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Development, application, and testing of an accessibility instrument for planning active mobility

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Abstract

Our transport system is both an enabler and a threat to sustainable development in cities. While providing opportunities and prosperity, urban transportation is accompanied by severe consequences such as land seizure, global warming, and pollution. There is increasing awareness that travel demand is a derived phenomenon, and land-use patterns strongly influence our daily mobility choice. The concept of accessibility is promising by providing a holistic framework to interrelate transport with land-use. More than any other form of transport, active mobility (e.g., walking and cycling) depends on high local accessibility to destinations. Therefore, emerging ideas, such as the 15-Minute City propagate high proximity to destinations and the provision of appropriate infrastructure. Accessibility instruments function as a specialized Planning Support System (PSS) and can create high value for planning practice when shaping sustainable cities. However, research has shown that accessibility instruments are rarely adopted in practice. In addition to institutional barriers, it was found that accessibility instruments still do not meet expectations in practice, and the availability of data and resources remains an open concern.

Therefore, this dissertation presents a novel accessibility instrument called Geo Open Accessibility Tool (GOAT) that focuses on active mobility and local accessibility. It is a web-based tool combining different web and Geographic Information Systems (GIS) technologies and was developed in a co-creative and iterative process. The instrument is developed open source and was applied in numerous German and international case studies.

The tool requirements were derived by exploring the existing tool landscape through testing and literature review of 26 accessibility instruments. Accessibility instruments have undergone significant developments in the last few years. Improvements in GIS, new web technologies, and the rising availability of (open) data have facilitated the fast development of these new tools. Nevertheless, the review still identified a lack of open source and transferable instruments that allow on-the-fly scenario building while focusing on active mobility. Furthermore, a clear gap was identified between fully-featured proprietary desktop and (open) web tools. Therefore, by focusing on an open, interac-

tive, and transferable web tool, the typical shortcomings of existing accessibility instruments were addressed during the development of GOAT.

One focus was developing data strategies to enable powerful and affordable accessibility instruments. A novel population disaggregation procedure was developed that produces population data on the building access level with low data requirements. Furthermore, Point of Interest (POI) data originating from OpenStreetMap (OSM) was refined and fused with additional data sets. In addition, data was contributed to OSM through different means, such as mapping events with volunteers and a mapping mode in GOAT. The different data strategies made it possible to apply the tool in practice.

Finally, the usefulness of GOAT in practice was studied. In particular, the tool was used for real-world planning questions and assessed by 42 planning professionals in workshops. Four core use cases were identified and users appreciated the tool's interactivity and easy-to-use interface. However, further improvements to the tool are necessary, including enhancing the implemented indicators, increasing its usability and integrating it with existing GIS software.

The developed tool offers a valuable contribution to the landscape of accessibility instruments. It is recommended that future research focus on the open technical challenges that GOAT and other accessibility instruments still face. Furthermore, tool developers should strive for continuous exchange with the planning practice to meet real-world requirements, support teaching accessibility, and aim to use accessibility for sustainable development.

Zusammenfassung

Unser Verkehrssystem ist sowohl ein Motor als auch eine Gefahr für die nachhaltige Entwicklung in Städten. Während es Entwicklungschancen und Wohlstand ermöglicht, geht städtischer Verkehr mit schwerwiegenden Folgen wie Flächenverbrauch, Erderwärmung und Umweltverschmutzung einher. Es gibt ein wachsendes Bewusstsein dafür, dass die Verkehrsnachfrage eine abgeleitete Größe ist, und die Raumstruktur unsere täglichen Mobilitätsentscheidungen stark beeinflusst. Das Konzept der Erreichbarkeit ist vielversprechend, da es einen ganzheitlichen Blick auf die Verknüpfung von Verkehr und Raumstruktur bietet.

Die aktive Mobilität (z. B. Fußverkehr und Radverkehr) ist mehr als jede andere Art von Fortbewegung auf eine gute lokale Erreichbarkeit zu Zielen angewiesen. Daher propagieren neue Ideen, wie die 15-Minuten-Stadt kurze Wege zu Zielen und die Bereitstellung von geeigneter Infrastruktur. Erreichbarkeitsinstrumente fungieren als spezialisierte Planning Support System (PSS) und können einen großen Mehrwert für die Planungspraxis in der Gestaltung nachhaltiger Städte schaffen. Die Forschung hat jedoch gezeigt, dass Erreichbarkeitsinstrumente selten in der Praxis eingesetzt werden. Neben institutionellen Barrieren wurde auch festgestellt, dass Erreichbarkeitsinstrumente in der Praxis noch immer nicht den Erwartungen entsprechen, und die Verfügbarkeit von Daten und Ressourcen bleibt ein offenes Problem.

Daher wird in dieser Dissertation ein neuartiges Erreichbarkeitsinstrument namens Geo Open Accessibility Tool (GOAT) entwickelt, das sich auf die aktive Mobilität und lokale Erreichbarkeit konzentriert. Es ist ein webbasiertes Tool, das unter Nutzung von verschiedene Web- und Geoinformationssysteme (GIS) in einem ko-kreativen und iterativen Prozess entwickelt wurde. Das Instrument wird Open Source entwickelt und wurde in zahlreichen deutschen und internationalen Fallstudien eingesetzt.

Die Anforderungen an das Instrument wurden abgeleitet, indem 26 bestehende Instrumente in Tests und durch Literaturrecherche untersucht wurden. Erreichbarkeitsinstrumente wurden in den letzten Jahren stark weiterentwickelt. Verbesserungen in GIS, neue Webtechnologien und die zunehmende Verfügbarkeit von (offenen) Daten haben die rasche Entwicklung neuer Instrumente begünstigt. Dennoch wurde in der Unter-

suchung ein Mangel an quelloffenen und übertragbaren Instrumenten, mit dynamischer Szenarienentwicklung und einem Fokus auf der aktiven Mobilität festgestellt.

Darüber hinaus wurde eine deutliche Lücke zwischen voll funktionsfähigen proprietären Desktopsoftware und (offenen) Web-Tools identifiziert. Durch die Fokussierung auf ein offenes, interaktives und übertragbares Webtool wurden daher während der Entwicklung von GOAT die Herausforderungen bestehender Erreichbarkeitsinstrumente adressiert. Ein Schwerpunkt war die Entwicklung von Datenstrategien, um leistungsfähige und erschwingliche Erreichbarkeitsinstrumente zu ermöglichen.

Es wurde eine neue Methode zur Disaggregierung von Bevölkerung entwickelt, die mit geringem Datenaufwand Bevölkerungsdaten auf der Ebene des Gebäudeeingangs bereitstellt. Darüber hinaus wurden Point of Interest (POI) aus OpenStreetMap (OSM) verfeinert und mit zusätzlichen Datensätzen fusioniert. Darüber hinaus wurde die OSM-Datenbank auf verschiedene Weisen ergänzt, z. B. durch Mapping Partys mit Freiwilligen und einem Mapping Mode in GOAT. Die verschiedenen Datenstrategien ermöglichten die Anwendung des Tools in der Praxis.

Schließlich wurde der Mehrwert von GOAT in der Praxis untersucht. Insbesondere wurde das Tool für reale Planungsfragen eingesetzt und von 42 Planungsexperten:innen in Workshops bewertet. Es wurden vier Hauptanwendungsfälle identifiziert, Benutzer:innen schätzten die Interaktivität und die einfache Nutzeroberfläche des Tools. Es sind jedoch weitere Verbesserungen des Tools erforderlich, darunter die Verbesserung der implementierten Indikatoren, die Erhöhung der Benutzerfreundlichkeit und die Integration in bestehende GIS-Software.

Das entwickelte Tool stellt einen wertvollen Beitrag zur bestehenden Landschaft von Erreichbarkeitsinstrumenten dar. Es wird empfohlen, dass sich zukünftige Forschung auf die offenen technischen Herausforderungen konzentriert, denen GOAT und andere Erreichbarkeitsinstrumente noch gegenüberstehen. Darüber hinaus sollten sich die Entwickler:innen von Instrumenten um einen kontinuierlichen Austausch mit der Planungspraxis bemühen, um den Anforderungen der Praxis gerecht zu werden. Zudem sollten Erreichbarkeitsinstrumente das Erreichbarkeitskonzept lehren und für die nachhaltige Entwicklung eingesetzt werden.

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List of Abbreviations

ALKIS Amtliches Liegenschaftskatasterinformationssystem.

API Application Programming Interface.

ATKIS Amtliches Topographisch-Kartographisches Informationssystem.

COVID-19 Coronavirus Disease 2019.

EPSG European Petroleum Survey Group / Nowadays EPSG Geodetic Parameter Dataset.

EU European Union.

GIS Geographic Information Systems.

GOAT Geo Open Accessibility Tool.

GTFS General Transit Feed Specification.

JOSM Java OpenStreetMap Editor.

LOD Level of Detail.

MVT Mapbox Vector Tile.

OGC Open Geo Spatial Consortium.

OSM OpenStreetMap.

OSS Open Source Software.

PL/pgSQL Procedural Language/PostgreSQL.

POI Point of Interest.

PSS Planning Support System.

RMSE Root-Mean-Square Error.

SQL Structural Query Language.

TUM Technical University of Munich.

USA United States of America.

VGI Volunteered Geographic Information.

WebGIS Web Geographic Information System.

WFS Web Feature Service.

WMS Web Map Service.

XML Extensible Markup Language.

Part I

Introduction, state of the art, and research design

Chapter 1

Introduction

1.1 Background

A critical debate about the role of transportation in urban contexts is taking place in cities worldwide. It is undeniable that transportation networks and technology are key enablers of economic prosperity. However, they are accompanied by an array of externalities. Transportation can place local communities at severe risk and threaten local and global sustainability. Globally, it is estimated that 3.7 million people die prematurely because of outdoor air pollution, largely because of transport emissions (WHO, 2019). Meanwhile, it is estimated that 1.35 million people die annually due to crashes in road traffic (World Health Organization et al., 2019). In the European Union (EU), 26% of the carbon dioxide emissions were related to road transportation in 2018 (Statistisches Bundesamt, 2021). At 62% passenger cars and motorcycles are the main contributors. Across multiple sectors, carbon dioxide emissions fell by 23% in the EU between 1990 and 2018. However, in the same period, carbon dioxide emissions caused by road transportation rose by 24% (Statistisches Bundesamt, 2021). The adoption of electric cars in Europe will accelerate fast until 2030 (IEA, 2021). In 2030, 7% of the global vehicle fleet in the stated policy scenario, and 12% of the global vehicle fleet in the sustainable development scenario will have an electric engine (IEA, 2021). At the same time, large portions of the vehicle fleet will still be powered by a combustion engine, and even if electric, energy will often come from fossil fuels. Meanwhile, a change in vehicle technology does not answer the scarcity of space in cities. In cities like Munich, 17% of the area is dedicated to transportation (Geisser & Lenk, 2017). Additionally, traffic congestion severely affects the quality of life in cities.

There is increasing awareness that simply expanding transport infrastructure or providing additional mobility options cannot solve the described problems. Instead, it is suggested that mobility and therefore the need for transport is understood as a derived phenomenon. Since people strive for accessibility to destinations, increasing people's accessibility should be the primary concern (Handy, 2020; Levine, 2019; Silva et al., 2019; Venter, 2016). Meanwhile, Silva and Larsson (2019) have highlighted the risks of accessibility planning that addresses accessibility problems solely by transport or mobility measures. Instead, a stronger focus is suggested on increasing proximity to destinations (Silva & Larsson, 2019). Strengthening proximity might be particularly relevant since, during the last decades, a general decline in local accessibility could be observed in many western countries due to the concentration of activities (Silva, 2020). The fast trending concept of the 15-Minute City and variations such as the 10-Minute or 20-Minute City are part of a counter-movement. The 15-Minute City concepts provides a clear message that is widely understood and can be defined as an "urban setup where locals are able to access all of their basic essentials at distances that would not take them more than 15 min by foot or by bicycle" (C. Moreno et al., 2021).

1.2 Motivation

Overall, the concept of accessibility has great potential to provide an integrated framework for sustainable transportation and land-use planning (Bertolini et al., 2005). Carfully increasing accessibility can be understood as the pre-condition for sustainable mobility (Couclelis, 2000). By creating proximity to opportunities and providing access to sustainable forms of transportation, alternatives to the personal car can facilitate more sustainable transport and land-use patterns. Applying accessibility, therefore, has the high potential to make transportation and urban development more sustainable (Bertolini et al., 2005; Bertolini & Silva, 2019; Levine, 2019). While there is hope that accessibility is increasingly adopted (Handy, 2020), Planning Support System (PSS) in general (Geertman et al., 2017b; Russo et al., 2017; te Brömmelstroet, 2017) and, more specifically, accessibility instruments to operationalize the theoretical concept are not yet widely used in practice (Bertolini & Silva, 2019; Boisjoly & El-Geneidy, 2017b; Hull et al., 2012; Papa et al., 2015; te Brömmelstroet et al., 2016; te Brömmelstroet et al., 2014; Wulfhorst et al., 2017). This phenomenon is commonly described as an implementation gap, and past research has identified different explanatons for it. Levine (2019) underlined that classical mobility measures persist because transport engineers and spatial planners are asked to use them. Furthermore, there is evidence that accessibility is often conceptually misinterpreted (Levine, 2019).

te Brömmelstroet et al. (2016) highlighted that tool development is often disconnected from the users, running the risk that the actual problems in the planning practice are not addressed. Furthermore, a lack of data makes the application of accessibility instruments challenging and expensive (Boisjoly & El-Geneidy, 2017a; Papa et al., 2015; te Brömmelstroet et al., 2014). Others have claimed that there is a lack of knowledge (Boisjoly & El-Geneidy, 2017b) and resources (te Brömmelstroet et al., 2014) to use accessibility analyses in practice. Users asked for more interactive instruments providing real-time scenario calculations (Silva et al., 2017; te Brömmelstroet, 2017; te Brömmelstroet et al., 2014; Wulfhorst et al., 2017). Another concern is that accessibility instruments are often perceived as "complex, inflexible, incomprehensible, and rigid black boxes" (Papa et al., 2015).

1.3 Research objectives

This research aims to develop a novel accessibility instrument. This work is an applied research project that makes use of ongoing technological development. Previous research identified the close involvement of potential users as a core requirement for developing a usable and useful accessibility instrument (Bertolini & Silva, 2019; Silva et al., 2017; te Brömmelstroet et al., 2016; te Brömmelstroet et al., 2014). Meanwhile, numerous cities worldwide are willing to foster active mobility and adopt concepts such as the 15-Minute City (C40 Cities, 2020). The concept of the 15-Minute City aims to increase local accessibility. Local accessibility, in contrast to regional accessibility focuses on short and frequent trips to different destinations (Handy, 1993). Silva and Altieri (2022) described local accessibility as proximity-based and regional accessibility as mobility-based.

As active mobility relies on the ability to travel short distances to destinations, high local accessibility is the basis for a high share of active mobility. Active mobility typically groups the transport modes of walking and cycling (Koszowski et al., 2019a). However, also other typically non-motorized modes (e.g., skateboards) fall under this category. From the own perspective all forms of mobility that require substantial physical activity can be classified as active mobility. However, this research focuses on walking and cycling.

The willingness to gear mobility toward a higher share of active mobility from practice, paired with the low availability of planning support when shaping active mobility, provides a unique opportunity to bridge the implementation gap, particularly for active mobility and local accessibility. Consequently, this dissertation proposes a tool development that focuses on creating an interactive, transferable, web-based, and open solution called Geo Open Accessibility Tool (GOAT), which focuses on planning active mobility and local accessibility. It aimed to make accessibility analyses for active mobility applicable to a much wider group of users. Accordingly, the GOAT aims to serve as a valuable contribution to the landscape of accessibility instruments and help shape sustainable mobility.

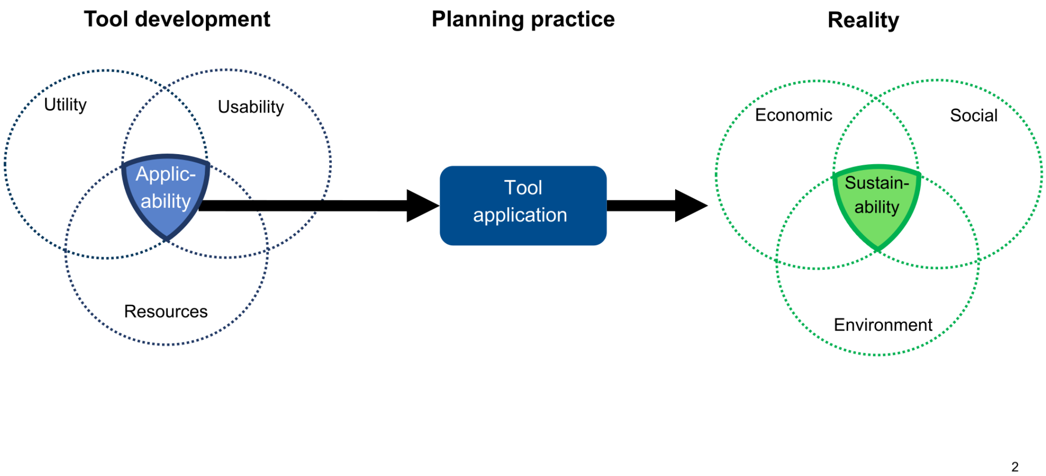

Figure 1.1: Research aim

In sum, the contributions of this research is the development of a useful (combining utility and usability) accessibility instrument, which can be applied with a reasonable amount of resources. Consequently, a widely applicable accessibility instrument should be developed. A more straightforward application of accessibility in practice ultimately can contribute to a more sustainable reality in transport and land-use development (see Figure 1.1). While, an assessment of how the development influences transport and land-use development is beyond the scope of the thesis, it serves as the vision and underlying motivation of the thesis. More specifically, the research objectives of this dissertation are as follows:

- Identification of areas in which accessibility instruments should be developed further to meet the shortcomings of existing accessibility instruments.
- Development and application of an interactive, transferable, web-based, and open accessibility instrument for active mobility and local accessibility.
- Development and application of novel and open data strategies to collect, prepare and fuse spatial data to facilitate more powerful and affordable accessibility instruments.
- Assessment and discussion of the usefulness of the developed instrument for the planning practice.
- Collection and sharing of the expertise of the co-creative development of an accessibility instrument with practice and other tool developers.

1.4 Thesis structure

This dissertation is comprised of nine chapters. It starts with an introduction to the research topic in Chapter 1, followed by a short literature review in Chapter 2 on the essentials of accessibility research. Afterward, the three research questions and main goals are presented in Chapter 3. While the primary goal is the development of the novel accessibility instrument GOAT, the three research questions address tool requirements, data management, and tool assessment. In Chapter 4 the research design is presented, characterized by the tool development, tool application, and the co-creative involvement process of practitioners, researchers, and students. As a paper-based dissertation, the following three chapters present each one scientific paper:

- Paper 1: Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility. Pajares, E., Büttner, B., Jehle, U., Nichols, A., Wulfhorst, G.

- Paper 2: Population Disaggregation on the Building Level Based on Outdated Census Data. Pajares, E., Muñoz Nieto, R., Meng, L., Wulfhorst, G.

- Paper 3: Assessment of the usefulness of the interactive accessibility instrument GOAT for the planning practice. Pajares, E., Jehle, U., Hall, J., Miramontes, M., Wulfhorst, G.

The synthesis and discussion of the main research findings are presented in Chapter 8. The results are split into sections per research question and one for the main goal. Finally, in Chapter 9 the conclusion is presented, consisting of the study limitations, the discussion of future development paths, and final reflections. Figure 1.2 visualizes the structure of the thesis.

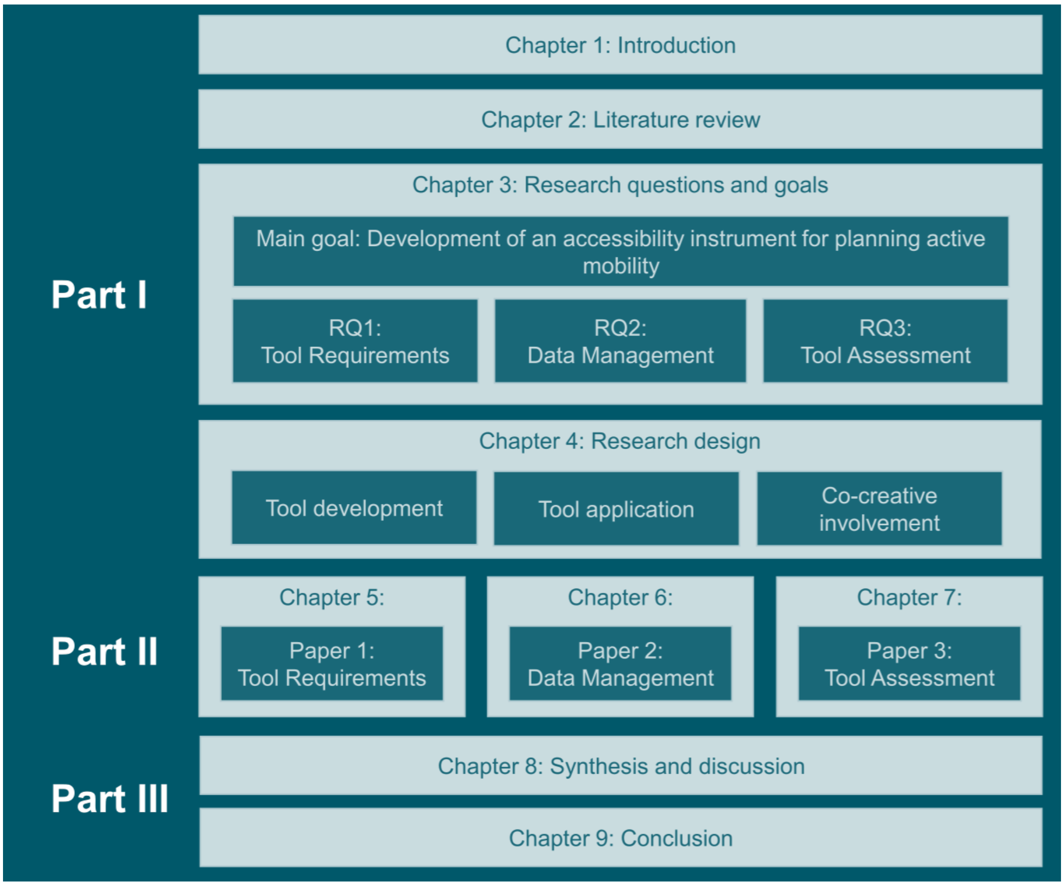

Figure 1.2: Thesis structure

Chapter 2

Literature review

2.1 Accessibility theory

Accessibility has faced the challenge that it was hardly tangible for a long time. Gould (1969) described the dilemma as "Accessibility (...) It is a slippery notion, however; one of those common terms that everyone uses until faced with the problem of defining and measuring it!". The first definition in literature dates back to Hansen (1959), who defined accessibility as "the potential of opportunities for interaction".

It is essential to differentiate mobility and transportation from accessibility in this context. Mobility can be defined as the "potential for movement" (Handy, 2002), while transportation is the "movement of goods and persons from place to place" (Britannica, The Editors of Encyclopaedia, 2019). Scholars agree that transportation is a derived phenomenon, that arises from the need of a person to realize activities that are not at the person's origin (Levine et al., 2012; Meyer & Miller, 1984). This need can be met by increasing mobility, such as expanding the highway network or increasing proximity to destinations (Levine, 2019; Levine et al., 2012). There are places (e.g., the city center) where mobility is low due to slow travel speeds, but accessibility is high thanks to the high density of opportunities. Meanwhile, in suburban or rural contexts, accessibility is lower despite the commonly higher travel speeds (by car) due to the low density of opportunities (Handy & Niemeier, 1997; Levine et al., 2012). Therefore, accessibility is related to the performance of transportation and land-use (Bertolini et al., 2005).

Overall, optimizing accessibility can be more appropriate than widespread mobility-focused transportation planning. As it serves the actual needs of people, which is realizing activities instead of traveling fast nowhere. Since Hansen's early definition, researchers have focused on developing appropriate ways to measure accessibility (Handy & Niemeier, 1997; Ingram, 1971; Koenig, 1980). Geurs and van Wee (2004) systematized and categorized different accessibility measures and proposed four components: transport, land-use, temporal and individual.

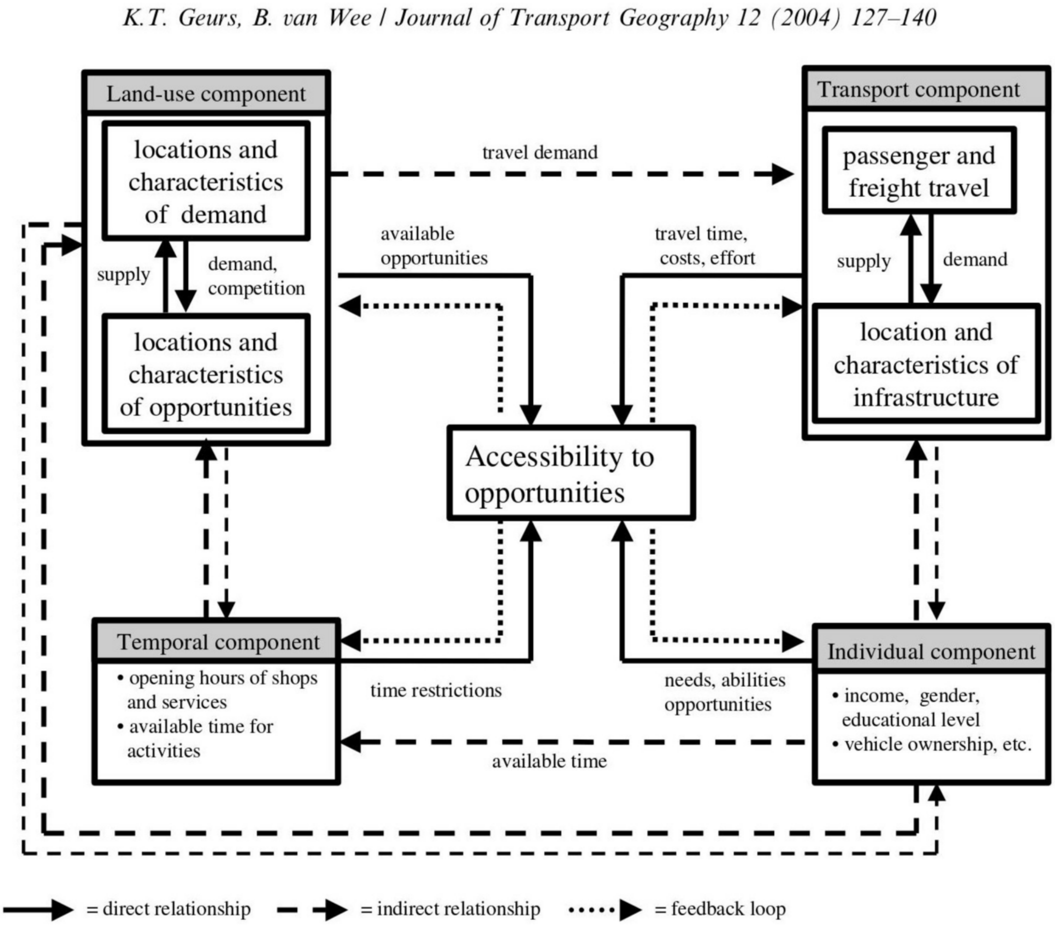

Figure 2.1: Four accessibility components
(Geurs & van Wee, 2004)

2.2 Accessibility measures

Ideally, an accessibility measure should include all four accessibility components (Geurs & van Wee, 2004). Accessibility measures can be classified as infrastructure-based, location-based, person-based, and utility-based (Geurs & van Wee, 2004). Infrastructure-based measures do not have a land-use dimension and instead solely capture the performance indicators of the transport system (e.g., travel speed). Person-based measures show accessibility from an individual standpoint. Therefore, personal constraints such as the daytime availability or the person's physical capabilities are considered (Geurs & van Wee, 2004). Person-based accessibility measures are based on the space-time geography defined by Hägerstrand (1970). Utility-based accessibility measures aim to picture the benefits (e.g., social and economic) associated with accessibility (Ben-Akiva & Stevan R., 1979; Geurs & van Wee, 2004; Handy & Niemeier, 1997).

The most widely used set of accessibility measures is location-based. These include contour and gravity-based measures (Geurs & van Wee, 2004; Handy & Niemeier, 1997; Iacono et al., 2010). A typical contour measure is the travel time isochrone, showing how far one can travel in a certain length of time. The first examples of isochrones were published in studies of the 19th century such as *Isochronic Passage-Charts* by Galton (1881) and *Isochronenkarte der österreichisch-ungarischen Monarchie* by Penck (1889). Nowadays, isochrones are often intersected with spatial data (e.g., points of interest or population) to compute the sum of reached opportunities in a given travel time, called cumulative opportunities (Geurs & van Eck, 2001; Geurs & van Wee, 2004). The isochrone as an accessibility measure has clear benefits as they are relatively easy to calculate and understandable by a wider audience (Bertolini et al., 2005; Geurs & van Eck, 2001). At the same time, one limitation of using cumulative opportunities is that there is no differentiation between different travel times within the cutoff range (Bertolini et al., 2005; Bhat et al., 2002; El-Geneidy & Levinson, 2006).

Gravity-based accessibility measures were first introduced by Hansen (1959). Unlike contour-based measures, accessibility to opportunities is evaluated by the generalized travel cost using an impedance function (Bhat et al., 2002; Geurs & van Eck, 2001; Handy & Niemeier, 1997). In this method, opportunities located further away are weighted lower than closer opportunities. This approach is in line with the first law of geography, which states that: ëverything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Accordingly, gravity-based accessibility measures can be expressed using the following formula:

$$A_i = \sum_j O_j * f(t_{ij})$$

In which A_i is the accessibility at location i, O_j are the opportunities at location j and t_{ij} is the travel cost between i and j. While the most common type of travel cost is travel time, different types of cost can be utilized to compute impedances such as monetary (Büttner, 2016) or emissions (Kinigadner, 2020). Furthermore, it is decisive which function is used for computing the impedance. The impedance function generally involves the traveltime and a sensitivity parameter that is commonly represented with the letter β. The following frequently used impedance functions were summarized by Kwan (1998):

- **Inverse Power**

$$f(t_{ij}) = \begin{cases} 1 & for\ t_{ij} < 1 \\ {t_{ij}}^{-\beta} & else \end{cases}$$

- **Negative Exponential**

$$f(t_{ij}) = e^{-\beta \times t_{ij}}$$

- **Modified Gaussian**

$$f(t_{ij}) = e^{t_{ij}^2/\beta}$$

- **Cumulative Opportunities Rectangular**

$$f(t_{ij}) = \begin{cases} 1 & for\ t_{ij} \leq t_{max} \\ 0 & else \end{cases}$$

- **Cumulative Opportunities Linear**

$$f(t_{ij}) = \begin{cases} (1 - t_{ij}/t_{max}) & for\ t_{ij}\ \leq t_{max} \\ 0 & else \end{cases}$$

As shown in Figure 2.2 different functions significantly influence the computed impedance. The shown impedance functions using the indicated sensitivity parameters and travel times in minutes. The negative exponential functions is frequently used (Iacono et al., 2010; Vale & Pereira, 2017). Vale and Pereira (2017) stated that "the literature supports the concept of a certain indifference toward marginal distances." This occurrence favors functions that are less sensitive to changes in the travel time in the beginning and fall off more quickly with increasing travel time. The presented functions, especially the Gaussian one, fall under this category. Already in early accessibility research, the Gaussian function was already considered superior to other functions (Bhat et al., 2002; Ingram, 1971).

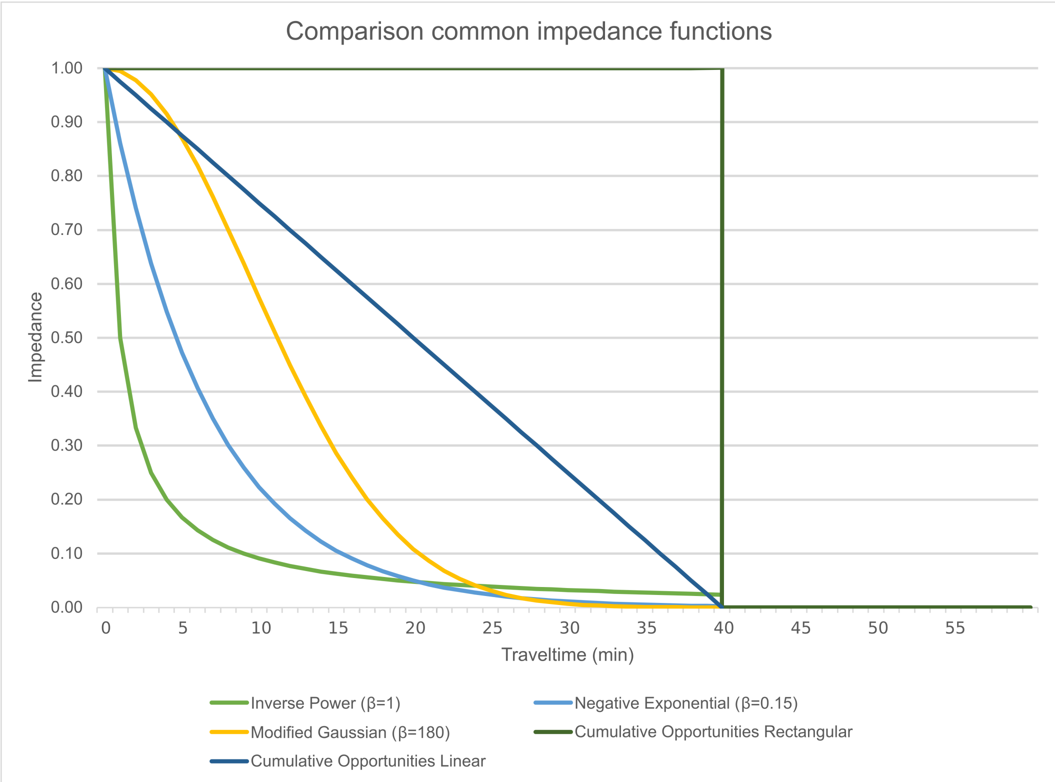

Figure 2.2: Comparison of the most common impedance functions (Own visualization based on (Higgins, 2019))

Meanwhile, still little application of the Gaussian function is observed (Vale & Pereira, 2017). The literature agrees that selecting a suitable impedance function should be influenced by the studied transport mode and trip purpose (Iacono et al., 2010; Vale & Pereira, 2017). Besides finding a suitable impedance function, appropriate sensitivity parameters strongly influences the inverse power, negative exponential, and modified Gaussian function. It has also been suggested that the sensitivity parameter should be calibrated with data from real-world travel behavior (Geurs & van Eck, 2001; Handy & Niemeier, 1997; Iacono et al., 2008). Meanwhile, suitable data for calibration is often unavailable. Classical household surveys are often not granular enough. Ideally, calibration would differentiate between POIs and population groups, as the impedance might vary significantly for different demographic attributes (e.g., age, gender, and social status) (Handy & Niemeier, 1997). Chapter 5.5.5 presents the gravity-based measure in GOAT; due to the lack of suitable data for calibrating the impedance functions, the sensitivity parameter can be adjusted. It was decided to use the modified Gaussian function, which was calculated with travel times in seconds.

