to Majk Shkurti, who majorly helped to implement the new functions into the frontend. He was always willing to help and has done a really good job.

Furthermore, I would like to thank the OSM Community which supported me with useful mapping advice and further development ideas.

Finally, I must express my gratitude to family and friends who have been a great help to me both professionally and personally over the past six months.

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List of abbreviations

DEM	Digital Elevation Model
GIS	Geographic Information System
GOAT	Geo Open Accessibility Tool
GPS	Global Positioning System
HCM	Highway Capacity Manual
JOSM	Java-OpenStreetMap-Editor
LOS	Level of Service
OSM	OpenStreetMap
POI	Point of Interest
SLD	Styled Layer Descriptor
StVO	Straßenverkehrs-Ordnung (Germany)
SQL	Structured Query Language
TUM	Technical University of Munich
XML	Extensible Markup Language

1. Introduction

For a long time, cities were planned primarily for cars. This led to problems such as congestion, air pollution and noise. The human component was strongly neglected, which does not match with the concept of the livable city that we are striving for today. To create better living conditions in urban areas, the focus needs to be shifted to sustainability, safety, health and liveliness. (Gehl, 2010) In this context, it is crucial to improve the mode share of active mobility. Above all, walking, as the most natural way to move, is of particular importance. By providing better conditions and improving neighborhood mobility, the walkability can be specifically strengthened (FGSV, 2014; Lovasi et al., 2011).

This thesis was preceded by the project “Access to Rail”, in which the requirements for a good pedestrian infrastructure were examined in detail. It was found that freedom from barriers and adequate illumination at night are two of the most important requirements for walking accessibility. However, these needs depend strongly on the individual person and their subjective feelings. (Pajares et al., 2019) For example, one third of the German population is temporarily mobility impaired (Deutscher Verkehrssicherheitsrat, 2005) and 28% of the population is over 60 years old (Statistisches Bundesamt, 2019), which results in different requirements, such as smooth surfaces and barrier-free footpaths. In order to provide good walking accessibility, all these different needs must be taken into account in the urban planning process, which makes providing appropriate infrastructure quite a complex challenge.

Accessibility instruments as planning support systems can help to face this challenge. However, there is a lack of accessibility instruments designed for walking analyses. The “Geo-Open Accessibility Tool” (GOAT), which is currently under development at the Chair of Urban Structure and Transport Planning at the Technical University of Munich (TUM), aims to close this gap as this tool is specifically designed to model walking accessibility.

Since an accessibility measure should ideally include all four components of accessibility (Geurs and van Wee 2013), which are the following: land-use component, transportation component, temporal component and individual component (Geurs and Van Wee, 2004), this thesis examines how those four components can be incorporated in GOAT.

2. Background

Before going into the detailed research question and the methodology used to address the topic, the scientific background and the most relevant literature is provided. The following subchapters discuss why walking is important, how good walkability and accessibility is defined, which accessibility instruments already exist and why GOAT is an important piece of the puzzle for a more sustainable mobility.

2.1. Importance of walking

Walking accounts for 22% of the overall modal split in Germany and even 27% in the metropolitan areas (infas, 2018). This is a significant share, which should be further promoted by appropriate measures, since walking has many advantages over other means of transport. Walking provides physical and mental health benefits for the general public (Chin et al., 2008; Jou, 2011; Lin et al., 2015). Walking is simple, social, for free, spatially efficient, climate as well as environmentally friendly and promotes the local economy (Jou, 2011) and wealth (Florida, 2014; Oishi et al., 2019). Taking all these advantages into account, walking can be considered as the most sustainable mode of transport (Jou, 2011; Norzalwi and Ismail, 2011). But walking is not only a mode of transport itself, walking is also needed to start and end a trip with any vehicle (Boesch, 1988).

Despite the high significance of walking, it does not receive the deserved attention of transport research and urban planning (Lo, 2009). Due to prioritization of motor vehicles, an undersupply of walkable environments can be found in many cities (Leslie et al., 2005). One of the most prevalent problems that hinder people from walking is the lack of proximity of origins to destinations (Cleland and Walton, 2004; Goldsmith, 1992), resulting from the disappearance of local activities (Silva and Larsson, 2018). But poor walking infrastructure that is not adapted to individual needs (e.g. disabilities) and often creates the feeling of insecurity due to insufficient protection from other traffic streams or bad illumination at night is also a common issue (Cleland and Walton, 2004; Pajares et al., 2019). Those issues need to be remedied. Especially in times of urbanization, climate change and urban air pollution (Brömmelstroet et al., 2014), focusing on more sustainable modes of transport is inevitable and providing a good walking infrastructure becomes essential for livable cities (Handy et al., 2002; Langdon, 2017).

However, for some persons it may just not be the habit to walk. In Germany, 83% of the population state that they enjoy walking, with higher usage leading to increased popularity (infas, 2018). This shows an enormous potential that should be used by providing the appropriate pedestrian infrastructure and promoting it respectively to achieve a more walking-oriented behavior of the population. For social equity, the definition of pedestrians in this thesis is further expanded to include those using wheelchairs or other aids.

2.2. Walkability

When talking about good pedestrian infrastructure, the term “walkability” is often used as a measure of how friendly an area is to walk. Walkability is influenced by various factors such as connectivity, sidewalk quality, land use patterns, traffic, safety and aesthetic qualities (Cervero and Kockelman, 1997; Frank and Pivo, 1994; Lopez-Bernal, 2013), which makes its evaluation a challenging process. Due to their slow speed and direct interaction with the environment, pedestrians are generally more aware and sensitive to their surroundings than drivers, which is highly related to the individual walking comfort (Handy et al., 2002). Therefore, a stronger focus on micro-features is needed to fully understand the interactions (Clifton et al., 2007). These are often not only objective, but rather subjective in nature (Lin et al., 2015).

Since the walkability of an area influences mode and route choice of the residents (Lopez-Bernal, 2013; Pajares et al., 2019), it is important for practitioners to understand the big picture in order to make the right decisions. There are various indices, factors and instruments trying to cover this challenge and evaluating the walkability of road segments using different indicators. For example, the Highway Capacity Manual (HCM) pedestrian “Level of Service” (LOS) assesses if the sidewalk width is sufficient for the number of pedestrians by measuring the amount of personal space that each person has, the ratio of sidewalk volume to capacity, the pedestrian flow rate and its speed. However, since walking comfort is not taken into account, the results often do not match the real perceived walkability. (Lo, 2009)

Another walkability measure is the “Walk Score”, which estimates neighborhood walkability by examining the access to nearby amenities (Walk Score, 2017). Carr, Dunsiger, and Marcus (2010) ascertained significant positive correlations between the Walk Score and several walking criteria of both objective and subjective nature. At the same time, however, the measure also correlates positively with reported crimes, which should in fact have a negative impact on walkability.

There are many other tools and methodologies to measure the walkability of a neighborhood, such as the "Pedestrian Environmental Data Scan" (PEDs) instrument (Wimbardana et al., 2018). Since comfort plays a major role in walkability but is difficult to measure, the tools and methodologies try to capture the walkability through different quality criteria. All these quality criteria used in the tools and methodologies have been summarized and are presented in Table 1. The criteria are ordered logically, the order gives no information about the relevance, as this may also depend on the local context.

Table 1: Quality criteria for walking and the corresponding sources

Quality criteria	Source
Sidewalk availability	(Handy and Clifton, 2001; Lo, 2009)
Sidewalk width	(Alfonzo, 2005; Southworth, 2005; Vural Arslan et al., 2018)
Pavement quality	(Alfonzo, 2005; Wimbardana et al., 2018)
Number of lanes	(Ewing, 1999; Southworth, 2005)
Traffic load and street noise	(Clifton et al., 2007; Lin et al., 2015; Pilipenko et al., 2018)
Share of heavy-load vehicles	(Saelens et al., 2003; Vural Arslan et al., 2018)
Speed limits	(Alfonzo, 2005; Saelens et al., 2003; Southworth, 2005)
Number of road crossings	(Handy and Clifton, 2001; Lo, 2009; Wimbardana et al., 2018)
Spatial separation between road and footpath	(Saelens et al., 2003)
Parking vehicles on the road or on the sidewalk	(Clifton et al., 2007; Saelens et al., 2003)
Illumination	(Clifton et al., 2007; Saelens et al., 2003; Wimbardana et al., 2018)
Cleanliness	(Saelens et al., 2003)
Vegetation	(Clifton et al., 2007; Lin et al., 2015; Wimbardana et al., 2018)
Weather protection	(Alfonzo, 2005; Pilipenko et al., 2018; Whyte, 1980)
Inner-city aeration	(Pilipenko et al., 2018)
Land-use	(Pushkarev and Zupan, 1971; Southworth, 2005; Wimbardana et al., 2018)

Number of POIs along the route	(Lin et al., 2015; Saelens et al., 2003)
Population density, liveliness	(Crane, 1996; Saelens et al., 2003; Vural Arslan et al., 2018)
Built environment	(Lin et al., 2015; Lo, 2009)
Pedestrian flow rate	(Lo, 2009)
Directness, connectivity	(Frank and Pivo, 1994; Handy and Clifton, 2001; Lo, 2009; Saelens et al., 2003)
Slope of the sidewalk	(Clifton et al., 2007; Handy and Clifton, 2001; Wimbardana et al., 2018)
Waiting time at traffic signal	(Huff and Liggett, 2014)
Width of the street crossing	(Handy and Clifton, 2001)
Freedom from barriers	(Lo, 2009; Vural Arslan et al., 2018; Zakaria and Ujang, 2015)
Orientation	(Hillier et al., 2007)
Social hotspots	(Saelens et al., 2003)
Street furniture	(Alfonzo, 2005; Vural Arslan et al., 2018; Whyte, 1980)
Public toilets	(Vural Arslan et al., 2018)
Drinking fountains	(Alfonzo, 2005; Whyte, 1980)

2.3. Walking accessibility

While walkability only considers the movement itself, walking accessibility also includes the reachable destinations which can provide even more important insights for sustainable urban planning (Jou, 2011). Accessibility can be defined as “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). Improving accessibility is a main objective of urban planners, but mainly focused on the car. To achieve more livable neighborhoods, the focus should be on improving walking accessibility (Jou, 2011; Krizek et al., 2009). By providing near-by activities and designing a walkable environment, the share of walking can be considerably increased (Handy et al., 2002).

Geurs and van Wee (2004) split accessibility into four components: *land-use component*, *transportation component*, *temporal component* and *individual component* (see Figure 1). The *land-use component* refers to the available opportunities at the destinations and the existing demand at the origin locations. The *transportation component* reflects the transport system – in this case walking with the appropriate infrastructure – that makes it possible to travel from the source of demand to the desired destination and includes the required time and effort. The *temporal component* refers to the change in accessibility during different times of the day or week, which is mostly influenced by opening hours and temporal changes in the transportation component, such as the illumination of footpaths. The *individual component* reflects personal abilities influenced by for example age, gender and health status. Depending on the individual component, barrier-free routing may be necessary, and the required walking time may change.

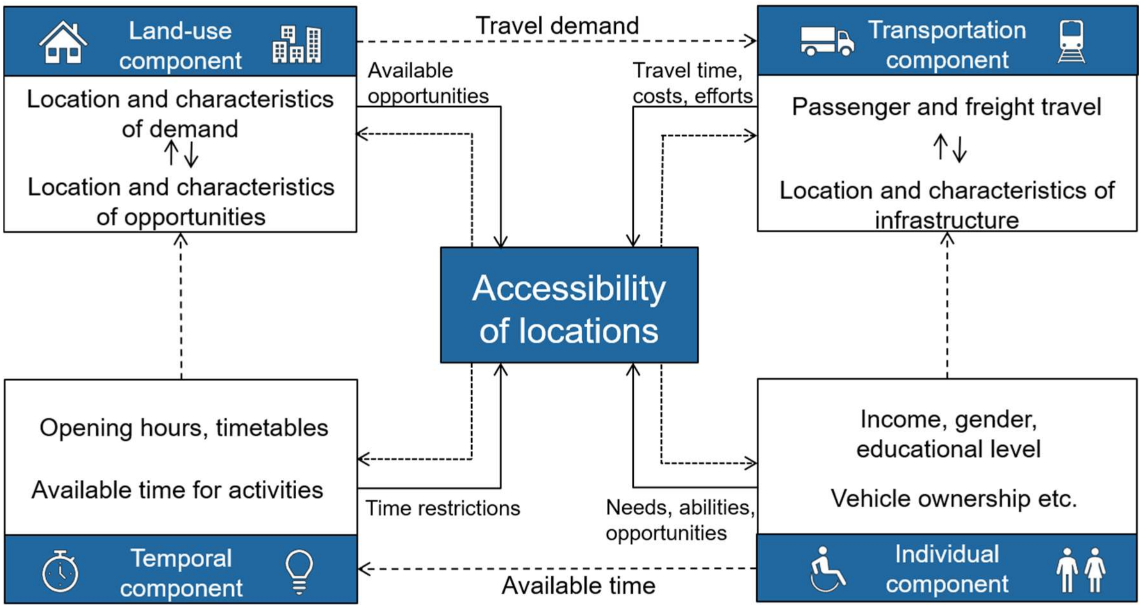

Figure 1: The four accessibility components (adapted from Geurs and van Wee 2004)

Ideally, all four components are considered in an accessibility measure (Geurs and van Wee 2013). This particularly applies to the mode walking with its specific characteristics, like the need for physical activity, varying objective or subjective safety levels during the day and the particular vulnerability of pedestrians (Iacono et al., 2010; Pushkarev and Zupan, 1971).

2.4. Accessibility instruments

Accessibility instruments, which incorporate these accessibility measures and indicators, are powerful tools to provide extensive planning support. In most cases these are Geographic Information System (GIS) applications. They are developed to assist the various research tasks involved in transport planning, spatial planning and the combination of both (Papa et al., 2015).

There are a variety of accessibility instruments designed for the different applications. Some of the instruments focus on the opportunities, e.g. by assessing the best location and size of new retail sites, like “The Retail Cluster Accessibility” (TRACE) or the “Method for arriving at maximum recommendable size of shopping centres” (MaReSi SC). Some instruments focus on the origins or people, e.g. by calculating the number of amenities than can be reached from one starting point, like the “Walk Score” (Walk Score, 2017). And some focus on the connectivity and route complexity, e.g. through calculation of walking catchment areas or assessment of the walking path network, like the “Spatial Integration Accessibility” (SIA), the “Angular Segment Analysis by Metric Distance” (ASAMD) or the “Measures of Street Connectivity” (Spatialist_Lines MoSC). (Hull et al., 2012)

Furthermore, some of the instruments only cover one specific mode or are only designed for one specific purpose, while others are more comprehensive and flexible and can be adapted to different use cases, such as the “TUM Accessibility Atlas” (Büttner et al., 2018) or the “Interactive Visualization Tool” (InViTo) (Pensa et al., 2019).

Also, some instruments are interactive and easily accessible online, such as the “Erreichbarkeitsportal der Metropolregion Hamburg” (Metropolregion Hamburg, 2019) or the “WebCAT” urban planning tool (Every Journey, Transport for London, 2019), while other instruments are static and were only applied for internal projects.

However, the majority of the accessibility instruments focus on cars and public transport, while walking and cycling are underrepresented (Hull et al., 2012; Krizek et al., 2009). As a result, the scales of the applications are usually too large to perform the kind of fine-grained analyses that would be necessary at the neighborhood level. Also, there is a lack of incorporating all four accessibility components (Iacono et al., 2010). The characteristics of the population are mostly generalized and only rarely disaggregated to gender, age or physical condition. To provide comprehensive accessibility analyses, the individual needs on the provided infrastructure and its environment should be considered more carefully (Hull et al., 2012). Best would be to define a set of profiles for different user groups with functional limitations (Carlsson et al., 2002). To further include the temporal component, opening hours and temporal differences in the transportation network should be taken into account (Kim and Kwan, 2003; Pushkarev and Zupan, 1971).

In addition, most accessibility instruments do not offer the possibility to model self-developed scenarios, but only reflect the current situation. However, in order to be useful for urban planning practices, this feature should be available to illustrate the effects of possible planning projects. (Hull et al., 2012)

The requirements for a good accessibility instrument are therefore very high. One of the main challenges is the so called “rigor-relevance dilemma”, as developers mainly concentrate on the rigor but users are more interested in the relevance (Silva et al., 2019). Thus, it is important to find the right balance between level-of-detail and usefulness. As a good tool needs to be understandable, transparent, flexible und easy to use (Brömmelstroet et al., 2014).

2.5. Geo Open Accessibility Tool

In order to overcome all these shortcomings and to make the concept of accessibility more tangible, GOAT was launched as open source web-tool for accessibility analyses. GOAT was developed by Elias Pajares in the context of his master thesis at the Chair of Urban Structure and Transport Planning at TUM. In contrast to most of the existing tools, GOAT is currently focusing on walking and will soon be expanded to include cycling. The tool allows to perform dynamic accessibility analyses at neighborhood level, such as the calculation of walking isochrones and visualization of reachable Points of Interest (POIs) within a certain amount of time (see Figure 2). The accessibility calculations of GOAT are based on the gravity-based measure, developed by Geurs and van Wee (2004):

$$A_i = \sum_{j=1}^{n} D_j \, exp^{(-\beta c_{ij})}$$

This measure calculates the potential accessibility A_i of opportunities D in zone i to all other zones n, dependent on the generalized cost of travel c_{ij} and the cost sensitivity parameter β. For visualization, alpha shape isochrones with adjustable α-parameter are used.

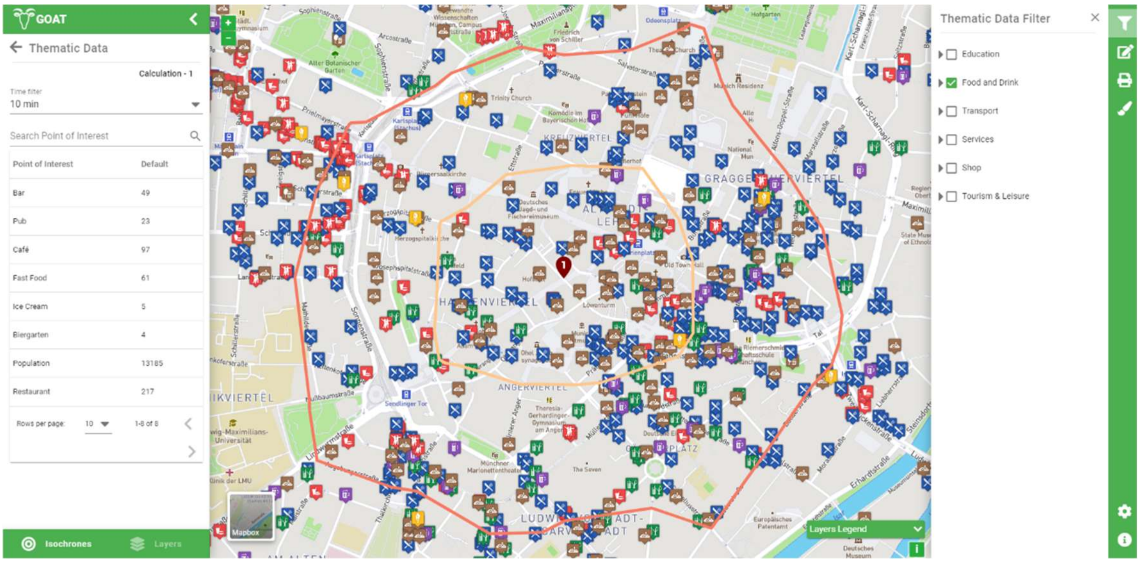

Figure 2: Screenshot of GOAT showing a 10-minutes walking isochrone from a starting point in the city center of Munich and the surrounded POIs of the category "Food and Drink" (GOAT-Community, 2019a)

In addition to the isochrones that show which amenities a user can reach, multi-isochrones show the catchment areas of amenities and indicate from which areas the population has no access to them within a given walking time. Combined with heatmaps, accessibility deficits get clearly visible (see Figure 3).

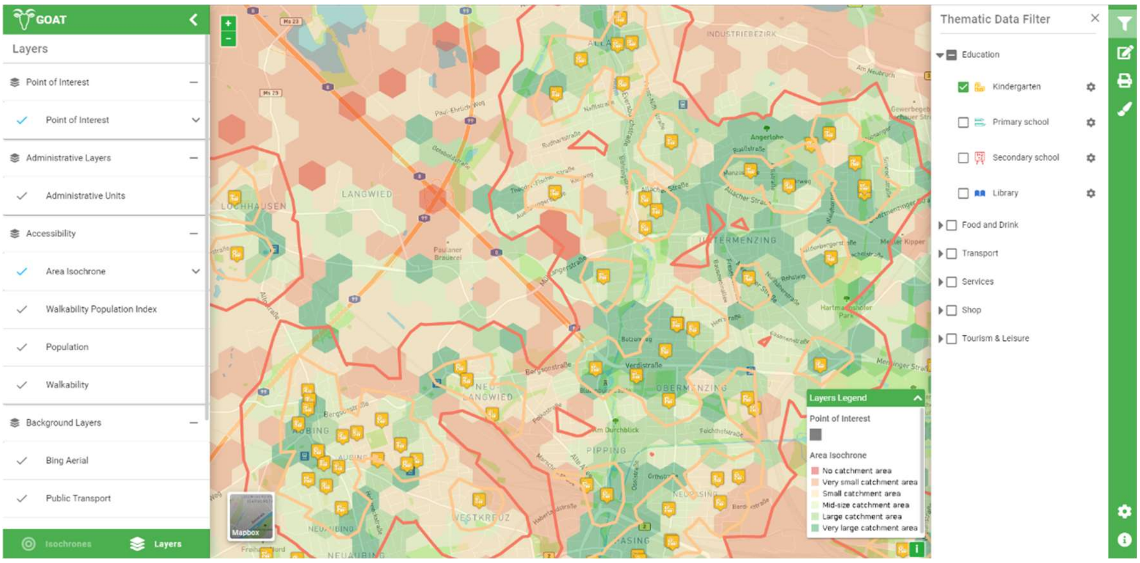

Figure 3: Screenshot of GOAT showing multi-isochrones for the 10-minutes walking accessibility catchment areas of kindergartens in the eastern districts of Munich (GOAT-Community, 2019a)

Furthermore, interactive scenarios can be calculated (e.g. construction of a new bridge across a river) and the resulting changes in accessibility assessed, as shown in Figure 4. GOAT thus offers a range of useful functions for city planners and decision-makers and acts as an important piece of the puzzle for a more sustainable mobility.