2.3 Accessibility instruments

Accessibility instruments are usually GIS-based tools that aim to translate the accessibility concept into operational planning support. Papa et al. (2015) state that:

> "Accessibility instruments (...) are a type of planning support system (PSS) designed to support integrated land-use transport analysis and planning through providing explicit knowledge on the accessibility of land uses by different modes of transport at various geographical scales."

Generally, accessibility instruments simplify the complex and often subjective nature of accessibility. The term accessibility instrument is comparatively new; it was mainly consolidated in the COST Action project on "Accessibility Instruments for Planning Practice in Europe" (Hull et al., 2012; te Brömmelstroet et al., 2014). Accordingly, there might be cases in which another term is used. Accessibility instruments are often referred to as accessibility tools. However, the literature does not clearly distinguish between occasional accessibility analyses, commonly created using GIS software, and an accessibility instrument. An accessibility instrument is understood as a specialized tool mainly designed to perform accessibility analyses in this dissertation. Accordingly, other tools capable of conducting specific accessibility analyses, such as macroscopic transport models, trip planners, or multi-purpose GIS software do not fall under this category. In Chapter 8.1.1, a classification of the different technical components is proposed. A wide range of accessibility instruments exist for different purposes (Silva et al., 2019; TUM - Chair of Urban Structure and Transport Planning, 2021) and analyses are conducted for different transport modes and spatial scales (Papa et al., 2015; TUM - Chair of Urban Structure and Transport Planning, 2021). The concrete planning questions and data availability might influence the tool's design and application in practice. Furthermore, tools are developed as desktop applications, software extensions, or web tools (TUM - Chair of Urban Structure and Transport Planning, 2021). So far, most of the tools have been developed in academic projects and have shown dynamic development but, to some extent, also immaturity. Furthermore, academic developments always risk being discontinued when project funding ends. A richer insight into the tool landscape and potential for new developments is provided in Chapter 5.

Chapter 3

Research questions and goals

This chapter presents the research questions and the main goal. Previous research has underlined the great potential of accessibility-based planning. Moreover, it has been emphasized that accessibility instruments are not frequently used in the planning practice. Therefore, a collaborative development process through the involvement of planning practitioners has the potential to develop useful instruments. Furthermore, the rapid growth of web technologies and GIS and the increasing availability of (open) data facilitate faster and more affordable development. Accordingly, there is a high potential for developing a new generation of interactive accessibility instruments based on open technology and transparent indicators.

3.1 Main goal

The main goal is the development and application of the accessibility instrument GOAT. As discussed in Chapter 1.3 the development and application of the development tools should ultimately contribute to more sustainable development. The particular focus of the development can be summarized as follows:

Development of an open source, interactive, and transferable accessibility instrument for planning local accessibility by active mobility.

Due to its deterministic nature, the development is defined as a goal rather than a research question. The main goal is addressed throughout the research process and can be understood as an important deliverable of the presented work. It reacts to the identified gaps in accessibility research and instruments. Moreover, it is closely interrelated with the three research questions, and it is the basis for answering the three research questions. RQ1 is starting ground for tool development. In comparison, the tool development provides the basis for RQ2 and RQ3. Overall, this dissertation understands the development as an enabler to answering the research questions and, more importantly, to help answer real-world planning questions. The tool development should be understood as a vehicle to support sustainable urban and transport planning by using accessibility as a holistic framework.

3.2 RQ1 Tool requirements

In which areas do accessibility instruments have to be developed further to better support planning practice when planning for active mobility?

There is a rising awareness of the need to promote active mobility and local accessibility. At the same time, PSS are rarely applied in practice (see Chapter 2.3 and 7.6). While the implementation gap is a general trend across all transport modes, the lack of other planning tools (e.g., macroscopic transport models) for active mobility and the rising importance of providing favorable conditions for active mobility show a particular need. Consequently, this dissertation concentrates on the implementation gap in active mobility planning. This research question focuses on studying and classifying existing accessibility instruments. In particular, it assesses if highly desired features by the planning practice in the past, such as interactive scenario building, are implemented and if the tools support walking and cycling. Furthermore, the tool access, transferability, and type are examined to understand the ease of applying the tool in practice.

3.3 RQ2 Data management

How can data refinement and fusion strategies enable powerful and affordable accessibility instruments?

Accessibility instruments are data-driven tools; therefore, the availability of data paired with the need to harness its full potential is essential. The ever-increasing availability of suitable data offers increased opportunities for a new generation of accessibility instruments, facilitating analyses on the local scale. Overall, the data is the basis for the development of powerful accessibility instruments. At the same time, high data collection or acquisition costs often make accessibility instruments unaffordable. The data needed for an accessibility instrument is diverse and strongly influenced by the study area and concrete planning questions. In the context of the dissertation, the availability of population data on the building level and high-quality POIs data are particular challenges. Therefore, this research question focuses on developing a novel population disaggregation method based on widely available data. Moreover, data fusion strategies are designed to combine diverse sets of POIs. This is accompanied by exploring how collecting of Volunteered Geographic Information (VGI) in OpenStreetMap (OSM) can increase the data quality and availability.

3.4 RQ3 Tool assessment

Is the accessibility instrument GOAT of useful support in the planning practice?

This research question critically examines whether the developed accessibility instrument GOAT is useful when planning active mobility and local accessibility. Usefulness is differentiated into two components utility and usability. In this context, utility describes whether the developed tool provides relevant analyses for concrete planning questions and usability focuses on the ease and intuitiveness of GOAT for the planning questions. If possible, the results are broken down into individual use cases (e.g., infrastructure planning walking) and discussed on a more aggregated level. Areas where the instrument already meets the requirements in practice and where it does not are highlighted. Accordingly, the tool assessment serves as the basis for the reflection on the quality of the instrument and future development paths.

Chapter 4

Research design

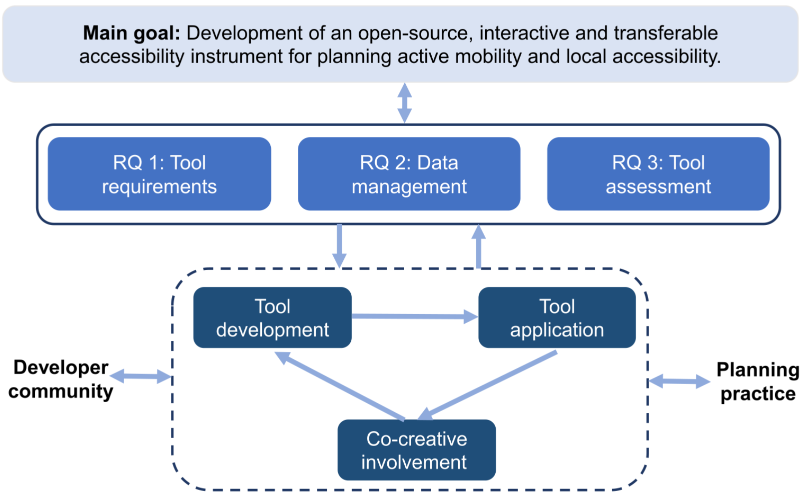

Figure 4.1: Connections between main goal, research questions, and methods

The dissertation follows the research design visualized in Figure 4.1. The starting point was the identified need for a new accessibility instrument, and concrete development needs were further expanded in RQ1. Additionally, the requirements identified in the literature and the research process were translated into the presented main goal (see Chapter 3.1). Three research questions were also developed that summarize the scientific contribution of the thesis. An iterative software development cycle characterizes the research design. The tool was first developed with basic functionality; it was then applied and intensively tested through the co-creative involvement of practitioners. Accordingly, the tool development was accompanied by an early application of the tool. First, the tool was applied in one study context and, later, in several case studies. The open access provision of the application facilitated early involvement of the developer community and especially of the planning practice, which was the target user group of the development.

4.1 Tool development

The development of the tool GOAT (see Figure 4.2) was first initialized in the author's master's thesis (Pajares, 2017). During the master's thesis, a prototype was developed, serving as a minimum viable product that facilitated online testing of its functionality. In early 2018, the tool development was continued at the Chair of Urban Structure and Transport Planning at TUM. Accordingly the development in the scope of this dissertation started in early 2018. Until October 2019, the development was realized without external funding, and therefore progress was relatively slow. Nevertheless, by the end of 2019, GOAT 0.1 was released, with many features that GOAT still contains today.

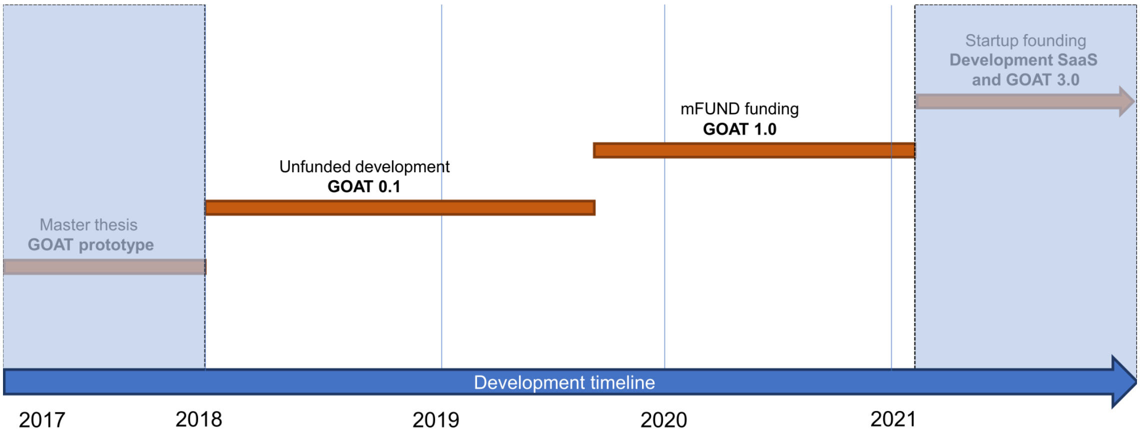

Figure 4.2: Development timeline

From November 2019 until February 2021, the GOAT development was supported by the mFUND initiative (BMDV, 2022). This project funding facilitated the development and implementation of new features such as accessibility analysis for cycling and provided the project context for the co-creative involvement of practitioners (see Chapter 4.3). The project ended with the release of GOAT version 1.0 (GOAT-Community, 2021c). Since early 2021, the development of GOAT has been continued by the startup Plan4Better and in joint research and application projects with TUM, as well as other practice and research partners. However, this dissertation focuses on the tool's development from early 2018 to the release of GOAT 1.0 in March 2021. The development was realized as an open source project (GOAT-Community, 2021c) that involved other researchers and developers. The author led the development team, translating the needs identified through co-creative involvement into concrete technical requirements. Furthermore, the author conceptualized and implemented the tool architecture and the backend development, which contained most of the tool logic and indicators. The frontend software development and DevOps were supported by additional developers most notably Majk Shkurti (Majk Shkurti, 2022). The contributions of different collaborators to GOAT's codebase can be explored in the project's Github repository (GOAT-Community, 2021d).

4.2 Tool application

Table 4.1: Applied GOAT versions

Study context	**Project**	**Year**	**Live deployment**
Municipality of Munich	First version and mFUND	2018	Yes
Municipality of Fürstenfeldbruck	mFUND	2020	Yes
Municipality of Freising	mFUND	2020	Yes
County of Freising and Erding	Mobility concept for Mittlere Isarregion and Ampertal	2019	No
Municipality of Freiburg	Plan4Better project	2021	Yes
Municipality of Boca Raton	Plan4Better project	2021	no
Municipality of Istanbul	Plan4Better project	2021	No
Municipality of Bogotá	Master's thesis (Munoz Nieto, 2020)	2020	Yes
Municipality of San Pedro Garza García	Master's thesis (Ivanov, 2021)	2021	Yes
Municipality of Matosinhos	Study project (Viertler, 2020)	2020	Yes
District of Hasenbergl (Munich)	Master's thesis (Jehle, 2020)	2020	Yes
District of Neuperlach and Maxvorstadt (Munich)	Bachelor's thesis (Ben Hassine, 2019)	2019	No
County of Starnberg	Study project (Schott, 2020)	2020	No
Municipality of Augsburg, Wolfratshausen and Münsing	Bachelor's thesis (Diepolder, 2020)	2020	No
Municipality of Magdeburg	Bachelor's thesis (Zuckriegl, 2021)	2021	No
Municipality of Berlin, Heidelberg, Cottbus, Flensburg, Neustadt a.d. Donau, Eppelborn, Oschersleben, Nordkirchen, Zorneding, Ronneburg, Seeshaupt and Rackwitz	Master's thesis (Viertler, 2020)	2020	No
Municipality of Magdeburg	Bachelor's thesis (Zuckriegl, 2021)	2021	No
Municipality of Atlanta	Study project (Hanekamp, 2021)	2021	No

The different deployments varied in focus (see Chapter 4.1). Some experimented with new features, others tested the transfer to a new study context, and others were used in workshops or real-world consulting projects. While various versions of GOAT were used for the application over the years, they can all be considered pre-releases of GOAT version 1.0. Not all versions were deployed live on a server; many were only set up locally for testing and application. The deployed version were provided open access so everyone could test the tool. Furthermore, as the tool is open source, other parties transferred it to the author's knowledge to additional study contexts.

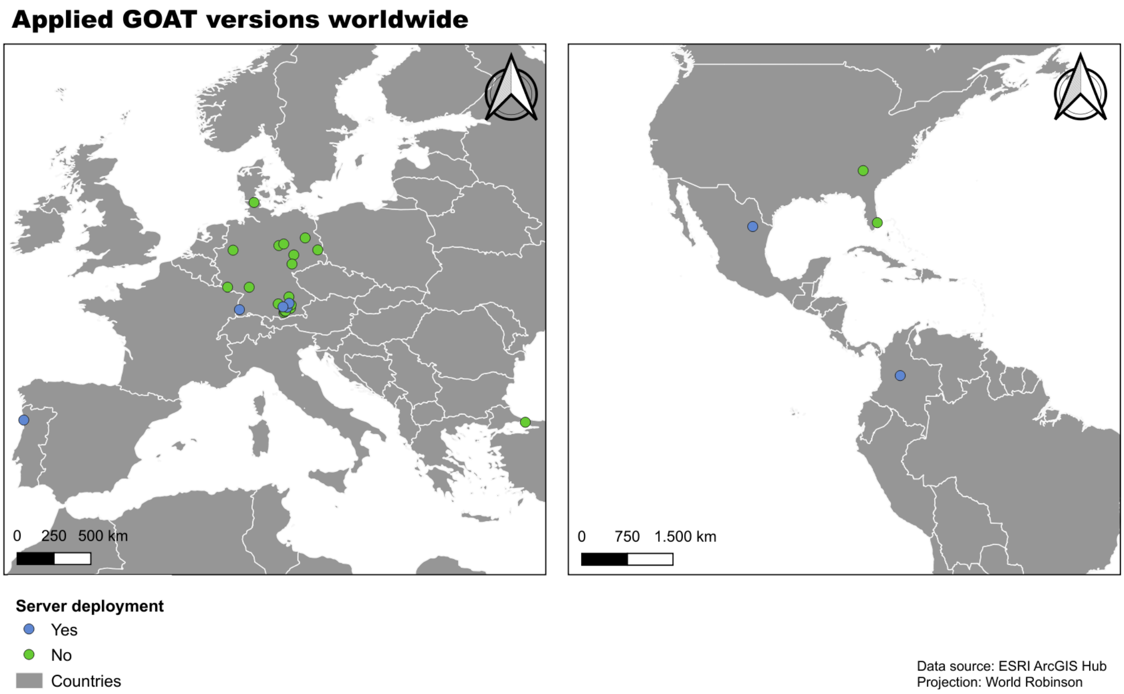

Figure 4.3: Applied GOAT version worldwide

This dissertation primarily focuses on the application of GOAT in Munich, Freising, and Fürstenfeldbruck. Therefore, most of applications happened in the Munich region (see Figure 4.3) due to the dedicated funding that facilitated the development of most features within the mentioned municipalities as a study case. Furthermore, the funding allowed the version to remain online for a longer time frame and to receive more extensive feedback. The different versions were usually equipped with different data sets. In addition, the data was enriched with data collected in OpenStreetMap and Mapillary. A complete overview of the core data sets used can be found in Chapter 5.

4.3 Co-creative involvement

Different groups have tested and used the tool since its first release in early 2018 (see Figure 4.4). Feedback and new ideas were considered whenever possible during the development process. The open access provision of the tool on the project website allowed individuals to test the tool independently and spontaneous and unstructured feedback was obtained either via e-mail or orally. Furthermore, a website with a blog and activities on social media (i.e. LinkedIn and Twitter) was used to communicate the project's progress and engage with the community. The largely unstructured and spontaneous feedback is difficult to quantify but approximately 15 e-mails with feedback were received and posts on LinkedIn typically received around 30-40 reactions (i.e., likes or comments). More intensive exchange and testing were realized through interactions with the tool developer and research community at TUM. Research exchange was broadened with the national and international community at scientific conferences, workshops, and meetings.

The TUM environment allowed using GOAT in different teaching formats from late 2018. Besides the involvement of the students in their theses' projects (see Chapter 4.2), the live version of the tool for the City of Munich was used by the students in lectures, workshops, and projects to perform accessibility analyses. The students provided feedback on the tool's functionality and indicators, and use cases for the software were discussed.

The most influential exchange was realized through eight workshops with planning professionals from Fürstenfeldbruck, Freising, and Munich in 2020. Three of the workshops were early testing cycles held in Fürstenfeldbruck, where the practitioners tested new features. The feedback was then directly considered during the development process. Later in 2020, five application workshops were organized in all three cities. This second round of workshops focused on using GOAT for concrete planning questions and evaluating the tools' usefulness for solving real-world planning questions. The workshops aimed to assess the tool and identify additional development needs. Another synthesis workshop was organized in late 2020 with experts from all three municipalities. All three case studies were discussed during this workshop, and conclusions were drawn.

The series of workshops was the most structured exchange format and produced the most valuable, well-documented results. The rich feedback from the numerous other exchange formats also helped reflect on the realized development and identify further development needs. Further documentation on the workshops is provided in Chapter 5 and 7.6.

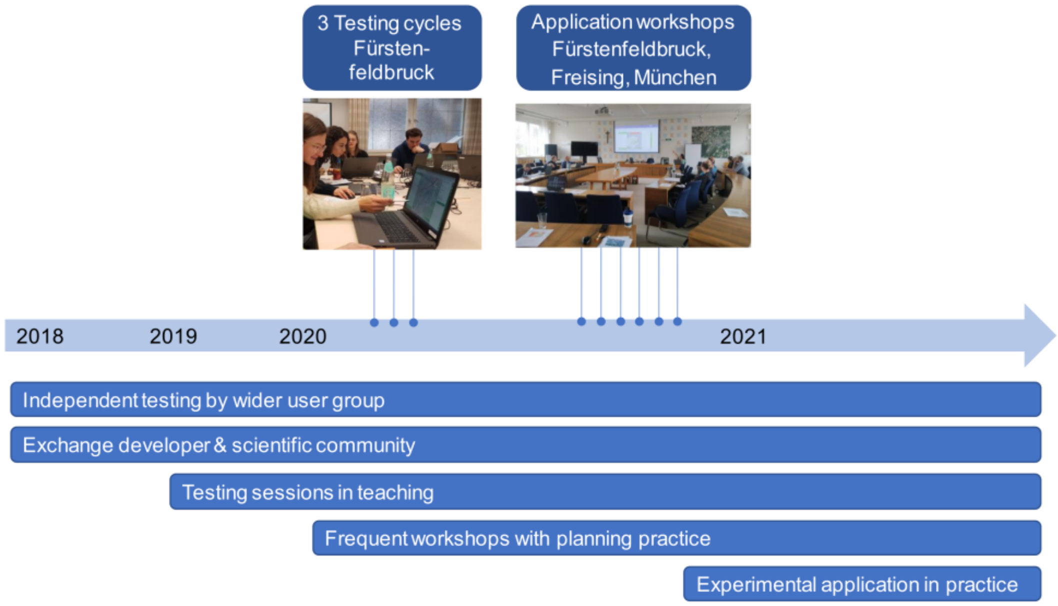

Figure 4.4: Different involvement formats

4.4 Link between research questions and scientific papers

The three research papers presented in the following chapters are closely connected to the three research questions and the main goal (see Table 4.2). The development carried out to achieve the main goal provided the context to answer the research questions. At the same time by answering the three research questions in the papers, achieving the main goal was supported through rich knowledge and novel methods. Accordingly each paper presents its literature, methodology, and results. The main goal serves as the overall framework. RQ1 and RQ3 were identical in the research papers and the research questions presented in the dissertation framework. RQ2 played a special role; due to the wide nature of data fusion and refinement, it was decided to focus in Paper 2 on a specific problem in the domain. Paper 2 presents a novel population disaggregation procedure. Therefore, the presented procedure provides an example of answering RQ2 in a domain. Accordingly, all three research papers are highly intertwined with the presented framework and the dissertation project.

Table 4.2: Link between scientific papers and research questions

Main goal and research questions	Paper 1	Paper 2	Paper 3
Main goal: Development of an open source, interactive, and transferable accessibility instrument for planning local accessibility by active mobility.	x	x	x
RQ1: In which areas do accessibility instruments have to be developed further to better support planning practice when planning for active mobility?	x		
RQ2: How can data refinement and fusion strategies enable powerful and affordable accessibility instruments?		x	
RQ3: Is the accessibility instrument GOAT of useful support in the planning practice?			x

Part II

Scientific papers

Chapter 5

Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility

This chapter has been published by Pajares, E., Büttner, B., Jehle, U., Nichols, A., Wulfhorst, G.: Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility. Journal of Transport Geography (2021), 93, 103080. https://doi.org/10.1016/j.jtrangeo.2021.103080

Abstract

The rise of concepts such as the 15-minute-city represents the growing importance of accessibility by active mobility. In order to promote accessibility, accessibility instruments are developed that have substantial potential to assist practitioners in decision making processes. Therefore, this research starts with an up-to-date overview on the suitability of accessibility instruments when planning for active mobility. It was found that accessibility instruments were significantly further developed in the last few years and there is a rising number of tools that contain novel features. However, it was identified that there is a clear lack of tools specifically designed for modeling active mobility that are open source, include interactive scenario building, and can easily be transferred to new study areas.

Therefore, an interactive accessibility instrument named Geo Open Accessibility Tool (GOAT) was developed, which is open source, transferable, and has an easy-to-use web interface. This instrument has been developed following an iterative software

development process in close cooperation with practitioners from three municipalities in the region of Munich, Germany. The practitioners tested the tool independently in numerous workshops in order to provide feedback, which was integrated into the development. Furthermore, the tool was tested and transferred to more than 20 German municipalities, the City of Bogotá (Colombia) and Matosinhos (Portugal). First results show that the collaborative and open development process produced a user-centric solution, which bears the high potential to make planning for active mobility more effective and efficient.

5.1 Introduction

5.1.1 The role of active mobility and accessibility

Sustainable transportation is one of the key challenges in modern societies around the world. There is an increasing awareness that the numerous and significant negative effects of transportation threaten all three pillars of sustainability (European Environment Agency, 2020). There is currently a trend for increased urbanization and it is expected that 68% of the world's population will live in cities by 2050, ranging from 82% in North America and 43% in Africa (United Nations, 2019). In general terms, this trend will likely further intensify the challenges already being faced (Giduthuri, 2015; Rode, 2013).

Urban areas are the main showcases of the aforementioned negative effects of transportation, and at the same time are where most of the solutions are being developed or are already practiced. Among them, shifting transport from mainly carbon-based and motorized individual transport towards non-motorized/active mobility is one of the most promising solutions.

Unlike other forms of transport, active mobility combines unmatched benefits, such as carbon neutrality, space efficiency, and positive health impacts (FGSV, 2014; Koszowski et al., 2019b). Walking and cycling are gaining additional momentum in the current COVID-19 crisis, in which walking and cycling are being favored by many citizens over public transport, while cities worldwide are providing more space for active travel at a previously unseen pace (Dunning & Nurse, 2020; Laverty et al., 2020). Likewise, public transport is suffering and the risk of increasing car use is a serious threat to sustainable transportation (Aloi et al., 2020; Beck & Hensher, 2020). Increased attention to concepts such as the 15-minute-city – which is based on proximity of activities – by the C40 Cities (C40 Cities, 2020) is more than just a spark of hope.

Cities with high walking and cycling modal shares (number of trips), such as Amsterdam with 42% in 2008, Copenhagen with 47% in 2014 (European Platform on Mobility Management, 2020), or Munich with 42% (Follmer & Belz, 2019) are demonstrating that active mobility can and is already playing a major role in urban mobility. Also, active mobility is crucial for feeding public transport. At the same time, it is evident that a precondition for high shares of active mobility is a relatively dense and diverse urban structure. In cities such as Munich, the densest and most diverse urban areas are also those with the highest share of walking and cycling. Accordingly, the shares of active mobility significantly decrease when examining less dense and less diverse areas (Follmer & Belz, 2019; Nobis & Kuhnimhof, 2018).

This clearly indicates that active mobility not only requires transport infrastructure but also holistic solutions that consider both the spatial and transport perspective. The concept of accessibility, therefore, appears as a particularly appealing theoretical framework for addressing transport and urban planning challenges from an integrated perspective. Accessibility was first defined in 1959 as “the potential of opportunities for interaction” (Hansen, 1959). Accessibility focuses on the dynamics of land-use and transport (Geurs & van Wee, 2004), through evaluating (1) the spatial distribution of available activities and (2) the ease with which they can be reached from a given point (Koenig, 1980).

Accessibility can be operationalized with the help of accessibility instruments, which are Planning Support System (PSS) used to express and evaluate accessibility (Papa et al., 2015). Research throughout the COST Action TU1002–Accessibility Instruments for Planning Practice revealed that accessibility instruments are generally welcomed by practitioners, but are not yet widely used in practice. It was commonly pointed out that the tools have high potential to provide valuable insights in decision making, but are still not meeting the expectations of planners and decision makers, who are the main user groups (Papa et al., 2015; Silva et al., 2019; te Brömmelstroet et al., 2016). Furthermore, Boisjoly and El-Geneidy (2017b) identified that missing knowledge and data availability are key barriers for working with accessibility in practice.

5.1.2 Objectives, research questions and structure

There are numerous reasons for the widely described implementation gap in the field of accessibility, which will be further expanded on in Chapter 5.2. This research is specifically focused on the availability and nature of accessibility instruments, and more specifically, is focused on their suitability for planning active mobility. Therefore, this research is rooted in the hypothesis, that there is still a lack of accessibility instruments that are specifically suitable for the planning practice when planning for active mobility. The aim is to identify areas in which existing accessibility instruments lack in functionality. Through an overview and classification of the existing accessibility instrument landscape the following research question will be answered:

In which areas do accessibility instruments have to be developed further to better support planning practice when planning for active mobility?

This paper will have a specific focus on characteristics such as type of tool, supported transport modes, dynamic calculations, and access to the tool. A detailed review of the used accessibility measures was not carried out because there was a specific focus on characteristics, which were extracted from previous research in Chapter 5.2.2 and on identifying if tools are supporting active mobility.

The identified gap will be the focus of the second part of this research. The aim is to fill the described gap with a practical and development-driven process in which an interactive accessibility instrument for walking and cycling, called Geo Open Accessibility Tool (GOAT) (GOAT-Community, 2021e) is developed. This open source accessibility instrument is tailored to the needs of practitioners when planning for active mobility. As an expert web-tool, it operationalizes accessibility and focuses on areas where current tools lack in functionality. Although technically driven, a strong focus is on the application in practice and real-world planning questions.

Chapter 5.2 will start with a literature review and will be followed by the research design in Chapter 5.3. An overview of the diverse methods consisting of literature review, software development, and workshops will be provided. This section will be followed by an overview of existing accessibility instruments and an assessment of the suitability of the reviewed tools for active mobility planning in Chapter 5.4. Chapter 5.5, the most extensive chapter, will summarize the concept and technical architecture of GOAT. Due to the complexity and the number of included features, the focus will be on providing an overview of the core technical components, the used accessibility measures, the used data, and findings from the collaborative development with practitioners. In Chapter 5.6 the potential and limitations of the developed application GOAT will be critically discussed. Finally, Chapter 5.7 will conclude the paper and highlight upcoming research challenges.

5.2 Literature review

5.2.1 Quantitative planning support for active mobility

It is not uncommon for researchers to use some sort of quantitative analysis, to assess active transport. This is especially true when looking at research that focuses on the concept of “walkability” (Choi et al., 2016; J. Zhang et al., 2019). However, quantitative methods are generally used as a means to an end. In other words, the emphasis is often on the outcome of an analysis rather than the actual methods being used. This makes sense since most research wants to know how easy it is to walk or bike in a specific area, such as near schools (Humberto et al., 2020) or a particular city (Choi et al., 2016; Dhanani et al., 2017; J. Zhang et al., 2019), how specific user groups use active mobility (D'Haese et al., 2016; Gorrini & Bandini, 2019), or how specific variables, such as built-environment characteristics (Appleyard, 2015; Charreire et al., 2012; Nourian et al., 2018), affect the use of active mobility. Quantitative methods are used to answer these questions, but little thought is put into the appropriateness or effectiveness of these methods in actual planning practice. These tools and methods may be effective at measuring and assessing active transport through a variety of lenses, but whether or not planning practitioners can use them or find them useful is a different story.

It is unclear if – and to what extent – these quantitative, evidence-based methods are actually used by practitioners to plan for and assess active mobility. This is not a new concern. Other researchers have already identified this issue and proposed their own data-driven models (Hackl et al., 2019). While new tools and models for planning and assessing active mobility are always welcome, they often have their downsides and may be too complicated, dependent on inaccessible data, and not particularly interactive or flexible. In their data-driven model developed as a response to the lack of evidence-based decision making in planning, (Hackl et al., 2019) use a variety of data sources to simulate incremental effects of individual planning measures. However, the current model is dependent on Austrian data sources and more work needs to be done to transfer it to planning practice. While this is on the right track, the current version of the tool is neither intuitive nor open source, thus limiting its versatility. Other tools may be more applicable to different areas, but might be too narrowly focused on health impacts of walking and cycling instead of a holistic view (Kahlmeier et al., 2017). These examples help to illustrate the need for tools that are accessible to users with different skill-sets, transferable to different areas, and applications that are flexible enough to allow for the analysis of many different aspects of active transport and accessibility. Furthermore, one should not to forget the importance of including both land-use and transport in a model. Accessibility and accessibility instruments in particular promise planning support systems to fill this gap. Further developing and promoting planning support systems can close the gap between academics and practitioners and are mutually beneficial to both.

5.2.2 Literature review accessibility instruments

The first 40 years of accessibility instruments highlight the emphasis on mathematical precision, as well as debates around the payoff and appropriateness of different types of accessibility measures (Geurs & van Eck, 2001). By the mid-2000s it became evident that the development of accessibility instruments was disconnected from the implementation side, leading to a fractured relationship between practitioners and the varied landscape of tools (te Brömmelstroet et al., 2016). More specifically, calls were made for tools that better balance the schism between being scientifically sound, and being useful for practitioners (te Brömmelstroet et al., 2016).

Much of the recent literature on accessibility instruments strives to understand their potential for cross-disciplinary planning support, and why they have yet to be widely implemented in planning practice. This sentiment can be traced back to Geurs and van Eck (2001) which provided one of the first discussions on the "usability" of accessibility instruments. Although usability at this time was still closely tied to the precision of the tool, this discussion marked the start of a desire to understand that usability (or a lack thereof) might help explain the relatively slow implementation of accessibility instruments in planning practice.

More recently, this question has been taken up by a major European COST Action project on "Accessibility Instruments for Planning Practice in Europe" which provides a comprehensive update on accessibility planning, while proposing usability as a catalyst to increase and accelerate the adoption of accessibility instruments. The first part/report of the COST project provided an extensive overview of planning instruments in Europe, further clarifying the somewhat contradictory research streams that continue to co-exist. On the one hand, accessibility instruments have focused on "increasing complexity and thoroughness", while on the other, research emphasizes "the importance of simple, usable and understandable instruments for planning practice" (Hull et al., 2012).

The usability of accessibility instruments became a focus of the second part/report of the COST Action, which guided planning practitioners in a workshop implementation process before collecting feedback regarding usefulness and usability (te Brömmelstroet et al., 2014). This work produced a range of important findings. Firstly, it reaffirmed that urban and transportation planners alike found widespread value in accessibility instruments, but that the barriers to their greater adoption were both technical (ease-of-use of the tools) and political (regarding broader organizational shifts and institutional capacity). Importantly, this real-world feedback from planners also highlighted visual outputs as the most influential, and suggested that on-the-fly capabilities would improve the value of tools (te Brömmelstroet et al., 2014).

The overlap between research versus practitioner oriented tools has been further explored from the perspective of accessibility instrument developers themselves (Papa et al., 2015). For example, nearly all of the accessibility instruments investigated by the COST Action were reported by the developers as being suitable for spatial and transportation planners, while half of these were also identified as suitable for research (Papa et al., 2015). The prevalence of these "broad-band" tools highlights the lack of a functional distinction between rigorous, detail-oriented tools and simplified tools, at least from the perspective of accessibility instrument developers.

Accessibility instrument developers also identified long calculation times and a lack of on-the-fly experimentation as the top barriers for the implementation of their tools (Papa et al., 2015). Papa et al. (2015) furthermore are stating that "In planning practice the concept of accessibility is often misunderstood, and instruments developed to support practitioners are seen as complex, inflexible, incomprehensible, and rigid black boxes."

These technical aspects were expanded on by te Brömmelstroet et al. (2016) who developed technological rules for accessibility instruments aimed to support (1) usability and (2) usefulness. This work identified that an effective way to balance complexity and usability is to identify measures that serve a user's specific needs.

To date little research has been done that specifically studies the application gap of accessibility instruments for active mobility. However, building models for active mobility in general can be regarded as particularly challenging considering the difficulties in procuring data at a high-resolution and the diversity of people's mobility behavior. Furthermore, the fact that there is a lack of evidence-based planning for active mobility (see Chapter 5.2.1) highlights the need for accelerating development in this field.

Venter (2016) identified promising trends for accessibility instruments such as the rise of open data and tools that facilitate engagement with the community. Fast development in core technologies required for accessibility instruments, such as geo information system (GIS) and data management, but also the rise of web technologies, are triggers for the rise of improved or new accessibility instruments for all transport modes. Furthermore, in various fields, the Open Source Software (OSS) approach has proven to be fruitful (Chesbrough, 2003; Munir et al., 2018). A look at successful open source projects from the transport and GIS fields, such as OpenTripPlanner or QGIS, shows that the envisioned collaborative development approach is feasible and is producing successful innovations. This goes hand in hand with the rising potential of open and crowdsourced data, as the wide adoption of data from OpenStreetMap (OSM) shows. Despite the challenges of OSM data accuracy and completeness, it allows tool developers worldwide to have detailed street network data to model active mobility.

5.3 Methodology

The workflow of this research is summarized in Figure 5.1. As indicated above, the research started with the review of diverse literature on accessibility in the field of transport and spatial planning. Literature dealing with accessibility instruments and their use in planning practice was focused on in particular.