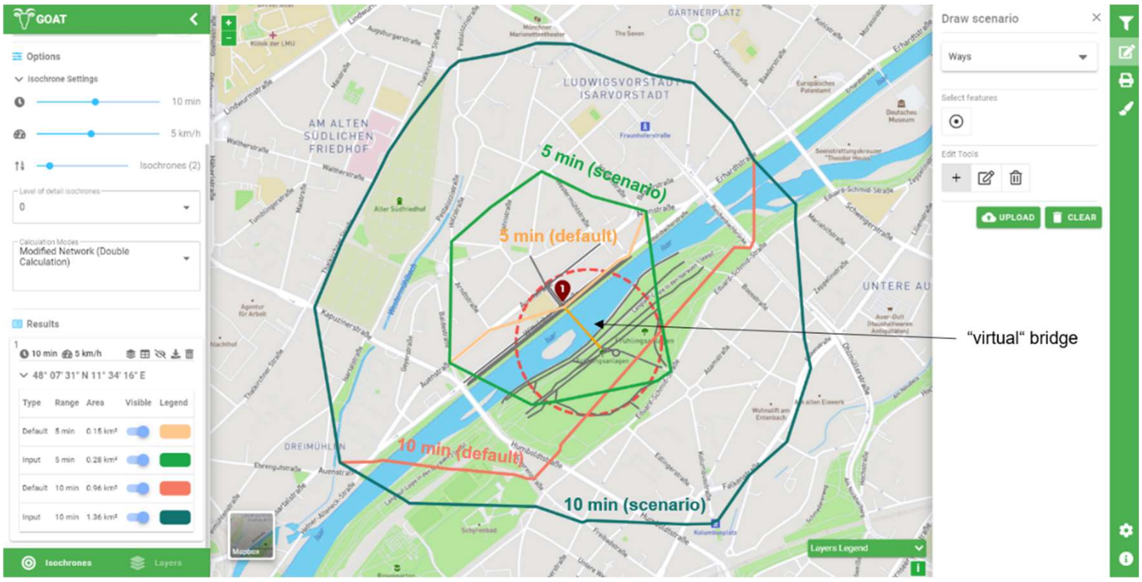

Figure 4: Screenshot of GOAT showing the accessibility differences between the current situation (yellow + orange isochrones) and a drawn scenario (green + blue isochrones) (GOAT-Community, 2019a)

It is currently available as a test version for Munich and can be transferred to any study area worldwide. (GOAT-Community, 2019b)

2.6. Open data

One of the former main problems of accessibility instruments was the lack of reliable data (Krizek et al. 2009; Geurs and van Wee 2013). This has been greatly improved by the increasing availability of open data, such as volunteered geographic information (Connors et al., 2012). One of the most popular and successful platforms for open geographic data is OpenStreetMap (OSM) (Fan et al., 2014; See et al., 2013). Due to its semantic accuracy, OSM is often the best data source for walking and cycling analyses (Zielstra and Hochmair, 2011) and is universally applicable thanks to the detail of its possible attributes (Gil, 2015). Although the OSM-dataset can be considered as rather complete in many urban areas (Graser et al., 2014; Haklay, 2010; Neis et al., 2011), the data accuracy is highly dependent on the local context and case of application (Gil, 2015).

There are numerous tools that use and progress the OSM-data to visualize specific attributes. For example, in the webtool “Street Lamps in OSM” all mapped street lamps are visualized (ubahnverleih, 2019) and with the “Parking lanes viewer” information on parking lanes can be shown and edited (zlant, 2019). The tool “finde.cash!” shows all close-by ATMs and bank branches and indicates with different colors whether they are currently open (osm-maps, 2017). The “wheelmap” created by SOZIALHELDEN e.V.

does the same for wheelchair accessibility of all kind of amenities. Another tool that includes information on wheelchair usability is the “Openrouteservice”, which provides routing and isochrone calculation for different routing profiles and allows the user to make specific adjustments of the routing settings, e.g. which surface is suitable or which minimum path width is required (Heidelberg Institute for Geoinformation Technology, 2019).

Despite the wide range of information available in OSM and the tools that use it, most of them focus only on one specific topic, such as opening hours or wheelchair accessibility, rather than combining them.

Since GOAT is meant to be an open tool, the use of open data is also part of the philosophy. For street network, buildings, POIs and land-use, OSM is used as the standard data source. (GOAT-Community, 2019b) One of the main goals of this thesis is to use the rich spatial dataset from OSM to extend GOAT by further aspects.

3. Research question

In order to make GOAT a more comprehensive tool for accessibility analyses, all four accessibility components (see Chapter 2.3) and their interdependencies should be incorporated. In GOAT the land-use component is currently represented by using population data to generate travel demand and by using POIs to provide available opportunities. The transportation component is represented by the walking path network and the corresponding walking time. Currently, all footpaths are evaluated equally, regardless of their characteristics. These two components are thus already reasonably well represented in the tool, even though there is potential to model the transportation component more realistically. In contrast, the individual component is so far only considered by providing adjustable walking speeds. Secondly, for the temporal component first attempts to include the opening hours of POIs were made by a previous bachelor thesis (Hassine, 2019), but before this option can be reliably implemented, further adjustments are necessary. Other factors, such as lighting, which changes during the day and affects walking comfort, are currently not included in the tool.

The research question of this thesis is, how can all four accessibility components be incorporated in one common accessibility instrument? In the hereby considered context of GOAT, this more specifically means: How can GOAT be extended to better incorporate the temporal and individual component of accessibility? How can the transportation component be modeled more realistically? And which quality indicators should therefore be considered?

As the project “Access to Rail” has shown, sufficient illumination is one of the most important quality indicators for walking (Pajares et al., 2019). This indicator is influenced by the temporal component, as well as the individual component, since each person may have different sensitivity levels for illumination. Besides, barrier-free accessibility was classified as particularly important (Pajares et al., 2019), not only for wheelchair users but also for persons with temporary mobility impairments, e.g. carrying heavy luggage or pushing a baby buggy. This need is highly dependent on the personal abilities influenced by age, gender and health status. By developing different routing profiles (elderly, wheelchair, safe-night), an attempt will be made to meet these user-specific characteristics, through accordingly adjustments in route choice and walking time.

The development of the safe-night routing will be a first step to show the influence of the temporal component by including the illumination and the resulting conveniently usable footpath network by night. However, not only the transportation component is subject to the influence of the temporal differences, but also the land-use component is influenced by changes in the availability of accessible destinations defined by opening hours. This thesis eagers to visualize this change in accessibility by implementing a time picker in the frontend, which allows the user to choose a reference time, and by optimizing the existing backend functions to dynamically react on the given input and only considering the open amenities.

To improve the transportation component, it will be examined how further quality indicators of walking comfort, such as sidewalk width, surface and availability of street crossings, can be integrated. Information about car traffic, e.g. maximum speed, number of lanes and parking regulations, also seem to be insightful, as they also influence walking comfort. The aim is to create new layers for the individual attributes, which the user can display in the frontend to get a better picture of how walkable an environment is.

In Figure 5 the schema of the four accessibility components developed by Geurs and van Wee (2004) is applied to GOAT and shows all components and associated attributes that are supposed to be integrated into GOAT by the end of this thesis.

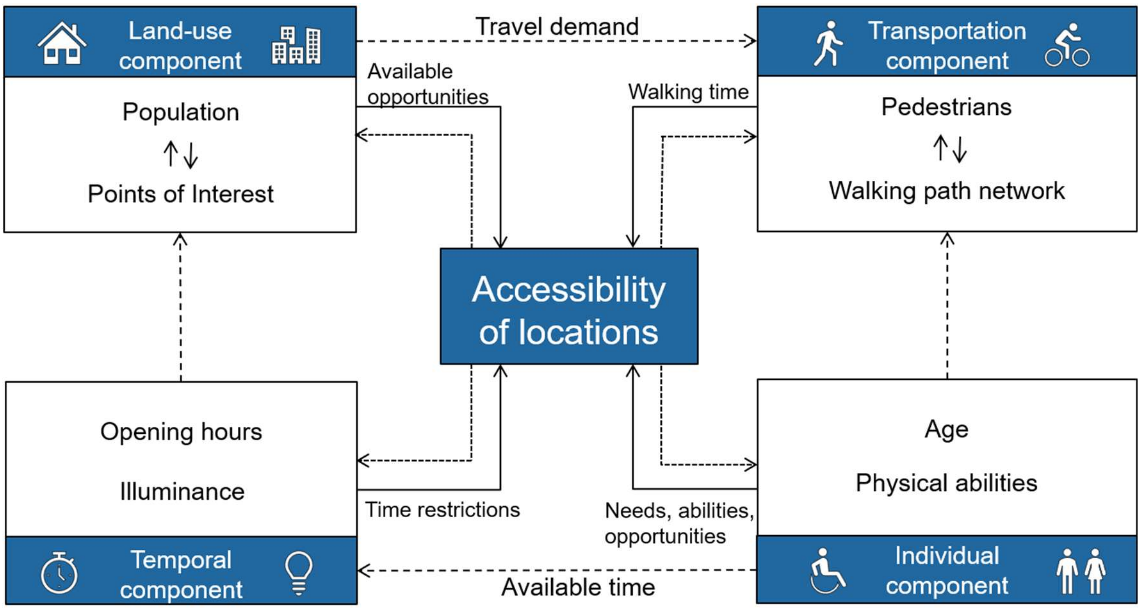

Figure 5: Integration of the four accessibility components in GOAT (adapted from Geurs and van Wee 2004)

Finally, besides the development of a more individualized routing and the integration of objectively measured walkability layers, it will be aimed to also integrate subjective views. There is certainty that subjective feelings affect walking accessibility essentially (Pajares et al., 2019), but since it cannot be measured, it is difficult to weigh their influence. Thus, other ways have to be found to illustrate the interdependencies. The further idea of this thesis is to test, how a visual link between objective measurements of pedestrian infrastructure and subjective point-related pedestrian statements on perceived walking accessibility can be created.

By embedding the new options in the GOAT user interface, the accessibility analysis can be carried out interactively and provide valuable insights into how different groups of people are influenced in their accessibility by different temporal and individual settings. The results are aimed to help decision makers as planning support tools in favor of designing more walkable and inclusive environments.

4. Overview of the methodology

This chapter gives an overview of the methodology used in this thesis. The exact approaches used for the different steps are explained in the corresponding chapters below.

The implementation of detailed analyses options, including all four accessibility components, depends heavily on constraints, such as data availability and computational complexity (Geurs and van Wee 2013). Therefore, good data sources were needed to ensure useful results. As the focus of this thesis is on POIs and footpaths, for which OSM is regarded as the best available open data source (Zielstra and Hochmair, 2011), OSM is used. Despite the high level of completeness of the total amount of objects (Haklay, 2010), important attributes such as sidewalk availability or path width are rarely mapped (Mobasheri et al., 2015). Thanks to the open crowd-sourcing structure of OSM, required attributes can easily be added by any user. This procedure was tested in the context of this thesis. First, attributes to be defined were recorded. Therefore, all walking quality criteria listed in Table 1 were reviewed to determine whether they can be recorded in OSM and which tags are provided for this purpose (see Table 2).

Table 2: Capability of recording the walking quality indicators in OSM

Quality criteria	Recordable in OSM	Provided tags
Sidewalk availability	Yes	sidewalk
Sidewalk width	Yes	sidewalk:width
Pavement quality	Yes	surface, smoothness
Number of lanes	Yes	lanes
Traffic load and street noise	No, can only be assumed by road category and number of lanes	-
Share of heavy-load vehicles	No	-
Speed limits	Yes	maxspeed
Number of road crossings	Yes	crossing
Spatial separation between road and footpath	Represented through geometry	-
Parking vehicles on the road or on the sidewalk	Only parking on the road can be mapped	parking

Illumination	Yes	lit
Cleanliness	No	-
Vegetation	Yes	natural
Weather protection	Limited, can only be represented through vegetation or roofs	-
Inner-city aeration	No	-
Land-use	Yes	landuse
Number of POIs along the route	Yes	amenity
Population density, liveliness	No	-
Built environment	Can be represented via the infrastructure but hard to evaluate	-
Pedestrian flow rate	No	-
Directness, connectivity	Represented through street network	-
Slope of the sidewalk	Yes	incline
Waiting time at traffic signal	No	-
Width of the street crossing	Yes	width
Freedom from barriers	Yes	wheelchair
Orientation	No	-
Social hotspots	No	-
Street furniture	Yes	amenity
Public toilets	Yes	amenity
Drinking fountains	Yes	amenity

In order to test the methodology developed in this thesis, a study area was defined. All quality indicators that were rated as recordable in OSM were later captured in the mapping process for the entire study area, with exception of vegetation. Mapping these features would have required much effort, and the expected added value with regard to the walkability analysis would be rather low. For other areas, where sun protection is more decisive, this assessment might be different.

The attributes captured in OSM are then processed in different routing profiles to reflect the temporal and the individual component of accessibility. Although the individual component has an infinite number of possibilities in terms of physical abilities and personal characteristics, representing all possible variations would be too detailed and not useful for a model. Therefore, this thesis concentrates on providing a few user profiles, which can be customized to the specific case of application.

Some quality indicators, such as social hotspots, cannot be captured in OSM and are generally difficult to measure objectively. In order to obtain a complete picture of walkability, it is therefore inevitable to integrate self-reported statements on perceived walking quality. This thesis shows how these subjective feelings can be combined with the objective measurements by bringing them together in a common tool.

The methodical procedure deployed in this thesis can be divided into five main sections (see Figure 6).

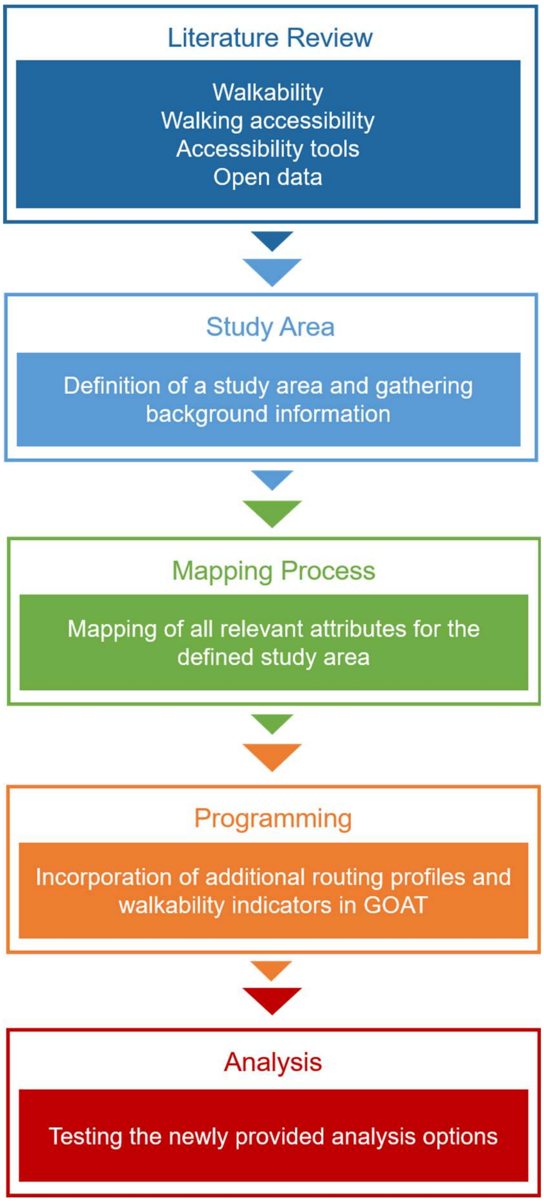

Figure 6: Methodological structure

To introduce the topic of this thesis, the relevant literature has been summarized in Chapter 2. Afterwards, Chapter 5 gives an overview of the chosen study area and its characteristics. Then, the mapping process carried out for the study area is explained (Chapter 6). Regarding the mapping process, the backend functions were first edited to provide the new routing options (Chapter 7) and then the frontend was adapted to visualize the added features and to view the new layers, including a test layer for self-reported statements on perceived walkability (Chapter 8). In Chapter 9, an analysis for the study area was carried out using the new functions of GOAT to examine their usefulness. Finally, Chapter 10 reflects and critically evaluates the results of this thesis.

The GOAT version developed in this thesis can be found on the accompanying digital medium. All functions and files that were adjusted within the frame of this thesis are listed in the Appendices.

5. Study area

For spatial differences in walking accessibility to become visible, a diverse environment is required. Therefore, the district parts “Hasenbergl-Lerchenau Ost” and “Lerchenau West” (hereinafter referred to as “Hasenbergl-Lerchenau”) of district 24 “Feldmoching-Hasenbergl” of the City of Munich were chosen as study area, as this area is versatile and known as a former social hotspot. In Figure 7 the selected area is highlighted in blue.

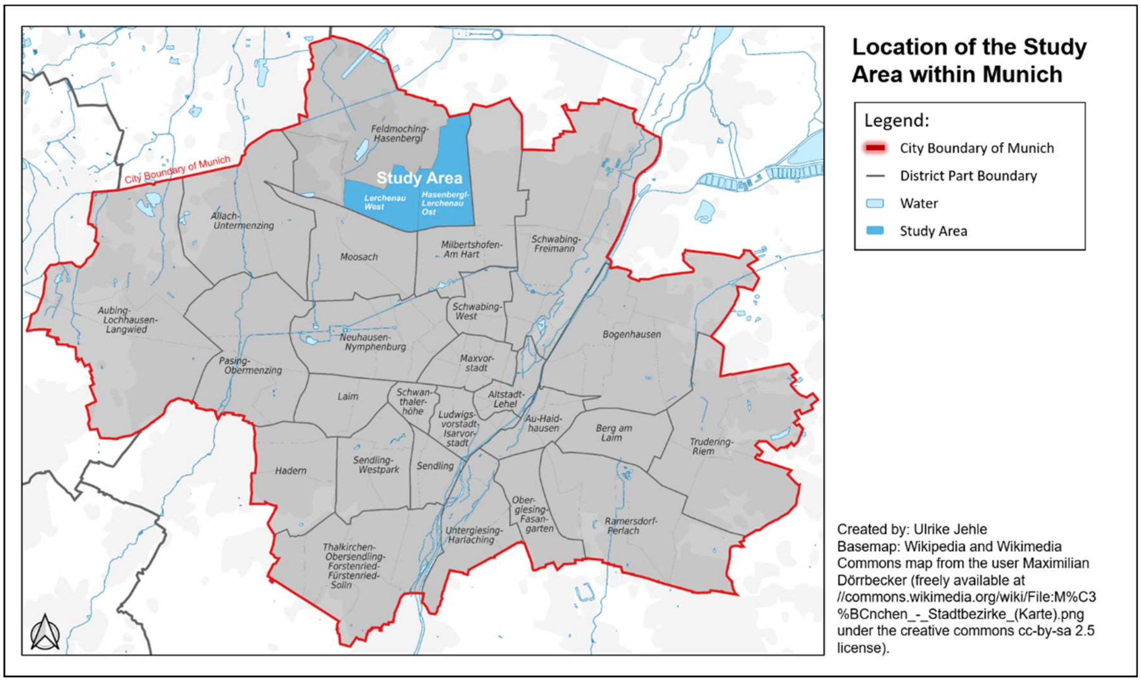

Figure 7: Location of the study area within Munich

Hasenbergl-Lerchenau is located in the north of Munich, bounded by the Reigersbach in the west, the railway area in the south, the Schleißheimer Straße in the east, and a concatenation of the city boundary of Munich, agricultural areas, the Weitlstraße, the Malvenweg, the railway line Munich-Regensburg, the Lerchenauer Straße, the Georg-Zech-Allee, the Feldmochinger Straße and the Am Schnepfenweg in the north. Figure 8 gives an overview of the spatial conditions and the names of the local subdistricts.

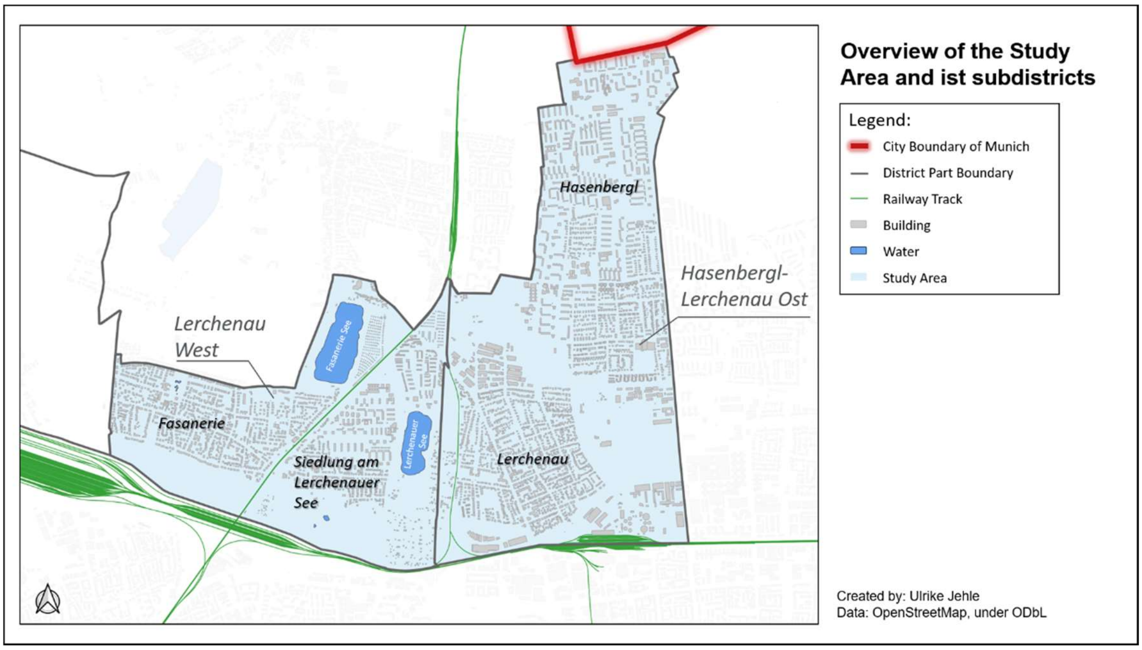

Figure 8: Overview of the study area and its subdistricts

The area has a diverse structure, including small single-family homes and large social housing blocks, as well as car-oriented commercial zones and pedestrian-oriented recreation areas (see Figure 9). Of particular interest is the high proportion of unlit footpaths, which will have influences on the temporal accessibility component. Also, there is high variability in sidewalk availability and sidewalk width.

Figure 9: Diverse structure of Hasenbergl-Lerchenau (left image: Lechenauer See, right image: Glockenbecherstraße)

5.1. Historical Background

The name Hasenbergl can be traced back to the Bavarian electors who hunted rabbits in this area south of Schleißheim Castle (Jocher-Wiltschka, 2011). The topography was conspicuous, in the completely flat area a small clay hill was to be found here. Due to the occurrence of rabbits, the hill was called “Kaninchenberg” (*English: “rabbit hill”*). In the 19th century this name was gradually replaced by “Hasenbergl” (*English: “hare hill”*) (Landeshauptstadt München, 2015a).

The Lerchenau area has long been nominal characterized by the numerous larks that can be found there. Even before the settlement was founded there was a restaurant called “Lerchenau” (*English: “lark meadow”*) (Landeshauptstadt München, 2015a).

At the beginning of the 20th century, “Fasanerie” and “Lerchenau” emerged as the first settlements in this area (Statistisches Amt der Landeshauptstadt München, 2019). In the 1920s, the two settlements counted around 40 houses (Landeshauptstadt München, 2015a; Strobach, 2019). Both settlements expanded to accommodate war refugees and immigrating employees from large companies such as BMW (Strobach, 2019). From 1960 onwards, the settlements “Hasenbergl” and “Lerchenauer See” were built due to housing shortages, with over 96% municipally subsidized apartments (Jocher-Wiltschka, 2011; Statistisches Amt der Landeshauptstadt München, 2019). In the 1980s Hasenbergl was regarded as a social hotspot (Immobilienreport, 2019) with a high concentration of low-income groups and a high share of youth unemployment (Landeshauptstadt München, 2015b). In the 1990s, the city attempted to revitalize the area by declaring it as a redevelopment area and investing subsidies to expand educational opportunities, improve infrastructure and enhance the quality of life (Landeshauptstadt München, 2015b). But despite the city's many efforts, the district is still not entirely free of its bad reputation.

5.2. Social Structure

The study area covers an area of 869 ha with a population of 46,953 inhabitants. Figure 10 shows the social structural data for the two subdistricts Lerchenau West and Hasenbergl-Lerchenau Ost in comparison to Munich.

Today, Hasenbergl-Lerchenau has a foreigner share of 32.9% which is above the Munich average of 28.1% and an unemployment rate of 4.9%, which is as well above the Munich average of 3.5% (Landeshauptstadt München, 2018). It is noticeable that in the district part of Hasenbergl-Lerchenau Ost both the percentage of foreigners and the percentage of unemployed are significantly higher than in Lerchenau West.