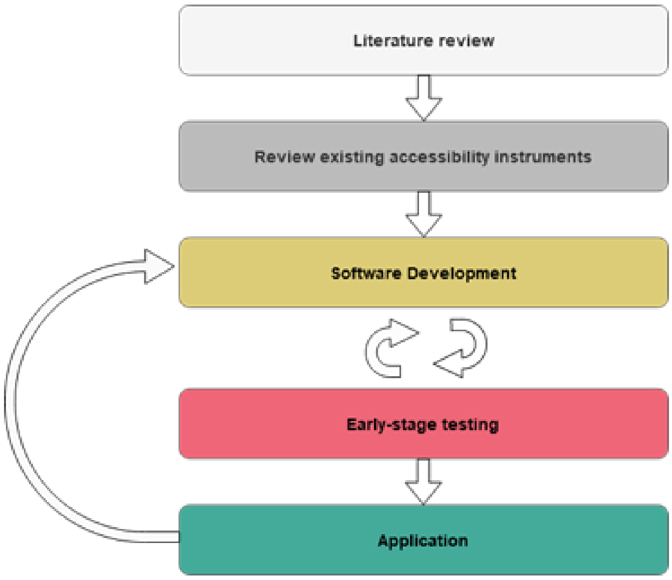

Figure 5.1: Research work-flow

5.3.1 Overview accessibility instrument landscape

The second step was a review of existing accessibility instruments that were designed to support planners and decision-makers. For this process, 25 accessibility instruments from seven different countries were reviewed and categorized.

The assessment considered accessibility instruments actively being developed and designed as PSS. An accessibility instrument was technically defined as a GIS application which makes use of a routing algorithm, spatial operations, and diverse spatial data sets. Furthermore, accessibility instruments are seen as applications that can be differentiated from an accessibility analysis by a generally more efficient use and a tool name.

Different strategies were used to obtain as many tools as possible in this overview. This process started by exploring the existing collection of instruments produced in the COST Action project on “Accessibility Instruments for Planning Practice in Europe” (Hull et al., 2012; te Brömmelstroet et al., 2014) and it continued by reviewing tools that were collected on the platform (TUM - Chair of Urban Structure and Transport Planning, 2021). This initial process was followed by applying a snowballing literature review of papers and reports. Finally, search engines and literature databases were queried with the keywords accessibility instruments and accessibility tool planning.

This review specifically focused on instruments that incorporate at least the transport and land-use component of accessibility (Geurs & van Wee, 2004). For the review, research papers, websites, reports, technical documentation, and platforms such as GitHub were used. Therefore, tools lacking documentation were not included in this review. In addition, only documents in English, German and, to some extent, Dutch were analyzed. Appendix 1 lists all reviewed tools and related sources.

The reviewed tools serve different purposes and include different transport modes. Furthermore, mostly contour-based and gravity-based accessibility measures are used. It is important to mention that there are a high number of tools that could be used for accessibility planning in one way or another, typically among them are routing libraries that generate isochrone maps or transport models that are capable of computing travel time matrices. These tools were not included in the review.

5.3.2 Tool development

Although the development of GOAT had already started in 2017 with a master thesis and continued in a dissertation project (Pajares, 2017; 2019), development was intensified in late 2019 and 2020 thanks to funding from the German Federal Ministry of Transport and Digital Infrastructure. Accordingly, the core part of the development happened chronologically, in line with the sketched diagram (see Figure 5.1). The development of GOAT makes use of diverse open source GIS software and web technologies. A detailed list of the used programs, libraries, and programming languages is provided in Appendix 2. As an open source project, the development is hosted, organized, and documented on the platform GitHub (GOAT-Community, 2022b). Besides the source code of the tool itself, is hosts used software packages, processing scripts, and the project website.

The tool is continuously being developed and managed at the Technical University of Munich (TUM). Additionally, external developers are partly involved in the project. The project follows an iterative software development cycle, which incrementally incorporates enhancements and new features into the software product (Korsaa et al., 2002; Larman & Basili, 2003). Although there is an initial direction of the tool development, the process can adjust to changing requirements and therefore excels with its flexibility.

Testing and deployment of the tool makes use of a continuous integration and continuous development (CI/CD) pipeline that allows simultaneous testing of different versions with varying data. After certain features are considered mature, they are released on the website and made available to the public.

5.3.3 Involvement planning practice

Testing was then conducted in a co-creation environment (Prahalad & Ramaswamy, 2004) through an intensive series of workshops. First, three test cycles were organized with the municipality of Fürstenfeldbruck in Germany. Each cycle lasted two months and consisted of a two-hour test workshop and a subsequent development process. In the testing workshops, the latest GOAT features were presented by the development team and then tested in-depth by a steady group of eight practitioners. Among them were three transport planners, three urban planners, one GIS expert, and one planner for social facilities. Their feedback was documented in minutes, summarized, and incorporated in the software development process if feasible. Therefore, requested and realizable features identified were documented on GitHub as issue and implemented. The improved version was then presented in the next testing workshop.

Secondly, four application workshops were organized with a total of 22 practitioners within the local context of the municipalities of Fürstenfeldbruck, Freising, and Munich, including both users already familiar with GOAT and new users. Therefore, a diverse group with different backgrounds and professions, with a common interest in accessibility planning, was selected Table 5.4. In addition, 15 researchers in the field of accessibility and spatial planning were involved in a separate workshop.

Table 5.1: Participants of the application workshops, clustered by profession and sector

Background / Profession	**Sector**	**Number**
Urban planner	Public	8
Transport planner	Private	4
	Public	3
Climate protection manager	Public	2
Landscape architect	Public	1
Civil Engineer	Public	1
Cycling representative	Public	1
Disability representative	Public	1
Politician	Public	1

The workshops were usually three hours long and were characterized by a short introduction followed by intensive application of the tool and a feedback round. This testing was done based on concrete local planning questions, that were relevant to the attending individuals and suitable for the instrument.

After the test cycles and application workshops, a synthesis workshop was held with practitioners from all three municipalities to recap the overall process and define future strategies. Due to the COVID-19 pandemic, three of the nine workshops were done with videoconferencing software instead of in person.

In addition, due to the open access nature of the application and advertisement on social media, at conferences, and beyond, users had the chance to test the tool independently with the help of tutorials and documentation. Feedback in this unstructured process was obtained occasionally via email, in personal discussions, or via an online survey. Two main objectives were pursued throughout the testing and application with practitioners. First, the valuable feedback from users helped by proposing improvements and testing the functionality of the instrument. Second, the aim was to elaborate on the question of whether the developed accessibility instruments and accessibility analyses are generally useful for supporting real-world planning processes. This research paper will focus on the first aim.

5.4 Current scene accessibility instruments

5.4.1 Overview current landscape of accessibility instruments

Technology is evolving fast and the emergence of new accessibility instruments can be observed in many parts of the world. Furthermore, there is ongoing development of already existing tools. The reviewed tools originated from eight countries, while more than half of them came from the USA (see Figure 5.2). This prominent role of the USA could be partly explained by the size of the country and its strong role in technological development in general, but also by the high availability of good open data, such as the US Census and timetable data in the General Transit Feed Specification (GTFS) format that are used by almost all reviewed instruments from the USA.

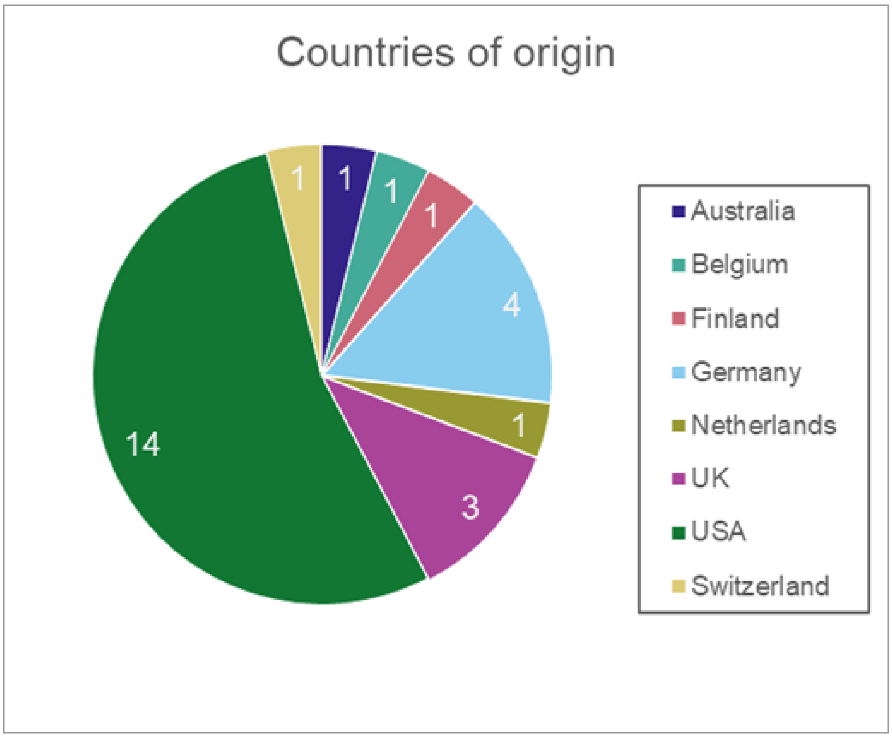

Figure 5.2: Countries of origin reviewed instruments

In Figure 5.3, the supported transport modes of the tools are summarized. Many tools perform analyses for several transport modes at once. Accordingly, some tools are counted more than once. Nevertheless, a relatively balanced distribution of supported modes can be observed. However, public transport is clearly dominant, as 22 out of 26 reviewed tools provide analysis for this mode. This trend is largely in line with the aim of many cities worldwide to improve public transport and foster sustainable mobility in general. It is striking that there are only nine accessibility instruments supporting analysis for cycling and seven of them are developed in Europe.

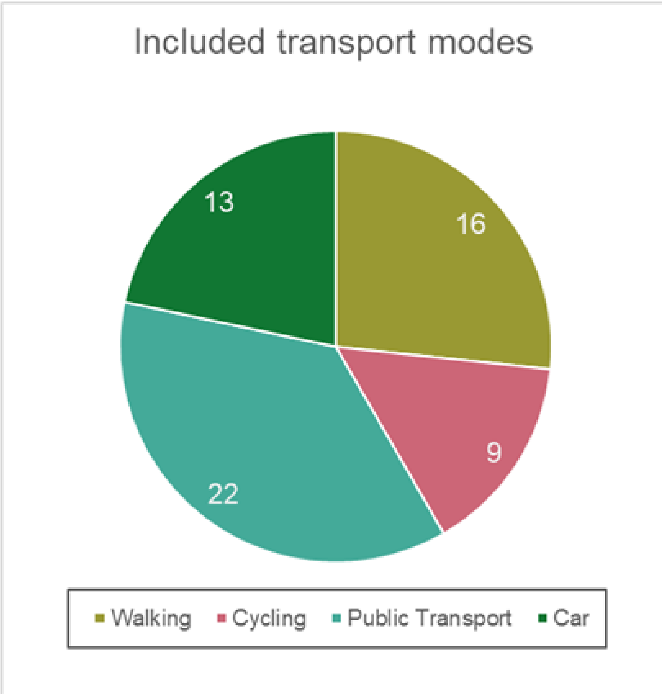

Figure 5.3: Implemented transport modes

As shown in Figure 5.4, there is a clear trend towards web tools; 22 of the instruments are either solely web instruments or provide an additional web interface. Four tools were also identified that distribute their results as a database containing precalculated accessibility metrics, and four tools that can be classified as desktop tools. The review also showed that the capability of scenario building to evaluate changes in accessibility, which was identified as very important in previous research (see Chapter 5.2.2), is already built into ten tools. However, it has to be stressed that not all tools with a scenario building feature allow modification of both transport infrastructure and land-use. Furthermore, the ease of performing a scenario greatly differs between the tools.

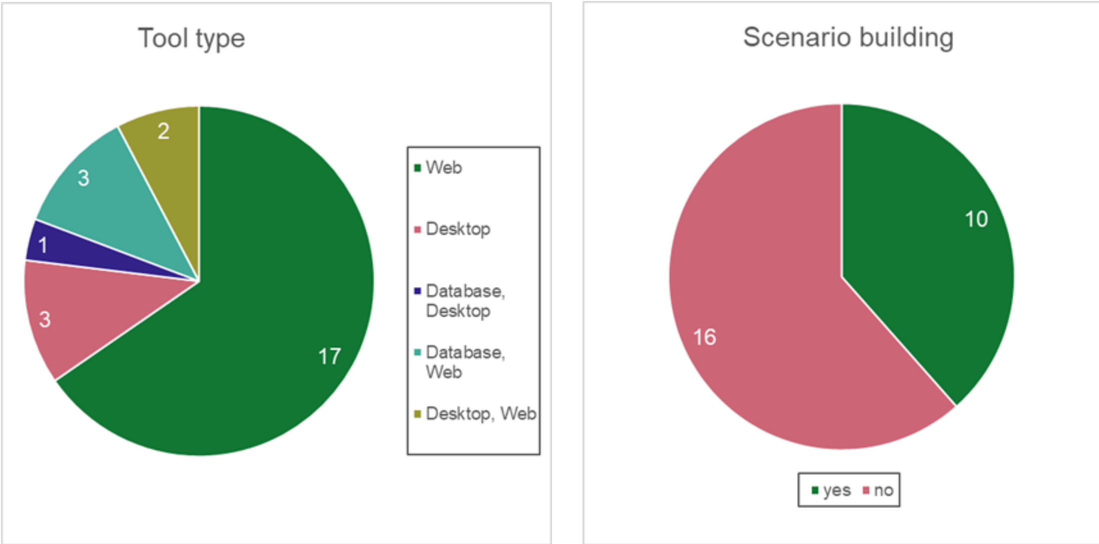

Figure 5.4: Tool type and scenario building capabilities

A look at the access to accessibility instruments (see Figure 5.5) reveals that most of the assessed tools are available via open access. Accordingly, they can be used free of charge but their source code is partly or completely closed-off. This is especially true for the large majority of web tools. At the same time, there are only four tools that are managed as open source projects and there are seven tools that are closed source. It is especially evident that the highly professionalized tools, namely *Sugar Access, Urban Footprint,* and *TRACC* are distributed as proprietary software or services. An interesting case is the software *Conveyal* which is open source and backed by a commercial provider and can be considered as a forerunner in the field of public transport accessibility analysis.

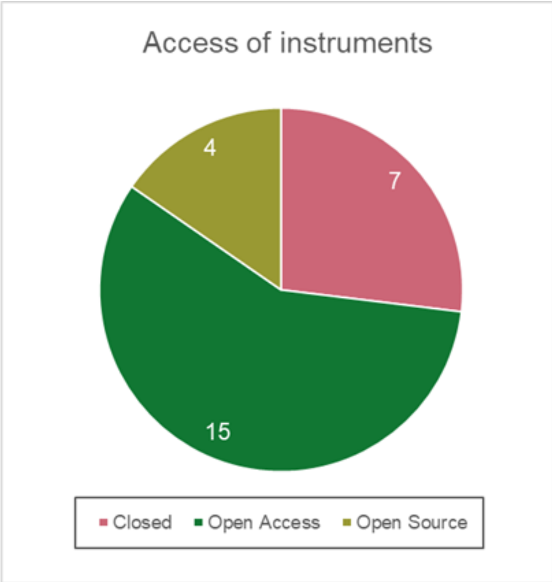

Figure 5.5: Access of accessibility instruments

An important aspect of every accessibility instrument is the data used. It is noteworthy that all tools use data from public sources, such as municipalities, transport agencies, or statistical offices, for the network and opportunity data (e.g. population or points of interest) (see Figure 5.6). Concerning the network data, there are also fourteen tools using data from OSM, especially for street networks when modeling walking and cycling as individual modes or in combination with public transport. Timetable data is the most widely used public network dataset, which is mainly available in the GTFS format. Seven tools also use proprietary data for the network, mostly services from providers such as Here or TomTom for street networks for car routing. All in all, most of the tools use a combination of different datasets for the network.

Opportunity data comes mainly from public sources. Only five tools are using OSM data and six tools use proprietary data in addition to public data. This can be explained by the fact that most of the opportunity data such as population or number of jobs are usually managed by public entities.

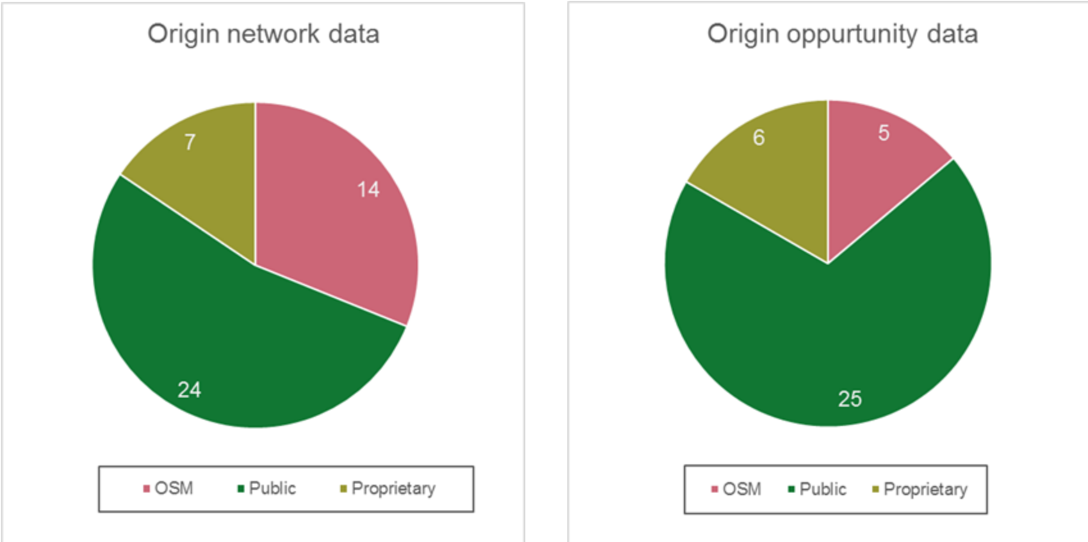

Figure 5.6: Data sources accessibility instruments

5.4.2 Application gap active mobility

In summary, during the last few years, accessibility instruments were significantly further developed. Former emerging trends, such as the use of open data like OSM (Venter, 2016), the development of web instruments, or freely available timetable data are now the norm rather than the exception. Despite this progress, it has to be emphasized that the availability of tools that are specifically designed for walking and cycling is still limited. Although there are 16 tools supporting walking and nine for cycling, among them only Sugar Access and TRACC provide the functionality to perform scenarios for both land-use and transport. At the same time, both are developed and distributed as proprietary software. Furthermore, the full-featured use of Sugar Access requires knowledge of the desktop GIS software suite ArcGIS.

Seeing that this research has not conducted tests with users applying the tools but was based on literature review and own testing, it is hard to conclude on the ease of using the different instruments and their usefulness in the planning practice. However, from the authors experiences there is a strong divide between fully-featured tools that require both procuring expensive software and expert knowledge and a wide range of open access web tools that focus on an easy user interface and basic analysis.

Furthermore, to spread the use of accessibility instruments, the ability to transfer the tools to diverse study areas would be essential. However, this review identified that not all tools are designed or distributed in such a way that they can easily be transferred. This can be explained with the challenge of data-structure uniformity and the simple market logic that providers focus on certain regions.

Although this is clearly impeding a wider dissemination of innovation in the field to different parts of the world, the fact that the majority of tools are not open source further restricts the wider application. Overall, this review has found no tool that is open source, includes easy scenario building for both transport networks and land-use, is transferable, and designed for walking and cycling.

5.5 Development of Geo Open Accessibility Tool (GOAT)

5.5.1 Scope of the instrument

The development of GOAT aims to react to the challenges described in section 5.2 and 5.4. It is envisioned that the tool will provide assistance as a PSS when planning for active mobility and local accessibility. With the help of contour and gravity-based accessibility measures (see Chapter 5.5.4 and 5.5.5), accessibility is calculated and visualized. Additional spatial data, such as modal split by district, data on pedestrian and cycling accidents, or land-use data can be integrated into the tool to complement the accessibility analyses.

Figure 5.7: Key strategic aims of GOAT

Figure 5.7 summarizes the key strategic aims of GOAT, which should leverage the useful application of the tool in practice. GOAT comes with the highly requested feature of interactive scenario building for transport and land-use changes. Through the web interface of GOAT, users can interactively add, modify, or delete streets, points of interest, and buildings (population). Changes in accessibility are dynamically calculated and results are returned to the user. Accordingly, a fast and iterative evaluation of transport and land-use measures is feasible. In addition, scenarios can be imported and exported. Depending on the available data, accessibility can be analyzed from (and to) different types of opportunities in space. Besides disaggregated population data on the building level, diverse points of interest such as supermarkets, gyms, restaurants, schools, and public transport stations are integrated.

The main target groups are practitioners, who have knowledge in the field of transport and urban planning. GOAT focuses particularly on professionals who either do not have the skills to perform accessibility analyses using other GIS software or favor a less time-consuming solution. Accordingly, GOAT can be regarded as a middle ground between simple WebGIS-applications for every user and a fully-featured GIS desktop software. Furthermore, the focus is rather on providing a user-centric solution backed with robust accessibility measures which can be implemented in diverse study areas, rather than the implementation of the novelest and sophisticated accessibility measures.

GOAT is currently available online as a demo version for the German cities of Munich, Freising, Fürstenfeldbruck, as well as Bogotá in Colombia. Another version is available for the Munich district Hasenbergl-Lerchenau, which was developed to test additional walkability features. Furthermore, the application has been transferred in different student and consulting projects to over 20 German municipalities and the municipality Matosinhos in Portugal.

5.5.2 Technical architecture

GOAT is technically a WebGIS-application and is built, as most of the web applications are, in line with the classical Server-Client-Architecture of the web (see Figure 5.8). Accordingly, resource and/or data-intensive calculations are processed in the backend, for which a spatial database is used. The results of any given calculation are provided to the client of the application via the middleware, which traditionally acts as the “glue” of a web application. The client part (or frontend) of the application is the part of the tool that is visible to the user and allows interaction via the interactive web map.

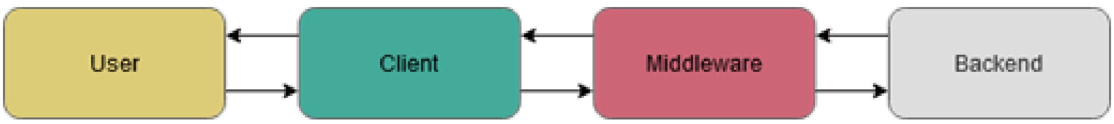

Figure 5.8: Simplified technical architecture of GOAT

The described architecture is built with a diverse collection of open source software and libraries (see Appendix 2). A spatial database using PostgreSQL with the PostGIS extension could be described as the backbone of the application. Not only does the database manage and structure the data, it also performs all spatial and non-spatial queries, routing, and other algorithms. Most of the actions are atomized, following the functional programming paradigm, into database functions.

For the setup, an automated procedure was developed that downloads the most recent OSM data and imports additionally provided data files into the database. Furthermore, a series of data refinement, data cleaning, and data fusion routines prepare the data for its use. The advantage of having the core functionality bundled in the database is the high performance of SQL for reading and retrieving structured data and the possibility to use the database as the core of the tool, either with the GOAT client or other third-party software, such as the desktop GIS software QGIS.

As middleware, an API written in Python serving vector data in the GeoJSON-format and vector tiles in the MVT format are used. The client is written in Javascript using the framework Vue.js and the library Openlayers, which is capable of handling spatial data in diverse formats. Alongside Docker, Kubernetes orchestrates the containers and deployments of GOAT for the different study areas.

5.5.3 Routing algorithm

The routing functionality is one of the core features of GOAT as it allows for the computation of travel times for the contour and gravity-based accessibility measures. There are several key factors that influenced the decision on a suitable routing approach. A solution was sought that allows to dynamically change the routing network within seconds in order to perform interactive scenarios via the web interface. It was decided not to use existing highly performant algorithms using contraction hierarchies, which pre-process the routing network by computing shortcuts (Kliemann & Sanders, 2016) because the time-consuming pre-processing would have to be done after each network change. These requirements were decisive for choosing the pgRouting (pgRouting Community, 2022) approach for the routing, which excels with its flexibility and its integration into PostgreSQL/PostGIS. A custom implementation for the driving distance algorithm using the classical Dijkstra shortest-path calculation (Dijkstra, 1959) was realized in a pgRouting fork to improve performance and customize the algorithm to the specific use case (Crnjak, 2020).

In general, a solution was needed that is highly flexible and allows for the implementation of diverse routing modes such as walking, wheelchair-routing, cycling, or electric bike. It was decided to find a pragmatic solution to the different data qualities and tagging schemes realized in OSM across the world by providing the option to customize the chosen network links in a configuration file when setting up GOAT. Per default, the street categories listed in Table 5.2 are excluded for all studied modes.

Table 5.2: Default excluded OSM highway categories

Excluded OSM street categories
motorway
motorway_link
motorway_junction
trunk
trunk_link
primary
primary_link

In addition, for the mode walking and wheelchair all paths were excluded that were labeled with the combination foot = 'no' or foot = 'use_sidepath'. For the cycling modes street categories labeled with bicycle = 'no' or bicycle = 'use_sidepath' were excluded. As the mode wheelchair-routing and electric bike is still experimental it will not be further emphasized here.

As average travel speed for walking 5km/h and for cycling 15km/h are specified. This average speed can be increased by the user to up to 25 km/h. Modelling realistic cycling speeds is of special complexity as travel time can be influenced by a multitude of factors such as road surface type, number of intersections, width cycleway, street gradient and many more. In order to simplify the underlying model, it was decided to only consider the street gradient and road surface type to compute the speed for each link. Accordingly, the travel time for each link was computed like the following:

$$t = \frac{L * (1 + I_g + I_s)}{v_\phi}$$

$t =$ traveltime $[s]$ $L =$ length $[m]$ $I_s =$ Impedance surface

$I_g =$ Impedance gradient $v_\phi =$ average speed

There is a well understood relationship between street gradient and cycling speed, however the degree to which street gradients influence cycling speed could only be studied more intensively with the appearance of inexpensive GPS sensors. Among others Schleinitz et al. (2017) recorded in a German case study around 17,000 km travelled by 90 cyclists using different bicycle types. For a standard bicycle they detected mean speeds of 12.9 km/h uphill, 18.8 km/h down-hill and 16.1 km/h free flow speed. Flügel et al. (2019) conducted a study with 721 cyclists travelling around 50,000 trips in the City of Oslo with both standard bicycle and electric bicycle. The study presents cycling speeds for gradients between -9% and +9% for the different bicycle types.

The results of the study from Flügel et al. (2019) were used to generate a relationship between the slope and a normalized impedance factor presented in Figure 5.9. For street links longer than 10 meters, sloped profiles were calculated in intervals of 10 meters and the calculated impedance factors were aggregated by the weighted length of the sub-segments per link. The elevation points for the street segments were computed using the inverse distance weighting method commonly known in geography and the European digital elevation model with the spatial resolution of 25 meters (Table 5.4).

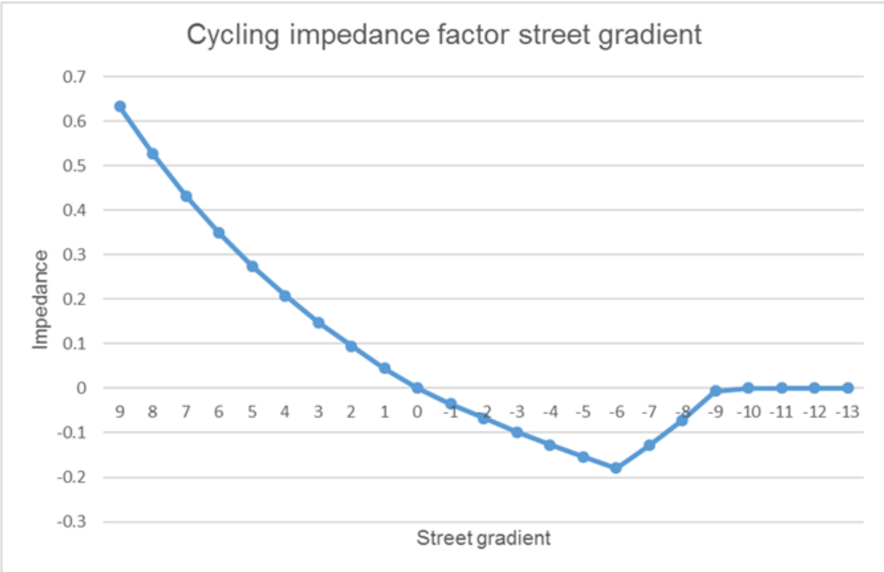

Figure 5.9: Cycling impedance factor street gradient

For gradients larger +9% it was assumed, that cyclists have to dismount and an impedance of 2 is assigned corresponding to a walking speed of 5km/h at an average velocity of 15km/h. For the relation between street surface and travel speed the impedance factors listed in Table 5.3 are used.

Table 5.3: Cycling impedance factor street surface

OSM Surface	Impedance factor
paving_stone	0.2
sett	0.3
unhewn_cobblestone	0.3
cobblestone	0.3
pebblestone	0.3
unpaved	0.2
compacted	0.05
fine_gravel	0.05
gravel	0.3
sand	0.4
grass	0.25
mud	0.4

5.5.4 Contour-based accessibility measures

As Contour-based or cumulative opportunity measures, travel time isochrones are computed. This measure can be considered as widely used (Geurs & van Eck, 2001; Geurs & van Wee, 2004) and is frequently favored because of its relatively easy computation and its good understandability (Bertolini et al., 2005; Geurs & van Eck, 2001). At the same time the biggest disadvantage of this set of indicators is its high sensitivity towards travel time (Geurs & Wee, 2013), which basically means that there is a strict cutoff value and there is done no differentiation between shorter and longer traveltimes within the chosen cutoff (Bertolini et al., 2005; Bhat et al., 2002; El-Geneidy & Levinson, 2006).

For GOAT contour-based accessibility measures were implemented in two ways. First as single travel time isochrones which can be computed by clicking on the map or defining a start address. The generated isochrones will be intersected with the opportunity data sets and the user can see points of interest as markers and cumulated in a table Figure 5.10.

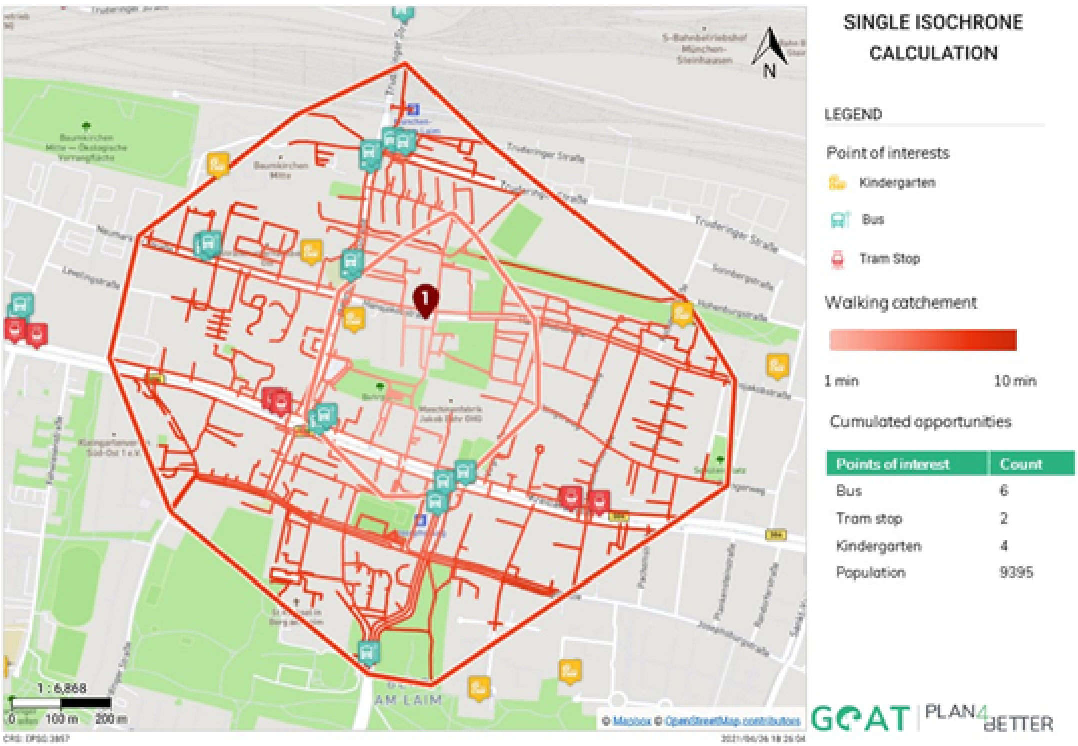

Figure 5.10: Reached network and single isochrone

Furthermore, multi-isochrones which are interpreted as isochrones from several starting points can be computed. By defining an area of interest (e.g. city district or bounding box) and one or several points of interest, the starting points are derived and isochrones are computed. As result, the multi-isochrones are intersected with population data disaggregated on the building level and the share of population having access to a specific point of interest can be identified (see Figure 5.11).

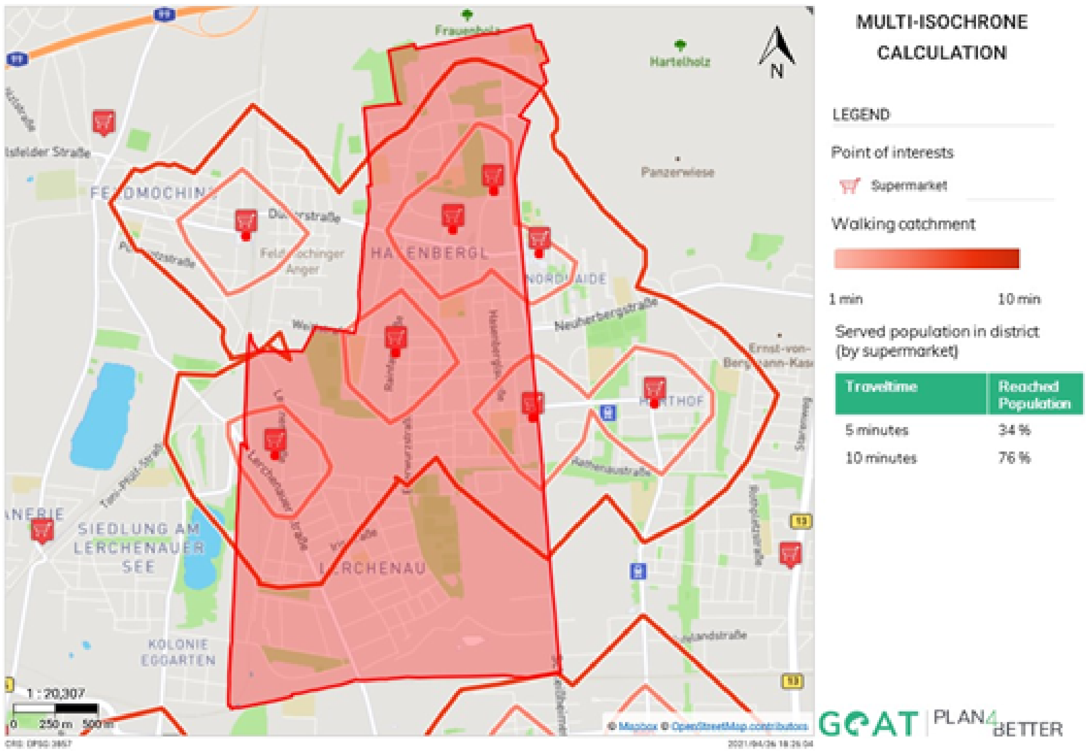

Figure 5.11: Multi-isochrone with served population by supermarkets

The described indicators can be computed for the different modes walking, cycling, e-bike and wheelchair. Cutoff values can be freely chosen in the range of 1 to 20 minutes and with diverse intervals. According to the German national household travel survey (Nobis & Kuhnimhof, 2018) the average travel distance for walking is 1.7 km and for cycling 3.9 km, while the medians are 1.0 km and 2.0 km. The provided travel time range can be regarded as trade-off, as it might not fully cover the observed travel behaviors in every case, however due to rising computational effort it was decided to limit travel times to 20 minutes.