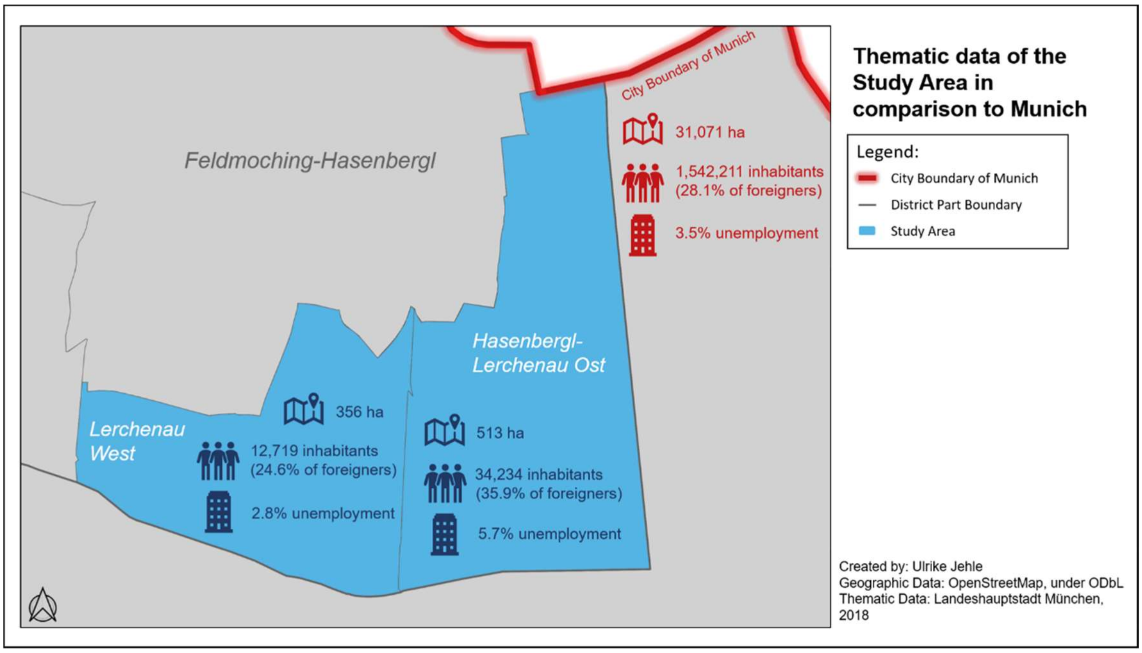

Figure 10: Facts about the study area in comparison to whole Munich

In Hasenbergl-Lerchenau the moving rate is very low (215.5 of 1,000 inhabitants moved in/out in 2018) in comparison to Munich (283.1 of 1,000 inhabitants). As a result, the average period of residence at the current address is 13.3 years and above the Munich average of 11.0 years. This may be due to the high proportion of households with children (22.5%) (Landeshauptstadt München, 2019a) compared to Munich (17.1%) (Landeshauptstadt München, 2019b), cheap and partly subsidized housing and an above-average share of elderly residents. Another reason for the low moving rate may be that Hasenbergl has the highest debtor rate in Munich at 15.73% (Landeshauptstadt München, 2017). The average age of the residents in Hasenbergl-Lerchenau is 41.6 years and slightly above the Munich average of 41.2 years. (Landeshauptstadt München, 2018)

5.3. Transportation

Hasenbergl-Lerchenau is connected by public transport to the city center with two rail-based transport stations in the study area. The underground line U2 stops at "Hasenbergl" and the suburban train S1, which connects Munich city center with the airport, stops at "Fasanerie". Several other stations of these two public transport lines are located near the study area. Furthermore, there are six bus lines (60, 170, 172, 173, 175 and 179) driving through the area and several lines passing near-by (Münchner Verkehrs- und Tarifverbund GmbH, 2019). In Figure 11, all underground trains, suburban trains and bus lines in and around the study area are shown.

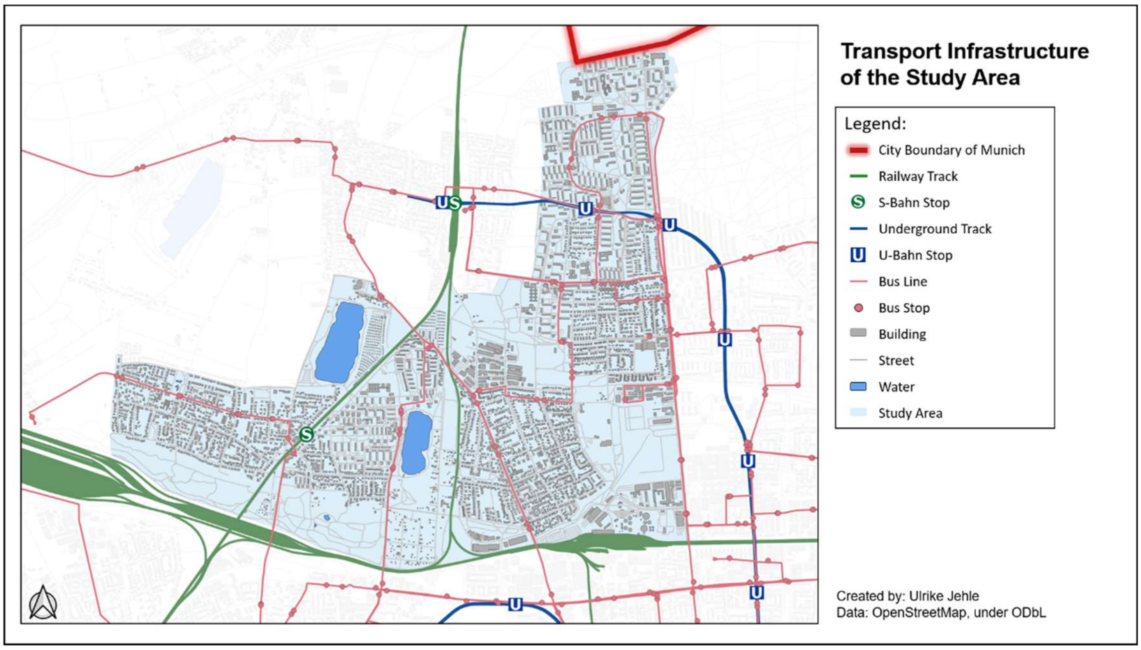

Figure 11: Transport infrastructure of the study area

With around 18,000 registered cars in Hasenbergl-Lerchenau, the average car density is 387 cars per 1,000 inhabitants and below the Munich average of 464 cars per 1,000 inhabitants (Landeshauptstadt München, 2018). This implies that residents are more dependent on other transport modes as public transport, walking and cycling.

5.4. Land-Use

Hasenbergl-Lerchenau is a predominantly residential area with a high share of council houses (Statistisches Amt der Landeshauptstadt München, 2019). Despite the low car ownership, there is a 20 ha car-oriented commercial area in the middle of the study area with supermarkets, a drugstore, a bakery and some other shops. The south-east of the area is industrial and influenced by the near-by production site of BMW. Another striking feature of this area is the high number of green spaces. The Lerchenauer See and the Fasanerie See are two large recreational areas in the study area.

In Figure 12 the land-use of Hasenbergl-Lerchenau is visualized. Shown in dark blue are community areas such as schools or public halls, which are evenly distributed throughout the district. It is striking that the two settlements Lerchenau and Hasenbergl are separated by a strip of farmland.

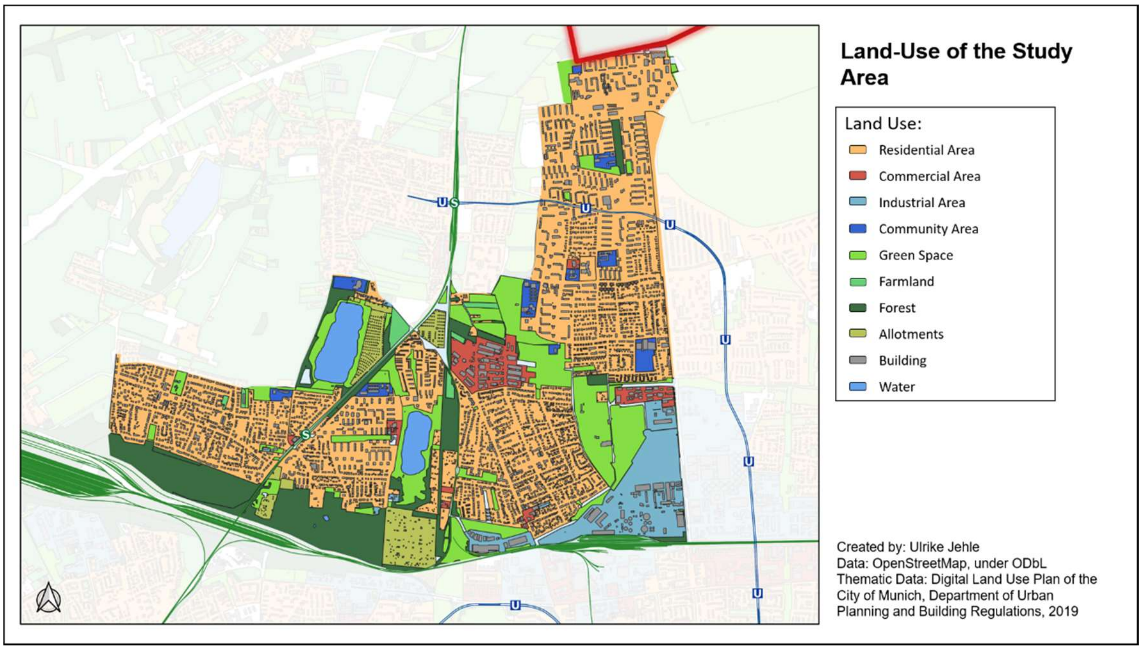

Figure 12: Land-use of the study area

Figure 13 shows the spatial distribution of the POIs in the study area. Most amenities are clustered along the Lerchenauer Straße, the Schleißheimer Straße and around the S-Bahn station “Fasanerie”. Smaller district centers can be found west of the Lerchenauer See, at the underground station “Hasenbergl” and at the intersection of Weitlstraße and Rainfahrnstraße.

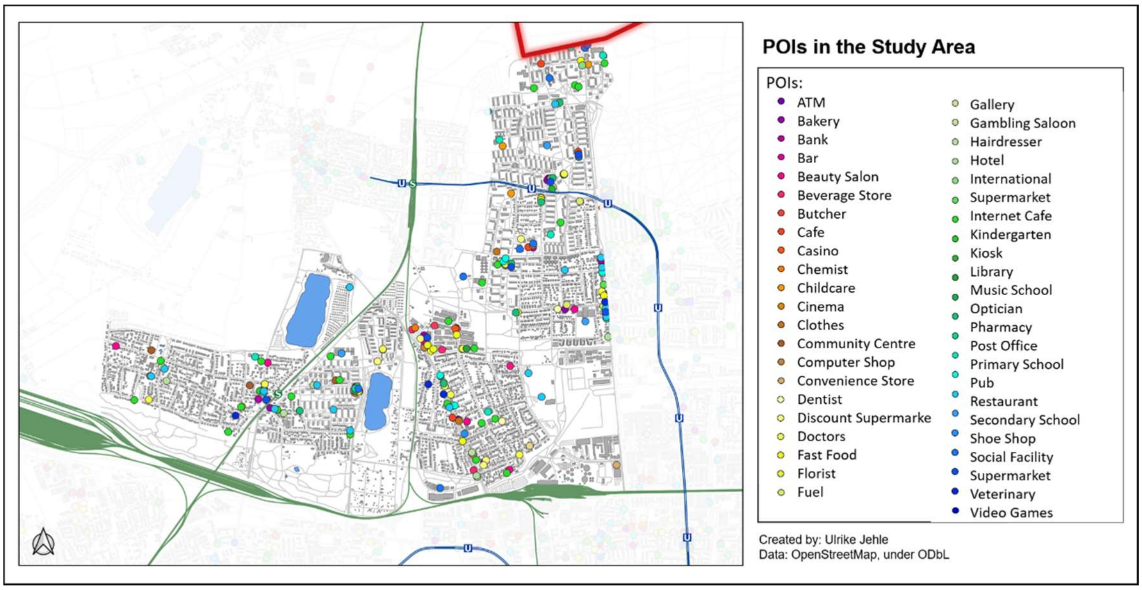

Figure 13: POIs in the Study Area

6. Data collection with OSM

In order to be able to carry out good analyses, reliable data were needed for the entire study area. Therefore, all relevant objects (paths, POIs) for this study were collected in OSM. In 20 days of on-site mapping and off-site data preparation, 2,000 paths with a total length of more than 200 km were edited in OSM. This chapter explains how the data was collected, which attributes and tags were captured and how the data quality was improved by the mapping process.

6.1. Data aggregation

The mapping process was performed following this general workflow:

1. Printing a map with all paths and POIs to get an overview.
2. On-site mapping with “Go Map!!”.
3. Checking with overpass turbo, whether all required tags were assigned to all paths.
4. Assignment of missing tags with the Java-OpenStreetMap-Editor (JOSM) or the iD Editor, or if necessary another on-site visit.

6.1.1. On-site mapping with “Go Map!!”

Most of the data was gathered on-site with the iPhone app “Go Map!!”. This app captures the current location via GPS and shows the surrounding OSM-data as well as a background aerial picture on the smartphone screen. By selecting an object, all corresponding tags are displayed and can be edited (see Figure 14). Also, new tags and objects can be added. The app provides some options that make it easier to edit the data. For example, objects can be duplicated, or tags copied and assigned to another object.

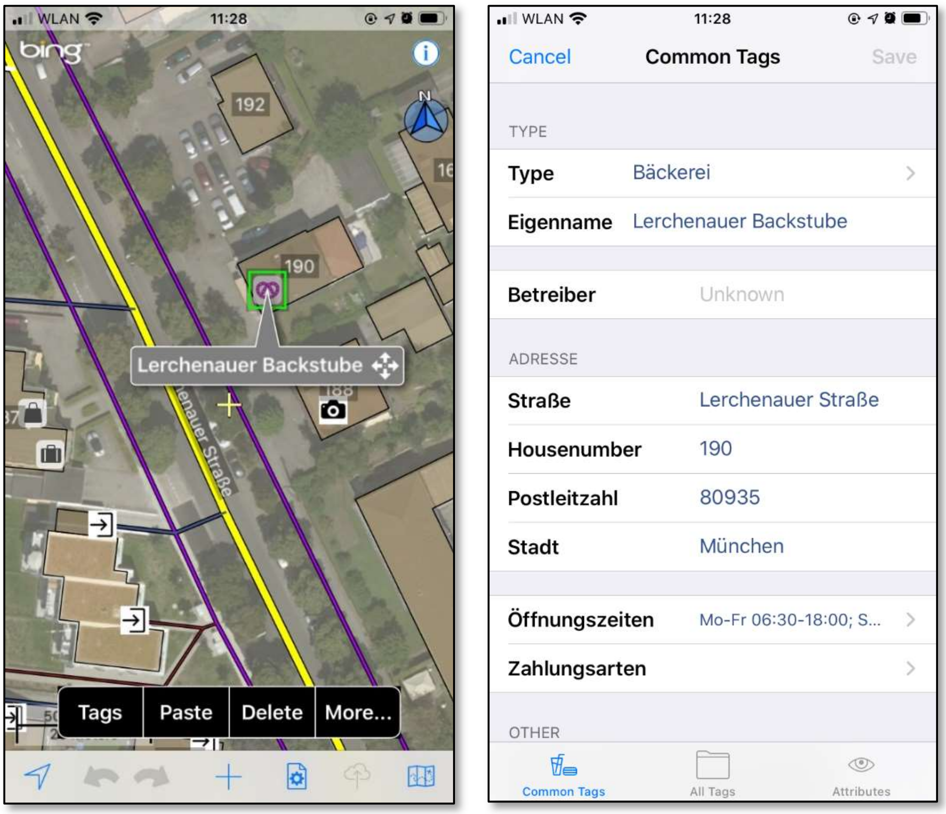

Figure 14: Screenshots of the app “Go Map!!” (Cogswell, 2019)

6.1.2. Query with overpass turbo

With the webtool overpass turbo (https://overpass-turbo.eu/#), queries on the OSM-data can be executed. This tool can be used, for example, to identify for which paths no width is stored, or which POIs have missing information about the opening hours.

A selection of the executed queries can be found in Appendix A. Figure 15 shows an example query and the resulting data.

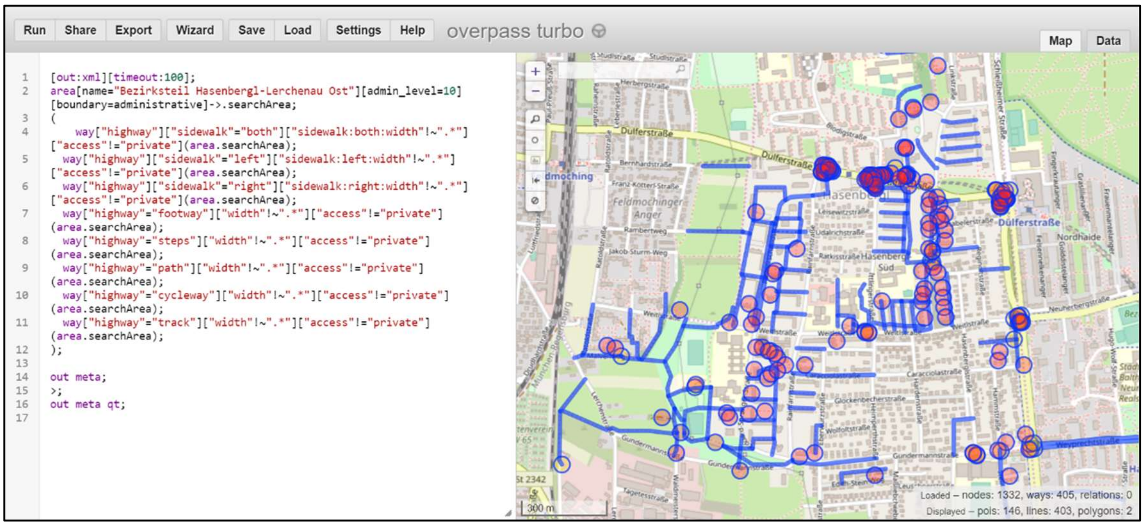

Figure 15: Screenshot of overpass turbo, querying all pedestrian paths with missing width (Raifer, 2019)

6.1.3. Mapping with JOSM

The resulting data from overpass turbo can directly be loaded in JOSM. There, the data can be further filtered and edited (see Figure 16). The finished changesets are uploaded to the OSM server.

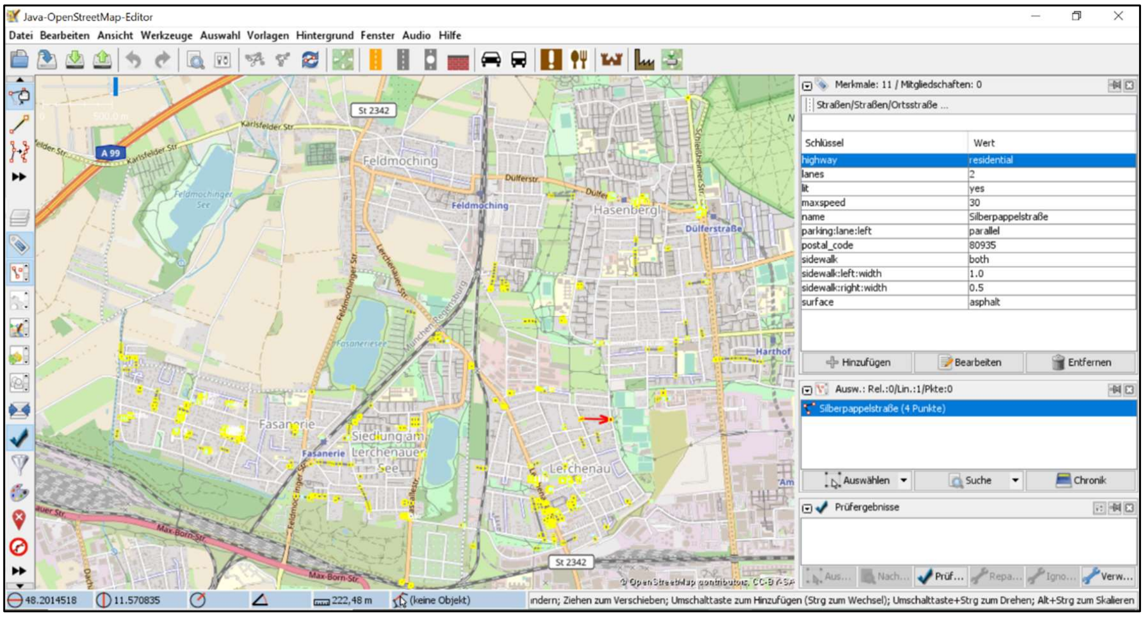

Figure 16: Screenshot of JOSM (Stöcker, 2019)

6.1.4. Mapping with iD Editor

Additionally, small edits of missing or faulty data are done with the OSM iD Editor. Via aerial background images and Mapillary pictures (georeferenced on-street pictures taken by users) information about illumination, street crossings, etc. can be assigned. Unfortunately, Mapillary datasets are only available for a few streets in the study area. Furthermore, detailed information about e.g. the sidewalk width cannot be captured through the pictures. Therefore, onsite inspections are indispensable.

6.2. Captured attributes and used tags

In OSM, objects are mapped as point (e.g. POI), line (e.g. street) or area (e.g. land-use). To each object several features can be assigned. This is done by using tags. Each tag consists of a key (e.g. *highway*, which classifies any kind of road or path) and a value (e.g. *footway*), written as *highway=footway*. In order to classify all route connections and accessible POIs for this thesis as desired, several tags are necessary. The number of tags required depends on the object type and its characteristics. Also, some tags are only useful in a certain combination. Figure 17 and Figure 18 show examples of two different paths and their assigned tags.

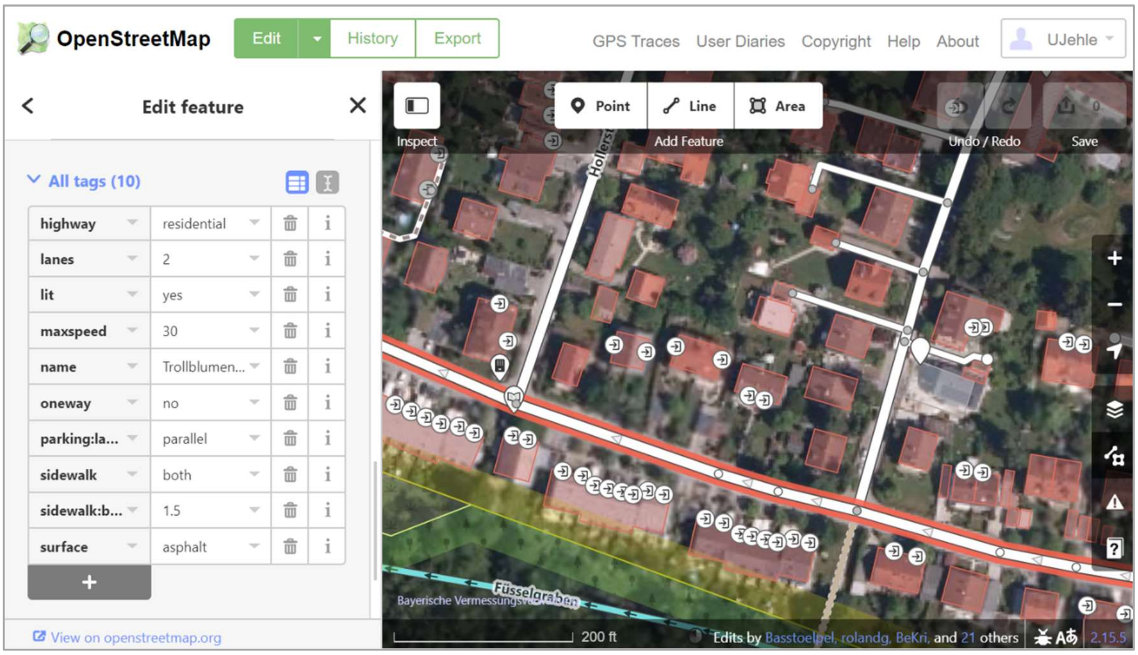

Figure 17: Residential street "Trollblumenstraße" with its assigned tags, shown in iD Editor (Housel and Morgan, 2019)

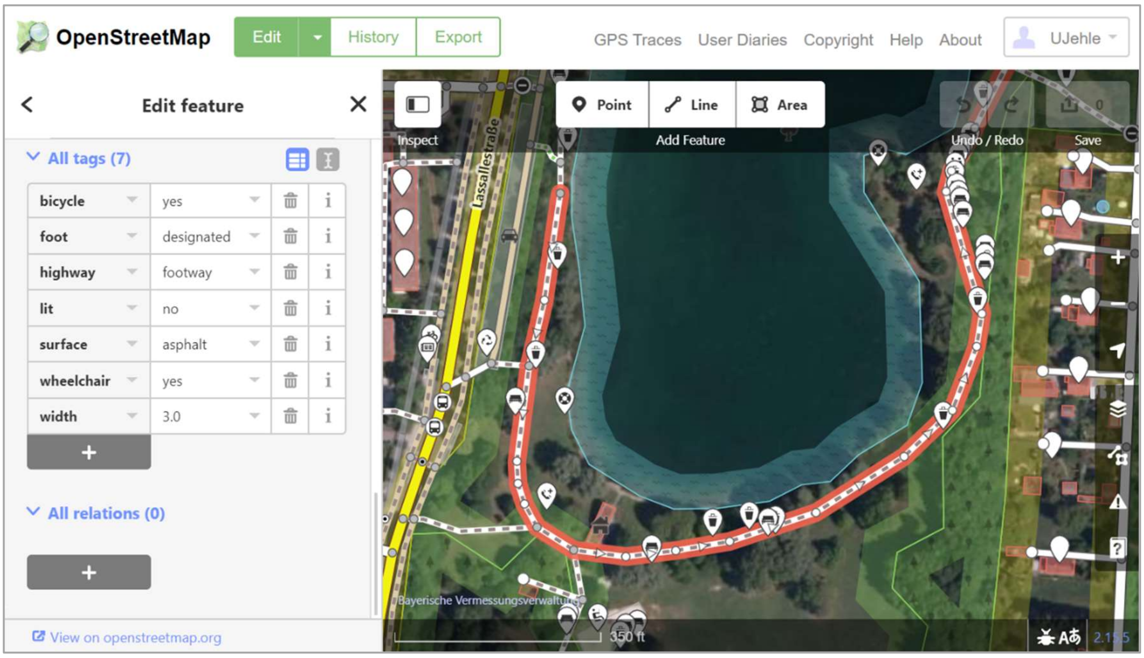

Figure 18: Footpath around the Lerchenauer See with its assigned tags, shown in iD Editor (Housel and Morgan, 2019)

All tags are valid for the entire section, which means that if an attribute changes along the path, the path was split. In the following subchapters all used tags are explained in detail.

6.2.1. Road type

The key *highway* is used to classify any kind of road or path. The road or path type is specified by the values listed in Table 3.

Table 3: Used values to the key *highway* (OSM Community, 2019)

Value	Explanation
secondary	Mayor roads in the study area, with the function of connecting settlements, the maximum speed is usually 50 km/h.
tertiary	Mayor roads, without function of connecting settlements, the maximum speed is usually 50 km/h.
residential	Minor roads, without function of connecting settlements, the maximum speed is usually 30 km/h.
living_street	Residential streets where pedestrians have legal priority over cars, marked with traffic sign 325 “verkehrsberuhigter Bereich” of the StVO.
service	Access roads to a property, parking lot etc.
track	Roads used mainly for agricultural or forestry purposes.
footway	Designated footpaths.
steps	Flight of steps on footways.
cycleway	Designated cycleways.
path	Non-specific paths.

6.2.2. Allowed access

Some *highways* have restricted access depending on the mode type or individual permission. In some cases, these restrictions may be directly derived from the value (e.g. a *footway* is designated for pedestrians and motor vehicles are not permitted). In general, the local signs provide information about the right of use. If there were no signs, it was assumed that access is permitted for each mode type and without individual permission.

Access rights can be specified for *foot*, *motor_vehicle*, *bicycle* or *all* together. The values used in the study area are listed in Table 4. This tag can not only be assigned to streets, but also to specific points in the network that regulate the access (see 6.2.15 Barriers).

Table 4: Used values to the key *access* (OSM Community, 2019)

Value	Explanation
yes	Public access is generally permitted (right of way).
no	No public access.
private	Access only with individual permission.
permissive	On private property, but open access to general traffic.
destination	Local traffic only.
designated	Designated route for a specific user group, usually pedestrians or cyclists, marked with traffic signs 237, 239, 240 or 241 of the StVO.
use_sidepath	If there is a close-by footpath/cyclepath which should be used.

6.2.3. Segregation of pedestrians and cyclists

If a *path*, *footway* or a *cycleway* is tagged with both *foot=designated* and *bicycle=designated*, it is further distinguished whether these two traffic streams are segregated or not by using the key *segregated* and the values shown in Table 5.

Table 5: Used values to the key *segregated* (OSM Community, 2019)

Value	Explanation
yes	Pedestrians and cyclists are segregated by clear markings, referring to traffic sign 241 “Getrennter Fuß-und Radweg” of the StVO.
no	Pedestrians and cyclists are not segregated, referring to traffic sign 240 “Gemeinsamer Fuß-und Radweg” of the StVO.

6.2.4. Width

For *footways*, *cycleways*, *tracks, steps* and *paths* the *width* was assigned (see Table 6). If the width varies irregularly, a mean value was assumed. Small beaten paths (“Trampelpfade”) are mapped consistent with a width of 0.5 m.

Table 6: Used values to the key *width* (OSM Community, 2019)

Value	Explanation
0.5 … 7.0	Width of the road in [m].

6.2.5. Number of lanes

For *secondary*, *tertiary*, *residential*, *service* roads and *living_streets*, the number of lanes were assigned (see Table 7).

Table 7: Used values to the key *lanes* (OSM Community, 2019)

Value	Explanation
1 … 4	Number of lanes.

6.2.6. Maximum speed

For *secondary*, *tertiary* and *residential* roads, the maximum permitted speed was recorded (see Table 8). For *service* roads there is usually no official speed limit, as they are mostly on private ground. *Living_streets* are legally limited to walking speed. As this is the same for all *living_streets*, the *maxspeed* must not be mapped additionally.

Table 8: Used values to the key *maxspeed* (OSM Community, 2019)

Value	Explanation
10 ... 50	Speed limit in [km/h].

6.2.7. Parking along the road

It was also documented where cars park along the road and how the parking spaces are arranged (see Table 9). This was the case in *secondary*, *tertiary*, *residential* roads and *living_streets*. The sides of the road (*right/left*) are captured in the mapping direction (marked with arrows in the OSM editor).

Table 9: Used values to the key *parking:lane:both/right/left* (OSM Community, 2019)

Value	Explanation
parallel	Parking parallel to the road.
diagonal	Parking at a diagonal angle.
perpendicular	Parking at a right angle to the road.
marked	Parking only in some marked areas.

6.2.8. Sidewalk availability

For *secondary*, *tertiary* and *residential* roads, it was specified whether there is a sidewalk or not and if so, on which side of the road the sidewalk is located (see Table 10). The sides (*right/left*) are captured in the mapping direction. As *service* roads usually have no sidewalk, the tag was only given if they exceptionally had one.

Table 10: Used values to the key *sidewalk* (OSM Community, 2019)

Value	Explanation
no	No sidewalk at all.
both	Sidewalk on both sides.
right	Only a sidewalk on the right side.
left	Only a sidewalk on the left side.
separate	Sidewalk is mapped as separate object.

6.2.9. Sidewalk width

If there was a sidewalk, the width was specified (see Table 11).

Table 11: Used values to the key *sidewalk:both/right/left:width* (OSM Community, 2019)

Value	Explanation
0.5 … 4.0	Width of the sidewalk in [m].

The width is a feature that is easy to measure but is influenced by many factors that change quickly and therefore cannot be mapped reliably. In some cases, the mapped width may vary from the actual usable width. The most frequently observed problem hereby was that cars were parked on the sidewalk. Since this is disorderly and should not be the rule, the entire pavement width was measured and this parking state was mapped with *parking:lane:both/right/left:parallel*. This is the same tag as used for parking on the street, but sidewalk parking has a much greater impact on walking comfort.

A further problem observed is vegetation (especially hedges) that protrude beyond the property boundaries onto the footpath and thus reduce the usable width. Figure 19 shows an example of a sidewalk that can only be used halfway due to obstacles.

Figure 19: Cars parked on the sidewalk and vegetation protruding beyond the properties impair the width of the sidewalk.

6.2.10. Surface

Furthermore, the surface of all *highways* was mapped (see Table 12). Some surfaces may restrict the accessibility, e.g. for wheelchair users.

Table 12: Used values to the key *surface* (OSM Community, 2019)

Value	Explanation
asphalt	Short for asphalt concrete.
concrete	Cement based concrete.
paving_stones	Relatively smooth surface paved with artificial blocks.
unpaved	Any unpaved surface. Only used when a more precise description was not possible.
compacted	Compacted surface containing of smaller and larger parts (e.g. sand and gravel).
fine_gravel	Smooth surface of fine gravel.
gravel	Coarse gravel, usually loosely arranged.
grass	Grass covered ground.
ground	No special surface, e.g. the case for beaten paths.

6.2.11. Smoothness

If the surface of a *sidewalk*, *footway*, *shared cycleway*, *track*, *path* or a *residential* road without *sidewalk* was exceptionally uneven or smooth, it was labeled with the tag *smoothness* (see Table 13).

Table 13: Used values to the key *smoothness* (OSM Community, 2019)

Value	Explanation
excellent	Usable by all vehicles, also with thin rollers as roller blade and skateboards.
good	Usable by vehicles with thin wheels as racing bikes.
intermediate	Usable by vehicles with normal wheels as city bikes and scooters.
bad	Usable by vehicles with robust wheels as trekking bikes.
very_bad	Usable by vehicles with high clearance.

Figure 20 shows an example of a road with *bad smoothness* and for comparison an example with *excellent smoothness*. Although there are recommendations for the use of the individual values, the boundaries are very fluid and are defined slightly differently by each user. The explanations given in Table 13 are taken from the OSM-Wiki (OSM Community, 2019). However, a road with a *good smoothness* could also be used by vehicles with thin rollers, it just might be not as comfortable as a road with *excellent smoothness*. Due to this fluid boundaries, it will be difficult to define in the further steps up to which smoothness a path can still be used by which user group.

Figure 20: left: Feldbahnstraße with *bad smoothness*; right: Wilhelmine-Reichard-Straße with *excellent smoothness*

6.2.12. Incline

If there was an incline on a *highway* - which was very rarely the case in this study area - it was mapped with the corresponding tag (see Table 14). The incline (*up/down*) is captured in the mapping direction (marked with arrows in the OSM editor).

Table 14: Used values to the key *incline* (OSM Community, 2019)

Value	Explanation
up	Path going uphill. Used for small inclines or steps.
down	Path going downhill. Used for small inclines or steps.
10% … 25%	Path going uphill with an incline of …%.
-10% … -25%	Path going downhill with an incline of …%.

6.2.13. Illumination

There are two ways of mapping the illumination in OSM. One option is to assign the tag *lit* to the street as way attribute. The second option is to map every single *street_lamp*. For this mapping process, the first option was used. Thus, for all *highways* was mapped, if they are lit or not (see Table 15). In some cases, this was difficult to define, especially when footpaths do not have their own streetlamps but are close to other lit paths. In such cases, it was decided at personal discretion whether the incoming lighting is still sufficient.

Table 15: Used values to the key *lit* (OSM Community, 2019)

Value	Explanation
yes	Path is lit.
no	Path is unlit.

6.2.14. Street crossings

Street crossings can be mapped as node or line with the key *crossing* and defined with the values provided in Table 16.

Table 16: Used values to the key *crossing* (OSM Community, 2019)

Value	Explanation
traffic_signals	Street crossing with traffic lights for the crossing stream.
uncontrolled	Street crossing without traffic signals but with road markings.
zebra	Zebra crossing.
unmarked	Street crossing without traffic lights or road markings.

By adding additional tags, the street crossing can be further specified. If the curb (*British English: "kerb"*) was lowered, the tag *kerb=lowered* was given. Furthermore, it was defined if it is accessible by *wheelchair* (see 6.2.16 Wheelchair accessibility) and if there is a *tactile_paving*.

6.2.15. Barriers

Barriers, which are built to limit the access to a specific user group or for temporal restrictions, can be mapped as node on a *highway* (see Table 17). They usually only exist on *footways*, *cycleways*, *paths* and *service* roads.

Table 17: Used values to the key *barrier* (OSM Community, 2019)

Value	Explanation
block	Large solid block.
bollard	Pillar in the middle of the road.
cycle_barrier	Barriers to cycle traffic. Usually a pair of staggered steel bars perpendicular to the way.
gate	Entrance that can be opened or closed.
lift_gate	Barrier that can be lifted. Usually used at the entrance of parking lots.
swing_gate	Similar to a lift gate but rotates sideways to open.

Merely constant barriers were recorded. Barriers such as fallen *logs* were not mapped, as they are only considered as a temporary situation.

The *barrier* type gives a rough indication of which vehicles can pass through. In order to define this exactly, the *access* needs to be additionally tagged (see 6.2.2 Allowed access). In the case of a temporal restriction such as at the gate to the community garden in Figure 21, the *opening_hours* were assigned.

Figure 21: The gate to this community garden can only be accessed from 8am until sunset, from 1 April to 31 October

6.2.16. Wheelchair accessibility

For publicly accessible *buildings*, *footways*, *shared cycleways*, *tracks* and *paths*, it was mapped if they are accessible by wheelchair. For *buildings*, there are clear guidelines which tag should be used for which situation (see Table 18).

Table 18: Used values to the key *wheelchair* (OSM Community, 2019)

Value	Explanation
yes	Unrestricted access for wheelchairs. Buildings have a stepless entry and stepless rooms.
limited	Partial access for wheelchairs. Buildings have an entry step but not higher than 7 cm and the most important rooms are stepless.
no	Restricted access. Buildings have an entry with a step higher than 7 cm and the most important rooms are not accessible.

For *highways*, the classification is more difficult as the boundaries are fluent. As a rule, highways were mapped as *wheelchair=yes*, if they are stepless and smooth. The tag *wheelchair=limited* was used when the path is accessible for wheelchairs, but not comfortable due to irregularities in the surface. The tag *wheelchair=no* was used for steps and unsuitable surfaces. For sidewalks, this key was usually not assigned, as they do not have steps and the accessibility depends on the width of the sidewalk. Wheelchair accessibility is therefore defined by the tag *sidewalk:width*.

6.2.17. Opening hours

In order to analyze the time-based accessibility, the opening hours of all relevant POIs (restaurants, bars, supermarkets, doctors, etc.) were recorded by using the tag *opening_hours*. The value to this tag composes of the English weekday abbreviation

(“Mo”, “Tu”, …, “So”) and the opening hours in data format hh:mm (e.g. 08:00-20:00). The different time intervals between weekdays or hours are separated by a hyphen (“-“). Days with the same opening hours and opening hours that belong to the same day are listed separated by commas (“,”). Days with different opening hours are listed separated by semicolon (“;”). Either all open days can be described, or exceptions for closed days can be added with “off”. Amenities without fixed closing times are mapped with the start time and “+” (e.g. Mo 08:00+). POIs that are always open are recorded with “24/7”. For amenities with opening hours depending on the season, month can be added by using the 3-letter abbreviated English month name (“Jan”, “Feb”, …, “Dec”). Opening hours depending on the duration of the daylight can be assigned with “dawn”, “sunrise”, “sunset” and “dusk”. In Table 19 some example values are given.

Table 19: Example values to the key *opening_hours* (OSM Community, 2019)

Value	Explanation
Mo-Fr 08:00-20:00	Open from Monday to Friday 08:00 to 20:00.
Mo,Tu,Th 08:00-20:00; We,Fr 09:00-12:00	Open on Monday, Tuesday and Thursday from 08:00 to 20:00 as well as Wednesday and Friday from 09:00 to 12:00.
Mo-Su 07:30-18:00; Tu off	Open from Monday to Sunday 07:30 to 18:00, except Tuesday.
Fr-Sa 18:00+	Open on Fridays and Saturdays from 18:00 with open end, e.g. used for pubs.
24/7	Always open, e.g. used for ATMs.
Apr-Oct Mo-Su 08:00-sunset	Open from April to October from 08:00 to sunset.

The opening hours can be mapped in different ways. Due to the many possibilities, this tag is very vulnerable to incorrect input data.

6.3. Data quality

Although the OSM-data in the study area was mostly geometrically correct and features such as the street network and buildings were almost completely mapped, for this study essential attributes were missing. The following subchapters compare the data accuracy for paths, POIs and street furniture before and after the mapping process.

6.3.1. Paths

For the paths, many attributes were rarely captured before the mapping process was done. For example, only 4.9% of all paths had information on illumination and only 2.9% of the roads on the sidewalk availability (see Table 20). The share of the data accuracy is calculated by dividing the number of paths with information by the total number of paths. The accuracy was calculated for different road types (indicated by the superscript numbers), depending on the attribute. For example, there is no need to record the maximum speed for living streets, since the regulation is based on the highway category and therefore already predefined. The here assessed shares are similar to the data quality observed for Heidelberg (e.g. sidewalk availability 2.2%) by Mobasheri et al. (2015) and thus probably normal for larger cities in Germany.

Table 20: Data accuracy before and after the mapping

Attribute	Before Mapping	After Mapping
Surface [1]	20.4%	79.4%
Number of Lanes [2]	24.5%	98.7%
Sidewalk Availability [3]	2.9%	98.1%
Footpath Width [4]	0.9%	83.2%
Lit [1]	4.9%	70.1%
Maximum Speed [3]	94.6%	99.7%
Parking along the Street [2]	15.5%	64.8%
Incline [1]	1.4%	3.7%

[1] share of all highways
[2] share of all living streets, secondary, tertiary and residential roads
[3] share of all secondary, tertiary and residential roads
[4] share of all footways, cycletracks, sidewalks, steps and paths

Through the mapping process, the data was considerably improved. Thus, information on sidewalk availability are now almost complete and illumination is mapped for 70.1% off all the paths. The remaining 29.9% are among others small paths to housing entrances, which have not been mapped. The same applies to private paths. The tag *incline* was only mapped if it was unequal to zero. As the area of Hasenbergl-Lerchenau is very flat, this was rarely the case.

6.3.2. POIs

In addition to the paths, over 1,500 nodes (including shops, restaurants, vending machines, post boxes, barriers, benches, playgrounds, etc.) were added or edited. The following sections show the data accuracy for all POIs contained in GOAT, bundled in the same categories as in the webtool. It provides information on how many POIs of one amenity type existed before and after the mapping process and what percentage of these POIs had information about opening hours and wheelchair accessibility. The bold numbers indicate where new objects were added, or outdated objects removed.

In the category “Education”, only one Kindergarten was missing in the dataset. Nevertheless, information about opening hours and wheelchair accessibility was rarely mapped (see Table 21). As for primary and secondary schools the service hours would be more important than the opening hours and those are different for each class, they were excluded from the mapping process.

Table 21: Data accuracy for the amenities in the category “Education”

Education	Before Mapping			After Mapping		
Amenity	Number	Opening Hours	Wheelchair Accessibility	Number	Opening Hours	Wheelchair Accessibility
Kindergarten	23	4.3%	4.3%	**24**	95.8%	66.6%
Primary School	6	-	0.0%	6	-	0.0%
Secondary School	3	-	33.3%	3	-	33.3%
Library	1	100.0%	0.0%	1	100.0%	0.0%

For the category “Food and Drink”, most amenities were mapped. Two Biergarten were removed to avoid duplicates, as they belong to restaurants. Information about opening hours and wheelchair accessibility has been improved (see Table 22), although a high share of the fast food restaurants are food trucks without regular opening hours. Same applies to some pubs, which open according to the demand.

Table 22: Data accuracy for the amenities in the category “Food and Drink”

Food and Drink	Before Mapping			After Mapping		
Amenity	Number	Opening Hours	Wheelchair Accessibility	Number	Opening Hours	Wheelchair Accessibility
Bar	2	50.0%	50.0%	2	100.0%	50.0%
Biergarten	2	0.0%	50.0%	**0**	-	-
Café	4	50.0%	25.0%	4	75.0%	100.0%
Fast Food	8	25.0%	37.5%	**9**	55.0%	88.8%
Ice Cream	0	-	-	0	-	-
Pub	6	0.0%	33.3%	6	66.6%	83.3%
Restaurant	15	40.0%	46.7%	**18**	94.4%	94.4%
Night-Club	0	-	-	0	-	-

"Transport" is the only category where all POIs were already recorded correctly before the mapping process (see Table 23). The opening hours were not regarded, as the service hours would be more important here.

Table 23: Data accuracy for the amenities in the category "Transport"

Transport	Before Mapping			After Mapping		
Amenity	Number	Opening Hours	Wheelchair Accessibility	Number	Opening Hours	Wheelchair Accessibility
Bicycle Rental	0	-	-	0	-	-
Car Sharing	0	-	-	0	-	-
Charging Station	2	-	0.0%	2	-	0.0%
Bus	63	-	15.9%	63	-	19.0%
Tram Stop	0	-	-	0	-	-
U-Bahn Entrance	8	-	100%	8	-	100.0%
Rail Station	2	-	100%	2	-	100.0%
Taxi	2	-	0.0%	2	-	50.0%

In the category "Services" it was noticeable that many dentists and doctors were missing in the dataset (see Table 24). For some of these, no opening hours could be found and wheelchair accessibility could not be assigned, as it was not visible from the outside of the building whether the doctor's office is accessible barrier-free.

Table 24: Data accuracy for the amenities in the category "Services"

Services	Before Mapping			After Mapping		
Amenity	Number	Opening Hours	Wheelchair Accessibility	Number	Opening Hours	Wheelchair Accessibility
ATM	4	0.0%	50.0%	**6**	83.3%	100.0%
Bank	6	33.3%	33.3%	**5**	100.0%	100.0%
Dentist	2	50.0%	50.0%	**6**	66.6%	100.0%
Doctor	8	37.5%	62.5%	**22**	86.3%	86.3%
Fuel	2	0.0%	100.0%	2	100.0%	100.0%
Hairdresser	9	33.3%	22.2%	**11**	100.0%	100.0%
Pharmacy	8	62.5%	75.0%	8	100.0%	100.0%
Post Box	18	-	-	18	-	-
Recycling	23	-	-	**28**	-	-

In the category "Shop" a relatively high amount of shut down supermarkets was still included in the dataset. Those were removed in the mapping process. Furthermore, opening hours and wheelchair accessibility were completely mapped (see Table 25), except for one clothes store, which only seems to open for special events.

Table 25: Data accuracy for the amenities in the category “Shop”

Shop	Before Mapping			After Mapping		
Amenity	Number	Opening Hours	Wheelchair Accessibility	Number	Opening Hours	Wheelchair Accessibility
Bakery	10	50.0%	40.0%	**11**	100.0%	100.0%
Butcher	2	0.0%	50.0%	**1**	100.0%	100.0%
Chemist	1	100.0%	100.0%	1	100.0%	100.0%
Clothes store	3	0.0%	66.6%	**7**	85.7%	100.0%
Convenience store	2	100.0%	0.0%	2	100.0%	100.0%
Discount Supermarket	7	57.1%	57.1%	**6**	100.0%	100.0%
Greengrocer	0	-	-	0	-	-
Hypermarket	0	-	-	0	-	-
International Supermarket	0	-	-	**1**	100.0%	100.0%
Kiosk	2	50.0%	0.0%	2	100.0%	100.0%
Mall	0	-	-	0	-	-
Marketplace	0	-	-	**1**	100.0%	100.0%
Organic Food	0	-	-	0	-	-
Shoes	2	0.0%	0.0%	**1**	100.0%	100.0%
Supermarket	9	11.1%	44.4%	**6**	100.0%	100.0%

There are only a few POIs of the category “Tourism and Leisure” in the study area. One cinema was added, and opening hours and wheelchair accessibility assigned, if information were available (see Table 26).