For the calculation of the reached area, a concave hull algorithm is used, which provides an approximation of the reached area based on the reached nodes in the network. It was decided to use the most performant open source solution found on the web (Mapbox, 2016), which is based on the concave hull algorithm described by Park and Oh (2011). As parameters, a concavity of 2 and a length-threshold of 0.006 degrees (EPSG 4326) is used. The chosen settings do not allow for holes inside the polygon, which can lead to inaccuracies, especially in sparse networks and should be considered as further limitation of the presented measure.

5.5.5 Gravity-based accessibility measures

The concept of gravity-based accessibility measures is used for the accessibility heatmaps, which are currently only implemented for walking. Gravity-based accessibility measures are dating back to the research by Hansen (1959) unlike contours measures, gravity-based accessibility measures are not treating all reached opportunities equal but weights them by a cost, usually travel time using an impedance function (Bhat et al., 2002; Geurs & van Eck, 2001; Handy & Niemeier, 1997). The same researchers underlined the importance of choosing a suitable impedance function and it can be observed that a large variety of functions are applied. Commonly used functions are power, negative exponential, logistic and Gaussian functions (Geurs & van Eck, 2001; Geurs & van Wee, 2004).

More recently Vale and Pereira (2017) conducted a study testing 20 pedestrian accessibility measures and identified the modified Gaussian and exponential function as the most robust ones for modelling walking accessibility. Furthermore, the authors presented a new cumulative Gaussian function, which uses the cumulative opportunities approach at near distance using specifications of 200 or 400 meters and a second part of a modified Gaussian curve for larger distances. For the implementation in GOAT it was decided to use the modified Gaussian function, however further tests with other functions such as cumulative Gaussian are planned in the future.

Accessibility is computed using different sensitivity values, using seconds as travel time unit the following sensitivity values are implemented: β=150000, β=200000, β=250000, β=300000, β=350000 and β=400000. Depending on the amenity type, users have the possibility to pick suitable sensitivity values. However, by default, the value β=300000 is chosen. This can be translated into approximately 74.1% accessibility after 5 minutes, 30.1% accessibility after 10 minutes and 6.7% accessibility after 15 minutes of travel time to the respective amenity. Although further calibration by opportunity type is needed, the chosen values can be regarded as being in line with the aim that all basic needs should be available in 15 to 20 minutes of walking time.

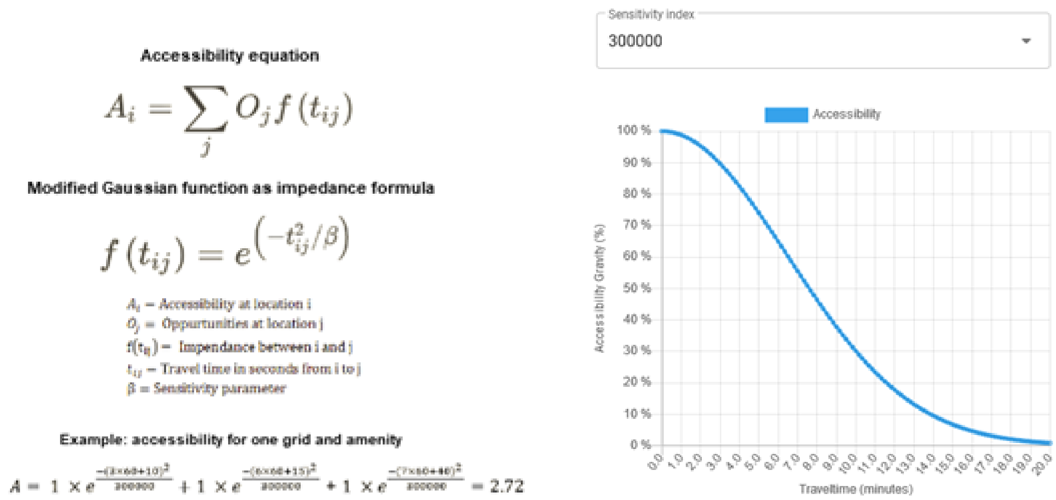

Figure 5.12: Computation of accessibility values using Modified Gaussian impedance functions

Accessibility is visualized dynamically on a hexagonal grid (see Figure 5.13) for the specified amenities, therefore travel times are computed for each point of interest. The chosen grid size can be adjusted but as a default value a uniform edge length of 150 meters is used, which can be considered as compromise between accuracy and performance.

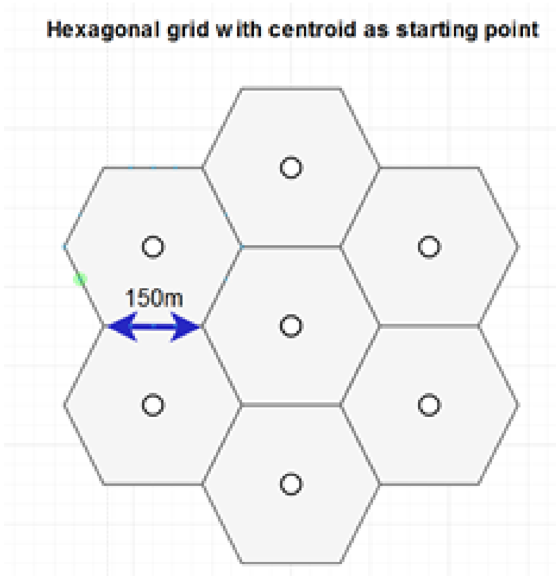

Figure 5.13: Hexagonal grid as spatial unit for the heatmap

For the calculation the centroid of each hexagon is used as a reference point for starting the routing operation with the maximum travel time of 20 minutes walking. For deriving the travel time per point of interest, the point of interest is snapped to the closest edge and an interpolated travel time is derived from the link for each destination (see Figure 5.14). In order to allow dynamic and performant computation, travel times and accessibility values are pre-calculated for the base scenario.

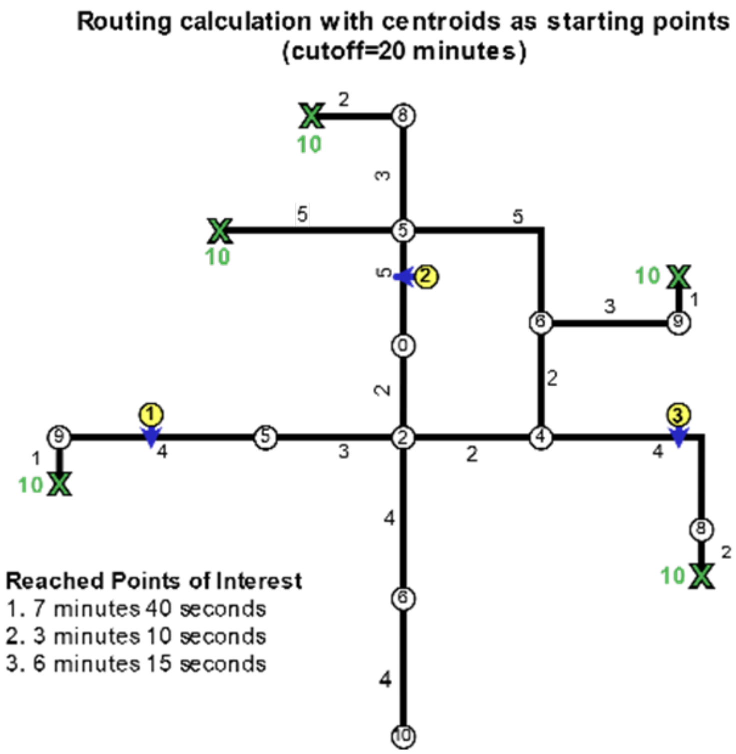

Figure 5.14: Deriving travel times per point of interest

The values are stored in the database and classification is done using statistical quintiles for comparing accessibility values between the different grid cells. In order to facilitate dynamic recalculation of accessibility in case of scenarios, affected grids are recomputed and the results are combined with the static pre-calculated grids.

5.5.6 Data

GOAT makes use of diverse spatial datasets. Due to the complexity and variety of data refinement and fusion routines developed, this section will provide only a brief overview of the data used. In principle, GOAT follows the strategy to use open and freely available data wherever possible and is built with strong integration with OSM. OSM data is imported as XML-dump from Geofabrik (2020) and the service Overpass API (OpenStreetMap Community, 2020). The data is imported into the database with different import scripts and frequent data updates can be realized in a highly-automated fashion. At the same time, not all required data can be found on OSM, therefore data from other sources such as statistical agencies or local municipalities is used. Ultimately, the data is collected directly in OSM using different editors in case the needed data cannot be found elsewhere. Table 5.4 provides an overview of data used for the GOAT versions deployed in the Munich Region. The data is imported completely automatically into the database and is combined with different spatial layers. As shown in the table, some datasets are essential for the accessibility analysis, such as the street network or points of interest, while others are solely used for visualization.

Table 5.4: Datasets used in the Munich Region

Dataset	Purpose	Source
Points of Interest	Opportunities dataset for accessibility analysis	OSM, own collection in OSM
Land-use	Population disaggregation	OSM, Landesamt für Digitalisierung, Breitband und Vermessung Bayern
Buildings	Population disaggregation	OSM, Landesamt für Digitalisierung, Breitband und Vermessung Bayern
Population grid	Population	ZENSUS 2011
Administrative areas with population	Population	Geodatenservice München, Bundesamt für Kartographie und Geodäsie, Landesverkehrsmodell Bayern
Street imagery	Visualization and Mapping Mode	Mapillary, own collection in Mapillary
Street network	Routing	OSM, own collection in OSM
Elevation	Routing	European Environment Agency (EEA)
Accidents pedestrians and cyclists	Visualization	Statistische Ämter des Bundes und der Länder
Diverse data on environmental quality	Visualization	Bayerisches Landesamt für Umwelt
Bike counting data	Visualization	Geodatenservice München
Modal split	Visualization	Mobilität in Deutschland (MiD)
Basemaps	Visualization	OpenStreetMap, Mapbox, Bing

5.5.7 Input practitioners

The design of GOAT was very much shaped by the feedback of the practitioners. In particular, feedback on improving new and existing features was incorporated directly into the development process. Furthermore, many additional features were requested (see Table 5.5). Some of these have already been implemented, but some require extended development efforts. Despite the large number of suggestions for improvement, the tool has been rated as highly useful and is already in use by some of the practitioners in their everyday work. Particularly positively evaluated was the simple handling, the interactivity and the easily understandable visualization of the analyses.

Table 5.5: Collection of requested features and their current development status

Requested Features	Development status
Wheelchair routing	Implemented
Scenarios on new buildings	Implemented
Additional POIs (e.g. playgrounds)	Implemented
Display of street crossings and traffic lights	Implemented
Visualization of external data (e.g. aircraft noise map, nature conservation areas)	Implemented
Import and export of scenarios	Implemented
Development of several parallel scenarios	Implemented
Accessibility to recreation areas	Under development
Management developed scenarios online (with user login)	Open
Provision of interactive tutorials	Open
Modification of path attributes (e.g. modeling bicycle highways)	Open
Weight opportunities according their size and quality (e.g. capacity of kindergartens, size of shop)	Open
Incorporate workplace data	Open
Visualization of subjective path qualities	Open
Incorporate landscape quality	Open
Spatial extension to whole Germany	Open
Expansion to other modes	Open
...	...

In general, the features requested by the practitioners were in line with the features identified as important in the literature review. The users were mostly impressed by the scenario capabilities and the ease with which they can do accessibility analyses. They conceived the accessibility analyses as highly useful, although not all of them were familiar with the concept of accessibility beforehand, but also asked for other additional analysis options. On the other hand, it was observed that many practitioners were thinking more about practical details, such as the attractiveness of the used colors and the look of the output maps, than about game-changing additional features. From a developer perspective it was important to balance the effort in implementing a new feature and the expected benefits for different planning questions, while keeping in mind the need for an high usability.

5.6 Reflection tool development

A new interactive accessibility instrument for walking and cycling was added to the tool landscape by using the development processes described in the previous section. A specific focus on (the implementation gap of) active mobility was placed on the challenges presented in section 5.4.2. It is important to note that the realized development is one possible solution approach next to many others in the field. Furthermore, the existence of an additional tool does not necessarily lead to a closure of the widely described implementation gap. However, the advantage of the open and collaborative development approach was the involvement of diverse groups in the process, which lead to an intensively tested and already applied technology. Though, the core characteristics of the instrument, – focus on active mobility, transferability, interactive scenario building, and the implemented accessibility measures – still requires further development.

There is a principle methodological weakness in measuring travel times based on street networks in a graph-like architecture using nodes and links for active mobility. In particular, pedestrians can walk independently from street networks and cross open spaces or streets at any place. This behavior is hard to model and is currently not modelled in GOAT. Routing through open space was researched by (Graser, 2016; Hahmann et al., 2018), who developed promising algorithms, which could be applied in GOAT. Furthermore, the unavailability of street network data that contains separately drawn sidewalks is still an open challenge. The frequently used OSM data usually only models separate sidewalks and bike lanes on main streets, if at all. Although early trials implemented routing for different user groups, this research is focused solely on travel time and does not include additional factors, such as safety or comfort levels when walking or cycling.

In literature normative and positive accessibility are differentiated when defining an appropriate accessibility measure (Páez et al., 2012). In this context, normative accessibility can be described as desired travel behavior and positive accessibility as the realized travel behavior (Vale & Pereira, 2017). Neither approach was thoroughly followed in this research, as the user was provided with a range of travel times and sensitivity factors. Accordingly, picking appropriate travel times for the contour-based accessibility measures and sensitivity values for the gravity-based measure is to a large degree in the hands of the users. While this simplifies the task from a development perspective, it adds additional complexity for the user when asking for explicit results. Using statistical quantiles based on the computed accessibility values for the gravity-based heatmaps as a classification method can cause further challenges. There is the risk of errors and inaccuracies, especially when the data set is small or accessibility is relatively evenly distributed.

It was claimed that GOAT is easily transferable, however it has so far primarily been transferred to German municipalities and only to two international study contexts. Although the technical architecture favors an easy transfer to different areas, it still has to be verified in further applications. Despite the possibility that most features of GOAT can be calibrated relatively easy through configuration files during the setup, a calibration for different study contexts is not provided and the default calibration is done for the German context. Accordingly, additional responsibility is given to people setting up the instrument in other areas.

Despite the fact that practitioners were intensively involved in the development process and first applications into real-world planning are realized, the users are mostly planners from the Munich Region so far. Therefore, the involvement of a more diverse group of practitioners would be crucial to better reflect varying requirements in the planning practice.

5.7 Conclusion

This work first focused on assessing the suitability of existing accessibility instruments for planning for active mobility. It was found that there is a vibrant community of developers that frequently develops new tools and improves existing ones. Accordingly, significant development could be observed since the end of the European COST Action project on “Accessibility Instruments for Planning Practice in Europe” in the year 2014. There are new tools that allow interactive scenario building and they are significantly easier to use. Furthermore, the rise of WebGIS-technology leverages the success of web instruments for accessibility planning and therefore provides a rising number of practitioners (and the public) with access to these types of analyses. Despite the fast progress the review has identified no tool that combines the following attributes: open source, easy scenario building for both transport network and land-use, and designed for walking and cycling. Furthermore, easy transfer between study areas is still a challenge for many of the reviewed instruments, mostly because of the lack of uniform data and the high adaptation of many tools to a specific purpose.

As a response to this still open field, the authors developed an interactive accessibility instrument named GOAT as an open source project. This application provides practitioners with extended functionalities, such as interactive scenario building, just-in-time calculations, and diverse accessibility measures via a web interface. The architecture of the application is characterized by its scalability and component-based design, which provides the high flexibility needed for use in varying contexts. The iterative software development cycle, which is characterized by strong mutual exchange with practitioners, has proven to deliver a user-centric solution.

Furthermore, the open access and source provision of the tool allowed diverse groups of people to test the tool and provide valuable feedback, which could be incorporated into the development process. Also, the open source distribution allowed people outside of the development team to transfer the tool and enrich the knowledge-base of the community.

While this process helped to answer some open questions, it raised significantly more and the tool still needs to be substantially further developed. More development is needed in a multitude of areas, such as the usability of the tool, better calibrated gravity-based accessibility measures, more sophisticated data fusion strategies, and more holistic walkability indicators that take into account individual accessibility analyses for different user groups.

However, at the same time it is still necessary to explore the actual usefulness of the application for real-world planning practice. Despite the extensive use of the tool in planning workshops, further use is necessary to identify the actual benefits of the instrument for accessibility-based planning in general. Therefore, it is planned to organize further testing workshops and in addition distribute the application to customers worldwide. At the same time, it is planned to develop the application further following the successful co-creative approach with practitioners. Among other activities the tool will be transferred to ten European cities and novel indicators on walkability will be developed. Furthermore, it is aimed to extend the tool GOAT to other transport modes such as public transport, motorized transport and inter-modal transport in the future.

The first results are promising seeing that the tool helped diverse groups of practitioners experience accessibility analyses for the first time for themselves. In principle this could help boost the understanding of accessibility, break silos, and train practitioners methodologically. This would be very much in line with the fact that accessibility planning, like any other skill, can best be learned by a combination of theory and practice.

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Chapter 6

Population Disaggregation on the Building Level Based on Outdated Census Data

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Abstract

A wide range of disciplines require population data with high spatial resolution. In particular, accessibility instruments for active mobility need data on the building access level. Data availability varies by context. Spatially detailed national census counts often present the challenge that they are outdated. Therefore, this study proposes a novel approach to hybrid population disaggregation. It updates outdated census tracts and disaggregates population on the building access level. Open and widely available data sets are used. A bottom-up population estimation for new development areas is combined with a top-down dasymetric mapping process to update outdated census tracts. A particular focus lies on the high flexibility of the developed procedure. Accordingly, users can utilize diverse data and adapt settings to a specific study context. Instead of requiring ubiquitous 3D building data, often unavailable free of charge, the approach suggests collecting building levels only in new development areas. The open-source software development was done using PostgreSQL/PostGIS as part of the co-creative development of the accessibility instrument GOAT in three German municipalities. A comparison with reference data from the population registry of one district was realized. On the building level, an R^2 of 0.82, and on the grid level (100 m $\times$ 100 m), an R^2

of 0.89 is reached. The approach stands out when land-use information is outdated; however, a spatially detailed census grid exists, but no ubiquitous 3D building information is available. Enhancements are proposed, such as improving the dasymetric mapping with machine learning and remote sensing techniques. Moreover, more reliable detection of new building development in already built-up areas is suggested to account better for urban densification.

6.1 Introduction

Up-to-date high-resolution population data are essential for understanding a dynamic environment and thus conducting accurate urban and spatial planning studies (Wang & Wu, 2010). High-resolution population data provide public authorities, non-governmental organizations, companies, and academics the possibility to design solid development metrics. This optimizes interventions in their respective communities (Qiu et al., 2019), organizes an accurate response to natural disasters (Garb et al., 2007; Hofstee et al., 2004; Nadim et al., 2006; Qiu et al., 2019), and is the foundation for many other studies. In contrast, aggregated data risks masking important hotspots and smoothing out spatial variations inside the population (Monteiro et al., 2018).

In the field of transport, studies related to non-motorized modes (walking and cycling) require high-resolution population data at the building scale. For instance, walking accessibility studies require detailed population data to calculate the benefited population within a specified walking or cycling distance to a new public transport station or a set of points of interest (Pajares, Büttner, et al., 2021; S.-s. Wu et al., 2008). Moreover, spatially disaggregated data are needed to define a more granular traffic analysis zone system, known as non-motorized traffic analysis zones (NM-TAZ), as an approach to analyzing walking and cycling inter-zonal trips (Jain & Tiwari, 2017).

Even though the demand for high-resolution population data is increasing, detailed databases often remain scarce or unavailable, due to limitations on the collection of individual micro-data (Moeckel et al., 2003; Šimbera, 2020). For confidentiality reasons, public data are aggregated (Huang et al., 2007; Monteiro et al., 2018), or could be available but not digitized (Jain & Tiwari, 2017; Mennis, 2009). Therefore, the census population data are usually grouped by census tracts (Mennis, 2003).

The use of raw census data has many implications to be considered before their use. First, census tracts polygons are designed according to administrative criteria to facilitate zone enumeration rather than specific demographic parameters (Bracken & Martin, 1989; Forster, 1985), which can mislead results for demographic studies due to the effect of the modifiable area unit problem (Openshaw, 1981). Second, due to their complexity and high cost, censuses are only conducted every 5, 10, or even 20 years, and therefore misrepresent the current population conditions; for instance, the latest German census was conducted in 2011 (Statistische Ämter des Bundes und der Länder, 2011), while between 2011 and 2020, the populations of cities such as Munich have experienced a growth rate of 9% (Bayerisches Landesamt für Statistik, 2015; 2021). New population distribution cannot be easily anticipated. However, new development areas attract new inhabitants at higher rates than established neighborhoods. While census tracts are not frequently updated, up-to-date population counts are often available on the city, district, or even sub-district levels. The lack of high-resolution data is treated through the application of spatial disaggregation methods (Goodchild & Lam, 1980). Spatial disaggregation is the process by which information on a coarse spatial scale is transformed into finer scales (Qiu et al., 2019). There are a variety of approaches, each based on different assumptions about the distributional information (Bracken & Martin, 1989). Disaggregation methods can be grouped into two categories: areal interpolation methods and statistical modeling methods (S.-s. Wu et al., 2005). Statistical methods consist of constructing stochastic models to generate simulated (or synthetic) distributions of population (Akiyama et al., 2013), for example, the iterative proportional fitting method (Beckman et al., 1996; Moeckel et al., 2003).

Areal interpolation methods consist of transforming data from a source zone to many smaller and non-intersecting target zones (Huang et al., 2007; Mennis, 2003). Areal interpolation methods can be further classified into two categories, based on whether they use ancillary data or not (Huang et al., 2007). Areal interpolation with ancillary information uses external data, usually land use or transportation networks, to refine population interpolation. Dasymetric mapping is one of the most popular methods in this category (Wright, 1936), which consists of refining polygons by discarding uninhabited areas obtained from ancillary data (Batista e Silva et al., 2013; Eicher & Brewer, 2001; Jain & Tiwari, 2017). Areal interpolation without ancillary data can be either point-based or areal-based (S.-s. Wu et al., 2005). Point-based methods rely on census points to create a continuous representation of the population (Bracken & Martin, 1989; Bracken, 1991; Huang et al., 2007). The continuous surfaces then support a wide range of spatial analytic processes (Langford et al., 1990). The areal-based methods, also known as volume-preserving methods, target the calculation of the proportional distribution of the population with weighted factors (Hofstee et al., 2004; Huang et al., 2007; Jain & Tiwari, 2017; Qiu et al., 2019; Wang & Wu, 2010; S.-s. Wu et al., 2005). Their advantage is the use of control units, which preserve the total number of the population.

Most recent studies propose to combine different methods to increase the accuracy, often starting with a dasymetric process (Monteiro et al., 2018). The hybrid process combines a dasymetric analysis with a fit regression model, dasymetric techniques with machine-learning algorithms (Monteiro et al., 2019; Šimbera, 2020). A two-step disaggregation is proposed based on a dasymetric processing and a weighted distribution method using 3D building information (Qiu et al., 2019).

As the finer population at the building level has gained importance, different research has studied population disaggregation at this level. LiDAR data were used to detect building characteristics, such as footprint and volume to obtain detailed population data (Chen et al., 2021; Xie et al., 2015). Bast et al. (2015) disaggregated population on the building level using OSM and population counts on the municipality level (Bast et al., 2015). The population was recently also disaggregated to a 10 m × 10 m grid for the whole of Germany. Using remote sensing techniques, building settlement structures and buildings volumes were derived from Sentinel-1 and Sentinel-2 data. The disaggregation combines a bottom-up population estimation with a top-down dasymetric mapping process (Schug et al., 2021).

The review of the presented studies is far from complete, but it can be concluded that: First, a comprehensive spectrum of disaggregation approaches exists depending on the available information type and the study purpose. Second, there is no systematic framework for data disaggregation (Huang et al., 2007), and in the worst case, each study has to develop their own models. This problem tends to occur due to the diversity of input data and use cases that makes the standardization process more complex. Furthermore, deriving accurate population data on the building level without ubiquitous 3D building information is particularly challenging. Besides the fact that 3D building data does not exist in every context, it is often expensive to procure. For example, standardized building data are available nationwide in Germany in the CityGML specification LOD 1 and LOD 2, but the data are not openly accessible in many German states (University of Rostock, 2021).

In this context, this paper proposes a standardized four-step hybrid approach to calculate high-resolution population data at the building-access level, based on widely available data sources. It uses a bottom-up population estimation for new development areas and a top-down dasymetric mapping process. Outdated census tracts are updated to a respective target year and then disaggregated to the building access level. There is no intention to derive additional demographic characters. Particular attention is paid to the balance between standardization and flexibility of the data used for the procedure. Accordingly, mostly open-source databases, like OpenStreetMap (OSM) or National Open Data Portals, are utilized. A focus is placed on developing a reusable and highly flexible script that can cope with varying data quality. This process is realized with population data on the district level and land-use data from the target year. While it is generally expected that 3D building data would improve the procedure results, the presented approach aims to work without ubiquitous 3D building data. Instead, it suggests the collection of building levels only for selected building footprints in new development areas.

6.2 Materials and methods

6.2.1 Study Context

The approach is developed as part of the Geo Open Accessibility Tool (GOAT) project (GOAT-Community, 2021c), an open-source planning instrument focused on modelling active mobility and local accessibility. One of the main data sources for the application is population numbers at the building access level. GOAT was developed in a co-creative process in collaboration with practitioners from the City of Munich, Freising and Fürstenfeldbruck in southern Germany. Therefore, the development of the presented procedure was applied to the mentioned municipalities visualized in Figure 6.1.

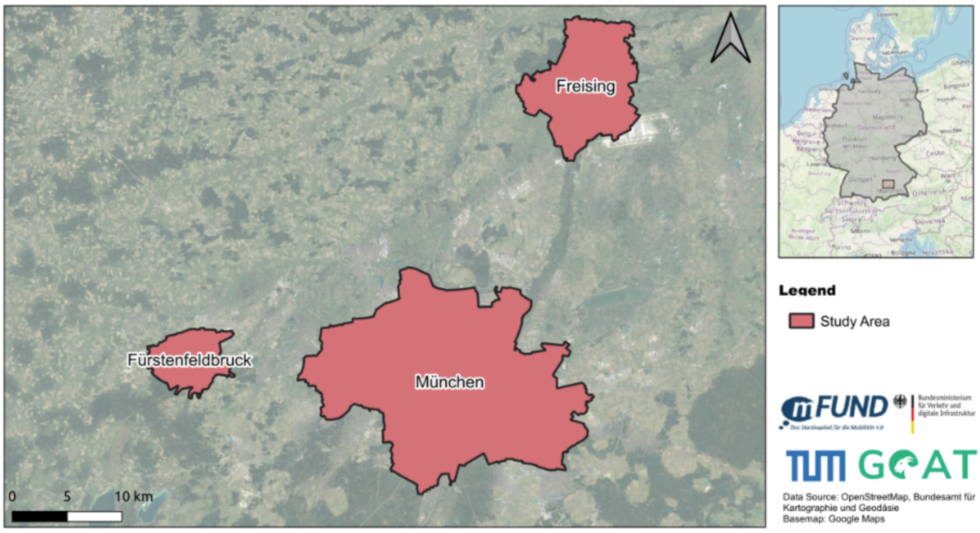


Figure 6.1: Studied municipalities.

In the last few years, all three municipalities have experienced significant population growth. Munich is the Free State of Bavaria capital, with approximately 1.488 million inhabitants, and Germany's third-largest city. It thus outnumbers the much smaller municipalities of Freising (48,872 inhabitants) and Fürstenfeldbruck (36,843 inhabitants) (Bayerisches Landesamt für Statistik, 2021). All three municipalities have a historical center and contain areas with diverse spatial typologies. The City of Munich is the most densely populated municipality in Germany, with a population density of 4777 inhabitants per km^2 (Statistische Ämter des Bundes und der Länder, 2021). Accordingly, urban spatial typologies dominate many districts. However, the outer districts also comprise suburbs with relatively low density and high-rise housing estates developed in the 1960s and 1970s. Freising and Fürstenfeldbruck are less densely populated and contain rural settlement structures in their outer districts. In the City of Munich, new housing development is almost exclusively realized in multi-family dwellings, either in new development areas or through densification in the existing built environment. Moreover, in the municipalities of Freising and Fürstendfeldbruck, a trend toward multi-family dwellings can be observed.

6.2.2 Data

The Table 6.1 lists all data sources used in this study with their respective reference year. The listed data can be considered a sample, as the developed procedure works with data from other contexts representing the same objects. Furthermore, if not available, only parts of the data sets are required (see Section 6.3.1).

Table 6.1: Data used for population disaggregation.

Data Set	Official Name	Data Provider	Reference Year
Land-use	Urban Atlas LCLU 2018 (European Union, Copernicus Land Monitoring Service & European Environment Agency (EEA), 2018)	European Environment Agency (EEA)	2018
Land-use	OpenStreetMap raw files (Geofabrik GmbH Karlsruhe, 2021)	OpenStreetMap contributors	2021
Land-use	ATKIS Basis-DLM (Landesamt für Digitalisierung Breitband und Vermessung, 2020)	Landesamt für Digitalisierung, Breitband und Vermessung Bayern	2020
Points of Interest	OpenStreetMap raw files (Geofabrik GmbH Karlsruhe, 2021)	OpenStreetMap contributors	2021
Building attributes	OpenStreetMap raw files (Geofabrik GmbH Karlsruhe, 2021)	OpenStreetMap contributors	2021
Building footprints	ALKIS Hausumringe (Landesamt für Digitalisierung Breitband und Vermessung, n.d.)	Landesamt für Digitalisierung, Breitband und Vermessung Bayern	2020
Census Germany	Census Germany (Statistische Ämter des Bundes und der Länder, 2011)	Statistische Ämter des Bundes und der Länder	2011
City districts with population numbers	Stadtbezirksteile	City of Munich, Freising, Fürstenfeldbruck	2021

All data are represented as spatial vector data in the XML format, as Shapefile or GeoPackage. The presented data sets are either openly accessible or provided free of charge by the local public authorities. The data were downloaded in the specific raw formats for the study and converted into the spatial reference system EPSG 4326. Later, the data were imported into the spatial database system (see Section 6.2.3) for processing.

In Figure 6.2, most of the used data sets are visualized. Three different sources were used for land-use data. While the land use data originating from the official ATKIS Basis-DLM contain only formally defined land-use categories, the data from OSM also contain categories that contributors defined. Furthermore, the land use data from OSM can contain overlapping geometries, which is not the case for the other land use data. The land use information from Urban Atlas is standardized by the European Environment Agency and again contains a different classification.

As reference data set for the comparison with the disaggregated population (see Section 6.3.6), counts on the address level were provided by the City of Freising for their largest district, Lerchenfeld. These data originate from their municipal population register. In Germany, there is an existing obligation to register at a specific address. Therefore, the data can be regarded as remarkably accurate.

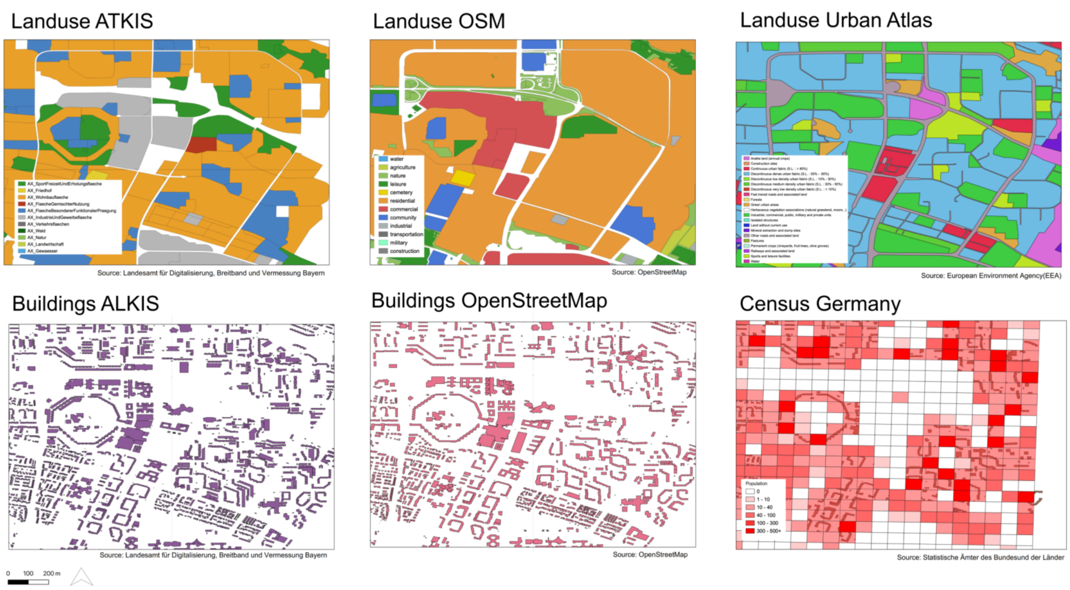


Figure 6.2: Core spatial data used.

Building footprints were used from the official source ALKIS and OSM. The building footprint of ALKIS usually consists of one building per address. A building in OSM may correspond to several buildings in ALKIS, and vice versa. While building footprints are not mapped everywhere in OSM, almost all buildings exist in OSM for the study context. Furthermore, the OSM data on the building footprints were usually more up-to-date than the available data from ALKIS. Due to the active OSM community in the study area, new buildings are usually mapped during construction. Although the building type is collected in ALKIS, this information was not shared by the public authority. Accordingly, the available building footprints in ALKIS do not contain information on the use of the building. This information, however, exists for approximately 66.17% of the buildings in OSM in the City of Munich.

Finally, the Census of Germany is a vector layer with the population for each census tract. In this case, each census tract is represented by a 100 m × 100 m square grid and was last updated in 2011. In addition to the total population, census tracts contain demographic information, such as age groups and citizenship. The German census is repeated every ten years (the next one in 2022); the currently available data is out-of-date.

6.2.3 Software

GOAT is a WebGIS application created with various open-source software (see Figure 6.3). For the development, the software was installed on a ThinkPad T470 with 16 GB of RAM and an i7 processor running the Linux distribution Ubuntu LTS 18.04. The setup was running with a Docker container. To set up the application, a step-by-step guide exists on the project website (GOAT-Community, 2021b).