Table 26: Data accuracy for the amenities in the category “Tourism and Leisure”

Tourism and Leisure	Before Mapping			After Mapping		
Amenity	Number	Opening Hours	Wheelchair Accessibility	Number	Opening Hours	Wheelchair Accessibility
Cinema	0	-	-	**1**	0.0%	100.0%
Theatre	0	-	-	0	-	-
Museum	0	-	-	0	-	-
Hotel	2	0.0%	0.0%	2	50.0%	50.0%
Hostel	0	-	-	0	-	-
Guest House	0	-	-	0	-	-
Gallery	1	100.0%	0.0%	1	100.0%	100.0%

6.3.3. Street Furniture

In order to make good analyzes of the street level quality, the street furniture was also mapped. Table 27 shows the number of amenities included in the dataset before and after mapping. Almost half of the mapped public telephones were outdated and thus deleted. For the other amenities, a lot of unmapped objects were added.

Table 27: Number of amenities included in the dataset

Amenity	Before Mapping	After Mapping
Bench	90	692
Barrier	192	229
Playground	35	99
Street Crossing	65	147
Telephone	15	8
Toilet	5	11
Waste Basket	28	318

7. Backend programming

After the necessary data had been collected, the GOAT functions were adapted to process the data and include them in the accessibility calculations. First, the routing functions were adjusted to provide different routing profiles, which include the mapped attributes. Then, the time-based accessibility of the POIs according to the opening hours was included by a new function and the multi-isochrone and heatmap calculation was adjusted to the new changes, as the routing functions influence these calculations.

The following subchapters explain, how the general programming workflow was performed, and which function adjustments were made in detail.

7.1. Workflow

The programming workflow was done in close collaboration with Elias Pajares and Majk Shkurti. Elias Pajares restructured the routing functions to allow the integration of the different routing profiles and supported the implementation of this thesis by adapting crucial functions. Majk Shkurti helped to connect the backend functions with the frontend. As thus several persons were working on the project simultaneously, GitHub was used as platform for collaborative development. To coordinate the work, the new branch “extend_routing” based on release v.0.1 was created out of the development branch of the goat-community. To this branch, all the programming work related to this thesis was pushed. Before a changeset was committed, all adjustments were tested on a local version of GOAT.

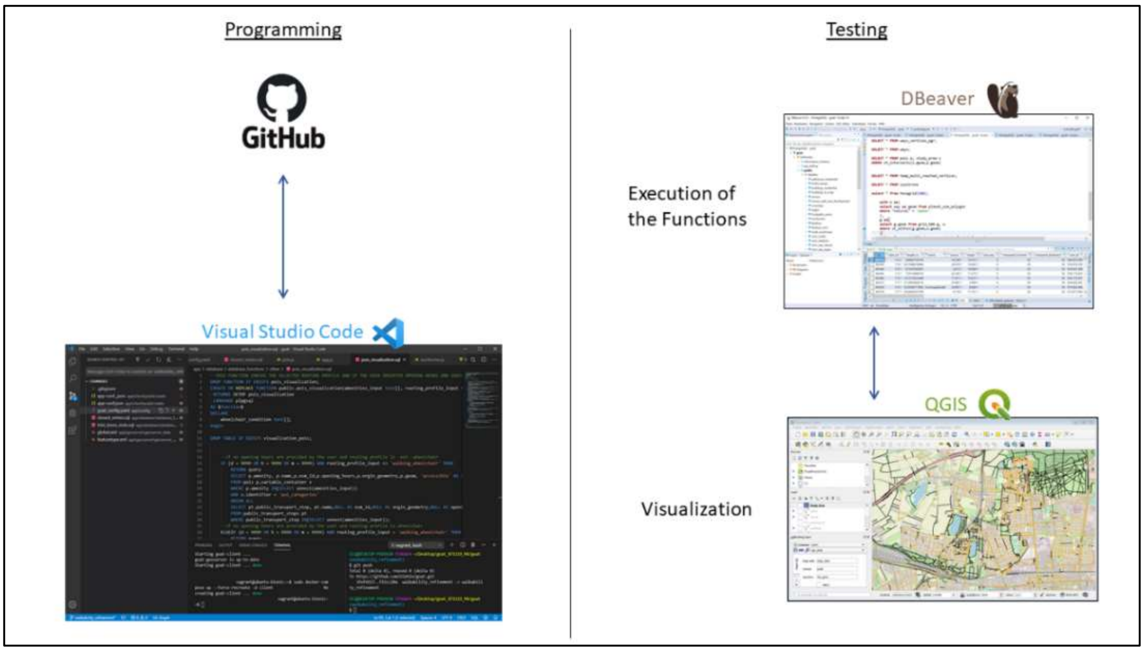

Figure 22: Programming and testing workflow

Figure 22 shows the general programming and testing workflow. The code editor Visual Studio Code was used to execute the commands to control the local GOAT version, connect to GitHub and edit the functions. New code sections were first tested with DBeaver on the local database and visualized with QGIS. As soon as a work package was completed and successfully tested, it was pushed to GitHub.

GOAT involves various libraries and programming languages. However, most of the backend functions adjusted for this task are written in PLpgSQL and refer to the object-relational database PostgreSQL which is complemented with geographic objects by the inclusion of the PostGIS extension. The script “types.sql” is used to define the function types. This script has been adapted to provide new function types according to the new functions and can, as all functions, be found on the digital medium of this thesis.

7.2. Adjustment of the routing functions

First, the routing functions were edited, to incorporate the four accessibility components. So far, the same standard routing profile was used for all calculations and only the walking speed could be adjusted manually. As part of this thesis, three additional routing profiles were created: elderly, wheelchair and safe-night routing. The elderly routing includes the same routing paths as the standard profile but reduces the walking speed. For wheelchair routing, only barrier-free paths and destinations are included. These two profiles represent the individual component with different physical abilities, while the safe-night routing, which only considers illuminated paths for routing calculation, represents the temporal as well as the individual component, as different persons perceive walking at night differently and many are afraid to walk in the dark.

The following subchapters explain in detail how the database was adapted to include the required data, how it is determined which paths are considered for which routing profile and how these conditions are included in the routing functions.

7.2.1. Data preparation

In order to implement the new routing profiles, it was necessary to include all the mapped attributes in the database. Therefore, those attributes were added as new columns to the table “ways” and filled with the corresponding tag values from the OSM raw data table “planet_osm_line” in the script “network_preparation.sql”. Since the column *width* is susceptible to wrong data input, the value was set to NULL if invalid characters, e.g. letters, are contained. For the attribute *incline* there are different tagging possibilities (see 6.2.12 Incline). To standardize the values, they are uniformly converted to percentage values.

Additionally, new predefined objects, such as wheelchair accessible surfaces, were added to the variable container, which are needed in the next steps for the different routing profiles. Subsequently, it was classified for all paths whether they can be used for safe-night and wheelchair routing.

7.2.2. Classification safe-night routing

For the safe-night routing, the additional column “lit_classified” was added to all paths, with the three possible values “yes”, “no” and “unclassified”. Whereby all paths classified as “no” were excluded for the routing. The classification was done, according to the following schema.

For the paths were the tag *lit* was assigned, the column “lit_classified” was set as the mapped value. Consequently, the tag *lit* is the highest condition. If no data was available for this tag, assumptions were made. Living streets, secondary, tertiary and residential roads were assumed to be lit while tracks and all paths with a ground, gravel, grass or general unpaved surface were classified as unlit. The decision tree for illustrating this logic is shown in Figure 23. Since there are no living streets, secondary, tertiary and residential roads with an unpaved surface, the decision tree for the observed study area categorically excludes that different classification values result from the tags *highway* and *surface*. Therefore, as soon as a classification value was reached, it was considered as final. As the conditions might differ dependent on local conditions, all of them can be adjusted in the variable container.

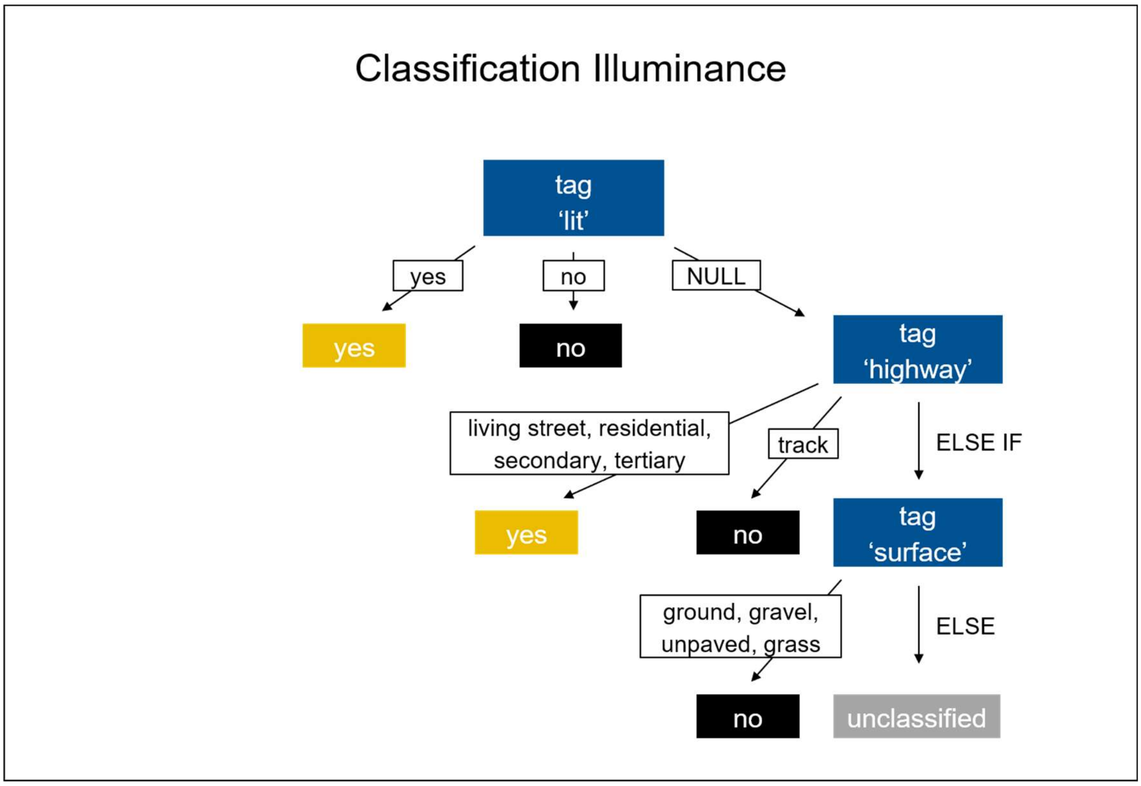

Figure 23: Decision tree to assign the value for the column "lit_classified"

As in OSM the illumination can be represented not only by assigning the attribute to the path but also by mapping the streetlamps, a 15 m buffer was created around the mapped streetlamps (see Figure 24). All streets that intersect with the streetlamp buffer and did not have the tag *lit* assigned, are also classified as lit.

Figure 24: Intersection of the street network and the streetlamp buffer

The queries following the explained decision structure, are included in the SQL script “network_preparation”. By combining the way attributes and the streetlamp buffers, all main paths of the study area could be classified as “yes” or “no” for the column “lit_classified”.

7.2.3. Classification wheelchair routing

For wheelchair routing, the classification was done following the same schema. The new column “wheelchair_classified” was added to all paths, with the four possible values: “yes”, “limited”, “no”, “unclassified”. Those are the same values as provided in OSM (see 6.2.16 Wheelchair accessibility). The values were assigned following the logic of the decision tree shown in Figure 25. The tag *wheelchair* is the highest condition, if this tag was mapped, the given value was also assigned as “wheelchair_classified”. If this tag was not given, the tags *incline*, *smoothness*, *surface*, *sidewalk*, *highway* and *width* were considered. If for one of those the condition leading to the value “no” was true, the tree stops and a “no” is stored. Otherwise, for the final value, the worst reached result is decisive.

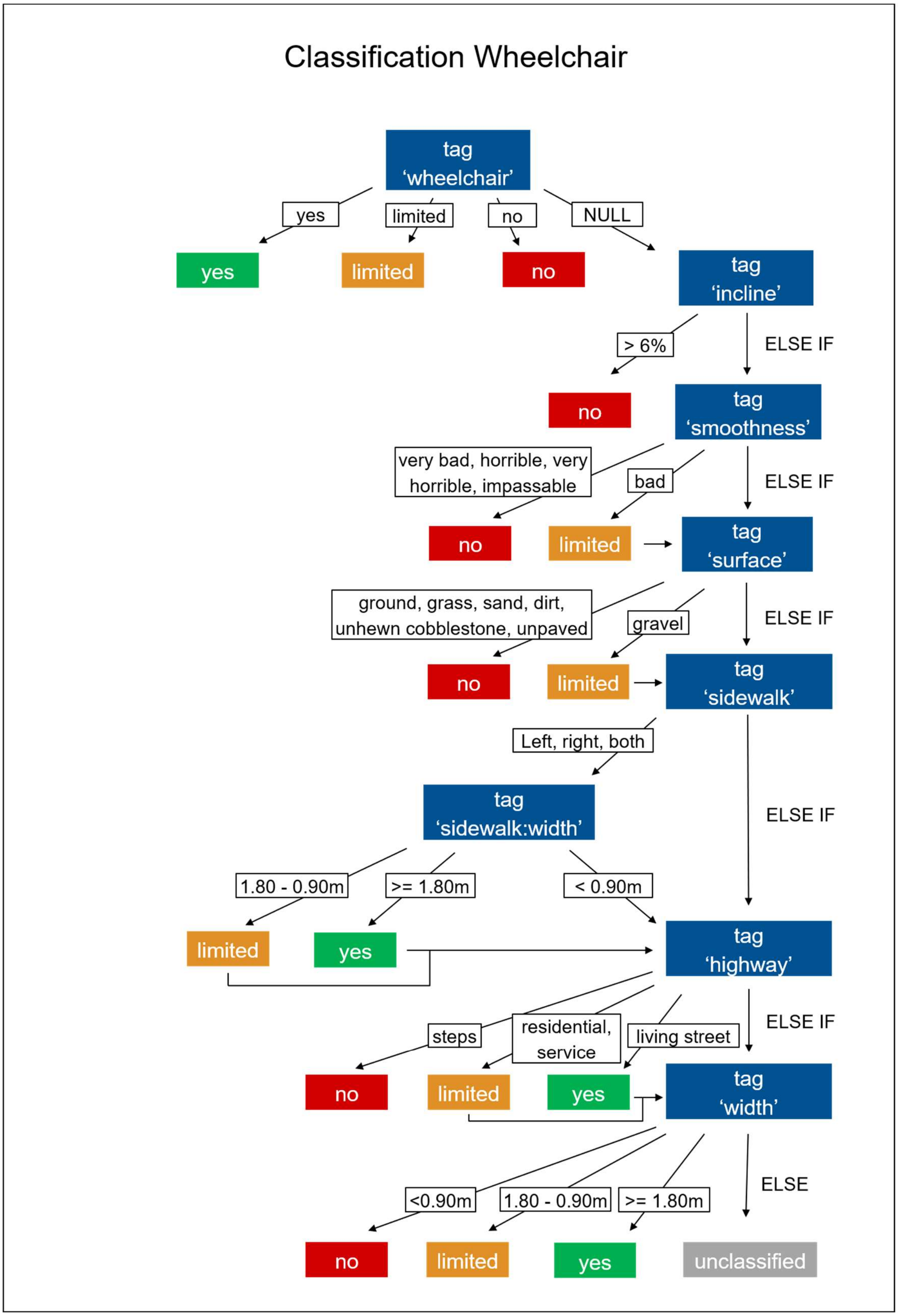

Figure 25: Decision tree to assign the value for the column "wheelchair_classified"

In the SQL script "network_preparation" the queries following the explained decision structure, are executed. The used conditions are defined according to DIN 18040-3 (DIN

Deutsches Institut für Normung e.V., 2014). But if desired, all conditions can be adjusted in the variable container.

All paths classified as “no” are excluded from the wheelchair routing.

7.2.4. Integration of the routing profiles

The routing and the isochrone calculation are divided into different functions. Figure 26 shows their architecture and explains the task of each function.

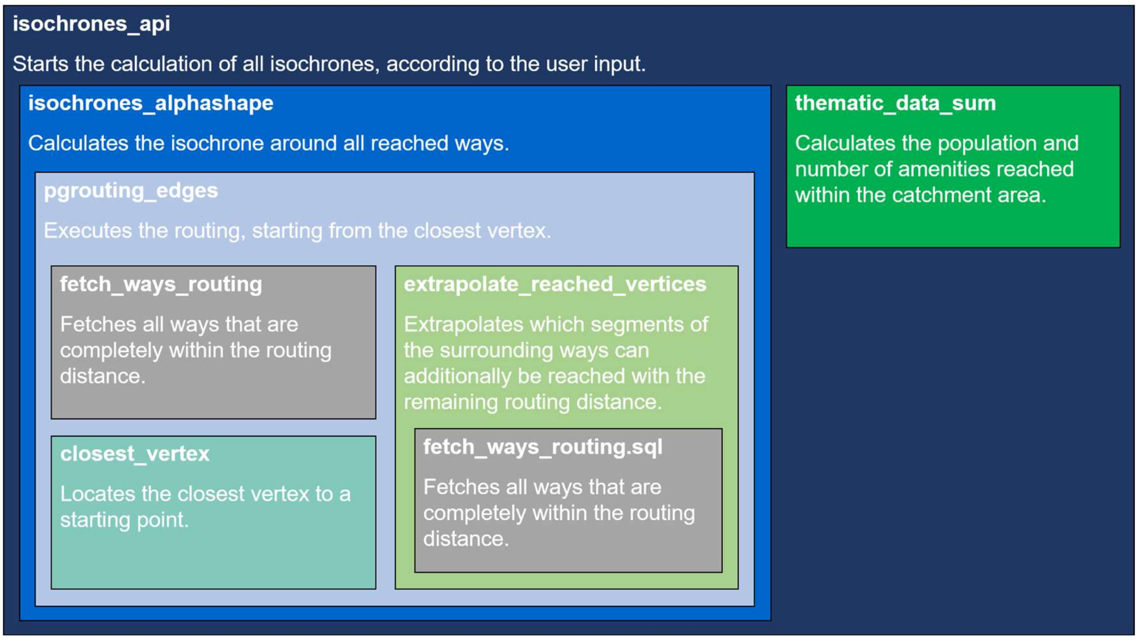

Figure 26: Architecture of the routing functions

In order to integrate the different routing profiles into the routing functions, the new input parameter “routing_profile” was added to all routing related functions. It can have the following values, which are defined in the “app-conf.json” file:

- “walking_standard”
- “walking_elderly”
- “walking_wheelchair”
- “walking_safe_night”

Regarding the upcoming integration of cycling, the routing profiles start with a “walking” prefix. The new parameter for the isochrones is passed from the frontend through adjustments in the “app.js” script.

The main function that needed to be modified to distinguish between the different routing options was “fetch_ways_routing”, as this function is responsible for selecting the appropriate paths for routing. Depending on which routing profile is passed to the functions, the return query is automatically adjusted in order to execute the right routing calculation (e.g. only considering illuminated path for the safe-night routing).

In the function “pgrouting_edges” the walking speed is adjusted, according to the routing profile. Based on various studies (Bendall et al., 1989; Coffin and Morrall, 1992; Graham et al., 2010; Khandoker et al., 2010), 3 km/h were selected as average walking speed for elderlies of an age of 80 or above. For the wheelchair routing, 5 km/h were used as default speed, although this is highly dependent on whether a manual or an electric wheelchair is used (Ikeda et al., 2003). Those values are stored and can be adjusted in the variable container, where the unit m/s is used, since this unit is needed for the following calculations. In order to commit the speed values, the input parameters of the functions “pgrouting_edges” and “isochrones_alphashape” were adjusted accordingly.

7.3. Adjustment of the reached POIs

After the routing profiles were integrated into the routing functions, the individual and temporal components were also included in the calculation of the reached POIs.

7.3.1. Wheelchair accessibility

To incorporate the individual component into the reached POIs, information about the wheelchair accessibility was added by extracting this tag from “planet_osm_point” and “planet_osm_polygon” and assigning it to the table “pois” in the same-named script. If the routing profile “wheelchair” is selected, only POIs accessible by wheelchair (i.e. with the tag *wheelchair* unequal to “no”) should be included in the accessibility analysis. In order to make this transparent to the user, the function “pois_visualization” was created, which distinguishes between the routing profiles and assigns the additional column “status”, which provides information about whether the POI is accessible for the selected routing profile or not. Based on this information, the POIs are visualized accordingly.

7.3.2. Time-based accessibility

Additionally, the opening hours of the POIs are included to represent the time-based component. As there are various options to store the opening hours in OSM, the module “osm_humanized_opening_hours” (available at: https://libraries.io/pypi/osm-humanized-opening-hours) was installed in Docker to extract the information. For testing purposes, this installation was done manually by executing the following commands:

```
$ sudo docker exec -it goat-database /bin/bash
$ pip3 install osm-humanized-opening-hours
$ exit
$ sudo docker exec -it goat-database python3
$ import humanized_opening_hours
```

Since this procedure required the installation to be repeated after each restart of the Docker container, it was optimized by integrating the installation process directly into the Docker setup. After installation, the module is stored in the python3 directory. To be able to use it for database queries, it must be imported into Postgres. This was done in the created function “check_open”.

The module “humanized_opening_hours” expects as input parameter a reference time in the format *year, month, date, hour, minute* as numeric and opening hours in OSM format (see 6.2.17 Opening hours). In the function “check_open”, those input parameters were received and submitted to the “humanized_opening_hours” module. As output, the module transfers whether the specified reference time is within the opening hours (“True”) or not (“False”). To achieve the right balance between accuracy and usability, it was decided to let the user choose only the day of the week, the hour and the minute, as the additional choice of year and month would not bring significant added value. Therefore, the year and month were set statically to “2019, 11”. As the modules expects the day of the week in numerical form, the day selected by the user in the frontend is converted into a number, using the reference week from 18. to 24. November 2019 (see Figure 27). Thus, “Monday” is submitted to the module as “18”, “Tuesday” as “19” etc. If no weekday, hour or minute is selected by the user, “9999” is submitted for this parameter, since “NULL” would lead to an incorrect data transfer. In case an incorrect data format of the opening hours is transferred that cannot be processed by the module, “Error” is returned. This also happens erroneously, if the opening hours span two days (e.g. Sa 20:00-03:00), as this data format is not supported by this module, although it is a standard OSM syntax. This syntax is rarely used in the study area, but in order to provide transferable analysis options, the implementation of a better module should be considered in the future.

Figure 27: Reference week used for the time-based accessibility calculation

In order to include the time-based accessibility calculations, the function “isochrones_api” was adjusted. If a reference time is provided by the user, the function “thematic_data_sum_time” is additionally executed and calculates the number of amenities that is open at the given reference time, using the “check_open” function. Figure 28 shows the updated routing function architecture.

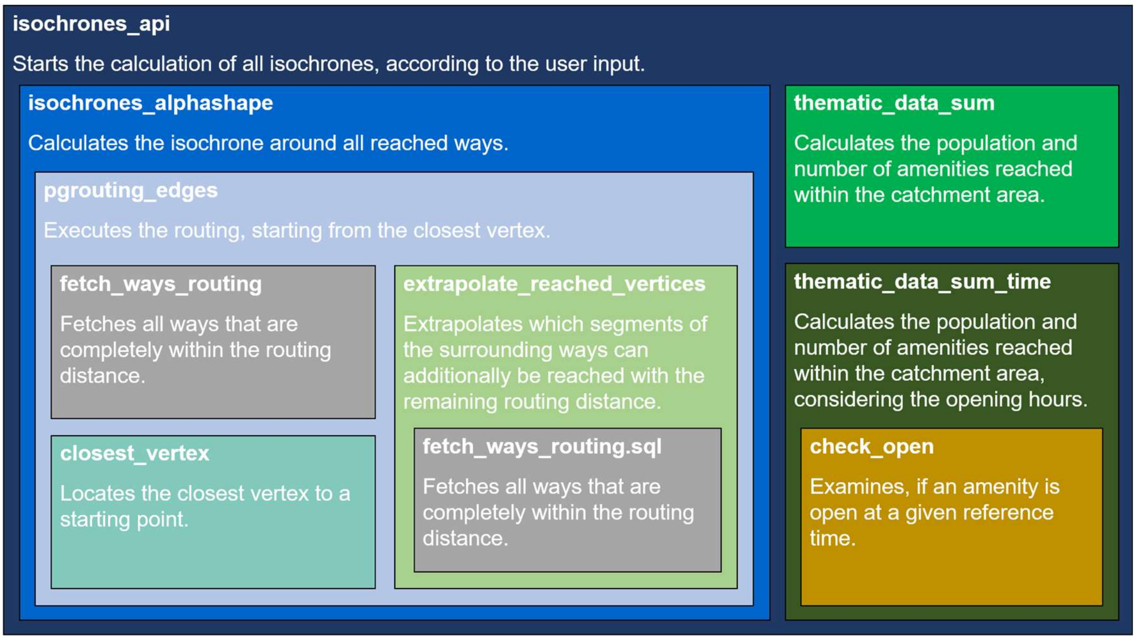

Figure 28: Architecture of the routing functions, including the time-based component

As it is not useful to provide time-based accessibility analyses for all amenities, the new object “amenity_opening_hours” is added to the variable container, containing all amenities that are dependent on opening hours. Thus, only those amenities are considered in the function “thematic_data_sum_time”.

To make the calculations transparent to the user, the POIs are displayed with different icons, depending on whether they are accessible with the chosen routing profile and reference time. Therefore, the function “pois_visualization” was adjusted to also include information about the opening hours. The contained queries were previously executed directly in the geoserver layer “pois_info”, but to distinguish whether a reference time was selected by the user, the queries were outsourced to this function, which is now accessed in the geoserver layer.

7.4. Multi-isochrones

As a next step, the multi-isochrones were adjusted to incorporate the individual component referred to the land-use, represented by the POIs, and to the transportation component, represented by the walking path network. Therefore, the routing profiles were integrated in the multi-isochrone calculation by adjusting the functions “pois_multi_isochrones”, “multi_isochrones” and “pgrouting_edges_multi”, which are structured as shown in Figure 29. Thus, if the routing profile “wheelchair” is selected by the user, the multi-isochrones are only calculated starting from POIs that are not tagged as *wheelchair=no* and for the routing, all paths categorized as not suitable for wheelchair are excluded. For the safe-night routing, paths classified as unlit are excluded accordingly. The routing profile is passed from the frontend as input parameter to the “pois_multi_isochrones” function, by adding it in the “app.js” script.

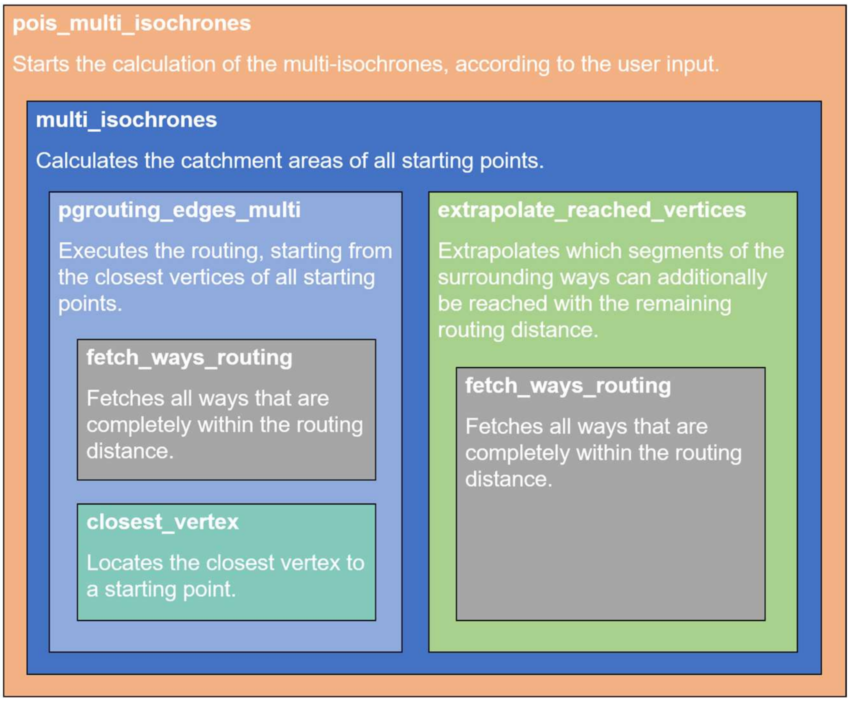

Figure 29: Architecture of the multi-isochrone functions

The time-based analysis option for the opening hours is not yet implemented in the multi-isochrones.

7.5. Heatmaps

Since the heatmap calculation makes use of the same basis functions as the routing and the multi-isochrones (see Figure 30), the function "precalculate_grid" had to be adapted to transfer the input parameters accordingly.

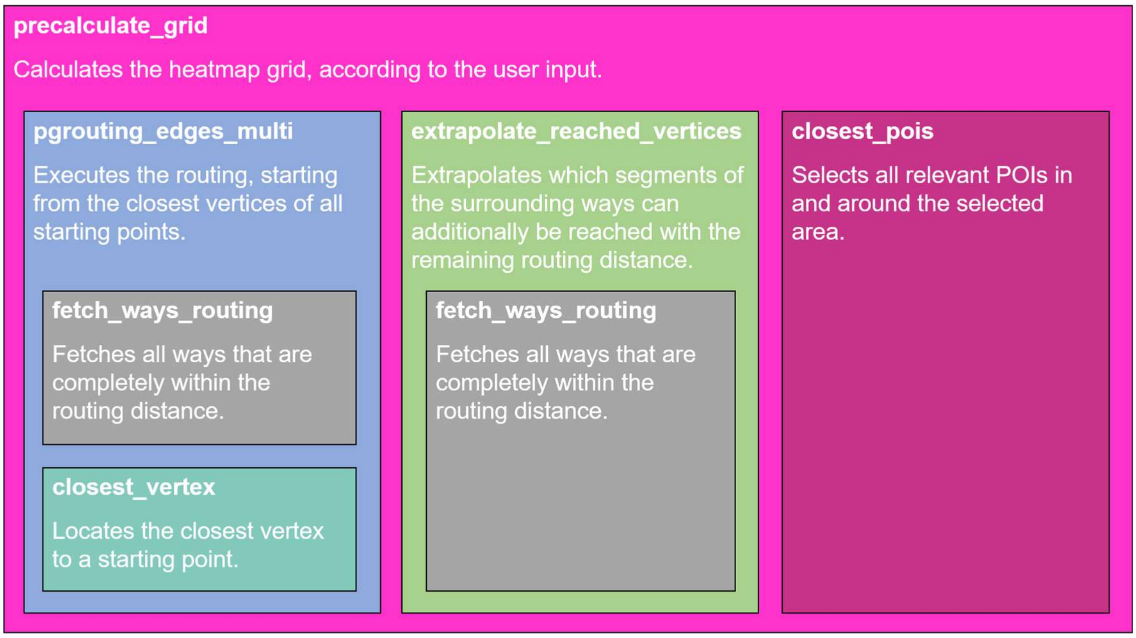

Figure 30: Architecture of the heatmap functions

Currently, the input parameters are only passed on and the heatmaps do not react dynamically to changes in the routing profile and reference time. This is because for each possible combination of options, the grid needs to be precalculated. Especially with the opening hours this leads to problems, as the number of additional options would cause high calculation times.

8. Visualization in the frontend

In order to include the new functions into the frontend and visualize the added features, the user interface was adjusted, and new layers created. The following subchapters explain in detail, which adjustments were made.

To provide the labels for the new objects in different languages, translations for all new objects were added to the language files “al.json”, “ar.json”, “cn.json”, “de.json”, “en.json”, “es.json” and “fr.json”.

8.1. Adjustment of the Interface

Since the new functions with incorporated individual and time-based component provide calculations for different user input options, the interface was modified to let the user choose those. In the file “isochrones.js” and “IsochronesOptions.vue” the left toolbar of the interface was adjusted to include a dropdown menu for the routing profiles. The different routing profile options with corresponding default speeds are defined in the “app-conf.json” file. The new input parameters are transferred to the backend via the script “app.js”.

Figure 31: Screenshot of the adjusted interface, the new options are highlighted (GOAT-Community, 2019a)

Because the integration of opening hours is only useful if appropriate data is available, it can be defined in the “app-conf.json” file, if the time-based accessibility options shall be included in the frontend. If this condition is set to “yes”, a slider for enabling the time-based accessibility analyses is provided in the right toolbar of the interface, which is defined in the “pois.vue” file. By enabling the slider, the menu for time-based calculations appears. Via a dropdown menu, the user can select the day of the week. Hour and minutes can be chosen by a time picker. A screenshot of the adjusted interface is shown in Figure 31.

Amenities for which time-based accessibility analyses are not useful (e.g. schools, for further explanation see 6.3.2 POIs) are greyed out in the frontend and cannot be selected if the user enabled the time-based calculation option. The excluded amenities are defined in the “app-conf.json” file and visualized via “pois.vue”.

8.2. Creation of new geoserver layers

As many way attributes and points were captured during the mapping process, which can improve the walkability analysis, new layers were created to make the gathered data visible. Therefore, first, new layers were created in geoserver and then incorporated in the frontend by adding them to the “app-conf.json” file. The corresponding styles were created as SLD-style in QGIS and then uploaded in geoserver and transformed to the standard geoserver xml schema. In the styles it is also defined, which label is displayed for which item in the legend. Therefore, for each language a separate label is provided. All created layer and styles are listed in the Appendix B.3 and B.4 and stored on the digital medium of this thesis. The adjustments are explained in detail in the following subchapters.

The new layers were clustered in the new layer category “Street Level Quality”. The precalculation of the therefore necessary tables is executed in the new script “layer_preparation.sql”. Since these layers are only useful if appropriate data is available for the study area, it can be customized in the “goat_config.yaml” file whether these precalulations should be executed or not.

For more data transparency, the feature GetFeatureInfo was enabled for all new layers by setting “queryable” to “true” in the “app-conf.json” file, which allows the user to click on each object and get feature information about the attached attributes. Furthermore, in this file the layer levels were defined, putting the point layers on the higher level and the line layers on the lower level, by adjusting the “zIndex”.

8.2.1. Illumination

The column “lit_classified”, which was assigned to each path and gives information about the illumination (see 7.2.2 Classification safe-night routing), is visualized via the geo-server layer “ways_lit“ and the corresponding style “style_lit”. In Figure 32, the resulting visualization is shown, displaying the lit paths in yellow, the unlit paths in black and the paths without data in grey.

Figure 32: Screenshot of the illumination layer (GOAT-Community, 2019a)

The data shown in this layer are the same used for the safe-night routing, while all unlit paths were excluded from the routing calculations.

8.2.2. Wheelchair usability

To visualize the data used for the wheelchair routing, the column “wheelchair_classified”, which was assigned to all paths and gives information about their wheelchair usability (see 7.2.3 Classification wheelchair routing), is displayed via the geoserver layer “ways_wheelchair” and the corresponding style “style_wheelchair”. Figure 33 shows the resulting layer. All red paths are not accessible for wheelchair users and therefore excluded from the wheelchair routing. The green paths are well suited for wheelchairs and the orange paths are only partially accessible (e.g. due to reduced width). For the grey paths, no data was available.

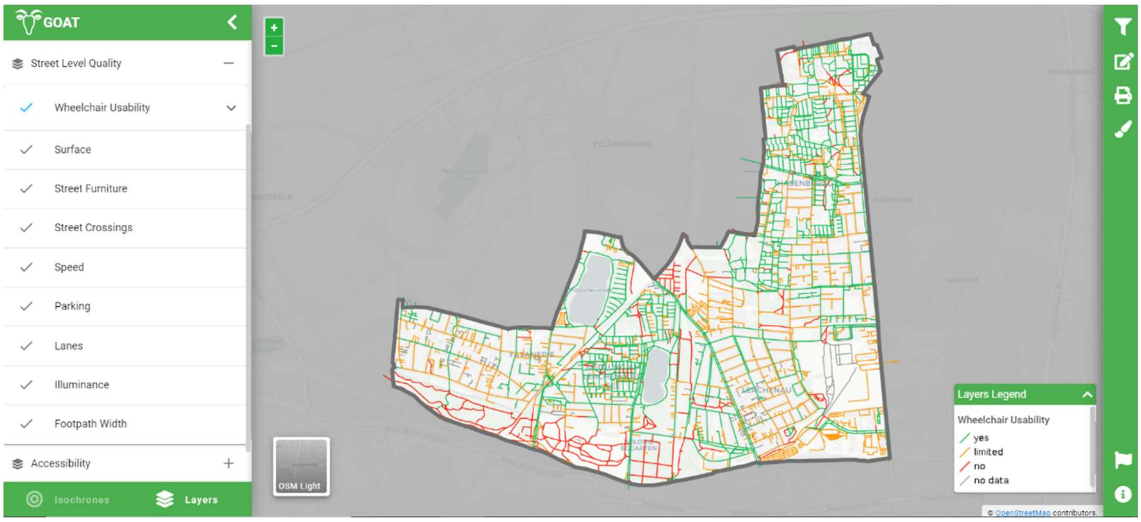

Figure 33: Screenshot of the wheelchair usability layer (GOAT-Community, 2019a)

Paths that do exclude walking (e.g. tagged with *foot=no*) are not visualized in this layer. Although, for the routing all paths are used as it would else lead to problems e.g. at street crossings where small links are missing between the sidewalks.

8.2.3. Footpath width

When displaying the footpath width, it was distinguished whether the footpath was displayed separately or assigned to a street with the tag *sidewalk=both/right/left* (see 6.2.8 Sidewalk availability). If the sidewalk was assigned to a street, the line was copied with an offset to the corresponding side. For sidewalks on both sides, the line was copied on both sides. Accordingly, the footpath width was assigned for each line. In the case of non-segregated cycle- and footpaths, the total width was divided by two. These preparations were made in the script “layer_preparation.sql”. The resulting footpaths width are then displayed via the geoserver layer “footpath_width” and the corresponding style “style_footpath_width”. Figure 34 shows a screenshot of the created layer.

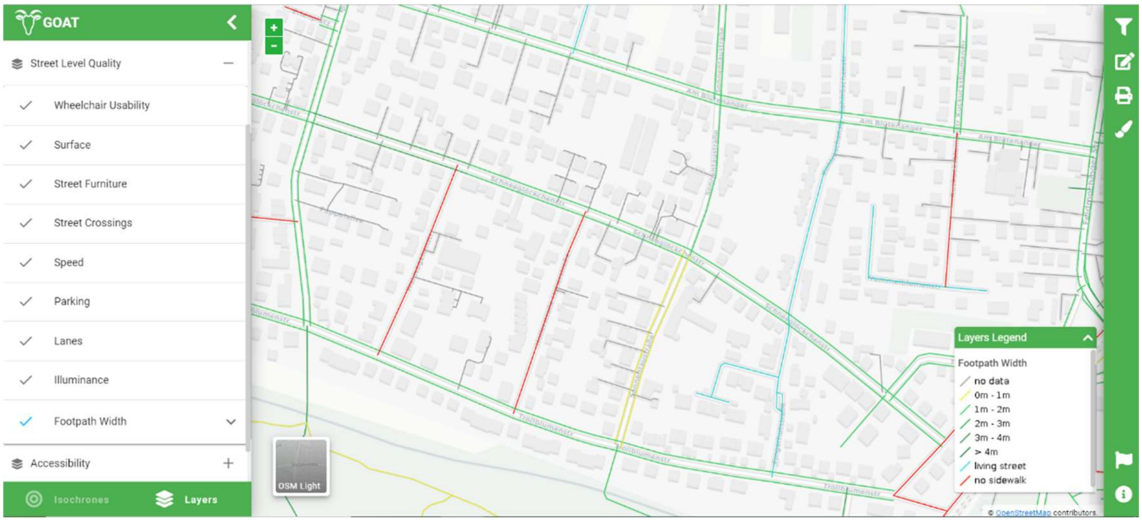

Figure 34: Screenshot of the footpath width layer (GOAT-Community, 2019a)

Visualized in yellow are footpaths with a width of 0-1 m, footpaths with a width of 1 m to >4 m are shown in different shades of green. The red lines are streets without sidewalk and the blue lines represent living streets.

In order to improve the visualization, the loose ends resulting from the offset lines could be trimmed in the future.

8.2.4. Surface

The surface of the paths, which was used to classify the illumination and the wheelchair usability, is displayed via the geoserver layer “ways_surface” with the corresponding style “style_surface”. Figure 35 shows a screenshot of the resulting layer. The different colors indicate the different surfaces.

Figure 35: Screenshot of the surface layer (GOAT-Community, 2019a)

8.2.5. Lanes

For all streets, the number of lanes was visualized via the geoserver layer “ways_lanes” and the corresponding style “style_lanes”. Figure 36 shows a screenshot of the created layer.

Figure 36: Screenshot of the lanes layer (GOAT-Community, 2019a)

8.2.6. Speed

Likewise, the allowed maximum speed was displayed via the geoserver layer “ways_speed” and the corresponding style “style_speed”. In Figure 37 the resulting layer is shown.

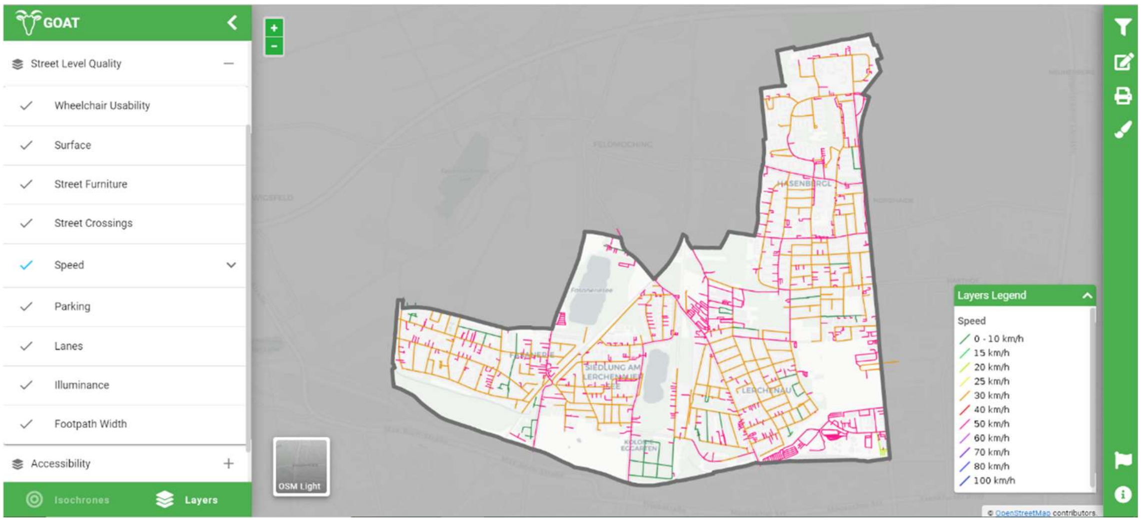

Figure 37: Screenshot of the speed layer (GOAT-Community, 2019a)

In OSM, the maximum speed can be mapped for both directions, but since *maxspeed_forward* and *maxspeed_backward* were usually the same in the observed study area, only *maxspeed_forward* was considered for the visualization. For study areas with different maximum speeds for both directions it might be helpful to display a separate line for each direction.

8.2.7. Parking

The local parking regulations were visualized via the geoserver layer “ways_parking” and the corresponding style “style_parking”. Similar to the footpath width, offsets were created in the script “layer_preparation.sql” to display information for both sides of the street. Figure 38 shows the visualized layer for an excerpt of the study area.

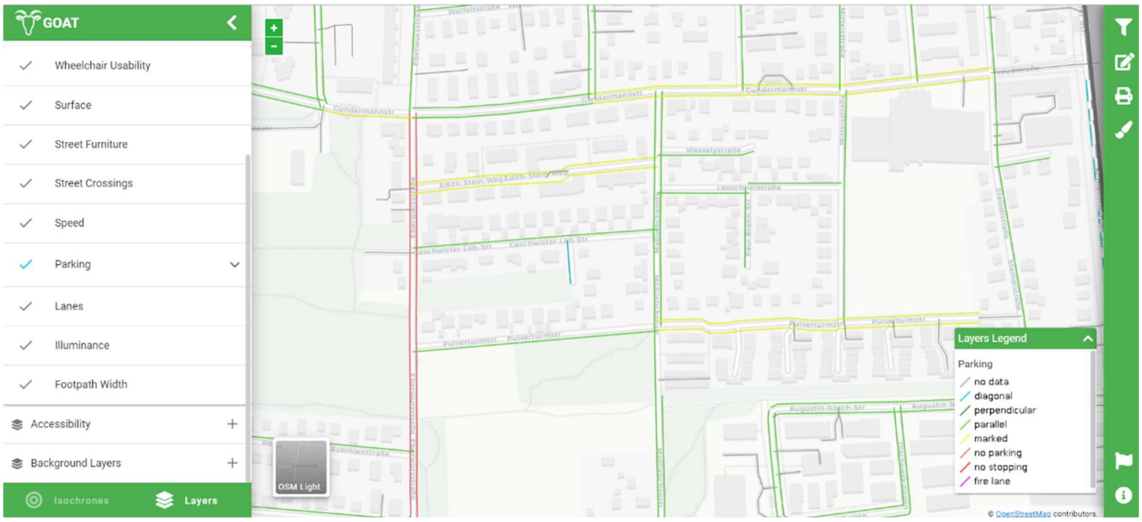

Figure 38: Screenshot of the parking layer (GOAT-Community, 2019a)

The red lines indicate, where parking is not allowed. Green lines represent parallel parking along the street and blue lines represent parking diagonal to the street. Where yellow lines are displayed, parking is only allowed in some marked areas.

Similar as for the footpath width, the loose ends resulting from the offset lines could be trimmed in the future, by creating a function that is then executed in the layer preparation for both layers.

8.2.8. Street crossings

Additional to the way-based layers, also two point-based layers were created. Via the geoserver layer “street_crossings” with the corresponding style “style_crossings”, all street crossings with traffic light or zebra crossing were displayed using small icons (see Figure 39). The extraction of the therefore required points from “planet_osm_point” was executed in the script “layer_preparation.sql”.