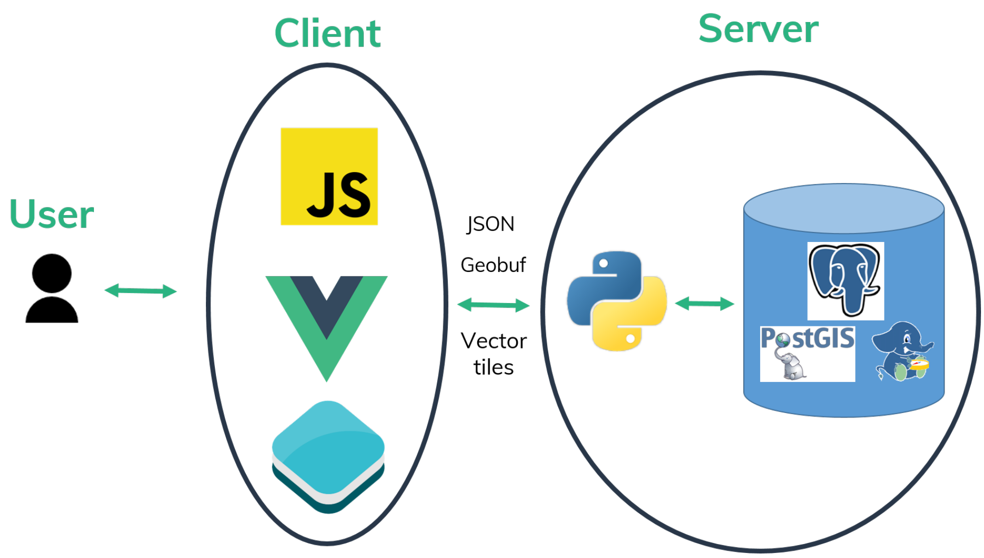


Figure 6.3: GOAT Architecture
(Plan4Better GmbH, 2021d)

The core of the application is a spatial database system consisting of PostgreSQL 12 and PostGIS 3. A custom Debian-based database image was used as the database docker image (GOAT-Community, 2021c). Accordingly, the presented procedure is written in SQL, making extensive use of the spatial functions provided in PostGIS. Besides classical SQL, the SQL Procedural Language PL/pgSQL is used to develop database functions and in anonymous code blocks. In addition, Python functions are developed to execute the different SQL scripts automatically and to import the required data. These functions are integrated into the GOAT setup routines. If running the GOAT setup, the procedure is executed automatically, but can also be triggered manually. Customization can be realized in the configuration file "goat_config.yaml" and when preparing the raw data. A detailed description of data preparation and the options for configuration are provided on the project website (GOAT-Community, 2021a). For the data visualization and the creation of maps, QGIS is utilized. The developed source code has been frequently published on Github and is available here (GOAT-Community, 2021b). If data were collected, it was performed directly with the OSM iD editor and JOSM. The most recent changes in the OSM database were frequently fetched using the daily dumps and the Overpass API.

6.3 Results

The population disaggregation approach presented in this paper is composed of four steps: 1. Fusion of Building data and Dasymetric mapping, 2. Detection of building entrances and new development areas, 3. Updating of census tracts, and 4. Population distribution. As part of the workflow, data verification and collection is suggested in the respective areas. To ensure high flexibility of the procedure, users can customize important settings in a configuration file.

The overview of the procedure can be seen in Figure 6.4. The developed table schema will be presented in the following section, and then the individual steps will be elaborated further.

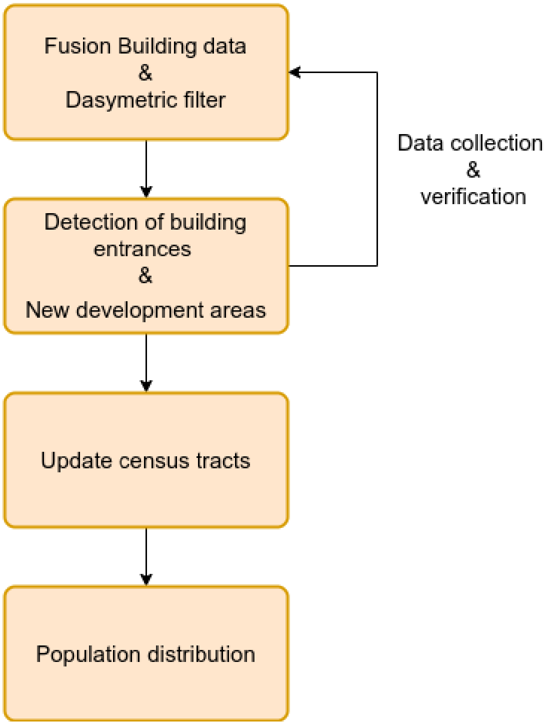


Figure 6.4: Overview procedure.

6.3.1 Table schema

For the presented data (see Section 6.2.2), a suitable table schema was developed. Two schemas are defined for a high flexibility on the data used: required (see Figure 6.5) and optional (see Figure 6.6).

Buildings OSM

PK	gid	int4
not null	osm_id	int8
not null	building	text
	amenity	text
	building_levels	int2
	roof_levels	int2
	street	text
	housenumber	text
not null	area	int4
not null	geom	POLYGON

Study Area

PK	gid	int4
not null	name	text
not null	sum_pop	int4
	default_building_levels	int2
	default_roof_levels	int2
not null	geom	POLYGON

Census Tracts

PK	gid	int4
not null	pop	int4
not null	geom	POLYGON

Landuse OSM

PK	gid	int4
not null	osm_id	int8
	landuse	text
	amenity	text
	tourism	text
	name	text
not null	geom	POLYGON

Figure 6.5: Required input tables.

For required tables, there are only defined minimum data requirements. Accordingly, only data from OSM, census tracts and administrative boundaries with up-to-date population data are needed. While the required data is sufficient to make the procedure work, especially when OSM Data lacks completeness, the optional data tables are suggested to obtain better results. Furthermore, not all attributes, but only the attributes labeled with 'not null' in Figures 6.5 and 6.6, are required.

As output schema, the tables in the Figure 6.7 are produced as either intermediate or final results. While the presented table attributes and data types are identical to the SQL implementation, the table names differ slightly to read the figures better. A translation of the table names into the names used in the SQL scripts is in the Appendix C.

Buldings Custom

PK	gid	int4
	building	text
	amenity	text
	building_levels	int2
	roof_levels	int2
	height	float
not null	area	int4
not null	geom	POLYGON

Landuse Custom 1

PK	gid	int4
not null	landuse	text
	name	text
not null	geom	POLYGON

Landuse Custom 2

PK	gid	int4
not null	landuse	text
	name	text
not null	geom	POLYGON

Fixed Population

PK	gid	int4
not null	population	float
not null	geom	POINT

Figure 6.6: Optional input tables.

Fused Buildings

PK	gid	int4
	osm_id	int8
not null	building	text
not null	residential_status	text
	amenity	text
not null	building_levels	int2
not null	building_levels_residential	int2
not null	roof_levels	int2
	height	float
	street	text
	housenumber	text
not null	area	int4
	gross_floor_area_residential	int4
not null	geom	POLYGON

Census Tracts New Development

PK	gid	int4
not null	pop	int4
not null	geom	POLYGON

Updated Census Tracts

PK	gid	int4
	pop	int4
	new_pop	int4
not null	geom	POLYGON

Population

PK	gid	int4
not null	population	float
not null	geom	POINT

Residential Entrances

PK	building_gid	int4
not null	gross_floor_area_residential	float
not null	geom	POINT

Figure 6.7: Data structure output tables.

6.3.2 Fusion of building data and dasymetric mapping

As visualized in Figure 6.8, this first step consolidates the different building data sets. Therefore, the OSM data (if available, custom building data) are fused by spatial intersection. If available, a priority is given to the custom building data set, and fusion is performed based on the largest share of spatial intersections, in case there are multiple intersections. If available, attributes such as building type and building levels are combined from OSM and custom building footprints. If the height of buildings is known, the number of floors is computed using average height per building level. If neither the height nor the building levels are available, a default number of building levels is assigned per district of the study area. In the study, this average varied from one to five, depending on the district and municipality. This value was derived from the author's knowledge of the study context, and was assigned to each district. Another option will be assigning the observed average from a reference data set, such as OSM if building levels are available for a statistically significant number of buildings.

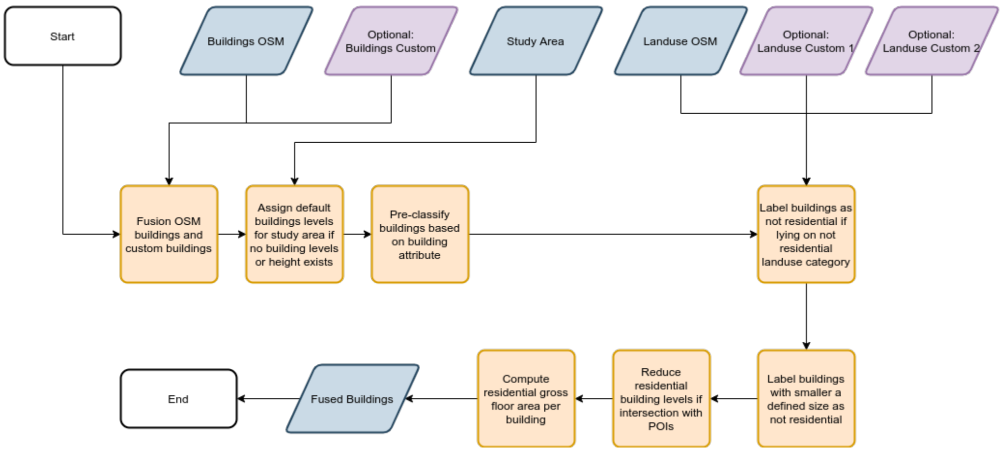


Figure 6.8: Fusion building data and dasymetric mapping.

Next, dasymetric mapping is performed to identify buildings with residents. Simplified binary classification is applied to categorize buildings into "with residents" and "no residents". Therefore, buildings are first classified using the attributes building and amenity, which specify the use of the building. For the classification, users can define a list of residential and non-residential categories in the configuration file. However, as is common in OSM, there is no specification on the building type. Therefore, other auxiliary data are needed to classify the buildings further. Land use data from OSM is used as the default data set, and (if available), two more custom land-use data sets can be provided. For each of the land use data sets, a configuration of different categories contains information on whether the buildings are residential or not. Accordingly, land use categories such as industrial or commercial can be labeled as non-residential, while residential use can be labeled as residential. If multiple files are provided, a hierarchy between the land-use files can be defined if the data sets assign contradicting categories to the buildings.

A particular challenge, however, is the detection of outbuildings such as detached garages or garden houses. In this case, a final filter is applied using a minimum residential building size of square meters to label these non-residential buildings. Similar to other settings, this filter can be customized to the local study context. After that, ground floor commerce is identified using a set of points of interest from OSM. If buildings have ground floor commerce, the residential floor levels are reduced by one floor. If no ground floor commerce exists, it is assumed that all floors are residential. Finally, the residential gross floor area is calculated per building using the following formula:

$$G = A \times (NBL + 0.5 \times NRL) \tag{6.1}$$

where G is the residential gross floor area in m^2, A is the area of the building footprint in m^2, NBL is the number of residential floors and NRL is the number of roof levels. As the final result of this step, a fused building data table is saved and made available for the subsequent steps. The final result of the process is visualized in a chosen neighborhood in Munich in Figure 6.9.

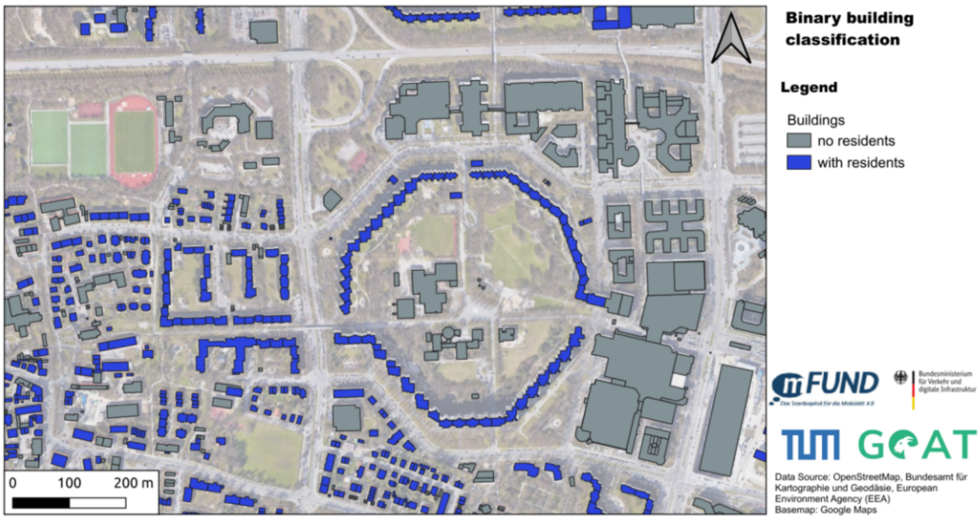


Figure 6.9: Binary classification buildings.

6.3.3 Detection of building entrances and new developments areas

In this step, the procedure is intended to estimate access points to buildings and identify census tracts recognized as areas of new residential development (see Figure 6.10).

The entrances and addresses are identified from OSM point data (if available) or based on the edge of the building closest to the OSM street network. If several access points are identified in one building, the residential gross floor area is equally distributed. It is also possible to complement data by feeding in custom population point data sets. This optional data set allows one to specify the exact number of residents for a given access point. If buildings intersect points from the custom population data set, their population is considered static for the upcoming steps.

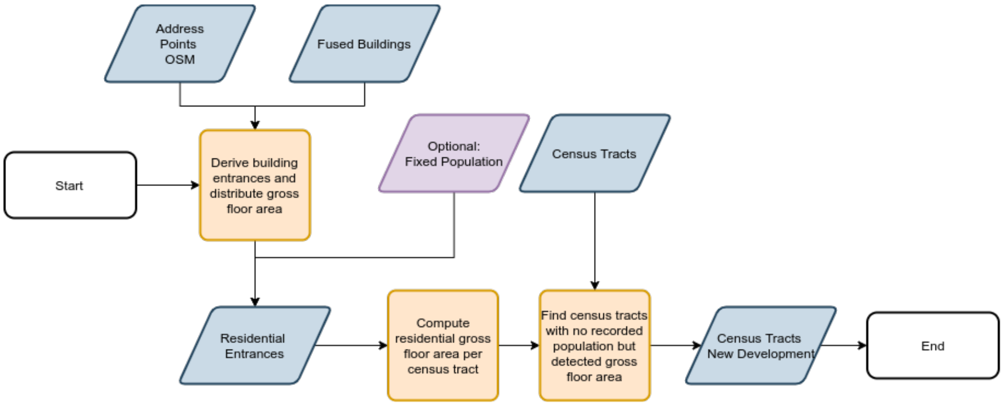


Figure 6.10: Detection of building entrances and New development areas.

Subsequently, these entrances containing building-related data are compared with census tracts. If the census tract has no recorded population but contains a residential access point, it is labeled a census tract with new development. The population is computed bottom-up using the residential gross floor area and an average gross floor area per resident for these selected new census tracts. The average gross floor area per resident is defined per municipality. According to official statistics, the net living area per person is 39 m^2 in the City of Munich and 49 m^2 in the Munich region (Stadt München, 2018). Following this, parameters for average gross floor area 50 m^2 for the City of Munich and 60 m^2 for Freising and Fürstenfeldbruck were chosen. However, the procedure allows one to freely chose a suitable gross floor area in the configuration.

For the bottom-up estimation, the building data quality in the tracts with new development is critical. Therefore, the table “Census Tracts New Development” is created. It is suggested that the building type and the number of building levels are collected directly in OSM for buildings located in these tracts. An alternative could be to acquire commercial building data for the selected areas. While the upcoming procedures also work without further data collection, it is highly suggested to improve the final result. Since only a fraction of census tracts are usually affected, the resources needed for this step are relatively small. Once data collection is realized, the previously described steps should be repeated. The final result of the process is visualized in Figure 6.11 for an exemplary neighborhood in a new development area in Munich. The buildings visualized in the new census tracts have four to five stories and flat roofs with no commerce on the ground floor. This area can be classified as a typical new development area in the outer districts of Munich.

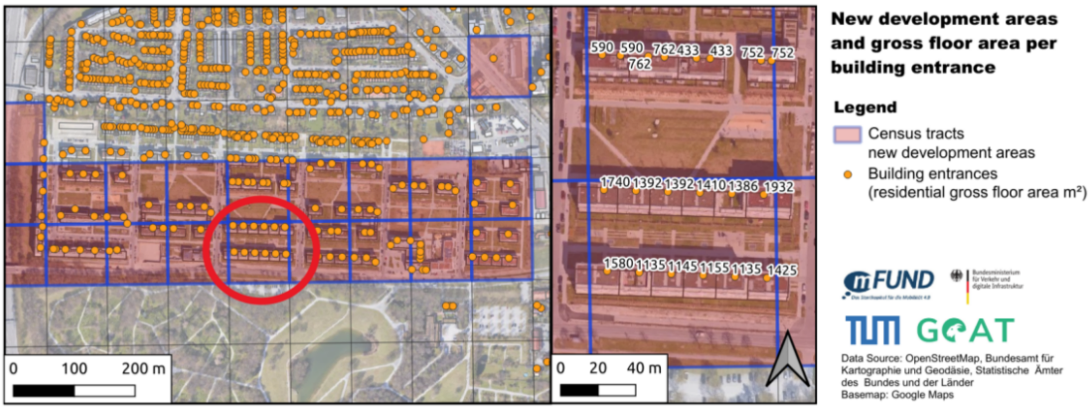


Figure 6.11: New development areas and gross floor area per building entrance.

6.3.4 Updating of census tracts

In this step, the population per census tract is updated to meet the population number of the study area as a control unit in the respective reference year (see Figure 6.12). Therefore, a combination of a bottom-up and top-down approach is implemented. First, the population is computed using a bottom-up approach for the census tracts detected as “new development areas”. Accordingly, for all census tracts, the intersecting building entrances are taken, and population numbers are computed using an average gross floor area per resident as follows:

$$P = \sum_{i=1}^{c} GA_i / AGR \tag{6.2}$$

where P is the computed new population for the census tracts, c is the number of intersecting building entrances, GA_i is the gross floor area assigned to the entrance, and AGR is the average gross floor area needed per resident.

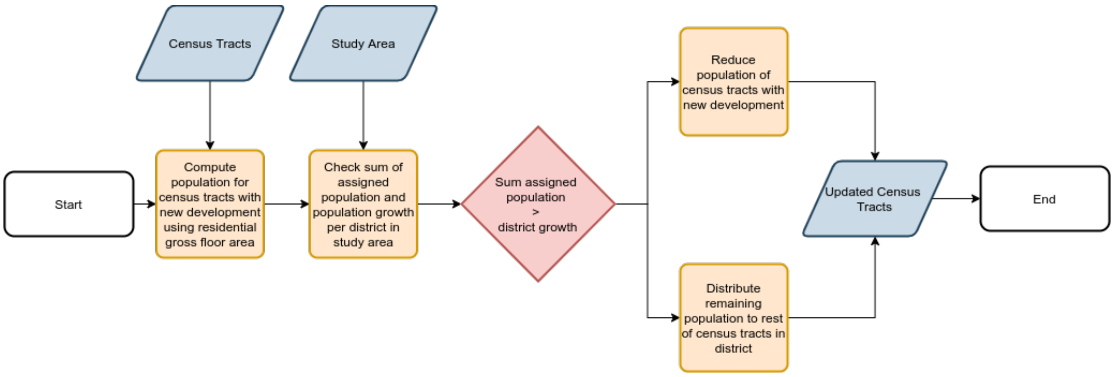


Figure 6.12: Update census tracts.

Consequently, the population assigned by the bottom-up distribution will be corrected using the total population of the related district of the study area as a control unit through a top-down approach. It is checked whether the sum of the newly assigned population growth matches the overall growth in the related district. In case the population in the new development areas exceeds the overall population, the newly assigned population in the tracts is adjusted. If the distributed population is lower than the overall growth, the remaining population is distributed proportionally according to the residential gross floor area to all remaining census tracts. By that, densification in already built-up areas should be modeled. As a final result, a census table with updated population numbers is stored. The combination of bottom-up and top-down approaches ensures that the population in the census tracts does not exceed the total population of the respective study area.

6.3.5 Population distribution

In a final step, the population from each census tract is distributed proportionally to the residential entrances using the residential gross floor area (see Figure 6.13). Inaccuracies which come with assigning default building levels per district are reduced, as due to small grid sizes, building levels are likely homogeneous within the grid. The disaggregated population data are saved as vector point data sets in the database.

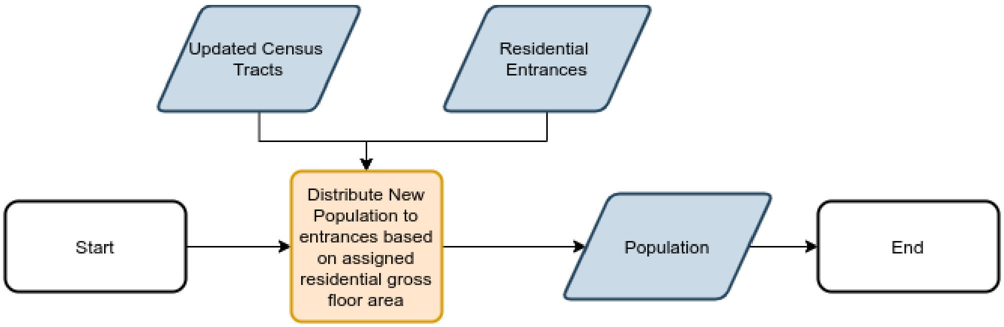


Figure 6.13: Population distribution.

The data are aggregated on a hexagonal grid with an edge length of 150 m for visualization purposes. The map in the Figure 6.14 shows the distribution of the population in the City of Munich. Despite the overall very high density, the large green areas within the city and main transport infrastructures are clearly visible as uninhabited. The zoomed-in map further visualizes how the population is distributed on the building entrance level. To the author's knowledge, the displayed buildings have five stories and consist of ten flats per building, of varying sizes.

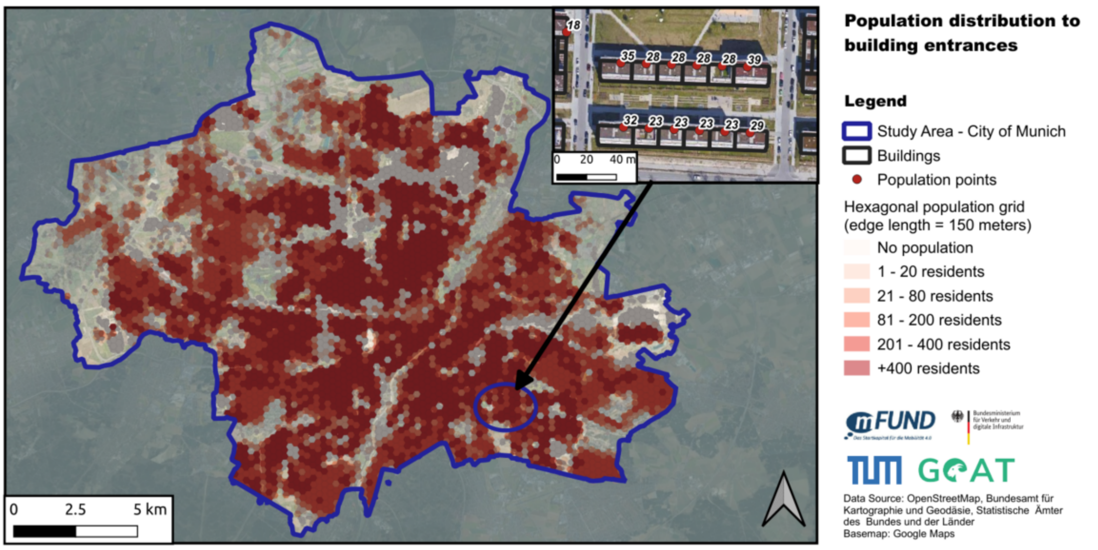


Figure 6.14: Population distribution.

6.3.6 Comparison with the municipal population registry

For the comparison, the district of Lerchenfeld in Freising was selected. The reason for this was the availability of suitable reference data. The district had, in 2020, a population of 13,135 inhabitants, and had growth of 13.8% since 2011. It is very heterogeneous in terms of building structure and demography. It is characterized by single-family housing, detached housing, and multi-story building of up to nine building levels. There are also major commercial and industrial areas in the district. Urban growth has happened since 2011, mostly in new multi-story buildings with three to four building levels. Besides greenfield development, existing neighborhoods were densified. A particularity in the area is the existence of two complexes for the housing of refugees, particularly with high population density. Although the reference data can be regarded as very accurate, there are two significant limitations. First, assigning the provided population on the address level to a specific building was not always possible. Not all buildings had address information, and sometimes, one population point represents several buildings. Second, the inspection revealed implausible outliers. There were buildings with a comparatively low living area, but many residents and non-residential buildings with residents. In the population registry, persons can be registered at a specific address, but live at another location. Nevertheless, the provided data are considered the most suitable one for the comparison.

The disaggregated and recorded population point data were summed up on the building level, and their relative difference is visualized in Figure 6.15. There could be both over- and underestimations of population detected. Moreover, there are also neighborhoods with an exceptionally high correlation of disaggregated and recorded data. The highest mismatch was yielded on the building complexes for refugees. There were up to 450% more residents registered compared to the disaggregation (see Figure 6.16). Another significant outlier was a nursing home for the elderly classified as a non-residential building, due to consideration of this edge case in the dasymetric mapping not being appropriate. While these strong outliers are few, they affect the quality of the disaggregation for the whole district, as the missing population is assigned to other buildings, resulting in an overestimation. This was observed mainly for single-family houses. It can also be observed that identical buildings face a high relative mismatch of population numbers for single-family houses. This is most likely related to differences in the household structure and age. However, with the available data, differences in age or household size could not be considered on the building level. Overall, an R^2 of 0.82 was achieved for the disaggregation on the building level, as shown in the Figure 6.17.

Further comparisons were realized on the level of the census grid (100 m $\times$ 100 m), as shown in Figures 6.17 and 6.18. Due to the lower spatial resolution, the correlation between disaggregated and recorded populations was higher. As a result, an R^2 of 0.89 was reached. Despite the higher correlation, still, significant outliers are visible, mainly in the previously described cases. A correlation between unmodified population numbers from the census registered in 2011 and the recorded population in 2020 is shown in Figure 6.19. Without updating the population data, a significantly lower R^2 of 0.78 on the grid level would be achieved.

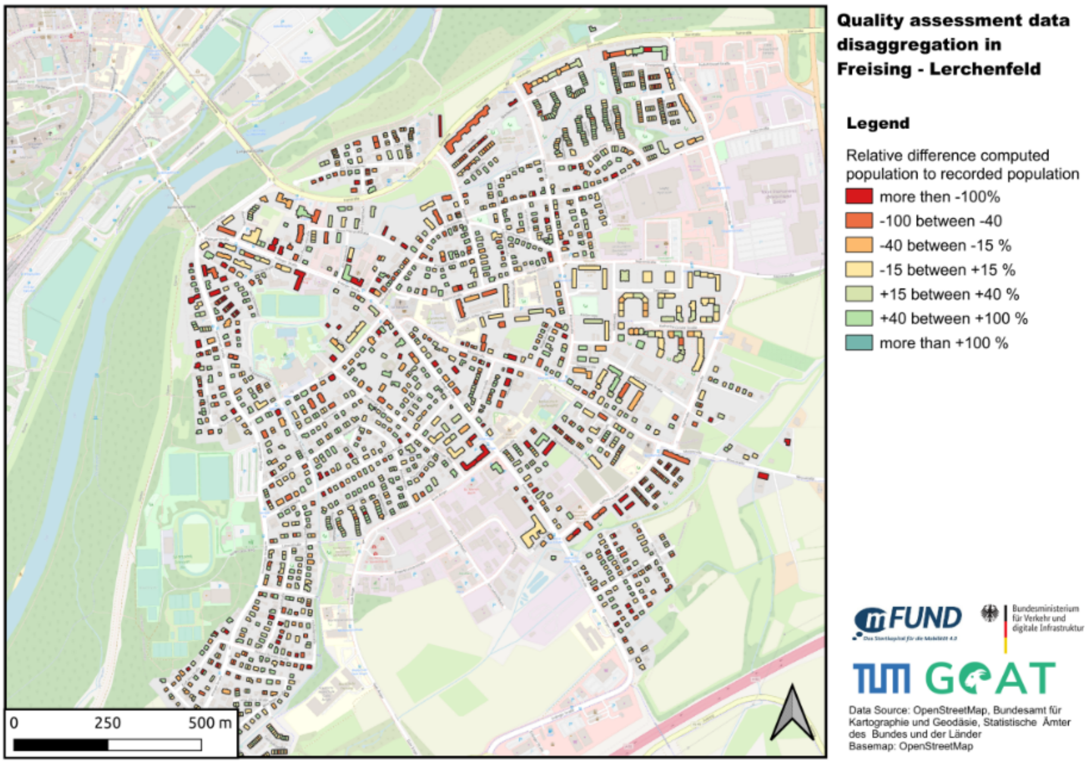


Figure 6.15: Comparison disaggregated and recorded population data on the building level.

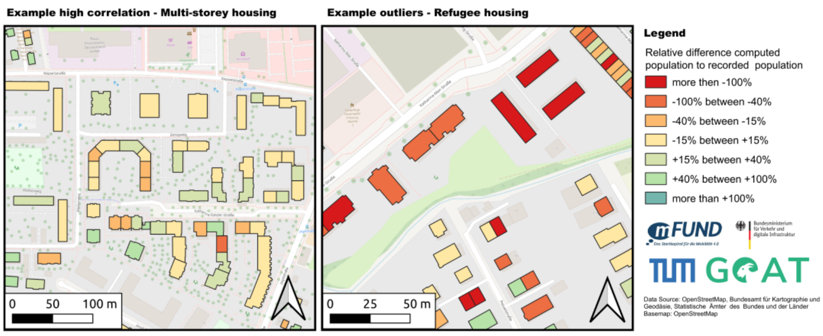
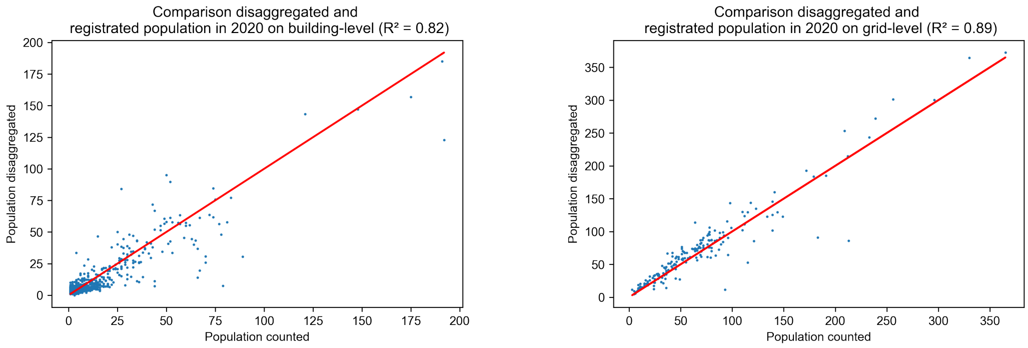


Figure 6.16: Comparison disaggregated and recorded population data correlation examples.



(**a**) (**b**)

Figure 6.17: Correlation disaggregated and recorded data on (**a**) building-level and (**b**) grid-level (100 m $\times$ 100 m).

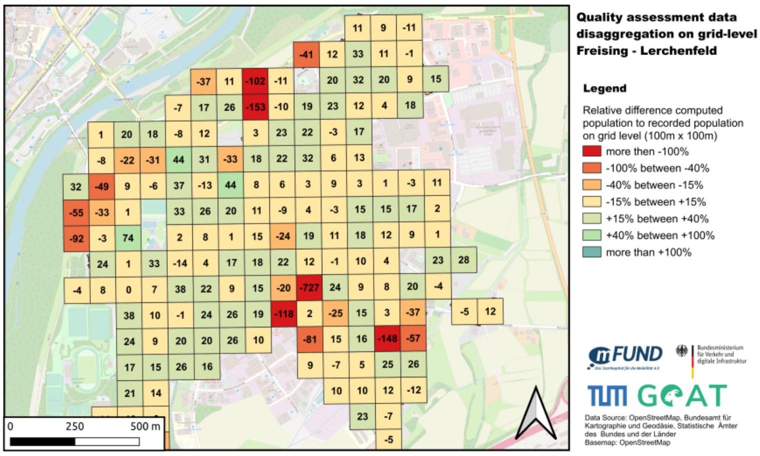


Figure 6.18: Comparison disaggregated and recorded population on grid-level.

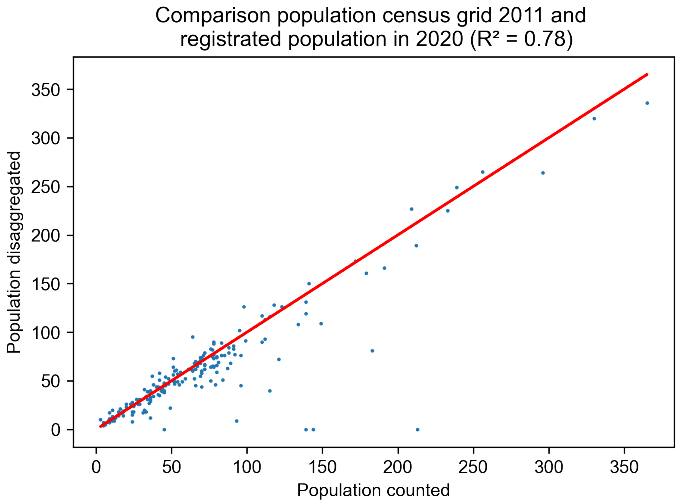


Figure 6.19: Comparison census population from 2011 and recorded population 2020.

6.4 Discussion

The methodology was applied in three growing municipalities in southern Germany. The results were used for accessibility analyses in planning workshops, with urban and transport planners in the studied municipalities. A comparison with recorded population data on the address level for a selected district in the municipality of Freising indicates a relatively high quality of the produced data. However, it also shows that the population is significantly over- or underestimated for selected buildings. As the total population is used as a control unit for the district, significant deviations for selected buildings can strongly influence the results for the remaining buildings. The comparison of data from the census of 2011 and the recorded data from 2020 shows that the procedure updates the data successfully, and quality is higher than without the update.

An explicit limitation of the presented approach is that the procedure expects, a priori, that the population grows in the respective study area. It would be feasible to adjust the scripts to model population decline. However, it has not yet been implemented. Further testing would be needed to see if the procedure produces relevant results when the population declines. Another methodological weakness of the presented solution is the insufficient attention paid to new housing development in areas with a population in the outdated census tracts. As the population is initially assigned to census tracts that previously had no population and only afterward is the remaining growth assigned to all other already inhabited census tracts, the phenomena of urban densification are not captured well enough. However, detecting new development in a separate tract without historical building footprints is particularly challenging. The procedure assigns the same average gross floor area for all districts within a study area with the current design. This is a limitation as the average living area can vary significantly between different neighborhoods and building types.

While collecting data on building levels improves the results of the procedure, it requires additional resources. Therefore, fallback values in the configuration files can be favorable in larger regions and regions with homogeneous buildings levels. An interesting source for further exploration could be building heights derived through remote sensing. Due to the absence of area-wide building heights, emphasis is placed on estimating building heights using freely available data such as products from Sentinel and Landsat. Building heights were estimated on a 1 km grid for Europe, the XML, and China using a random forest model and training data sets from the different regions (M. Li et al., 2020; X. Li et al., 2020). A validation showed an R^2 of 0.81 for the building height estimation (M. Li et al., 2020). On the national scale, significantly higher resolutions of 10 m were achieved using Sentinel 1 and Sentinel 2 data. Machine learning regression models were utilized with robust training data sets composed of almost 15 million buildings in LOD 2. A frequency-weighted RMSE of 2.9–3.5 m was achieved (Frantz et al., 2021).