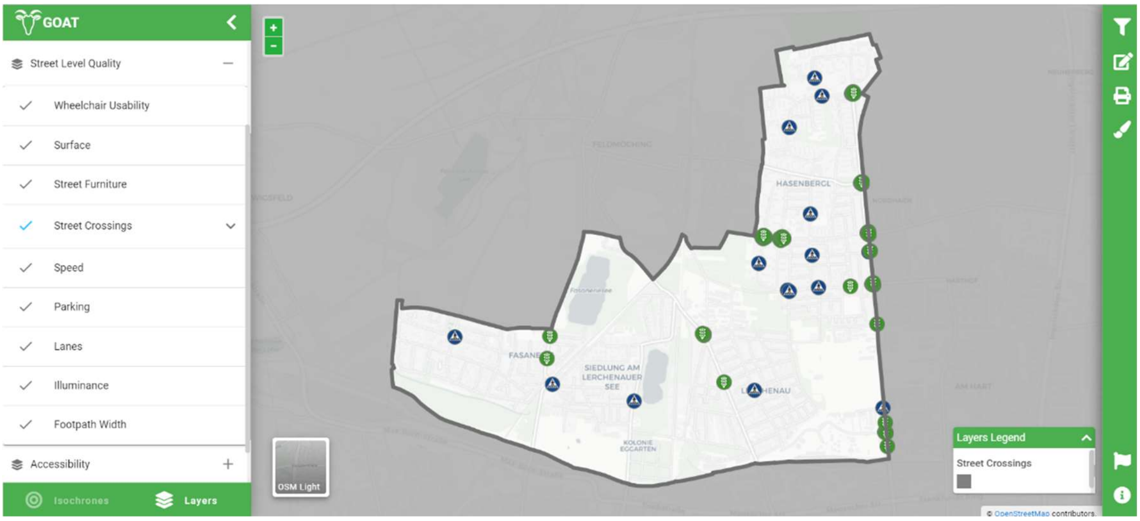

Figure 39: Screenshot of the street crossing layer (GOAT-Community, 2019a)

With the GetFeatureInfo function, additional information to the street crossings (e.g. if tactile paving is installed) can be displayed by clicking on an object.

8.2.9. Street furniture

The street furniture, including benches, public toilets, fountains and waste baskets, was displayed via the geoserver layer “street_furniture” and the corresponding style “style_street_furniture”. A screenshot of this layer, which can be of particular interest for assessing the walking quality for elderly people or for statements about the livability of an area, is shown in Figure 40.

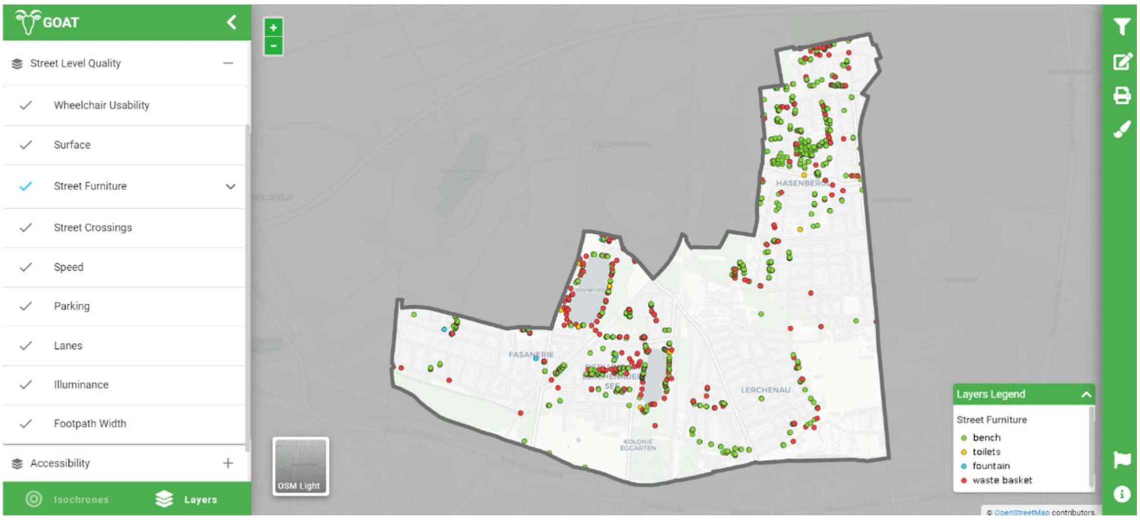

Figure 40: Screenshot of the street furniture layer (GOAT-Community, 2019a)

The layer is currently load statically and does not react on changes of the routing profile or the opening hours. In future, the layer could be improved by integrating wheelchair accessibility and the opening hours of the public toilets. Furthermore, it can be considered to add other objects, such as playgrounds, to this layer, however a balance should be found between level-of-detail and usefulness.

8.2.10. POIs

In addition to the newly created street level quality layers, the already existing layer “pois_info” and the corresponding style “pois” were updated to show icons in different shades, depending on whether the POI is accessible or not. In Figure 41 a screenshot of the resulting layer is displayed.

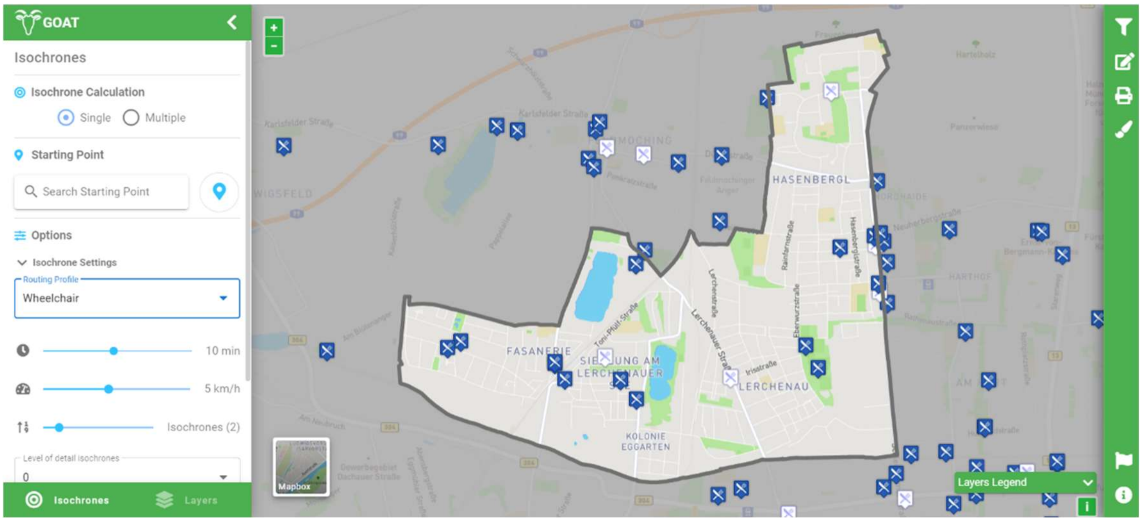

Figure 41: Screenshot of the POIs layer with adjusted icons (GOAT-Community, 2019a)

The white icons with the colored symbols indicate which POIs are not accessible for the chosen routing profile and time.

8.2.11. Self-reported perceptions

As the objective measured street level quality criteria cannot cover the entire concept of walkability, also self-reported statements by pedestrians about their perceived walking quality should be included to provide a more comprehensive picture. To show how this could be implemented in GOAT, some pedestrians were interviewed in the study area and asked to give statements about the perceived walkability. These statements were then stored in a new table and implemented in the GOAT database via the created script “self_reported_statements_test.sql” and visualized in geoserver via the layer “user_statements” and style “style_user_statements”. To personalize the statements, avatars are displayed as icons depending on the gender and age of the respondents. When an avatar is clicked, the statement is displayed using the GetFeatureInfo function (see Figure 42).

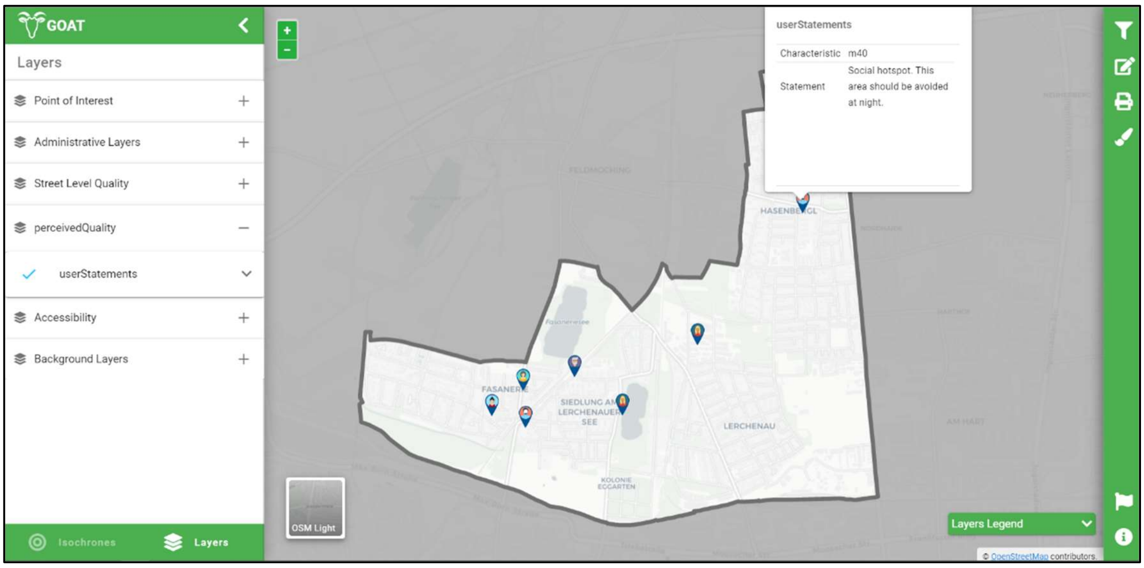

Figure 42: Screenshot of the layer with the user statements (GOAT-Community, 2019a)

9. Analysis

The newly implemented functions allow different analyses to be carried out. The following sections provide an analysis for the study area in order to illustrate how the added data and options can be used.

9.1. Walkability

By examining the street level quality layers, the walkability of the area can be assessed. Contrary to expectations, the subdistrict Hasenbergl, formerly notorious as a social hotspot, has better measured conditions in terms of walkability (sidewalk availability, sidewalk width etc.) than the single-family house settlement Fasanerie (see Figure 43). This is probably due to the fact that the Hasenbergl was designed according to a holistic overall concept, while the Fasanerie gradually grew unstructured from additional single-family houses. Thus, almost all footpaths in Hasenbergl are apart from the main traffic roads, have sufficient width, are barrier-free and paved with paving stone. While in the Fasanerie a high share of roads without sidewalk and limited wheelchair usability can be found. But on the same time, parking is allowed on both sides of the roads. This is a quite unfair allocation of space. In order to improve walkability, those parking lanes could be reduced and therefore good barrier-free sidewalks built.

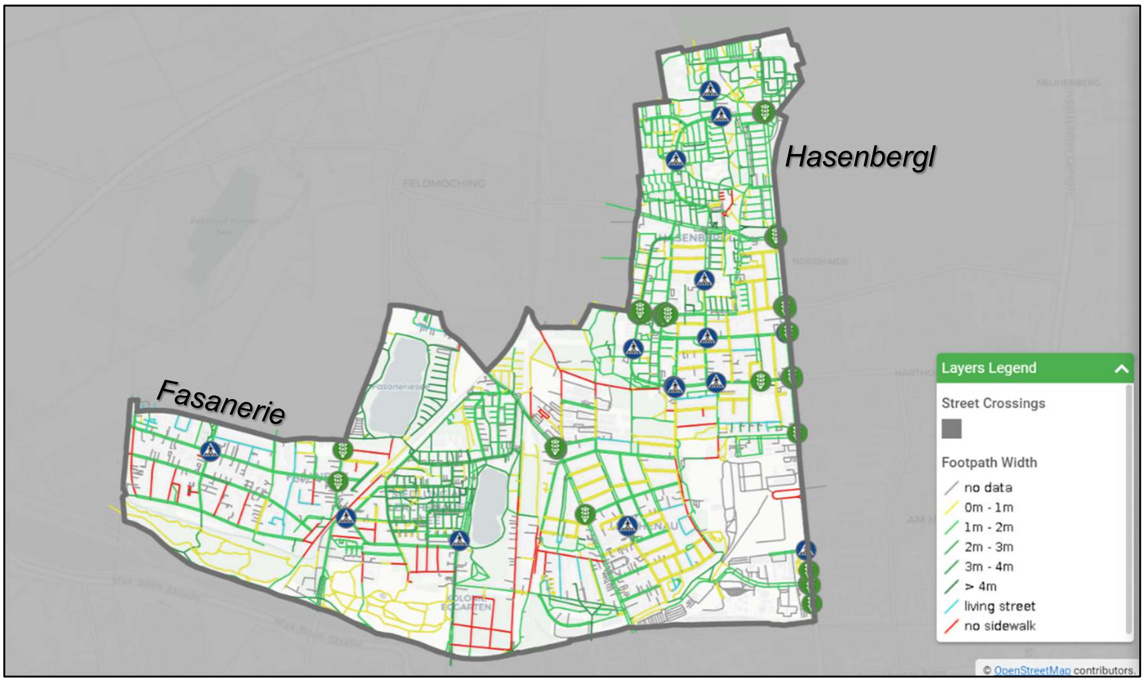

Figure 43: Screenshot of the footpath width and street crossing layers (GOAT-Community, 2019a)

It is also noticeable that there are only a few road crossings, especially in the south-western part of the study area. As there are some roads with high traffic loads, dangerous crossing maneuvers often have to be carried out or long detours have to be accepted.

Regarding the high share of elderly in the study area, street furniture is important. The street furniture is mainly concentrated around the two lakes and in the northern part of Hasenbergl. In the remaining parts of the study area, especially in the residential areas Fasanerie and Lerchenau, street furniture is rarely found. This may hinder elderly and mobility impaired people from walking, as they may need a rest after a certain walking distance.

If the subjective statements are compared with the objectively measured characteristics, it is noticeable that these are only correlated to a limited extent and the subjective perception depends on many more factors than were objectively recorded. For example, a family reported about dangerous situations occurring on a living street due to delivery services driving too fast around a badly visible curve. Regarding the captured attributes, this street would be rated with a very good walking quality, but considering the individual perception, the picture changes. By including the individual statements as an additional layer in the interactive map, these differences are highlighted and the focus on the personal component is strengthened.

9.2. Safe-night routing

Safe-night routing and the corresponding illumination layer allow to examine how accessibility changes from day to night if a pedestrian only wants to use lit paths and shows where gaps in the illuminated street network occur. The analysis of the collected data for the study area reveals that there is a high share of unlit paths, that do serve as important links for pedestrians. Figure 44 shows a screenshot of the illumination situation in the study area.

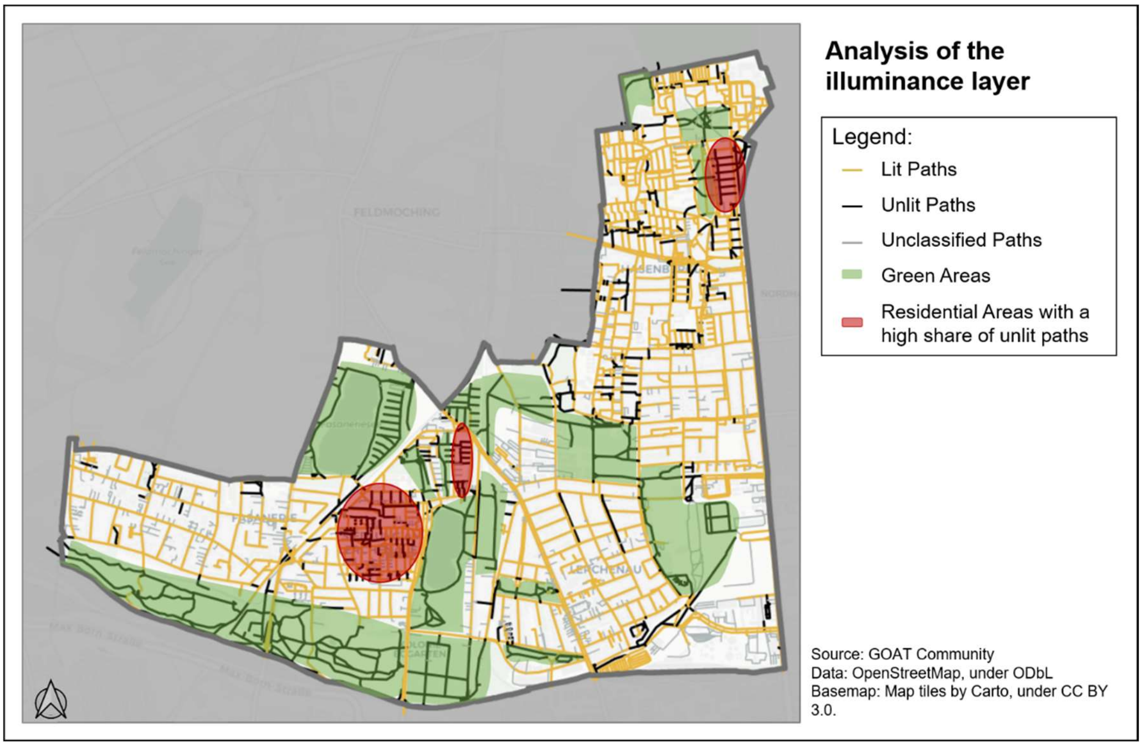

Figure 44: Analysis of the illumination layer

Especially the footpaths through green spaces and forest areas, that are highlighted in green, are mostly unlit. Although there are lit connecting paths through the large forest area in the south at regular intervals. But for example, the two recreation areas around the lakes are completely unlit. In addition, some residential areas, which are highlighted in red, have a high share of unlit footpaths.

To examine the impact of those unlit paths on accessibility, isochrones were calculated. Figure 45 shows an accessibility comparison between standard and safe-night routing from a starting point within a residential area using a 7-minutes walking isochrone. The contraction of the isochrone indicates that accessibility is significantly reduced if this temporal component is considered. Also, the reached population shrinks from 2,850 to 1,350. By illuminating main links through the green areas, night accessibility could be highly improved.

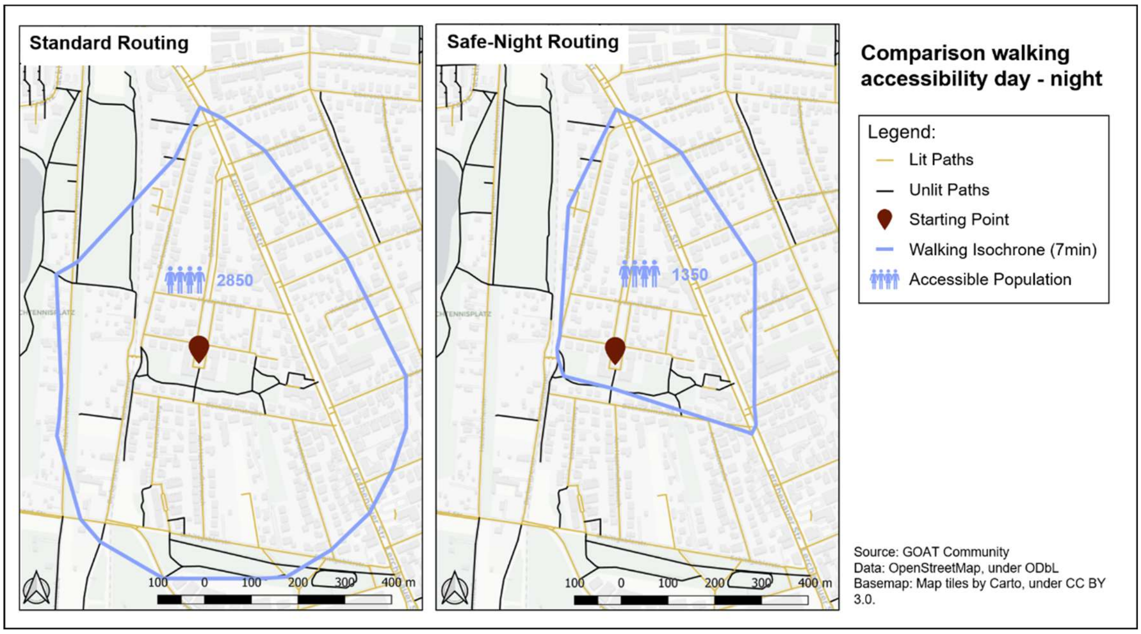

Figure 45: Accessibility comparison between standard and safe-night routing (left: standard routing, consideration of all paths; right: safe-night routing, only via illuminated paths)

For analyzing accessibility to certain amenities, multi-isochrones were calculated. For most everyday amenities, such as supermarkets or bus stops, the differences in the reached population between standard and safe-night routing are only marginal, as these amenities are usually clustered and the important connecting routes to them are almost completely illuminated. Most of the unlit areas are green spaces and therefore not populated. The greatest differences thus occur in the accessibility of leisure facilities such as sports fields or local recreation areas.

9.3. Wheelchair routing

When considering wheelchair accessibility, it can be stated that, with the exception of the forest area in the south of the study area, almost all areas are accessible. Just few paths are not suitable for wheelchairs. In the Siedlung am Lerchenauer See, for example, a large part of the connecting paths between two major residential streets is not barrier-free, as stairs are used as a design element. Figure 46 shows the resulting accessibility differences using a 3-minutes walking isochrone starting from this area. Regarding the reached population, 330 less people can be accessed by wheelchair. But more striking are the amenities. By wheelchair, only a postbox and a restaurant can be reached within 3 minutes while by standard routing, additionally a pharmacy, a doctor, a bakery, a taxi station, a bus station, a hairdresser, a church and a kindergarten can be accessed. By removing the non-functional stairs, wheelchair accessibility could be highly improved.

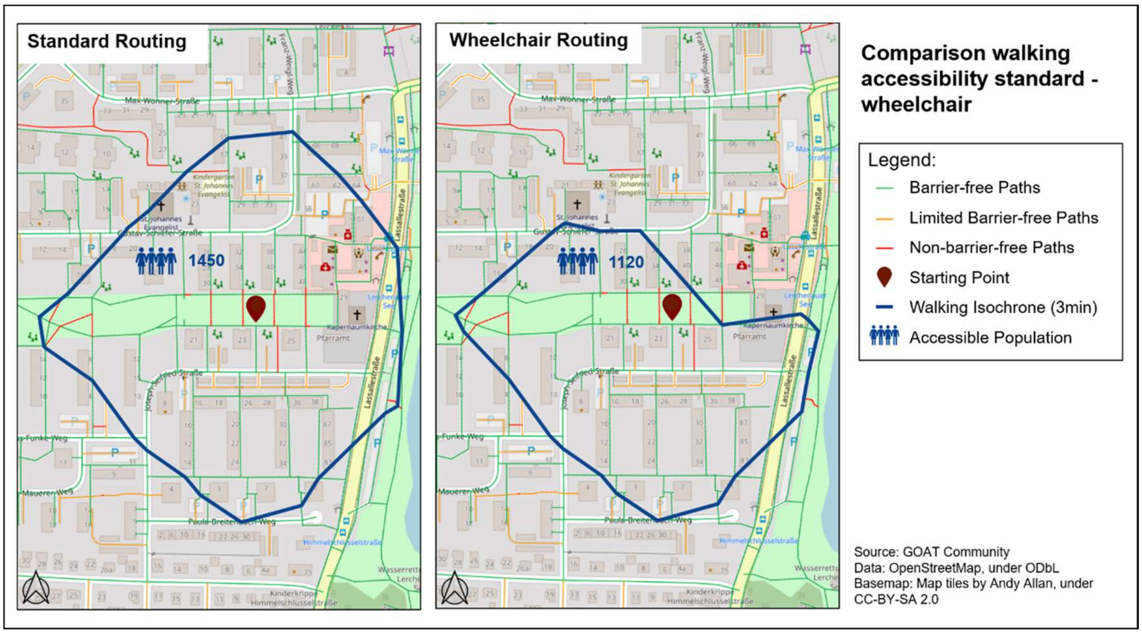

Figure 46: Accessibility comparison between standard and wheelchair routing (left: standard routing, consideration of all paths; right: wheelchair routing, exclusion of non-barrier-free paths)

Also, a high share of the paths is only limited useable by wheelchairs, e.g. due to reduced width. Means they are suitable for one wheelchair but if another wheelchair is oncoming, runaround might be difficult.

By calculating multi-isochrones, wheelchair accessibility of important amenities, for example of doctors, can be evaluated. Figure 47 shows the comparison of the standard 10-minutes walking catchment area around all doctors and the same using the wheelchair routing profile. It results, that approximately 8,880 persons out of a total population of 46,950 do not have barrier-free access to a doctor within a 10-minute walking distance. When changing the multi-isochrone distance to 15 minutes, almost the entire population (46,420 of 46,950 inhabitants) lies within the catchment area. Similar results are achieved for other amenities. Thus, it can be stated that wheelchair accessibility in the study area is quite good. Accessibility gaps only occur where the population density is low.

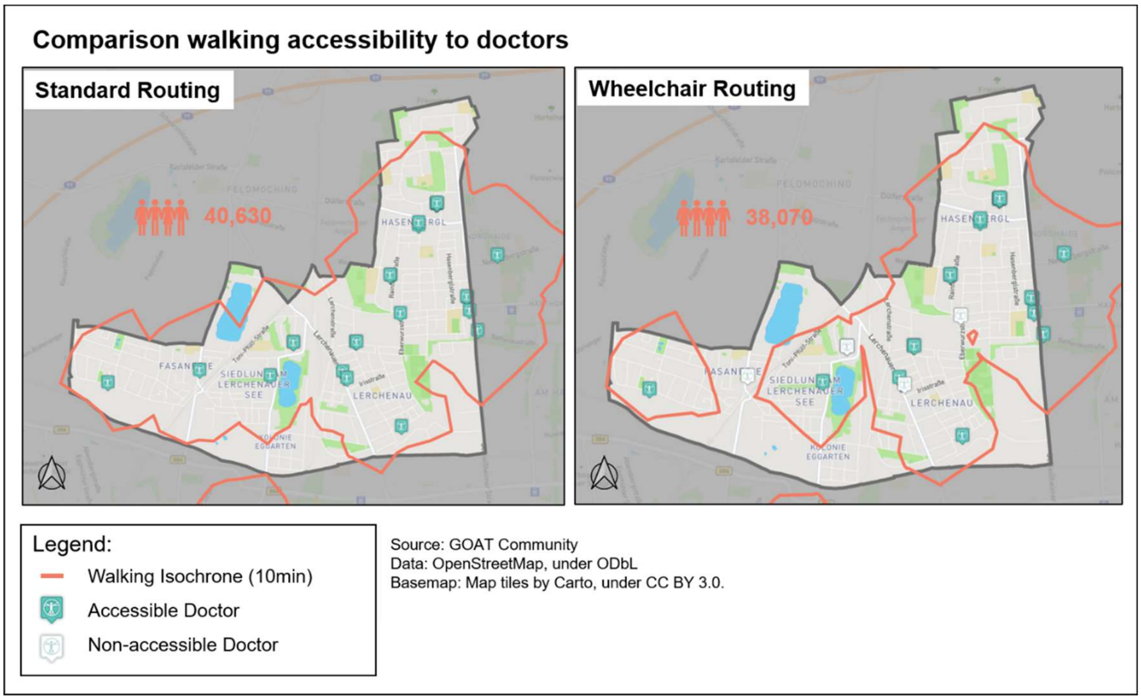

Figure 47: Comparison of walking accessibility to doctors, using 10-minutes isochrones

Nevertheless, the wheelchair accessibility to doctors could be improved by the barrier-free renovation of existing practices and the provision of a new doctor where a high population but no doctor can be found (e.g. in the northern part of the study area, see Figure 48).

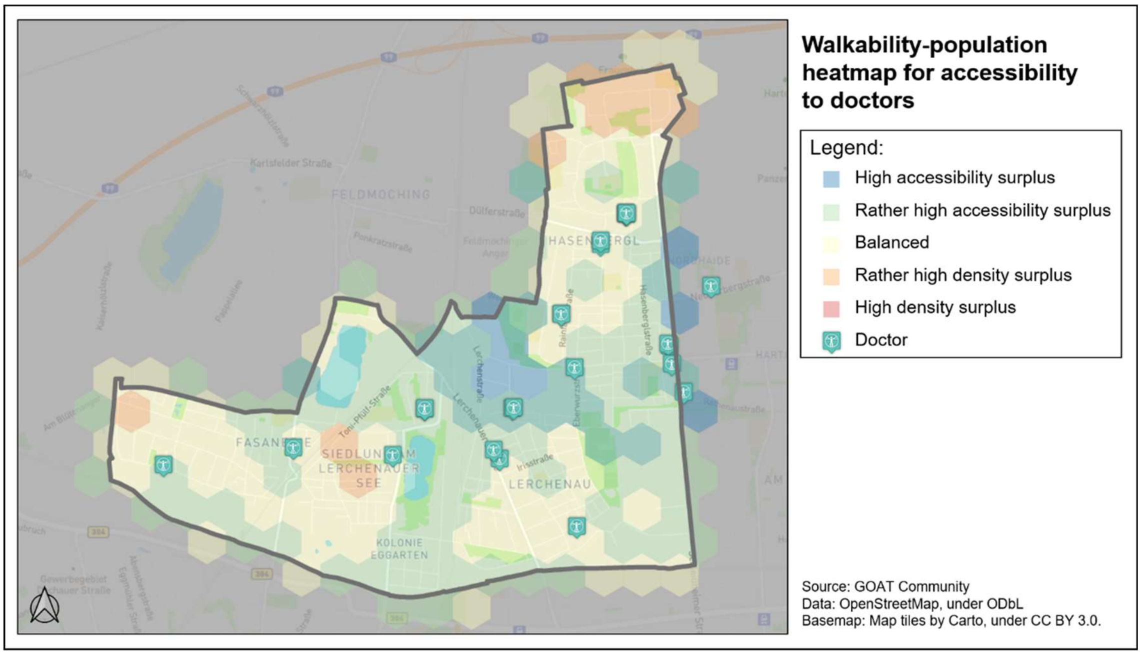

Figure 48: Walkability-population heatmap for accessibility to doctors

9.4. Accessibility of POIs

Regarding the shopping facilities in the study area, it is noticeable that shops and especially the supermarkets are concentrated along the Schleißheimer Straße, which creates an accessibility surplus. While in other parts of the study area, such as Fasanerie and the Siedlung am Lerchenauer See, accessibility deficits can be found (see Figure 49).

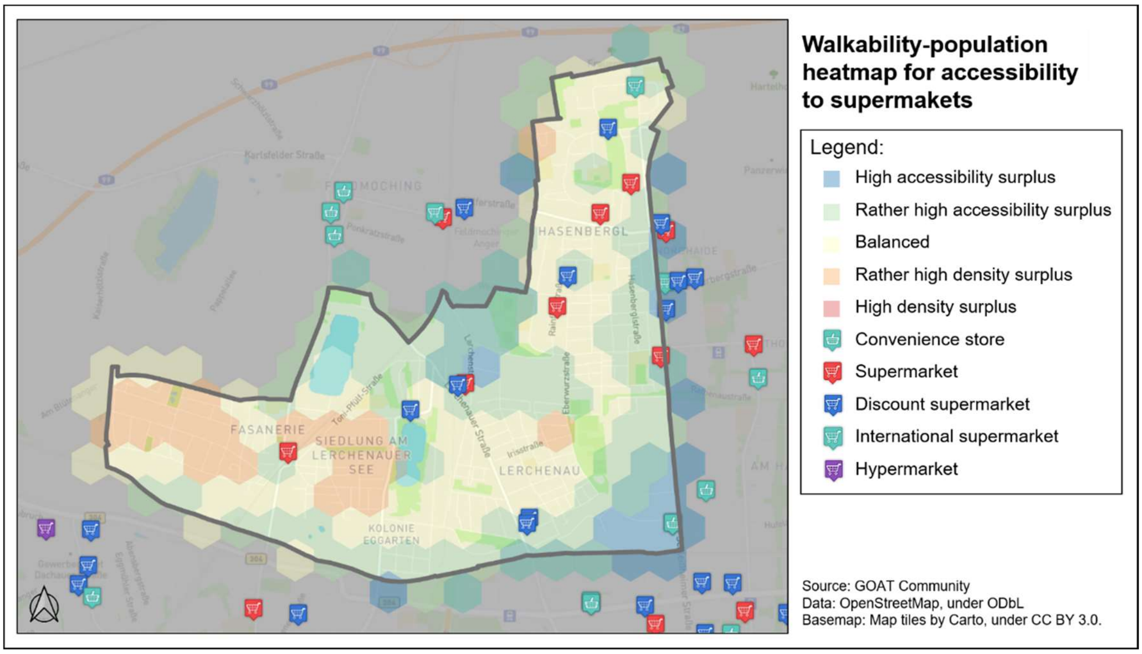

Figure 49: Walkability-population heatmap for accessibility to supermarkets

Through the integration of the opening hours of the POIs it is also possible to analyze accessibility changes over time. Thus, it can be seen, that after 20:00 only two convenient stores are accessible, both belonging to fuel stations near Schleißheimer Straße (see Figure 50). One of them is open 24/7 as the only amenity in the entire study area, except for four ATMs.

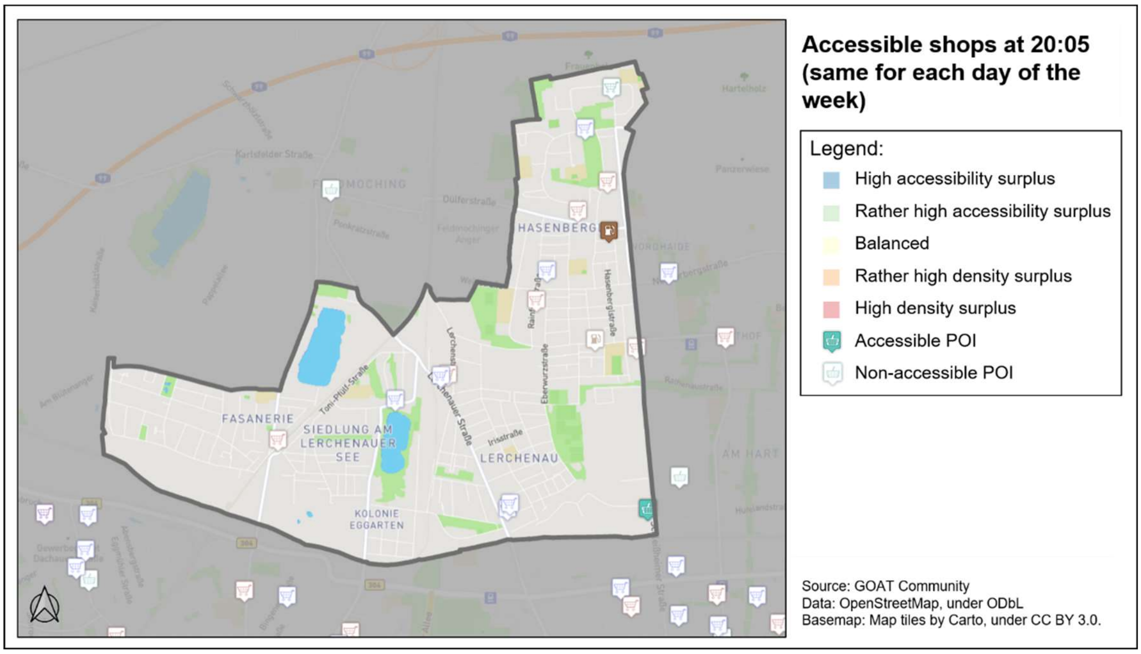

Figure 50: Accessible shops in the study area after 20:00

Considering the food and drink amenities, it is apparent that the picture is different at every time of day and day of the week. The fewest amenities are open on Mondays, while on Saturdays the variety of open restaurants and bars is the largest.

For restaurants, the spatial distribution of amenities is different than for supermarkets. The Fasanerie and the settlement at the Lerchenauer See can show a slight accessibility surplus to supermarkets in relation to the population, while the Hasenbergl and Lerchenau have an accessibility deficit.

As car ownership in the study area is relatively low and the residents are more dependent on other transport modes, besides walking and cycling, public transport is of particular importance. When analyzing public transport accessibility, it is striking that the accessibility of high-quality rail-based public transport systems is rather low. Most of the areas are served by bus lines, although a high accessibility deficit can be found in the northern part of Hasenbergl. Bicycle and car-sharing are completely missing in the entire study area. Overall it can be stated that there is a high accessibility deficit to public transport in the study area, which makes the availability of good walking and cycling infrastructure even more important.

10. Conclusion

The aim of this thesis was to incorporate all four accessibility components into one common accessibility instrument. Therefore, GOAT was extended to better include the temporal and the individual component, as well as to represent the transportation component more realistically. This chapter concludes with the achieved results, discusses them and gives an outlook on future development potential.

10.1. Results

By providing three new routing profiles (elderly, wheelchair, safe-night) that influence route choice and walking speed, an attempt was made to better represent the individual component with its versatile user characteristics, as well as the temporal component and its influence on illumination at night. The resulting changes in accessibility can be visualized by calculating isochrones.

Furthermore, the opening hours of amenities were included and allow for time-based analysis via dynamic visualization of accessible POIs. With these improvements, GOAT provides a better understanding of how different groups of people are affected in their walking accessibility by changes in the temporal and individual components.

The supply of nine street level quality layers (illumination, wheelchair usability, footpath width, surface, lanes, speed, parking, street crossings, street furniture) provides additional information on different walkability criteria and attempts to represent the transportation component more realistically. These layers provide the user with useful information and allow weak points in the footpath network to be found easily.

As a supplement to the objective street level quality layers, self-reported user statements on subjectively perceived walkability were recorded and displayed as an additional layer. This turned out to be particularly valuable, as the perceived quality often differs from the objectively measured quality. It is therefore essential to include the subjective perspective in order to understand the entire concept of walking accessibility.

All four accessibility components are now incorporated in GOAT, even though this was a challenging task that necessitated some simplified generalizations. The developed prototype of GOAT was applied to the study area Hasenbergl-Lerchenau and proves to be a comprehensive tool for accessibility analyses.

10.2. Discussion

The individual component is highly varying according to physical abilities and personal characteristics. For example, some elderly persons can easily walk 20 steps, while others can only make one step and need a bench every 500 m to rest. The same applies at night, some persons do not mind walking a long distance without lighting, while others want to avoid unlit paths under any circumstances and are willing to accept long detours.

Currently, only three specialized routing profiles take the individual component into account. While this is an improvement, the generalized profiles cannot, of course, do justice to the numerous individual physical possibilities and characteristics. It would therefore be preferable to allow further individual customization options. However, too many options in the frontend can confuse the user. The challenge is to find an appropriate balance between accuracy and usability.

To better represent the transportation component, new attributes have been included. However, the new attributes currently only influence the route choice and have no effect on the walking time. It might be useful to provide different walking speeds at different street segments in the future. For the elderly routing profile, for example, the walking speed could be reduced on stairs. In addition, point-related information (e.g. road crossings or barriers) are currently not considered in the route choice or the resulting walking time. For example, in order to optimize the routing for wheelchair users, whether or not the curb is lowered should be taken into account. Furthermore, additional time losses may occur depending on the type of road crossings (e.g. traffic lights).

One of the main requirements for the newly provided analysis options is available data. Before the mapping was carried out, many paths in the study area were not recorded in as much detail as was needed for the analyses. This is unfortunately the case in many places. In order to make accessibility analyses more holistic, better data accuracy is needed. It is therefore important to encourage contributions to the OSM project. Despite the high mapping effort, the large number of mapping tools help to collect data efficiently. Furthermore, contributing and saving data directly into the OSM-database helps significantly to manage the data. In addition, there are some indicators that influence walkability but cannot be captured in OSM, such as traffic load. Therefore, it might be useful to find additional data sources and enable the possibility to integrate them into GOAT.

10.3. Outlook

Although this case study is a first approach to include all four components of accessibility, there is a high potential for further improvements. In particular, the individual component with its numerous features could be better represented. Therefore, additional adjustment options on individual preferences and abilities (e.g. maximum distance that someone is willing to walk on unlit paths or maximum number of steps that can be walked) could be provided as advanced settings. Furthermore, it might be instructive to add further routing profiles, for example the routing profile “child” which does not allow the crossing of big streets. As a completion for the individual component, it would also be useful to enable scenarios for changed path attributes (e.g. illumination of an unlit path) and visualize the resulting effects on accessibility.

The inquiry of self-reported user perceptions, which have been found to be particularly valuable, could be integrated directly in GOAT as an interactive option by allowing the user to upload georeferenced statements. This extends the tool by an additional level and makes it possible to display the walkability in a more holistic way.

In order to calculate walking times more realistically, time losses at street crossings and varying walking speeds on different links (e.g. due to incline or steps) could be taken into account in the future. Therefore, the capability to include point data in the routing algorithm must be developed. This would also allow for the consideration of barriers with time restrictions (e.g. at the entrance to parks or allotments) in the routing and thus improve the representation of the temporal component. Furthermore, the implementation of additional data sources in GOAT (e.g. DEM as additional source for the incline) can help to improve the accuracy.

The last points to be mentioned here are the multi-isochrones and heatmaps, for which the time-based accessibility analysis including the opening hours is currently not available. By providing these features, more holistic analysis options can be offered in the future. Furthermore, it could be insightful to include the reachable POIs into the multi-isochrone results (e.g. to show how many supermarkets can be reached within 5 minutes walking from all bus stops), in addition to the reachable population.

List of figures

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Appendices

Appendix A. Overpass turbo queries

A.1. Selection of all non-private pedestrian paths without width

```
[out:xml][timeout:100];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(
way["highway"]["sidewalk"="both"]["sidewalk:both:width"!~".*"]["access"!="private"](area
.searchArea);
way["highway"]["sidewalk"="left"]["sidewalk:left:width"!~".*"]["access"!="private"](area.se
archArea);
way["highway"]["sidewalk"="right"]["sidewalk:right:width"!~".*"]["access"!="private"](area
.searchArea);
  way["highway"="footway"]["width"!~".*"]["access"!="private"](area.searchArea);
  way["highway"="steps"]["width"!~".*"]["access"!="private"](area.searchArea);
  way["highway"="path"]["width"!~".*"]["access"!="private"](area.searchArea);
  way["highway"="cycleway"]["width"!~".*"]["access"!="private"](area.searchArea);
  way["highway"="track"]["width"!~".*"]["access"!="private"](area.searchArea);
);
out meta;
>;
out meta qt;
```

A.2. Selection of all non-private pedestrian paths without information about the illumination

```
[out:xml][timeout:25];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(
way["highway"]["lit"!~".*"]["access"!="private"](area.searchArea);
);
out meta;
>;
out meta qt;
```

A.3. Selection of all highways with information about the smoothness

```
[out:xml][timeout:100];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(
node["highway"]["smoothness"](area.searchArea);
  way["highway"]["smoothness"](area.searchArea);
);
out meta;
>;
```

```
out meta qt;
```

A.4. Selection of all highways, except of stairs, with information about the incline

```
[out:xml][timeout:100];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(
  way["highway"!="steps"]["incline"](area.searchArea);
);
out meta;
>;
out meta qt;
```

A.5. Selection of all street crossings

```
[out:xml][timeout:100];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(
  node["highway"="crossing"](area.searchArea);
);
out meta;
>;
out meta qt;
```

A.6. Selection of all highways that have been edited by the user UJehle

```
[out:xml][timeout:25];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(way["highway"](area.searchArea)(user:UJehle););
out meta;
>;
out meta qt;
```

A.7. Selection of all amenities and shops without information about the wheelchair accessibility

```
[out:xml][timeout:25];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
(
   node["amenity"]["wheelchair"!~".*"](area.searchArea);
   node["shop"]["wheelchair"!~".*"](area.searchArea);
);
out meta;
>;
out meta qt;
```

A.8. Selection of all shops without information about the opening hours

```
[out:xml][timeout:25];
{{geocodeArea:Bezirksteil Lerchenau-West}}->.searchArea1;
{{geocodeArea:Bezirksteil Hasenbergl-Lerchenau Ost}}->.searchArea2;
(.searchArea1;.searchArea2;)->.searchArea;
 (
  node["shop"]["opening_hours"!~".*"](area.searchArea);
);
out meta;
>;
out meta qt;
```

Appendix B. List of adjusted files

In the following subchapters, all files that have been adjusted within the frame of this thesis are listed with the corresponding file path. They can be found on the digital medium of this thesis and in the forked GOAT repository of the author on GitHub (https://github.com/UJehle/goat/releases) as release v0.1.

B.1. SQL scripts

check_open.sql	*(goat/app/database/database_functions/other)*
closest_pois	*(goat/app/database/database_functions/other)*
closest_vertex.sql	*(goat/app/database/database_functions/other)*
fetch_and_extrapolate.sql	*(goat/app/database/database_functions/other)*
isochrones_alphashape.sql	*(goat/app/database/database_functions/routing)*
isochrones_api.sql	*(goat/app/database/database_functions/routing)*
layer_preparation.sql	*(goat/app/database/data_preparation/SQL)*
multi_isochrones.sql	*(goat/app/database/database_functions/routing)*
network_preparation.sql	*(goat/app/database/data_preparation/SQL)*
pgrouting_edges.sql	*(goat/app/database/database_functions/routing)*
pgrouting_edges_multi.sql	*(goat/app/database/database_functions/routing)*
pois.sql	*(goat/app/database/data_preparation/SQL)*
pois_multi_isochrones	*(goat/app/database/database_functions/routing)*
pois_visualization.sql	*(goat/app/database/database_functions/other)*
precalculate_grid	*(goat/app/database/database_functions/heatmap)*
self_reported_statements_test.sql	*(goat/app/database/data_preparation/SQL)*
thematic_data_sum_time.sql	*(goat/app/database/database_functions/other)*
types.sql	*(goat/app/database/data_preparation/SQL)*

B.2. Other scripts

app.js	*(goat/app/api)*
app-conf.json	*(goat/app/client/public/static)*
goat_config.yaml	*(goat/app/config)*
isochrones.js	*(goat/app/client/src/store/modules)*
isochronesOptions.vue	*(goat/app/client/src/components/isochrones)*
pois.vue	*(goat/app/client/src/components/layers/filters)*
al.json	*(goat/app/client/src/locales)*
ar.json	*(goat/app/client/src/locales)*

cn.json	*(goat/app/client/src/locales)*
de.json	*(goat/app/client/src/locales)*
en.json	*(goat/app/client/src/locales)*
es.json	*(goat/app/client/src/locales)*
fr.json	*(goat/app/client/src/locales)*

B.3. Geoserver layers

footpath_width	*(app/geoserver/geoserver_data/workspaces/cite/database)*
pois_info	*(app/geoserver/geoserver_data/workspaces/cite/database)*
street_crossings	*(app/geoserver/geoserver_data/workspaces/cite/database)*
street_furniture	*(app/geoserver/geoserver_data/workspaces/cite/database)*
user_statements	*(app/geoserver/geoserver_data/workspaces/cite/database)*
ways_lanes	*(app/geoserver/geoserver_data/workspaces/cite/database)*
ways_lit	*(app/geoserver/geoserver_data/workspaces/cite/database)*
ways_parking	*(app/geoserver/geoserver_data/workspaces/cite/database)*
ways_speed	*(app/geoserver/geoserver_data/workspaces/cite/database)*
ways_surface	*(app/geoserver/geoserver_data/workspaces/cite/database)*
ways_wheelchair	*(app/geoserver/geoserver_data/workspaces/cite/database)*

B.4. Geoserver styles

pois	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_crossings	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_footpath_width	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_lanes	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_lit	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_parking	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_speed	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_street_furniture	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_surface	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_wheelchair	*(app/geoserver/geoserver_data/workspaces/cite/styles)*
style_user_statements	*(app/geoserver/geoserver_data/workspaces/cite/styles)*

Declaration of Academic Honesty

I hereby certify that I have written my thesis independently and have not used any other sources and aids than those cited.

Location, Date, Signature