Despite the increasing availability of data on building footprints and land-use, this might not be the case in every context. Accordingly, the procedure is not recommended for areas with missing building footprints and missing land-use information. The procedure also expects census data on a high resolution, and grid sizes of 100 m were used for the tests. Although not tested yet, it is expected that larger grid sizes would weaken the detection of new housing development areas, as census tracts with new development are identified by searching tracts with no population recorded in the reference year but having residential buildings in the target year. Moreover, the resolution of the districts of the study area influences the results of the disaggregation. Generally, it can be assumed that a higher resolution of the districts will improve results, and vice-versa.

The application has shown that dasymetric mapping works particularly well with several land-use files. However, it is still challenging to properly classify buildings that have no specific information on the use of the buildings, either from OSM or other data sources. Especially in mixed land-use areas, it is not trivial to detect which building contains residents or not. Furthermore, the detection of outbuildings solely by size can be error-prone.

Dasymetric mapping could be improved by the use of remote sensing techniques and machine learning. Lu et al. (2014) classified buildings into single-family, multi-family, and non-residential buildings using LiDAR data. Four different machine learning techniques were used: decision trees, aggregated decision trees, support vector machines, and random forest. Accuracies of 60–88% were reached. The best-performing one was supported vector machines in both urban and suburban areas. Diverse attributes falling into categories such as building shape attributes and spatial relationships with other land-use features were used (Lu et al., 2014). Although the mentioned study utilizes LiDAR data, the methods for the classification could partially be applied with the available vector data from OSM and public sources. With the wide availability of building footprints, the dimension of buildings could be utilized as a good proxy for building type classification. In the German context, officially labeled data on the building type could be retrieved from cadastre for states where the data are open access.

Moreover, street view imagery is utilized to classify building types. Using a convolutional neural network on geotagged imagery from Google StreetView, buildings were classified into diverse categories, such as industrial, office, and garages (J. Kang et al., 2018). As part of a German-wide population disaggregation, building areas were classified using random forest on Sentinel 1 and Sentinel 2 data. The procedure reached an overall accuracy of 81.4% (Schug et al., 2021). These mentioned examples indicate that the use of additional data sources and methods can improve the developed procedure.

While the presented solution produces population point data on a particularly high resolution, it lacks further socio-demographic attributes such as age, gender, or income. This makes it particularly unsuitable for activity-based land-use and transport models, which usually require a synthetic population. While advanced population synthesizers exist, as reported in (Farooq et al., 2013; A. Moreno & Moeckel, 2018; Müller & Axhausen, 2011), the objective of this study was to develop a well-performing and simple solution, which produces exclusively up-to-date population counts at a very high resolution under minimal data requirements.

A high-resolution population is relevant for a wide array of use cases. In countries such as Germany, population registries exist, which provide an up-to-date picture of population data on the address level. However, these data are usually sensitive and not shared with upper administrative bodies, researchers, or private businesses at a high resolution. Therefore, the developed procedure could be of special value for official statistics at the higher administrative levels or public service providers in the studied context. Meanwhile, in contexts where citizens are not forced to report on their home location, the procedure can also be relevant for municipalities by providing a granular disaggregation of the population.

6.5 Conclusions

The new population disaggregation approach demonstrates that population numbers can be disaggregated on the building level based on outdated census data. Unlike other existing solutions, the procedure works without ubiquitous 3D building data. It suggests the collection of building levels in OSM for new residential areas, or suggests the definition of average building levels per administrative district. Furthermore, diverse but easily available data sets are fused and utilized. This significantly reduces the data requirements and makes it possible to utilize the census tracts' spatially detailed but outdated population information. It can adjust to local requirements through configuration files and fuses data from varying sources to remain useful in varying contexts. Different configurations should be tested in the future and best practices documented for different contexts. As the procedure was integrated into the setup of the software GOAT, it can be executed in a highly automated fashion and can be directly used in the application. However, it is also possible to use the scripts independent of the GOAT application. Overall, the development is a pragmatic contribution to the existing landscape of population disaggregation. The solution is advantageous if an inexpensive approach is favored and good open data are available, but no 3D building information exists. This study was mainly intended to prepare population data for accessibility analysis on the neighborhood level. Meanwhile, it could be useful for other applications.

So far, the scripts have been primarily tested in the studied municipalities. However, further testing will be conducted. Large-scale tests in Germany are currently prepared, and tests in regions worldwide are envisaged. To date, the results have been verified by comparing them with recorded population data from one district. As described in Section 6.3.6, it could be feasible to reach higher correlations with data from population registries in other areas with less dynamic growth and fewer outliers. Further strategies need to be developed to detect and handle outliers. Due to the unavailability of data, no large-scale comparison can be realized yet. Whenever possible, this should be done in the future. Furthermore, data verification using data produced by other disaggregation algorithms or newly published census data are being sought. To improve the detection of new development areas, historical data on building footprints should be examined further. A potential source could be the OSM database, as timestamps exist for each feature created or modified. In addition, remote sensing techniques on satellite imagery could be tested to detect areas with changes in the built environment. This improvement could particularly help in identifying urban densification. As described in Section 6.4, the dasymetric mapping could benefit from remote sensing and machine learning. Promising is, in particular, the extension of the current binary building classification towards multiple classes, such as single-family housing, multi-family housing, mixed-use and non-residential. Further experimentation with deriving building type and gross floor area for residential purposes with the help of points of interest is targeted. Overall, it is seen that this work adds especially the following contributions:

- A standardized and adaptable yet pragmatic solution was developed to disaggregate the population on the building access level.

- Compared to many other solutions, no ubiquitous 3D building data or LiDAR data are necessary.
- An outdated census grid is updated to the target year, and therefore the spatially detailed but outdated census data are set in value.

Among others, the following are seen as the most important limitations:

- Dasymetric mapping is solely based on a boolean classification; accordingly, different residential buildings are not differentiated.
- A spatially detailed census grid, up-to-date population data on the district level, building footprints are necessary to obtain appropriate results.
- It is suggested to collect buildings level in new development areas, which means additional effort and limits scaling.
- More validation of the produced results is necessary to judge the accuracy finally.

Besides the aforementioned technical optimization, one might ask if it is sufficient to include only the static population. There are high temporal variations in the distribution of the population within a city region; most notably, the variations between day and night. Moreover, many applications such as accessibility instruments would benefit from showing the variations of population. Recent research (Rauch et al., 2021; Rosina et al., 2020) underscores the potential and feasibility of disaggregation procedures, which incorporate the tempo-spatial dynamics of the population in cities and regions. To specifically enrich accessibility instruments with temporal dynamic population data, further research and development are envisaged.

Author Contributions:
Elias Pajares: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Software, Visualization, Writing—original draft, Writing—review & editing
Rafael Muñoz: Conceptualization, Investigation, Methodology, Writing—original draft, Writing—review & editing
Liqiu Meng: Investigation, Supervision, Writing—review & editing
Gebhard Wulfhorst: Funding acquisition, Resources, Supervision

Chapter 7

Identification and discussion of use cases of an interactive accessibility instrument for active mobility planning

This chapter has been submitted by Pajares, E., Jehle, U., Hall, J., Miramontes, M., Wulfhorst, G.: Assessment of the usefulness of the interactive accessibility instrument GOAT for the planning practice. Journal of Urban Mobility (accepted).

Abstract

Accessibility instruments could serve as powerful support in assisting planning practitioners. Though, accessibility instruments are usually not yet applied in practice. Past research has identified that besides institutional barriers in adopting accessibility, there is still a lack of useful instruments. It is suggested that tool developers engage closer with planning practice to better meet requirements from practice. The authors developed an interactive and web-based accessibility instrument called GOAT, focusing on active mobility in a co-creative environment with urban and transport planning practitioners. This manuscript aims to answer two research questions. Which planning questions exist for GOAT in the field of transport and urban planning? Is the accessibility instrument GOAT of useful support in the planning practice?
First, suitable planning questions were identified. The tools' utility and usability for the planning questions were self-assessed based on the experience in five applications workshops with 37 planning professionals in four German cities. The assessment was realized by analyzing workshop minutes and worksheets for the different planning

questions. As a result, the usefulness was assessed for the planning questions and was summarized into four groups: Infrastructure Planning Walking, Infrastructure Planning Cycling, Location Planning, and Housing Development.

The assessment revealed that the tool helps answer common planning questions. In terms of usability, the tool could also be used by individuals unfamiliar with existing planning software after a half-day introduction. Meanwhile, practitioners requested further indicators and improvements in usability. Furthermore, stronger technical integration with existing systems should be envisaged. It is concluded that the involvement of planning practice was highly beneficial when developing and assessing the tool. Therefore, ongoing exchange and a long-term assessment of the tools' usefulness are suggested in the future.

7.1 Introduction

Active mobility is gaining escalating attention, while concepts such as the 15-minute city have been presented as a vision for sustainable cities (C40 Cities, 2020; C. Moreno et al., 2021; Pozoukidou & Chatziyiannaki, 2021). Promoting active mobility is consistent, as no other mobility option combines benefits ranging from space efficiency, carbon neutrality, livability, and positive health impacts (FGSV, 2014; Kahlmeier et al., 2021; Koszowski et al., 2019a).

There is consensus that active mobility, among others, requires an urban pattern characterized by relatively high density and diversity of opportunities, alongside appropriate transport infrastructure (Buehler et al., 2017; C.-D. Kang, 2015; Koszowski et al., 2019a; Stead & Marshall, 2001). In other terms, active mobility relies on high local accessibility (Silva & Larsson, 2019). The concept of accessibility, first defined by Hansen (1959), has been present in research for decades. However, little adoption in practice can be observed so far. Among other reasons, it is underlined that accessibility instruments are not yet meeting planning practice expectations (see Section 7.2.2).

Accessibility instruments are nowadays usually GIS-based tools to operationalize the concept of accessibility and therefore support planning processes. Accordingly, accessibility instruments are a subset of planning support systems (PSS) (Papa et al., 2015). PSS promise to be appropriate tools for evidence-based and effective planning (Geertman, 2006; Geertman et al., 2013; Klosterman, 1997). However, there has been an imbalance between the supply and actual use of PSS since the beginning. This phenomenon, usually labeled as the *implementation gap* is discussed intensively in literature (Geertman, 2006; Russo et al., 2017; te Brömmelstroet, 2010; Vonk et al., 2006). It is argued that PSS lacks usefulness (te Brömmelstroet et al., 2016) or relevance for the planning practice.

To develop more useful instruments it is suggested to actively involve planning practitioners when developing PSS (Russo et al., 2017; Silva et al., 2017; te Brömmelstroet, 2010). In this context, the authors developed Geo Open Accessibility Tool (GOAT) (Pajares, Büttner, et al., 2021), an accessibility instrument focusing on modeling walking and cycling. It was developed in an applied research project in a co-creative and open environment with planning practitioners. The authors aim to help bridge the gap between research and practice in accessibility planning with the presented instrument. Early testing and application in practice heavily influenced the ongoing development process despite the development's initial direction. Previous publications on GOAT mainly focused on its technical background and the development process (Pajares, Büttner, et al., 2021; Pajares, Muñoz Nieto, et al., 2021). Therefore, this presented manuscript focuses on identifying its relevance for practice.

In particular, it should be studied if there are existing planning questions in the field of urban and transport planning in which the instrument is of useful support in practice. This study defines usefulness by the tool's utility and usability (see Section 7.4.3).The following research questions should be answered:

- RQ1: *Which planning questions exist for GOAT in the field of transport and urban planning?*
- RQ2: *Is the accessibility instrument GOAT of useful support in the planning practice?*

While there is a clear focus on the instrument GOAT, some results can also be generalized. In particular, the presented results should help other tool developers to identify further development needs. Furthermore, the experience during the co-creative development process can help other tool developers. For the planning practice, this contribution can reveal the potential for accessibility-based planning and the use of accessibility instruments.

First, the literature review in Section 7.2 should provide a better understanding of the current state-of-the-art in the field of PSS and accessibility instruments. Afterwards in Section 7.2.2 the GOAT project is presented to provide the technical background for the study. Subsequently, in Section 7.4, the methodology consisting of literature review and the co-creative application workshops will be introduced. After that, the results will be presented in Section 7.5. A discussion and conclusion will follow in Section7.6.

7.2 Literature review

7.2.1 Planning support systems in practice

Harris first proposed the definition of PSS as a "systematic process of sketch-planning" (Harris, 1989). Geertman (2006) defines PSS as:

"the PSS, can be understood as geoinformation-technology-based instruments that incorporate a suite of components (theories, data, information, knowledge, methods, tools) which collectively support all or some part of a unique professional planning task"

The basic structure of PSS involves a database, model, and decision-making, which gives planners the ability to understand the inputs and outputs of the program (X. Zhang et al., 2016). In essence, a PSS is a tool for assisting urban planners with planning strategies, models, and visualizations (Geertman et al., 2017a).

With the advancement of interfaces and algorithmic planning, many examples of PSS applications are now available. Early programs such as *Online What If? (OWI)* and *UrbanSim* have been used in practice for the last 20 years for their ability to model interrelationships between transportation and population, for instance (Geertman et al., 2017a; Pettit et al., 2020). Some different uses for PSS include, but are not limited to, disaster management (Oki & Osaragi, 2017; Osaragi & Noriaki, 2017), transport management (Meng et al., 2017), and urban planning (Leao et al., 2017)). However, there is a distinction between systems that can present and visualize static data and ones where that can simulate scenarios and situations. Programs like *OWI*, *ENVISION*, and *CommunityViz* can be used for scenario planning by using static data and given specific parameters. On the other hand, programs like *UrbanSim* and *UrbanCanvas* are used as simulators and modeling tools for scenario planning (Pettit et al., 2020). Depending on different situations, different uses and programs can be designed to assist with respective solutions.

Essential to the functionality and widespread use of PSS are its usefulness, usability, and the understanding of such programs (Pettit et al., 2020), (Russo et al., 2017). te Brömmelstroet and Bertolini (2010) argue that with the growing importance of integrated sustainable land-use and transport planning, the most significant barriers for application in practice are different tools, priorities, and functional tasks between urban and transport planning offices. Some PSS tools can bridge this gap. However, they can and have also stood as an "implementation bottleneck" to the process when tool development and practice are not well-linked (te Brömmelstroet & Bertolini, 2010). These bottlenecks are broken down into three groups by (Jiang et al., 2020). The first group comprises the number of unusable PSS tools published that lack usable attributes, transparency, or evidence of their efficacy when used. The second group comprises a lack of acceptance by planning offices due to misunderstanding of the tools or perceived risk of use to make major decisions. Finally, the third group includes learning ability and time to use PSS properly. (te Brömmelstroet, 2017) challenges PSS applications one step further and criticizes the research field for its focus on the user-friendliness of the instruments rather than their usefulness.

There are many proposed solutions to these issues, with some already implemented in the PSS field. In general, there are many proposals for including different stakeholders in the development of PSS that can streamline communication and create a useful feedback cycle (Jiang et al., 2020; Vonk et al., 2006). Cooperation between PSS developers, particularly universities and planning offices, can also lead to better results in the application of PSS (Geertman & Stillwell, 2020; Luque-Martın & Pfeffer, 2020). Another suggestion by Geertman and Stillwell (2020) is better education within the planning field on PSS and its benefits on evidence-based planning decisions at early stages in planners' careers. The primary differentiation in land-use and transport planning challenges PSS integration into the fields.

The review of existing PSS literature shows that instruments have been developed for at least three decades. Meanwhile, there is a high awareness of the lack of successful practice applications. Lacking usefulness is of particular importance for this manuscript. The useful support in concrete planning questions is seen as a minimum requirement for applying the developed tool GOAT in practice. Further factors such as institutional barriers are seen as equally important but will not be addressed in this manuscript.

7.2.2 Accessibility instruments and their potential

The earliest known definition of accessibility to the field was by Walter Hansen as "the potential of opportunities for interaction" (Hansen, 1959). Since then, there have been attempts at further studying, understanding, and measuring accessibility. The broad spectrum of accessibility was categorized by Geurs and van Wee (2004) into four components: transport, land-use, temporal and individual. These different dimensions of accessibility can be operationalized using suitable indicators commonly known as accessibility measures. Geurs and van Wee (2004) define four groups of accessibility measures: infrastructure-based, location-based, person-based and utility-based. Ideally, an accessibility measure should take all four accessibility components into account (Geurs & van Wee, 2004). Accessibility instruments can be seen as a subset of PSS. Papa et al. (2015) defined accessibility instruments as:

"Accessibility instruments (AIs) are a type of planning support system (PSS) designed to support integrated land-use transport analysis and planning through providing explicit knowledge on the accessibility of land uses by different modes of transport at various geographical scales."

It is considered that they bear a large potential to provide planners with planning support when analyzing the complex relationship between transport and land-use (Hull et al., 2012; te Brömmelstroet et al., 2016; te Brömmelstroet et al., 2014). More specifically, it is stated that accessibility instruments have the potential to be utilized as a shared language between disciplines, namely urban and transport planning (Büttner et al., 2018; te Brömmelstroet et al., 2016). A further advantage of accessibility instruments is that they can produce analyses on various spatial resolutions and all transport modes, including walking and cycling.

Besides the described benefits, accessibility instruments are not yet widely used in practice (Bertolini & Silva, 2019; Boisjoly & El-Geneidy, 2017b; Hull et al., 2012; Papa et al., 2015; te Brömmelstroet et al., 2016; te Brömmelstroet et al., 2014). Accordingly, accessibility instruments face an implementation gap between research and practice like other PSS. Following the literature, there are several reasons for this. Levine (2019) is stating that strict mobility metrics persist because transport engineering and urban/regional planning are explicitly instructed to use them. Furthermore, it is mentioned that accessibility is often conceptually misunderstood (Levine, 2019). There is evidence of a 'disconnect' between the tool developers and the users (te Brömmelstroet et al., 2016). In addition, the availability of data is mentioned as a barrier to the broader application of accessibility instruments by tool developers (Papa et al., 2015) and practitioners (Boisjoly & El-Geneidy, 2017b; te Brömmelstroet et al., 2014). Also, practitioners report a lack of knowledge (Boisjoly & El-Geneidy, 2017b) and resources in their institutions for the application of accessibility (te Brömmelstroet et al., 2014). Past research has also shown that a powerful way to increase the usability and usefulness of tools being developed is the close involvement of potential users in the development process (Bertolini & Silva, 2019; Silva et al., 2017; te Brömmelstroet et al., 2016; te Brömmelstroet et al., 2014).

The research project (COST Action TU1002) showed that the feature that practitioners most desired was the real-time calculation of scenarios (Silva et al., 2017; te Brömmelstroet, 2017; te Brömmelstroet et al., 2014). Also, the potential of web technology to foster easier use and the involvement of more stakeholders are described to bear high potential (Büttner et al., 2018; Venter, 2016). An updated review of 26 accessibility instruments showed that instruments were developed significantly further, and many new tools were released. Following the fast development of WebGIS technology, a large share of web tools was observed among the studied instruments (Pajares, Büttner, et al., 2021). However, from the review (Pajares, Büttner, et al., 2021), no tool was found that combines the attributes: interactive scenario building for street network and land-use, open source development, focus on active mobility, and web-based. The development of GOAT was theoretically addressing the described gap and aimed to involve practitioners in the development process. Meanwhile, the concrete usefulness of the tool for practice remained unclear and, therefore, will be studied in this manuscript.

7.3 Accessibility instruments GOAT

In the following, a brief overview of the software GOAT is provided. Besides describing the core characteristics of the accessibility instrument, the technical architecture, data sets used, and core indicators are presented.

7.3.1 Overview GOAT project

The development of GOAT intends to help bridge the described gap between research and practice in accessibility. Currently, the instrument focuses on modeling accessibility for walking and cycling and local accessibility. In addition, it includes barrier-free and electric bike analyses. The GOAT project started with a Master's thesis (Pajares, 2017) and is currently taken forward as part of a dissertation project (Pajares, 2019; Pajares, Büttner, et al., 2021). The software is developed open source (GOAT-Community, 2021c). GOAT has been used in applied research projects and was transferred to at least 27 municipalities. Out of them, there were five international applications: Bogotá (Colombia), San Pedro Garza García (Mexico), Matosinhos (Portugal), Boca Raton (Florida), and Atlanta (USA). The rest of the applications were in the German context.

GOAT tries to position between a simple web tool and a fully-featured desktop GIS in terms of functionality. By positioning in this niche, GOAT shares some similarities with existing accessibility instruments like CoAXs (Stewart & Zegras, 2016), TRACC (Basemap Ltd, 2022) or Conveyal (Conveyal, 2022b). One core aim is that the application is usable by planning professionals not being familiar with GIS. Unlike most accessibility web tools, GOAT allows users to perform scenarios on the street network, points of interest, and buildings (Pajares, Büttner, et al., 2021). Based on the scenarios, changes in accessibility can be computed and visualized. Accessibility is interpreted using contour and gravity-based accessibility measures (see Section 7.3.3). A planning scenario can be drawn directly using the web interface or imported using the GeoJSON-format. Therefore, scenarios can be created outside of the application and re-import at a later moment. The development is characterized by an open and co-creative environment involving practitioners from the field of urban and transport planning.

In the following, the focus is particularly on three case studies in the Munich Region (Munich, Fürstenfeldbruck, Freising) and, to a smaller extent, on the case study in the city of Freiburg. The online version of the tool was launched in different years for the cities: Munich (2019), Fürstenfeldbruck (2020), Freising (2020), and Freiburg (2021). Meanwhile, the applied version of the tool and the used data sources varied between the different deployments. To the date of writing this manuscript, the tool was openly available online for the four mentioned cities. GOAT is provided open access on the project websites (GOAT-Community, 2021e; Plan4Better GmbH, 2021b). Besides the tool itself, the websites host step-by-step tutorials and documentation on the indicators, data, and software libraries being used.

7.3.2 Technical architecture

GOAT uses the classical server-client architecture of the web and is built solely using open source software (see Figure 7.1). The backend is built around a PostgreSQL database, which is spatially enabled by the extension PostGIS. The backend analyses are realized using SQL, PLpgSQL, and Python. The database contains non-spatial and spatial data, as well analytical functions for the computation of the implemented accessibility measures and spatial operations (e.g. spatial intersection). Traveltime calculations are done using a custom implementation (GOAT-Community, 2020a) of the pgRouting extension (pgRouting Community, 2022). The interaction with the database is handled by an API written in Python. The results of the analyses are communicated to the client using different non-spatial (JSON) and spatial formats (GeoJSON, Gebuf, Vector tiles). The client of the application is written in Javascript using the Vue.js framework and Openlayers as a map library.

The tool was equipped with diverse (spatial) data for the different case studies and installed on a cloud server using Kubernetes. Data is seeded into the application using different data preparation, disaggregation, and fusion steps. Depending on the region deployed, there are used different data sets. Meanwhile, GOAT can theoretically work solely with OSM and population data sets. However, other (open) data sources are used to yield a higher data quality and completeness. The most important data sets used are summarized in Table 7.1.

7.3.3 Implemented indicators

The instrument is modeling and visualizing accessibility through an interactive web map. It interprets accessibility using contour and gravity-based accessibility measures from the group of location-based measures (Geurs & van Wee, 2004). Furthermore, different spatial data such as data on traffic accidents, street imagery, land-use, and modal split can be visualized and styled on the map. Figure 7.2 visualizes the core indicators of the application.

As contour measures, two forms of isochrones are implemented. Single-isochrones are catchment areas from one starting location. The isochrone polygon shape intersects with the opportunity data set and population data to calculate cumulative opportunities. Results are visualized on the web map and a table. The second isochrone

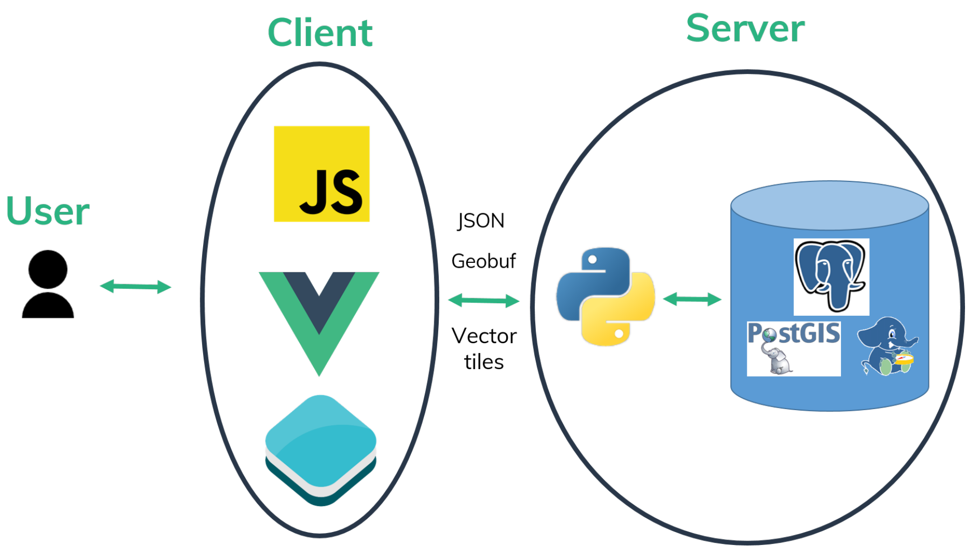


Figure 7.1: Technical architecture GOAT

Table 7.1: Data sets used

Dataset	Purpose	Source
Points of Interest	Opportunities data set	OSM, own collection in OSM, Provided by Municipalities
Land-use	Population disaggregation, Visualization	OSM, Landesamt für Digitalisierung, Breitband und Vermessung Bayern, Urban Atlas - European Environment Agency (EEA)
Buildings	Population disaggregation	OSM, Landesamt für Digitalisierung, Breitband und Vermessung Bayern, Provided by Municipalities
Population grid	Population	ZENSUS 2011
Administrative areas with population	Population	Provided by Municipalities, Bundesamt für Kartographie und Geodäsie, Landesverkehrsmodell Bayern
Street imagery	Visualization and Mapping Mode	Mapillary, own collection in Mapillary
Street network	Routing	OSM, own collection in OSM
Elevation	Routing	European Environment Agency (EEA)
Accidents pedestrians and cyclists	Visualization	Statistische Ämter des Bundes und der Länder
Data on environmental quality	Visualization	Bayerisches Landesamt für Umwelt, FreiGIS
Bike counting data	Visualization	Geodatenservice München
Modal split	Visualization	Mobilität in Deutschland (MiD)
Basemaps	Visualization	OpenStreetMap, Mapbox, Bing

type are multi-isochrones. For multi-isochrones, the user either defines an area of interest by drawing a study area polygon or picking one or more city districts. Based on the user selection points of interest categories are considered. The coordinates of points of interest are taken as starting points. The individual isochrones are unioned and intersected with the population data. As a result the multi-isochrones are shown on the map and the share of the served population located within the study area of choice is listed in a table in relative and absolute numbers. Both isochrone types can be calculated with all supported routing modes and reflect all forms of scenario building (network, points of interest, and buildings). The user can adjust travel speeds for the different routing modes.

A third indicator is described as a connectivity heatmap. In the authors ' opinion, the indicator can be positioned between infrastructure-based and contour-based accessibility measures. The heatmap is computed using a hexagonal grid with an approximate edge length of 150 meters per cell for walking mode (5km/h). Three isochrones (5, 10, and 15 minutes) are pre-computed using the centroid as a starting point for each grid cell. The size of all three isochrones is summarized per cell and compared with all other cells using statistical quintiles. The grids are colored from high (green) to low connectivity (red). Changes in the street network are reflected by recomputing parts of the heatmap and updating the statistical classification. As a gravity-based accessibility measure, an additional heatmap is implemented. The heatmap is created based on pre-computed traveltimes. Traveltimes are computed for walking (5km/h) for each grid to all points of interest within a 20-minute cutoff. Accessibility values are computed per grid using the widely applied formula:

$$A_i = \sum_j O_j * f(t_{ij})$$

As impedance function a modified gaussian function is implemented:

$$f(t_{ij}) = e^{t_{ij}^2/\beta}$$

The heatmap is dynamically created for the selected point of interest categories based on the pre-computed traveltimes. Furthermore, the user can customize the heatmap by giving each point of interest category a weight and choosing an appropriate sensitivity value. Therefore, individualized composite indicators can be built by the user. Currently, the gravity-based heatmap only reflects scenarios on points of interest.

7.4 Methodology

The following chapters provide an overview of the methods used for the study. It focuses on providing an overview of the user involvement during the development, the workshop protocol, and the method for assessing the instruments' usefulness.

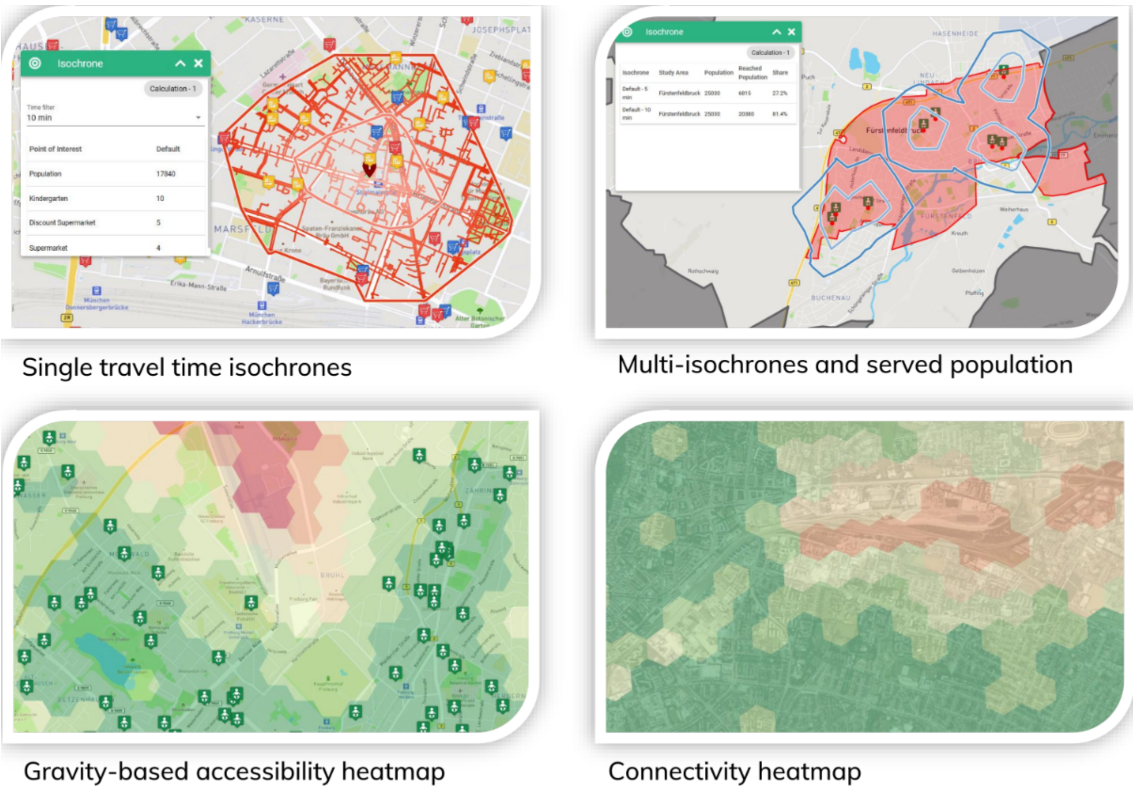


Figure 7.2: Core indicators GOAT

7.4.1 Overview user involvement

The input from practitioners influenced the development and application of the instrument. The open development and provision of the tool facilitated the involvement of diverse groups. In particular, three groups were involved: planning practice, research and developer community and students (see Figure 7.3). The process brought up ideas on new features proposed new use cases and helped understand user needs. A particular focus was given to exchange with the planning practice. Past research has shown (see Section 7.2.1 and Section 7.2.2) that the involvement of planning practice can help in developing more useful PSS. Involvement was realized through early testing workshops and later in application workshops (see Section 7.4.2). Besides practitioners' direct use of the tool, results or the tool itself were shown in presentations to planners and decision-makers. Alongside this, more informal exchange was carried out in personal meetings.

With ongoing development, the exchange with the research and developer community intensified. Besides early testing with German researchers, two workshops with international researchers were carried out. Next to scientific publication, the current development progress was continuously communicated in a blog and social media. Furthermore, feedback on users' experience was obtained via Social Media, E-Mail, and a chat group.

The involvement of students in different teaching formats was the third pillar of the co-creative development of GOAT. Direct contributions were realized in several students' theses, in which new features were developed, or the application was transferred to a new study context. The development was usually accompanied by internal or external testing of the tool. Furthermore, students used the demo version of GOAT in Munich in seminars and lectures to perform accessibility analysis or visualize spatial data. Due to the importance of (spatial) data for the development, students were also involved in four Mapathons, which aimed to collect data on street networks, buildings, and points of interest in OpenStreetMap (OSM). As part of this activity, a prototypical feature was developed in GOAT, which showed gaps in the OSM data set and provided a more structured crowdsourced mapping process. Despite the richness of the different involvement formats, the exchange happened largely unstructured and, in many cases, spontaneous. Therefore, in the following, a particular focus is given on the experience obtained in the application workshops.

7.4.2 Application workshops

For the early development phase, practitioners from the field of transport and land-use planning from the municipality of Fürstenfeldbruck were involved (Pajares, Büttner, et al., 2021). This first series of workshops primarily aimed to receive feedback on principle requirements of users and test different pre-release versions of the tool. Meanwhile, the main aim of the application workshops was to work on real-world planning questions using the tool. It was aimed to achieve an experience when using the accessibility instrument, which is close to the work reality of the practitioners. However, due to the unfamiliarity of the majority of the practitioners with accessibility measures and with using GOAT, the workshops also had characteristics of method and software training.

The workshops were organized in the citys' administrations of Fürstenfeldbruck,

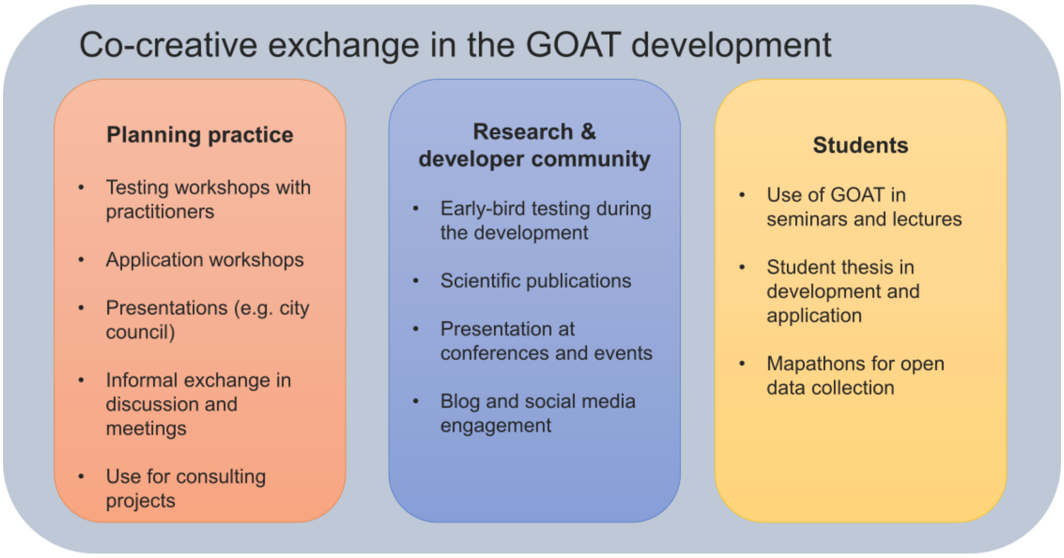


Figure 7.3: Main user groups involved in the development of GOAT

Freising, and Munich. An additional application workshop was organized with researchers from transport and land-use planning in Munich. The workshops took place in 2020. Due to the COVID-19 restrictions, two application workshops were organized remotely via teleconferencing. Overall, 37 persons attended the five application workshops, and each took approximately three hours. The practitioners were almost entirely coming from urban and transport planning. Approximately half of the practitioners focuses on urban and the other half on transport planning. From the authors' observations, the majority of practitioners though had a good understanding of the interrelation of both disciplines. One of the workshops was also joined by a politician from the city council.

Figure 7.4: Application workshop in Freising and Fürstenfeldbruck

The workshop design was inspired by the workshops conducted in the course of the COST Action TU1002 (Silva et al., 2017; te Brömmelstroet, 2017; te Brömmelstroet et al., 2014). However, the detailed workshop procedure was designed independently from existing protocols. The core difference between the workshops conducted in the

COST Action TU1002 was that the practitioners were operating the accessibility instruments themselves, and the tool developers only intervened for support. Before the workshops, the participants were asked to share relevant planning questions in their respective municipalities. Also, it was communicated which functionalities the tool has by sending videos, links, and learning material about the software via E-Mail. However, most practitioners were not familiar with the software before the workshop to the authors' knowledge. An exception were planners from the city of Fürstenfeldbruck, who have used GOAT in the test cycles. The workshops used the worksheet presented in Figure 7.5 and followed the protocol described in Table 7.2.

The research team documented observations, feedback, and discussion for each workshop. Although the focus during the workshops was on assessing the tool's usefulness, requests for new features or adaptions and bugs were documented. After the workshops, the participants had the chance to provide further feedback via E-Mail or telephone. An additional application workshop was realized in the city of Freiburg in summer 2021 as a videoconference with five participants. The workshop took two hours and was not supported by the working sheets. It was characterized by a short testing round and a discussion of the tool's functionality.

7.4.3 Usefulness assessment

Self-assessing the usefulness of an instrument under development is a complex challenge. The diversity of possible planning questions and the limited time the practitioners used the tool shows that there can be no definite answer. Therefore, the assessment should be seen as preliminary. The authors followed the assessment framework visualized in Figure 7.6. The assessment started with identifying suitable planning questions for GOAT. In the following, the practitioners worked on the planning questions as described in Section 7.4.2. Because of the high number of possible planning questions, the authors grouped them into thematic fields (see Section 7.5).

In the following, the usefulness was assessed for each thematic cluster by showing the used tool features and qualitatively discussing the usefulness based on the users' feedback. Following the literature review (see Section 7.2), past research has identified that it should be differentiated between the usability and usefulness of a PSS. In the context of this study, usability is seen as part of usefulness. Grudin (1992) and Nielsen (1994) suggest splitting the usefulness of software into utility and usability. Both aspects together define whether the software is useful or not. More specifically, utility is defined by Nielsen (1994) as:

"utility is the question whether the functionality of the systems in principle can do what is needed"

For the assessment of GOAT, the authors particularly examine if the instrument provides the planners with information relevant to them when answering a particular planning question. This also includes the appropriateness of specific indicators and the power to communicate the results to other stakeholders (e.g., politicians). Past research (see Section 7.2.2) identified that the tool interactivity, particularly the ability for real-time scenario building, is important. Therefore, the assessment of utility will set

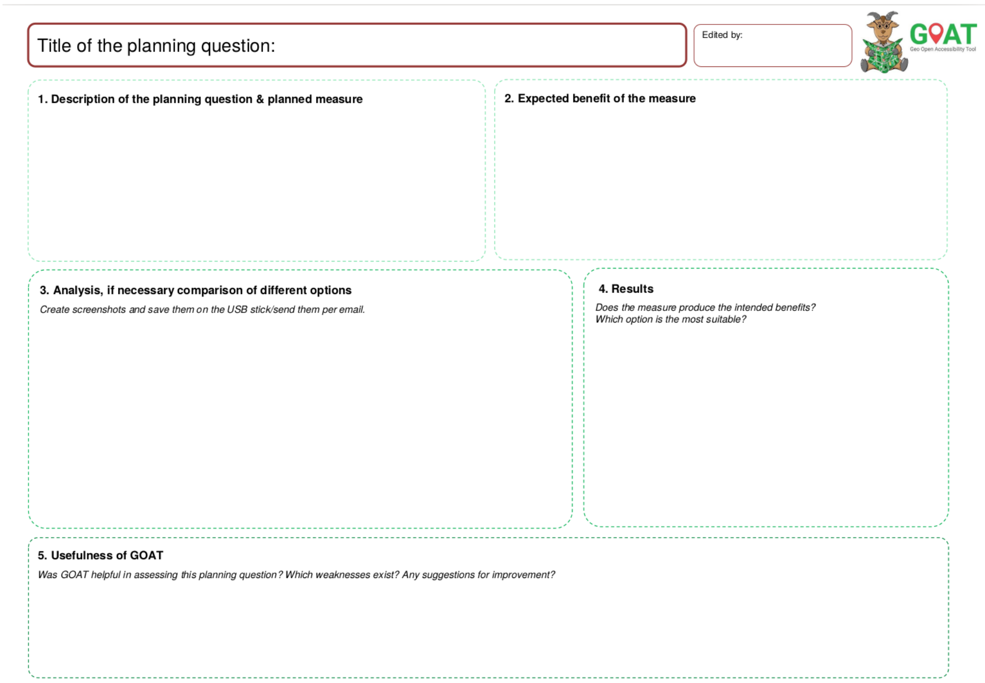


Figure 7.5: Worksheet planning workshops

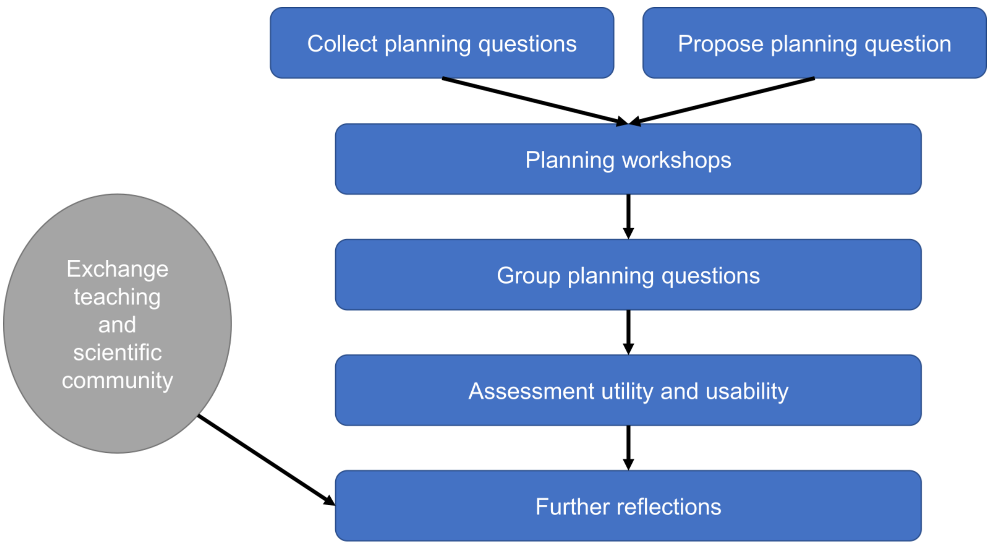


Figure 7.6: Framework assessment usefulness

Agenda item	Explanation
Welcome and a round of introduction (15 minutes)	Each person presented himself and described his core work-related responsibilities and interests. The aim was to build a relationship and understand the participants' motivation and interests.
Presentation of GOAT (30 minutes)	Two persons of the research team presented GOAT. The main aim was to show the core functionalities of the tool. Meanwhile, the practitioners could ask questions or describe planning questions they face in their daily work. The previously collected planning questions (via E-Mail) were expanded or complemented at the end. The introduction should provide enough information to get started on working with the tool.
Group work planning on planning questions (45 minutes)	A group of two to three practitioners for each planning question was formed. Each group should work on at least one concrete planning question using the tool on the territory of their municipality. They received a step-by-step guide showing the use of the tool. Meanwhile, they were supported by the research team in case of questions. The results of the analyses were documented on the worksheets and with screenshots. Furthermore, the results were within each group. The goal was that the practitioners obtain hands-on experience using the tool and assess its suitability for the respective planning question.
Coffee break (15 minutes)	During the scheduled break, the practitioners could take a rest. Furthermore, the research team had the chance to openly discuss their first experiences using the tool and possible ideas with the practitioners. Furthermore, the break should help to strengthen the relationship with the practitioners through the open exchange.
Group work planning on planning questions (45 minutes)	The participants continued working in the same group as before the break.
Presentation of the results per group/planning questions (15 minutes)	For each group, one practitioner presented the results of the analyses by explaining the content of the filled worksheet and by showing the analyses directly via the tool or with screenshots. The goal was to present all other attendees with the studied planning question and share their experience in using GOAT. Both the research team and the other practitioners could ask questions and discuss.
Open feedback and discussion (15 minutes)	Finally, the practitioners could openly express their feedback on the tool and propose possible enhancements. The goal was to give the practitioners the chance to provide unstructured feedback on the tool's usefulness and collect feature requests for upcoming versions of GOAT.

Table 7.2: Agenda planning workshops

this as one important criterion.

However, high utility alone would not necessarily result in a useful tool. Instead, high usability is very relevant for the assessment of PSS. More specifically, GOAT is assessed whether it is usable for individuals with no or limited knowledge of GIS. In general, usability can be defined as:

"the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2018).

Of particular importance was to assess if the tool was easy and intuitive to use for the different planning questions. Furthermore, there was attention to users' emotional experience when operating GOAT. Despite the broader involvement of stakeholders, it is worth mentioning that the assessment focused on the feedback from planners during the workshops. A challenge for this study is to extract and classify distinct conclusions from the recorded results. Overall the participation process yielded only minimal quantitative results. Therefore the assessment is mainly based on the qualitative description of the user feedback and user statements. Furthermore, the authors' complemented the assessment with their own observations. In the following result section, if statements are based on authors' observations, they are particularly labeled to provide transparency.

7.5 Results

The co-creative process resulted in identifying a wide range of possible planning questions. It was decided to generalize the planning question and group them into four categories: Infrastructure Planning Walking, Infrastructure Planning Cycling, Location Planning, and Housing Development. The most widely discussed planning questions in the context of the workshops are presented in Table 7.3.

For each group, exemplary analyses from GOAT, done during the planning workshops, are presented. They can be regarded as the most frequently performed analyses in the respective group. Section 7.5.1 bundles results for planning Walking Infrastructure, Section 7.5.2 for Cycling Infrastructure, Section 7.5.3 for Location Planning, and Section 7.5.4 for Housing Development. It has to be mentioned that the analyses for the different use cases can overlap due to the high interrelation of the studied questions.

7.5.1 Infrastructure planning walking

7.5.1.1 Provided features and analyses

Different indicators serve as benchmarks for street connectivity and accessibility of local amenities for planning walking infrastructure. The connectivity heatmap in GOAT allows the user to understand the degree of street network connectivity in the study area. Using the heatmaps (see Figure 7.7), the practitioners understood the street network connectivity. In the studied municipalities, especially rivers and rail tracks were

Use case group	**Planning questions**
Infrastructure Planning Walking	Where is a barrier for pedestrians concerning the street network connectivity?
	How does a new pedestrian bridge influence connectivity?
	What effect brings the temporary closure of a path on accessibility?
	How does accessibility for a person in a wheelchair change by the barrier-free upgrade of an underpass or bridge?
Infrastructure Planning Cycling	How does a new cycle bridge influence local accessibility?
	What effect has a new cycleway on accessibility?
	How do different cycleway attributes influence accessibility?
	What are suitable locations for bicycle parking infrastructure?
	How comfortable is it to cycle on a certain cycleway?
Location Planning	How fair is the distribution of different amenities in a municipality?
	Which share of the population has access to a specific amenity? Moreover, which areas are underserved?
	Where is a suitable location for placing a new amenity (e.g., supermarket, kindergarten)?
	What effect brings the closure of a specific amenity (e.g., pharmacy) to local accessibility?
	Is the population served sufficiently with public transport stops?
	Where is the potential for a new public transport stop or a mobility hub?
Housing Development	Where is the potential for urban densification?
	What are the effects of densification on local accessibility?
	Is the layout of the path network appropriate in a new development area to provide high local accessibility?
	How good is the population supplied in a new development area with different amenities?
	How are population density and local accessibility balanced for a specific amenity?

Table 7.3: Overview planning questions

identified as significant barriers. Users performed scenarios on the street network by adding, modifying, and deleting network elements. Accordingly, common infrastructural measures such as constructing a new footbridge, a temporary network closure, or a sidewalk extension were modeled. As shown in Figure 7.7, connectivity is significantly improved with the proposed bridge over the river. The areas that benefited the most are in the direct surroundings of the bridge.

Also, by using single and multi-isochrones, changes in accessibility were computed and visualized. As shown in Figure 7.8, a new pedestrian bridge over a river increases the catchment area. As a result, significantly more population and amenities can be reached from the respective location. The same calculations were done for the barrier-free mode. The effects of providing additional barrier-free crossings over a river are visualized in Figure 7.9. Depending on the data available in the city, users visualized street illumination, noise levels, street crossings, surface, and more.

7.5.1.2 Assessment of usability and utility

In general, the practitioners reported that analysis using isochrones was straightforward. The local knowledge of the planners confirmed barriers in the street network identified by GOAT. They were surprised by the ease of changing the network and the performance of the scenario building. Users valued that the computed isochrones can easily intersect with diverse spatial data such as population numbers and points of interest. The isochrones were also commonly understood by participants unaware of the accessibility concept. Several planners mentioned that the produced maps using isochrones could be powerful when presenting results to politicians. While the connectivity heatmap offers an area-wide benchmark, the users had more difficulties understanding the indicator. Also, computing scenarios using the connectivity heatmap take significantly longer than single isochrones. The provided documentation of the indicator helped to improve understanding and required more time. In some cases, the network modification produced unexpected results. Reasons for this were problems with data accuracy and sporadic bugs in the relatively complex feature. In the workshops, it was observed that new users had difficulties performing network scenarios for the first time. In the workshops, not all users managed to design a scenario themselves but required assistance from one of their colleagues or the research team. While most users were interested in the travel time-based isochrones, others also used additional layers such as noise levels. Some users mentioned the need to consider walkability-related factors (e.g., sidewalk width, noise levels) to provide a complete picture. As sometimes new paths or bridges showed only marginal changes in accessibility, one planner mentioned that: *"Accessibility analyses cannot really show the effects of this measure"*. Users also requested to provide classical origin-destination-routing to supplement the isochrone calculation.

7.5.2 Infrastructure planning cycling

7.5.2.1 Provided features and analyses

Due to the fast-rising attention to cycling in the studied municipalities, several practitioners were particularly interested in using GOAT for analyzing the cycling infrastructure.

Figure 7.7: Bridge scenario and changes in connectivity

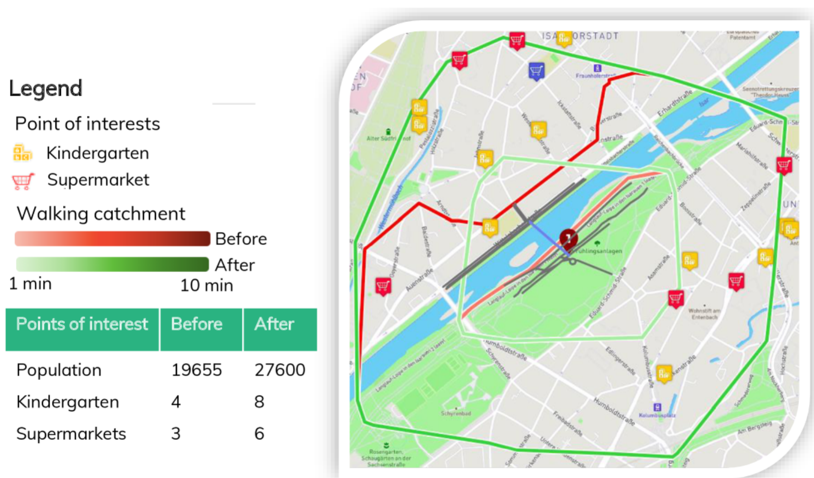


Figure 7.8: Scenario new pedestrian bridge over a river

There is no heatmap yet implemented for cycling infrastructure planning. Therefore only isochrones and multi-isochrones were used for cycling. However, similar to the network changes for walking, the cycling network can be changed. In addition, the road surface can be changed in a scenario. A common scenario in all three municipalities was to analyze the accessibility effects of a new cycling bridge over the local river as shown in Figure 7.10.

Other layers were also used for analysis. For instance, street imagery from Mapillary was used to inspect the cycleway quality and get a better understanding of the study area (see Figure 7.11). In the case of Munich, the data on cycleway quality from the local NGO Munichways (Munichways, 2021) was frequently viewed. Furthermore, data on cycling accidents were utilized to identify hotspots and particular needs for action.

7.5.2.2 Assessment of usability and utility

The user feedback revealed that, in general, computed travel times were perceived as realistic. It was highly valued that the travel time analyses included slope and surface type factors. Also, the ability to adjust cycling speeds and choose between different cycling profiles (standard or electric) was appreciated. However, it was also requested that the impedances (e.g., slopes, surfaces type) on the road network should be made more transparent. One user mentioned: *"I would like to have more transparency on the impedances applied for the cycling network"*. Others users mentioned that this would increase trust in the calculations.

Users also wished to model travel time differences between different cycleway types, for instance, between a narrow cycleway and a cycling highway. As this is not yet implemented, modeling the effect of high-quality cycling infrastructure could not be done so far. Due to the unavailability of appropriate data, travel time losses are only considered at major intersections with traffic lights. An average time loss of 30 seconds is applied for crossing the intersection in every direction. This was perceived as a limitation by some users. It was wished to model the effects of changes in the design of intersections or the traffic signal plan. Generally, it was claimed that the presented accessibility analyses could not model the effects of all discussed measures (e.g., traffic signal prioritization). The same was valid for walking analyses, but more planning questions related to cycling were not answered in the workshops. Meanwhile, as for walking analyses, the importance of additional comfort criteria (e.g., number of other cyclists) was raised.

As the catchment areas for cycling are much larger than for walking, the performance of the isochrone calculation is significantly slower. Especially for the computation of multi-isochrones uncomfortable long computing times of several minutes can affect the user experience. Furthermore, users missed a comparison of traveltimes between bicycles and cars. Users appreciated the additional data, particularly the street view imagery from Mapillary as GoogleStreetView imagery in Germany is usually either unavailable or out of date.

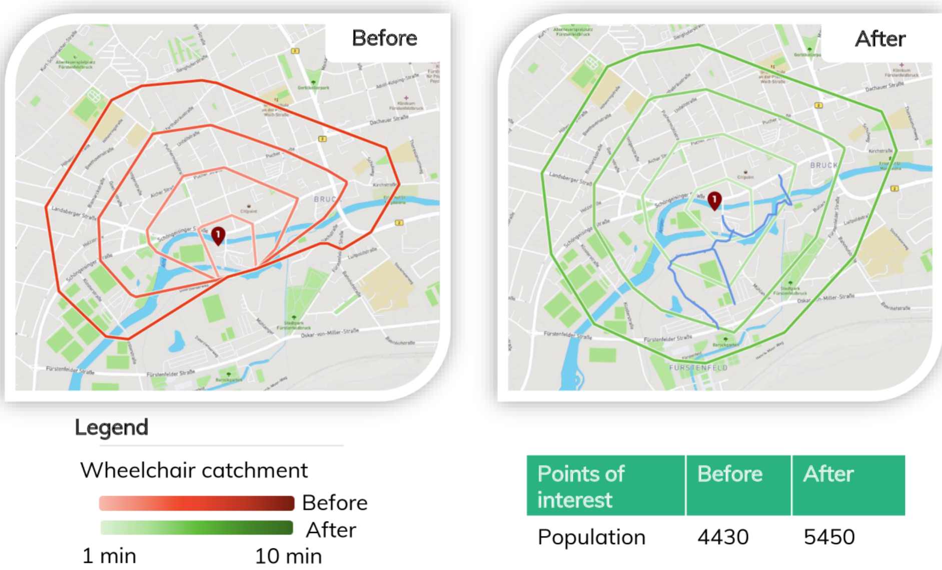


Figure 7.9: Scenario new barrier-free crossing

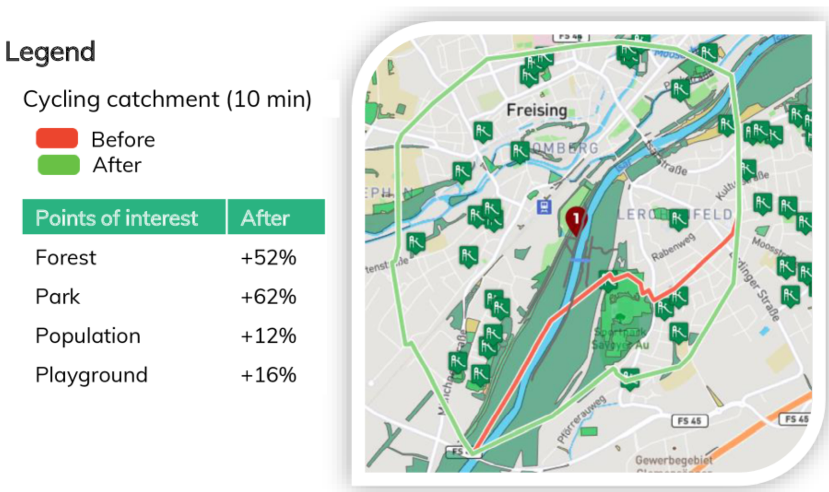


Figure 7.10: Analyses and data visualization for planning cycling infrastructure

7.5.3 Location planning

7.5.3.1 Provided features and analyses

GOAT was used for location planning, such as finding a suitable place for a new service or evaluating the served population with a particular amenity. With the gravity-based accessibility heatmap, the users evaluated the accessibility to a specific amenity for the city's territory. Therefore, underserved or not served areas were identified. By drawing scenarios, like adding a new bike-sharing station, the change in accessibility was modeled by the users. It was tested to add, modify or delete points of interest. Therefore, the accessibility effects of new and closed points of interest were evaluated. Figure 7.12 shows the accessibility effects of two new nurseries in the City of Fürstenfeldbruck.

The population heatmap was also used to assess the balance of accessibility levels and population density (see Figure 7.13). With the population density and local accessibility heatmap, accessibility was compared with the population density at the respective grid cell. Areas with a high population but poor accessibility were highlighted. As shown in Figure 7.14, the areas with the proposed new nurseries indicate a modest density surplus. With the proposed two new nurseries, the affected areas are balanced or have a modest accessibility surplus in the scenario.

7.5.3.2 Assessment of usability and utility

For location planning, mainly the described heatmaps and multi-isochrones were utilized by the practitioners. Generally, they classified the local accessibility heatmap as a powerful indicator to highlight the distribution of a certain point of interest. However, one user also mentioned that more quantitative output would be desired: *"Difficult, to only work with visuals, more quantitative results would be helpful"*

Although the sensitivity parameters of the gravity-based accessibility measure could be adjusted, the users did not do this. Instead, the default parameters were utilized. From the authors' observation, the users were already overwhelmed by many functionalities and therefore showed little interest in increasing complexity by calibrating the sensitivities. The multi-isochrones were seen as a powerful indicator to show which population share is served by a particular amenity. The scenario development for the points of interest was more straightforward than for the ways or buildings. Also, users liked how fast the heatmap reflected the scenarios. The combination of population densities and accessibility levels was seen as a good approach to balancing supply and demand. However, concerns were raised if it is sufficient to include population numbers solely. More specifically, data on the number of jobs or students at education facilities was considered essential to quantify the demand for some points of interest (e.g., supermarkets, public transport stops). Generally, population numbers are static and reflect people's location at night or early morning. Spatio-temporal changes in people during the day are not available. Also, due to the unavailability of data on opening hours for all points of interest, temporal changes in accessibility could not be modeled. The authors perceived modeling the temporal changes of accessibility due to varying opening hours at the beginning of the study as particularly important. However, this was barely requested by the involved practitioners.

Users generally confirmed that the accessibility levels for the different amenities

Figure 7.11: Analyses and data visualization for planning cycling infrastructure

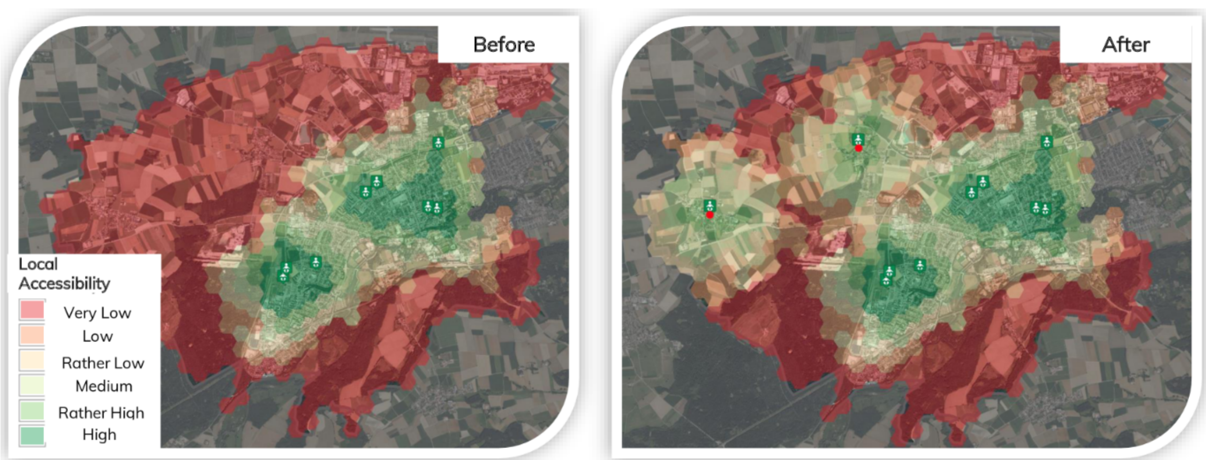


Figure 7.12: Location planning social facilities - nurseries in Fürstenfeldbruck

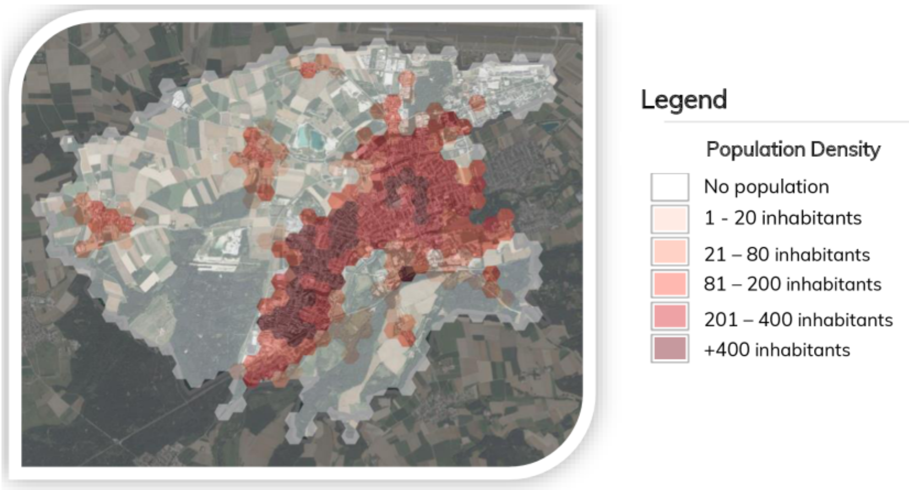


Figure 7.13: Population density heatmap, Fürstenfeldbruck

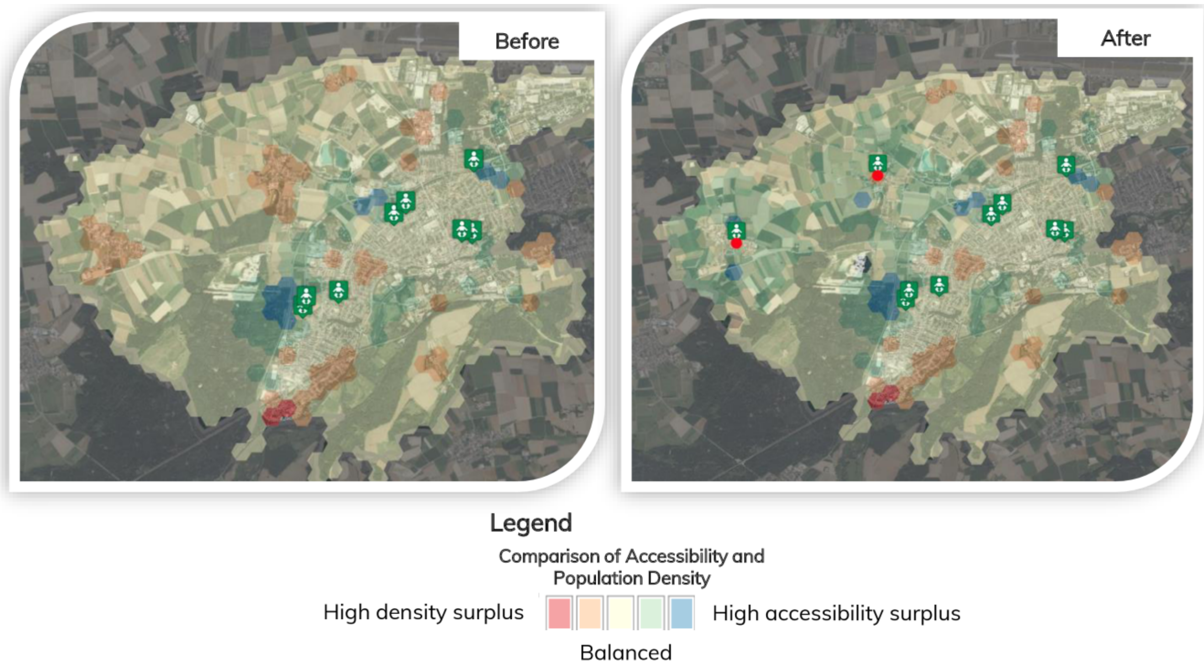


Figure 7.14: Comparison of accessibility and population density heatmap, Fürstenfeldbruck

match their personal experience. However, they also requested more tailor-fitted indicators to assess the demand for a particular service and the quality of an amenity. Especially for public transport stops, it was requested to incorporate factors such as service frequencies to quantify the attractiveness of the service better. Additional socio-demographic data on age, family status, and income were requested to understand better the needs and demands for a particular point of interest. At the same time, users mentioned that this raises the complexity of the analyses.

7.5.4 Housing development

7.5.4.1 Provided features and analyses

The distribution of the urban population is constantly changing. Common interventions in the urban environment are the construction and demolition of buildings. To model changes in the population distribution in GOAT, houses were drawn and imported via the interactive web map. With an adjustable average gross floor area per resident, the population is estimated per building. Furthermore, it is possible to delete existing buildings. With the scenarios, the users aimed to model changing needs of accessibility by using isochrones, multi-isochrones, and heatmaps. As shown in Figure 7.15, buildings were uploaded as GeoJSON from a building development plan in Munich. In addition, the planned street network was added to the scenario.

Figure 7.16 shows the accessibility to kindergartens in the new development area. There are three existing kindergartens accessible in 8 minutes walking time. For better accessibility of the new residents in the scenario, a new kindergarten is proposed at the east of the new development area. Accordingly, around 20.9% of the population has access in 4 minutes, and 100% of the people in 8 minutes walking. The example shows that GOAT can be used for planning urban development.

7.5.4.2 Assessment of usability and utility

The practitioners liked that an entire neighborhood could be modeled as a scenario. This was considered useful as new development areas could be evaluated concerning their local accessibility to diverse destinations. Furthermore, the feature was regarded as suitable for identifying places with high accessibility and, therefore, potential for urban densification. The implemented accessibility measures, especially the multi-isochrones, were used to quantify the share of residents having access.

In terms of usability, drawing new buildings were generally perceived as intuitive. Nevertheless, some users mentioned that drawing individual buildings and building entrances is too time-consuming. It was mentioned that a coarser resolution of the population would also be sufficient for many use cases. It was welcomed that buildings can be uploaded in the GeoJSON format. At the same time, the format was not frequently used by all participants. One user mentioned that it would be necessary to allow uploading data in the shapefile format. Despite the option to export and later import drawn scenarios, it was raised that it would be beneficial to save developed scenarios in the tool. While being true also for ways and points of interest scenario, users mentioned this would be particularly important for buildings as drawing them takes more time. Working with the practitioners also revealed that additional, more granular accessibility

Figure 7.15: Scenario with buildings uploaded from a building development plan and new road infrastructure

Figure 7.16: New buildings and kindergartens

indicators on the building level could provide valuable insights. One example could be providing information on travel times to selected points of interest when clicking on a building.

7.5.5 Overall assessment

During the workshops and beyond, the practitioners expressed direct feedback. This feedback was summarized and clustered into three categories: General (Table 7.4), Usability (Table 7.5), and Utility (Table 7.6). For reasons of comprehension, the comments have been translated from German. There was a focus on the overall evaluation of the instrument. Detailed feedback on bugs, data issues, and feature requests are not included in the collection. Instead, they were continuously documented and, if possible, directly considered in the development process. In (Pajares, Büttner, et al., 2021), a collection of the features requested can be found. Following the feedback, GOAT was assessed as a tool with high potential to be used in practice, but also the need for improvements was raised. The planners saw many use cases to apply the tool and stated that it adds value to the tasks they have to accomplish. As shown in Table 7.4, they generally liked using GOAT.

The large majority mentioned the instrument is usable (see Table 7.5), but also some perceived the interface as not intuitive and not self-explaining enough. A clear pattern can be found when tracking the statements back to the users. Participants who spent more time familiarizing themselves with the instrument perceived the tool as easier to use.

Planners from municipalities particularly valued that they could carry out the analyses themselves. They claimed that this helps to present results much faster to politicians compared to outsourcing the analyzes. To carry out studies beyond their municipal boundaries, they would like the tool to be available for neighboring municipalities. Planners from consultancies requested that GOAT should be available for the whole of Germany. They mentioned that it would be necessary to immediately access the tool without spending much time setting it up for their respective study area.

Some practitioners asked for better integration with existing software, such as desktop GIS and data platforms. The need to integrate with existing systems was described to avoid creating a technological silo in terms of software and data. Regarding the access to GOAT, there were different opinions. While some municipalities want to make the tool accessible to citizens, others have concerns about the disclosure and correctness of the data basis. Some representatives of the municipalities mentioned it could be helpful to integrate selected analyses into other existing web maps targeting citizens as users.

7.6 Discussion and conclusions

This research tried to answer two questions. Suitable use cases for the developed software GOAT should be identified. This was carried out by the involvement of planning practitioners, who proposed relevant planning questions, which were clustered into four groups. The collected list of planning questions cannot be completed by research design. Nevertheless, the different planning questions already cover a wide area. The

Positive feedback	Negative feedback
"GOAT has developed very positively, many good new features."	"Sceptic about making the tool accessible to the public, due to sensitive data and data accuracy."
"Very impressive tool."	"Walking and cycling are great, but multimodal analyzes are needed for mobility concepts."
"Very exciting project."	
"Great what you can do with Open Data."	
"Scientific background is a big plus."	

Table 7.4: User feedback - general

Positive feedback	Negative feedback
"Very easy to use (good user interface)."	"User interface is not user-friendly and intuitive enough."
"Easy to understand after a short training period."	"Familiarization with the software takes too long."
"Simple user interface."	"Too complex to involve citizens."
"Quick and easy comparison of different scenarios."	"Overwhelmed by too many functions."
"The results are easy to understand and striking."	"Functions are not always self-explanatory."
"Intuitive to use."	"Terminology not comprehensive."
"Analyses are easily possible without extensive GIS knowledge."	"Too complicated, I prefer to hire a GIS professional."
"Time- and cost-efficient tool."	
"Interactivity of the tool is good."	

Table 7.5: User feedback - usability

Positive feedback	Negative feedback
"Useful tool, e.g., to evaluate potential locations for additional bridges over the [local river]".	"Accessibility analyses cannot show the effect of all measures. Sometimes it is more about safety and comfort."
"Good, logical tool that would be beneficial in the early planning stages."	"Application of GOAT rather not possible in rural areas due to poor data availability."
"Well suited for visualization of current planning and as an argumentation aid."	"It would be great if GOAT could be integrated into our existing municipal GIS."
"Well suited for bringing analyses closer to politicians."	"At some places, no calculation was possible."
"Politicians are super grateful for the preparation and visualization of data as it helps to make decisions."	
"With the help of such tools, municipalities could do more planning tasks inhouse."	
"This could be a well-respected tool in transport planning, and there would be many use cases for the use of GOAT."	
"High potential of the tool, expansion to whole Germany would be a great added value."	
"Bundling functions (accessibility, visualization, etc.) and various data is an added value for planners."	
"Scenarios are very useful."	
"Very helpful for analyzing the cycling network."	
"Heatmaps are appealing."	
"For location planning and for calculating isochrones to assess accessibility, we could make good use of the tool."	
"We would like to continue to use GOAT for our planning tasks."	

Table 7.6: User feedback - utility

second research question tries to find answers to whether the developed accessibility instrument is of useful support in practice. This research faces the challenge of having no clear answer to this very complex question.

From the utility perspective, the involved practitioners reported that the analysis is suitable when answering many planning questions. In particular, the ability to perform scenarios was welcomed by the practitioners. Therefore, the request to perform on-the-fly scenario building identified by the COST Action TU 1002 project (Silva et al., 2017; te Brömmelstroet et al., 2016; te Brömmelstroet et al., 2014) could be confirmed. Many practitioners mentioned that GOAT could support when assessing changes in infrastructure for walking and cycling, mainly when focusing on accessibility effects of new, modified, or deleted street networks. As the tool interprets accessibility solely time-based, the accessibility analyses fall short when changes in walking or cycling comfort should be modeled. The additional spatial data (e.g., noise levels) provides further insights into the quality of street space.

Furthermore, it can be concluded that many of the tool's features are suitable for assessing the effects of land-use changes. Planners valued the ability to assess local accessibility and identify regions not served by a particular amenity. However, the planners also mentioned that the provided analyses only helped in some of their work and asked for ongoing expansion of the tool. The involvement of practitioners from both urban and transport planning, as well as the general mutual understanding when using GOAT, showed that accessibility can serve as a shared language between often disconnected disciplines, as suggested by Büttner et al. (2018). The usability of the software is vital. During the development, there was constantly the challenge to balance additional functionality and the ease of using the tool. As a result, GOAT might be much easier to use than a classical desktop GIS but is significantly more complex than an easy web map. Accordingly, GOAT can only be used effectively with approximately one day of training. This training can be realized via online tutorials but furthermore through in-person training. Despite the high efforts in making the tool more straightforward, the usability can still be significantly improved. A challenge of the co-creative involvement of the practitioners was that some reported improvements in terms of usability contradicted statements from other users. In general, it is suggested to make separated usability tests that use common methods such as contextual inquiry or session recording. Overall it is concluded that utility cannot be assessed independently from usability. Both criteria in this case study are, instead, often highly interrelated.

During the workshops, the need to combine the training of operating GOAT and practical teaching of the accessibility concept was seen. Many of the involved practitioners have heard of accessibility before, but none of them has used an accessibility instrument before. Similar to the observations of Boisjoly and El-Geneidy (2017b) accessibility is generally a known concept in the planning practice, but many have not used accessibility metrics in practice. The study can be seen as a tiny step to make the accessibility concept more known in the local planning practice. Accordingly, the benefits of engagement with the planning practice, which were raised by previous research Silva et al. (2017) and te Brömmelstroet et al. (2014), could be confirmed. Although the engagement with citizens using the tool was not tested, the tool is seen as too complex to be easily used by non-professionals. Meanwhile, it is seen as very beneficial to use GOAT in workshops with citizens and political decision-makers while being operated by a planning professional. The concept of seeing the professional as *'chaufeur'* is common from studies using participatory GIS (Haklay & Tobón, 2003).

The interoperability with existing systems (e.g., desktop GIS, transport models), is an aspect seen as necessary for adopting accessibility instruments in practice. By using standard data formats such as from the Open Geospatial Consortium (Open Geospatial Consortium, 2022) or by developing software plugins, interoperability can be strengthened. Overall, the continous exchange with the planning practice was a rewarding experience from the authors' perspective and it is suggested to continue on this path.

It is essential to underline the limitations of the presented study. First, the identified use cases were also influenced by the capabilities of GOAT. Many planners knew the scope of the software before and therefore were focusing on solvable planning questions. Accordingly, there might be many more relevant planning questions in the field. Second, the tool was, so far, primarily used in synthetic workshops settings. However, the use of planning software is usually characterized by planners using the software alone. Long-lasting and continuous feedback from planners using GOAT would be needed to produce a more solid picture. Furthermore, the focus was on documenting the experience in worksheets during the workshops. There was also prepared an online survey. However, only very few practitioners participated. Accordingly, the results were not used for the study. Therefore, a collection of anonymous feedback and eventually more honest feedback was not realized. An apparent methodological weakness of the study is that the tool developers themselves carried out the assessment. Self-assessment was great to bring the experience directly into the tool development. However, it also comes with a bias despite following a good scientific practice. It is suggested that independent colleagues assess the usefulness of the instrument in the future.

An eventually trivial aspect is the cost of implementing an accessibility instrument such as GOAT in practice. Despite being an open source tool, it needs to be maintained, hosted, and equipped with the necessary data. Accordingly, it is suggested that future development aiming for fast adoption of accessibility instruments should always keep the necessary resources in mind needed for operating in a real-world environment and the willingness to pay for the analyses. Also, even if mass adopted, the market for accessibility instruments will be a niche with few users compared to other fields in software development. Furthermore, it is crucial to find new in-roads in other domains to tap into new use cases (e.g., real estate development). Finding more use cases might be an appealing idea, not only from the idea of spreading accessibility analyses, but it can generate more resources for better tool development by joining forces in the future.

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Part III

Synthesis and discussion

Chapter 8

Synthesis and discussion

The three papers presented and discussed their respective results. Each paper targeted a specific dissertation component and addressed a different audience. This chapter summarizes and discusses the results for each of the three research questions.

8.1 RQ1 - Tool requirements

In which areas do accessibility instruments have to be developed further to better support planning practice when planning for active mobility?

Accessibility instruments have seen significant development over the last three decades, indicating that the implementation gap for accessibility instruments might be smaller soon. Nevertheless, few examples exist in which accessibility instruments are applied in practice. Based on the findings in Chapter 5, this section first proposes a generic technical structure of accessibility instruments and then highlights the areas that require further development.

8.1.1 Components of accessibility instruments

This sections describes the different technical components of accessibility instruments. Accessibility instruments are usually built using existing software and software libraries, mostly from the GIS domain. Despite the heterogeneity of used technologies, accessibility instruments use common components. The author's categorization into different components is visualized in Figure 8.1. The following components are described:

- **Data store:** Accessibility instruments are data-driven applications that usually contain one (or several) database(s) capable of handling spatial and non-spatial data. The most common data sets are network data sets modeling the transport network and opportunity data sets modeling the potential of the land-use system.
- **Routing:** A routing library capable of computing operations, such as shortest-path analyses, is necessary to compute travel costs (e.g., time, emissions, and monetary costs). Different algorithms are used depending on the analyzed travel modes.

- **Spatial operations:** The computation of accessibility measures and data preparation typically uses spatial operations such as intersections, buffering or geographic measurements.
- **Non-spatial operations:** Computational operations that do not involve geometries are used. The most common ones are classical algebraic and statistical operations.
- **Middleware:** The different operations are typically orchestrated and automated to produce accessibility analyses. Furthermore, the results of the analyses are prepared and transmitted using an Application Programming Interface (API) to be viewed in the user interface.
- **User interface:** The user interface is usually map-based and capable of visualizing spatial data through different map styles. Furthermore, the analyses are presented in tables, charts, or diagrams.

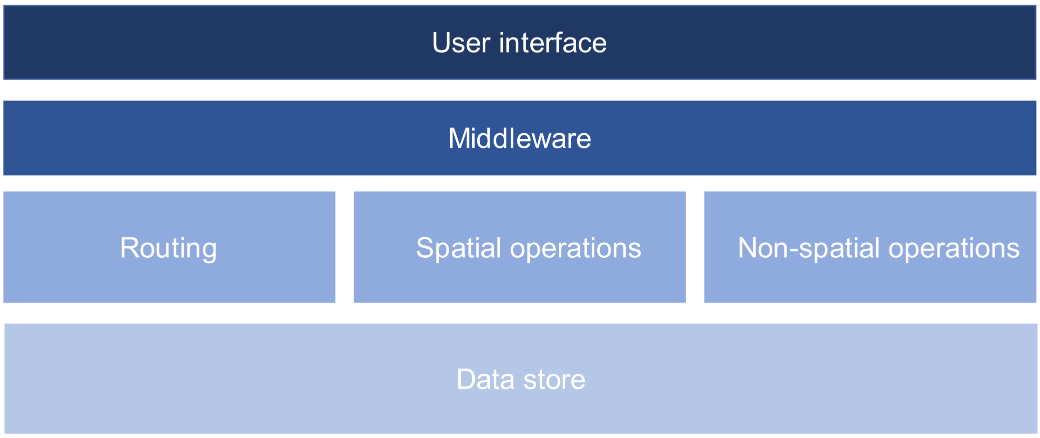

Figure 8.1: Components of accessibility instruments

The different components can be bundled in one or several software suites depending on the tool type. Standard desktop GIS bundles all the described components. Accordingly, accessibility instruments can be built inside their environments. In the case of web tools, the different components are usually allocated to both the client and backend using different technologies and programming languages. Furthermore, third-party APIs are widespread, particularly for routing.

8.1.2 Observed trends in the current accessibility instrument landscape

As discussed in Chapter 5 the accessibility instruments developed by an active community of developers are significantly heterogeneous. Compared to the tools tested during the COST Action project in "Accessibility Instruments for Planning Practice in Europe" (Hull et al., 2012; te Brömmelstroet et al., 2014) accessibility instruments have been developed significantly further. A clear tendency is toward web-based tools, that can be operated using a web browser. Consequently, web tools provide easier and often open access to the analyses making them available to a significantly larger group of users who might not be familiar with complex desktop GIS. With easier tools there is the potential that the accessibility concept is promoted further. Early accessibility instruments were developed in academic circles, and their development was often discontinued after project funding ended. Commercial providers and vibrant open source communities have developed an increasing number of instruments and relevant software libraries over the last few years. The extensive number of available open source components in routing algorithms, GIS libraries, and web technologies provides a rich ground for developing accessibility instruments. The broad adoption of open source libraries, such as OpenTripPlanner (Community OpenTripPlanner, 2021) for public transport routing, shows that there are powerful and free tools for developing a new generation of accessibility instruments. Therefore, the rising trend of open source development has the potential to significantly lower development costs and accelerate exchange between the developer communities.

New software goes hand-in-hand with the continuous improvement of computation power, facilitating real-time calculation on desktop computers and in the cloud. The dynamic assessment of scenarios related to land-use and transport changes is increasingly technically feasible. Nevertheless, there is a gap between professional, usually proprietary desktop accessibility instruments and comparatively simple open web tools. Currently, most serve as a client for visualizing accessibility maps and do not provide users the option to perform scenarios or rich interactions.

Many tools serve different target groups, and most of them only incorporate a part of the accessibility concept. Accessibility instruments generally focus on the transport and land-use component of accessibility. Additionally, most accessibility instruments rely solely on contour-based and gravity-based accessibility measures. Reducing tool complexity is a rational compromise since the data for more complex indicators may be unavailable, or the rise in complexity may jeopardize its usability in practice. Despite accessibility instruments increasing potential in planning active mobility, there is still a lack of practical applications. Furthermore, a comprehensive, ideally long-term, assessment of whether and to what extent the analyses actively support the planning process is still lacking.

8.1.3 Potential for the development of new accessibility instruments

The divide between feature-rich proprietary desktop software and (open) web tools (see Chapter 5) may explain the need for different user groups to be served. Moreover, it is possible to bridge the divide. Easy access could be combined with a more feature-rich experience needed in the planning practice. Web tools to build scenarios based on transport and land-use changes are scarce. Covering these two dimensions of accessibility is particularly important when evaluating integrated urban and transport planning strategies.

At the same time, most instruments still focus on modeling accessibility for motorized transport. Few instruments focus on active mobility and local accessibility (see Chapter 5). Therefore, realistic routing for walking and cycling and high-spatial-resolution analyses are necessary. Furthermore, accessibility instruments have often only been used in one particular geographical study context, and even the commercial tool providers typically focus on one specific region. Therefore highly flexible instruments that facilitate a transfer are needed. The most feature-rich instruments, however, are proprietary, despite the rising popularity of open source development.

Accordingly, there is significantly more need to continue releasing accessibility instruments and relevant software libraries open source, especially as their primary target group are public authorities. Public authorities increasingly aim to procure open source software when possible. A proof for this is the "Open Source Software Strategy 2020 – 2023" of the European Commission (European Comission, 2020) and the initiative "Public Money Public Code" of the Free Software Foundation Europe e.V. (Free Software Foundation e.V., 2021). The weakness of many open source projects is the lack of funding. Consequently, a suitable development and business model is needed that captures enough resources to maintain and expand the software.

8.1.4 Summary - tool requirements

Accessibility instruments are developed within a small GIS and planning support systems community. Technically, they consist of different components and are built using existing GIS software or libraries. To date, these tools have not been widely adopted in practice. The rising importance of active mobility in urban and transport planning and the unsatisfactory availability of accessibility for active mobility show special development needs. It is suggested that accessibility instruments tailored to active mobility should combine the following characteristics: web-based, interactive scenario building, transferable and open source.

8.2 RQ2 - Data management

How can data refinement and fusion strategies enable powerful and affordable accessibility instruments?

Given the importance of data for accessibility instruments such as GOAT, data management is seen as a core component of the tool. The availability of data on the suitable resolution for a reasonable amount of resources is decisive for the instrument's success. The data refinement and fusion scope were extensive, and this work primarily focused on developing methodologies suitable for the specific use case.

8.2.1 Workflow data preparation

GOAT includes a highly automated data preparation workflow (see Figure 8.2). The data is prepared incrementally, and the steps of data classification, refinement, and fusion varied. Many data preparation settings were customized to the specific study context. Accordingly, not all three steps were always used to process the data. After processing, the data sets are saved inside the data store.

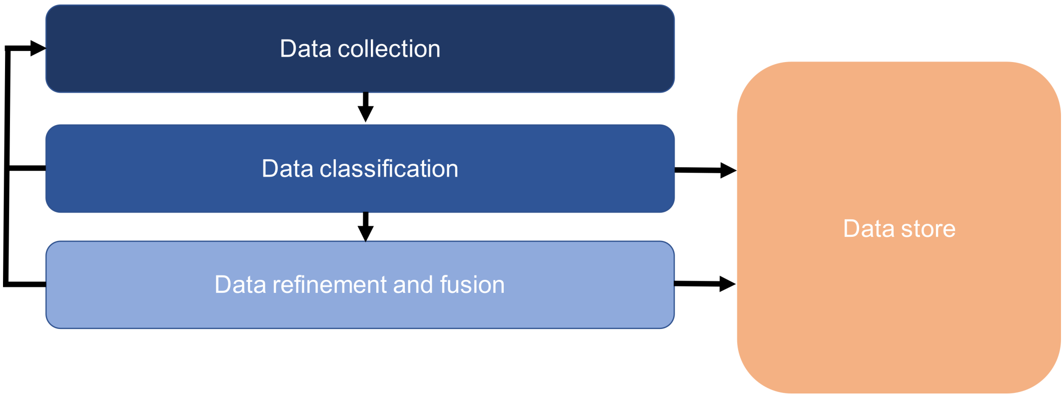

Figure 8.2: Workflow data preparation

Data sets were collected from a variety of sources. A list of the most widely used data sets for the deployment in the Munich region is shown in Table 5.4. Data collection focused on open data from public sources. Furthermore, the VGI from OSM played a special role. The default data source was OSM. Therefore additional data sets were classified as custom data sets. To improve OSM's data quality, potential gaps and errors were fixed where possible by editing the OSM's main database (see Chapter 8.2.3). OSM data was downloaded automatically and clipped to relevant study areas during the setup. Most of the data was geospatial vector data, with exceptions like the used digital elevation model, which was raster-based.

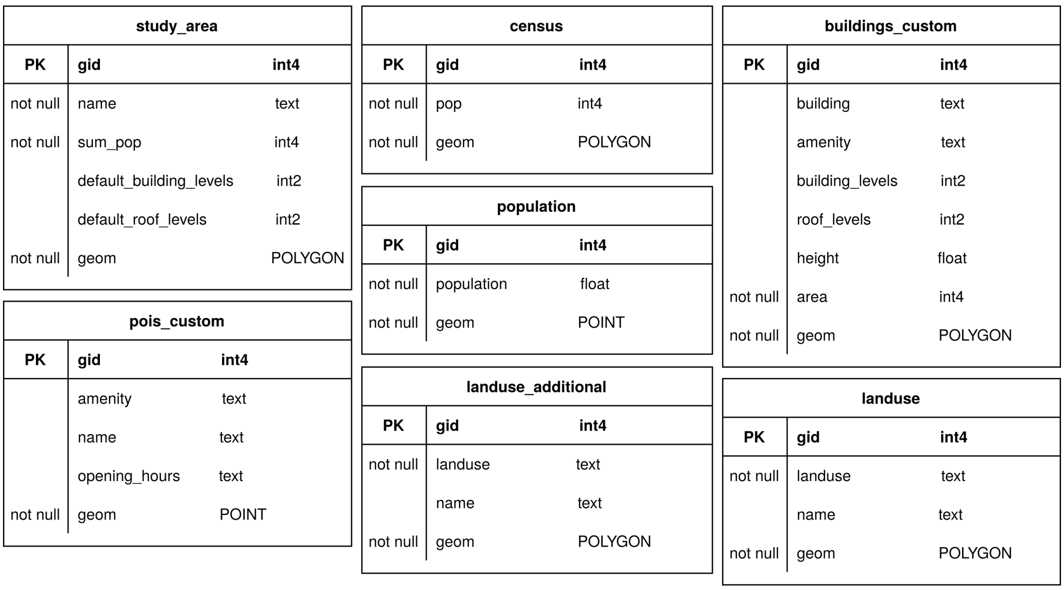

Figure 8.3: Schema of common custom tables

The different raw data sets were prepared to meet the predefined table schema (see Figure 8.3) for custom input tables during the data classification. Accordingly, raw data tables were renamed in correspondence with the names of the defined tables. Furthermore, attribute names and data types were converted to match the predefined schema. The predefined columns for the tables can be complemented by additional attributes if necessary. The data were converted if the data was not saved in one of the supported formats (i.e., SQL-dump and Shapefile). In addition, the geometries were converted into EPSG:4326, the predefined standard coordinate reference system for the GOAT database. Overall, the highly automated data preparation pipeline enabled the relatively fast setup of GOAT making it affordable to many different study areas (see Table 4.1).

8.2.2 Data refinement and fusion

During the explorative work of the data during the application of GOAT, a series of problems linked with quality emerged. The most common challenges were as follows:

- **Spatial resolution:** Accessibility analyses of walking and cycling require data at an exceptionally high resolution. In particular structural data used as opportunity data sets for accessibility analyses are often not present in the required solution. While macroscopic transport models commonly used in transport planning usually use data aggregated on the level of transport zones, GOAT requires data on the building or even building access level. The lack of high-resolution statistical data such as the number of residents or jobs in a study area poses a particular challenge.

- **Incompleteness and inconsistency:** A common problem when working with data is that it is often incomplete. For example, it is common that for POIs, particular objects are missing in the data set. The incompleteness of particular attributes is also typical. These issues are particular prevalent for OSM despite ongoing effort to improve them. As various users voluntarily collect OSM, the classification of specific features can be inconsistent. Accordingly, it is not uncommon that different tags are used for identical stores of a particular chain.

- **Out-of-date:** For spatial data, it is difficult to cope with the fast-paced dynamics of the real world. During the application of GOAT, one particular challenge was outdated POI data from OSM. OSM often cannot keep up with the frequent updates of pois in the real word. Furthermore, the national census, an essential data set to locate the population, in the case of Germany is from the year 2011. Data sets (e.g., land-use and street network) are usually updated instantly or once per year. Consequently, a significant mismatch in the reference years can exist.

- **Terms of use:** From the beginning, GOAT used data classified as open data to guarantee a transparent and affordable instrument. However, the availability of open data is often limited, even data from public authorities is often not open. Furthermore, commercial providers are either expensive or provide their services via APIs. However, the terms of use of many APIs impede saving the information, which is required for the current GOAT setup.

Suitable data refinement and fusion strategies were developed. The different routines were predominantly developed using SQL, PL/pgSQL, and Python for automation. Hence, the scripts were executed directly during the setup of GOAT to develop a flexible workflow that can be configured through a configuration file (see Appendix E) because of the diversity of data. The refinement of POIs in categories used by GOAT was realized through the configuration. For example, different supermarket chains were grouped as discount supermarkets or fast food chains based on their name. In doing so, the classification value that met the schema in GOAT was realized, and the consistency of the data was improved. In addition, POIs from other sources were fused with OSM data, and the combined data set was saved in the data store. The developed refinement and fusion steps enhanced the completeness and consistency of POI data.

The most complex data refinement and fusion procedures were presented in Chapter 6.5. The absence of population data on the building access level in the study context was addressed with the development. The unavailability of an up-to-date census grid and 3D building model necessitated the development of a new procedure. It updated the census grid using a bottom-up estimation for new development areas and a top-down dasymetric mapping process. Fine-scale population was generated under minimal data requirements and provided for the analyses. The comparison with reference data from the municipal population registry demonstrated the high quality of the generated data (see Chapter 6.5). Therefore, the procedure helped to overcome challenges with finding recent population data on a high spatial resolution. The developed procedures helped work the openly available data-sets and improve their quality to be used for GOAT. Therefore, they supported making the tool more powerful. However, a quantitative assessment of the extent to which the data processing steps improved the quality of the analyses in GOAT was not realized.

However, the different data preparation steps helped to only use freely available data. Therefore, no direct data acquisition costs were incurred, making the tool more affordable. At the same time the data processing steps are still far from universal to every study context. In addition, operating the procedures requires time and knowledge, which could raise costs. It is acknowledged that there is no clear answer to the affordability of the developed procedures. The investment in developing and using the refinement and fusion steps, should have been compared with the costs of acquiring comparable commercial data sets.

8.2.3 VGI contribution

The use of VGI, in particular OSM, is promising in terms of the high termporal dynamics of spatial data, the of open data, and high costs for commercial data sets. The data quality of OSM largely depends on the contributors' activity in the local context, and the completeness also strongly varies for the different map features (e.g., paths and buildings).

Therefore, this dissertation experimented with data collection in OSM to address the unavailability of suitable data. This data collection targeted specific data gaps that could not be fixed with data refinement or fusion. Therefore, it was experimented with different forms of OSM data collection (GOAT-Community, 2020b). The different formats were organized at the TUM Chair of Urban Structure and Transport planning. Several mapping parties were held, and volunteers were invited to join physical or remote events. The majority of users had not contributed to OSM before. Therefore, mapping was realized mainly using smartphone apps like StreetComplete or GoMap!!.

In addition, as part of the development of GOAT it was experimented with the development of a mapping mode, that highlights relevant mapping challenges of the particular GOAT deployment (see Figure 8.4). Missing data for buildings, pathways, or POIs were challenges in the mapping mode. Therefore, a more focused and organized data collection was realized.

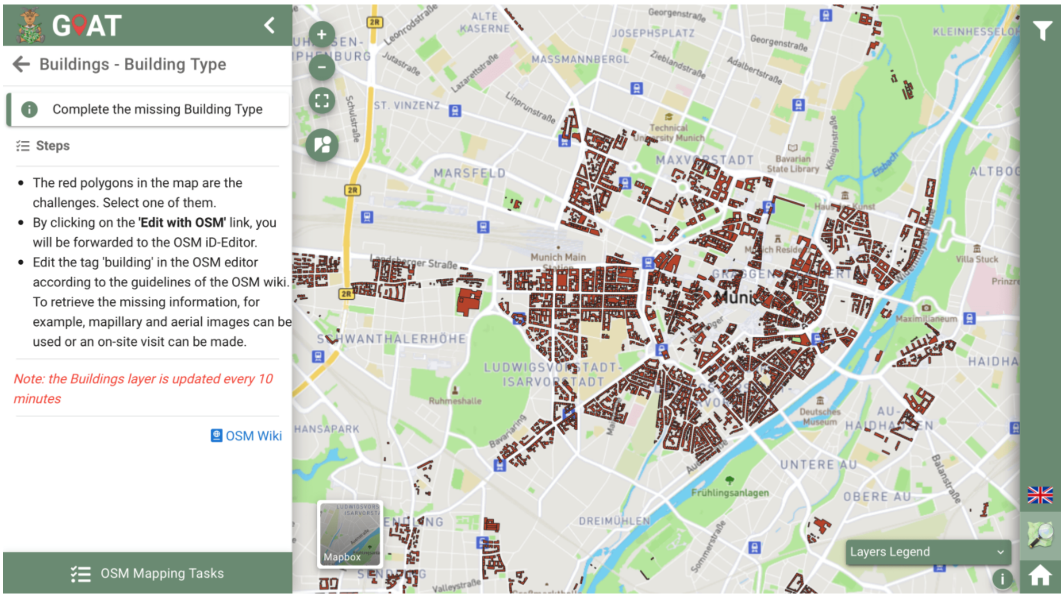

Figure 8.4: Mapping mode in GOAT

The mapping during the parties generally took approximately two hours and was completed in groups of two or three individuals. The teams that mapped the most received small awards to incentivize attendance. Furthermore, working students were paid to help with mapping for the applied GOAT versions. Additionally, students that applied GOAT in different study contexts as part of their theses (see Chapter 4.1) were encouraged to collect data in OSM.

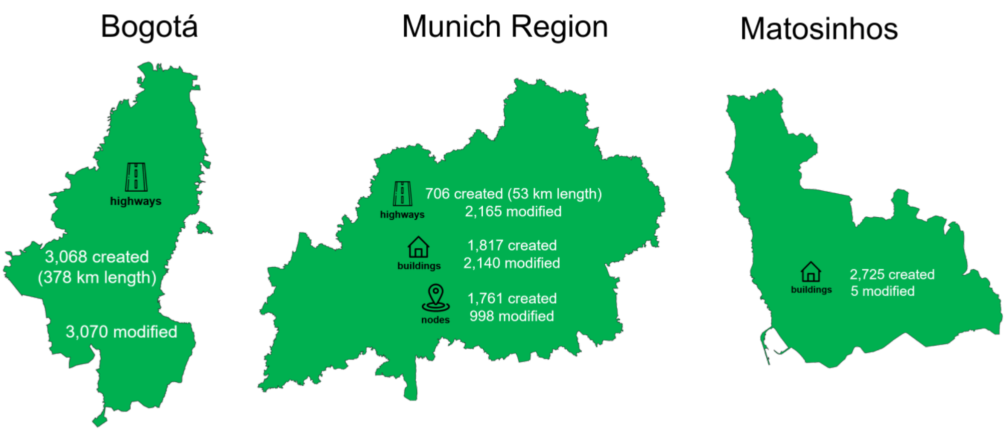

Figure 8.5: OSM mapping regions
(GOAT-Community, 2020b)

Overall data was collected from the Munich region, Bogotá, and Matosinhos (see Chapter 8.5). By spring 2020, 10,077 features were created, and 8,378 features were modified in OSM. A particular focus was mapping missing or incomplete buildings, highways, and POIs. The features shown in Figure 8.6 were collected.

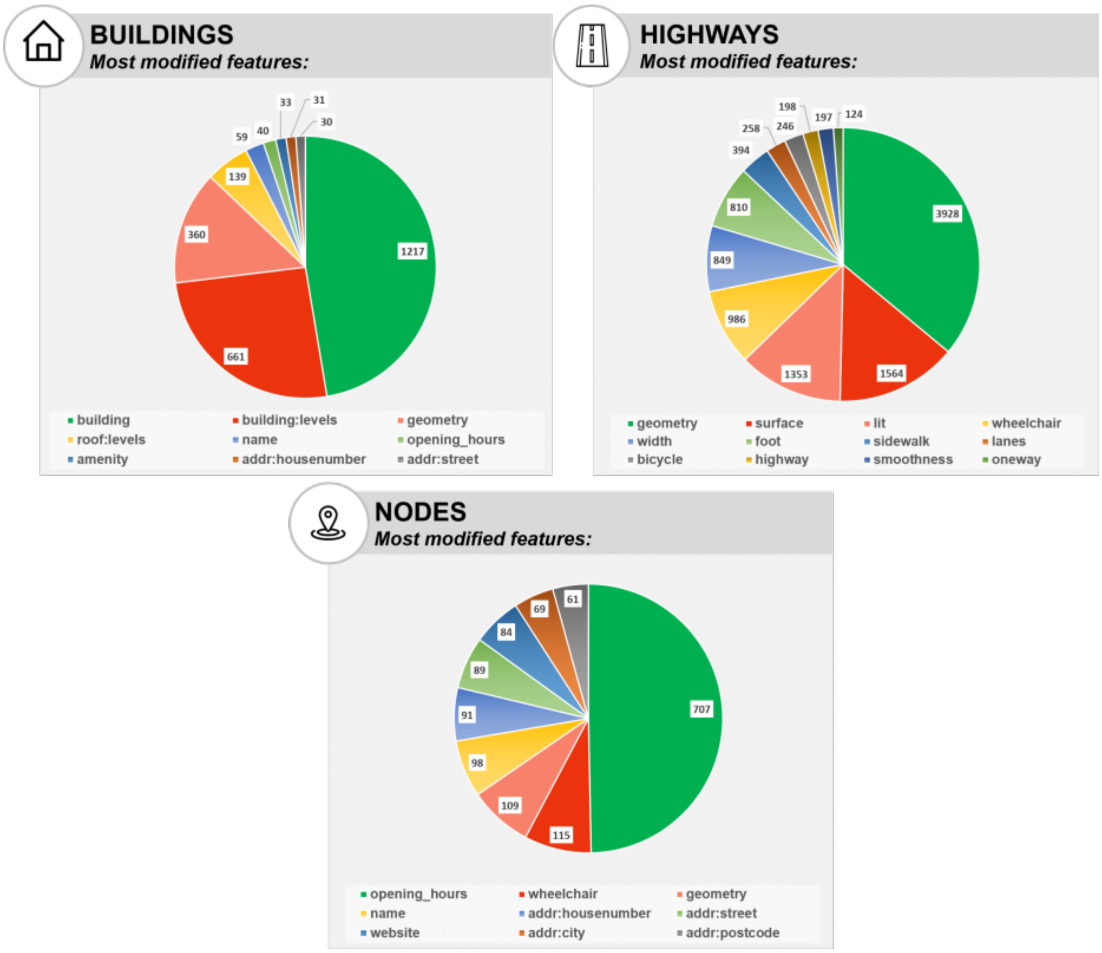

Figure 8.6: Feature types mapped (GOAT-Community, 2020b)

The total count of mapped features is substantial. However, it is only a tiny contribution compared to the on average 4.5 million map changes per day (OpenStreetMap Foundation, 2021). For the deployed GOAT versions, the data collection helped significantly in collecting enough data for using the tool and updating data. Especially the organized data collection by paid students and the student theses helped to improve data completeness for GOAT. In comparison, data collection during the mapping parties happened less systematically as events were voluntary. However, the mapping parties significantly raised awareness off the OSM project. Notably, most attendees were introduced to OSM mapping for the first time. The mapping parties were an important event to raise attention for the OSM project and gain long-term contributors, but it was not possible to systematically collect data in such a short time frame.

An in-depth data quality assessment before and after the mapping process was not carried out. The achieved data completeness greatly varied between the different map features. For example, the supermarket data for the city of Munich was improved to such degree that no supermarket was missing in OSM after manual inspection. Furthermore, in a supervised master's thesis (Jehle, 2020) for the development of new temporal and individual accessibility measures, almost all streets in one district of Munich were complemented with attributes such as sidewalk width, parking lanes and street illumination. These examples show that data collection can help to close data gaps and increase the quality of the analyses. For other map features (e.g., mapping buildings levels) though the mapping process was only a drop in the ocean, due to the substantial incompleteness in this field.

The effort to collect the data should not be underestimated. In some cases, students collected data for several weeks over the course of their theses. In a project that is also evaluated from an economic perspective such resources might not be available or the acquisition of commercial data sets could be economically more favorable. Therefore, it can be concluded that the data collection in OSM helped develop a powerful and affordable accessibility instrument in the specific environment where the tool development happened. At the same time, the cost-benefit ratio could be different particularly in a more commercially driven environment.

8.2.4 Summary - data management

The presented data management strategies attempted to provide the best data possible for the analyses with GOAT. The focus was on finding affordable workflows and producing data of suitable quality. For the study contexts, these procedures helped equip GOAT with data at a minimal costs. However, the findings cannot be generalized due to the university's specific development environment. Furthermore, the time-consuming, and costly process of preparing and collecting the different data sets was not assessed from an economic perspective. It was not assessed if the developed framework was superior to other procedures. Furthermore, it cannot be claimed that the methods are transferable in all cases. The complexity of working with diverse data and task size indicates that there cannot be a single and easy answer. Therefore, it remains unclear whether the developed procedures truly contributed to making GOAT a powerful and affordable tool.

8.3 RQ3 - Tool assessment

Is the accessibility instrument GOAT of useful support in the planning practice?

It remains unclear whether GOAT as an accessibility instrument is useful for the planning practice. In Chapter 7.6, the usefulness was thoroughly studied for specific use cases and at a more general level. The co-creative testing and application of GOAT in different case studies (see Chapter 4.3) showed that GOAT was useful in four generalized use cases: infrastructure planning walking, infrastructure planning cycling, location planning, and urban development. Based on the findings in Chapter 7.6, the key results regarding the tool's utility and usability are presented below.

8.3.1 Utility Assessment

Overall, numerous concrete planning questions were identified in which the analyses provided by GOAT were considered helpful. There were also planning questions that could not be answered or could only be partially answered. A list of the studied planning questions can be found in Table 7.3. The positive and negative aspects of its reported utility and own reflections are summarized below.

Positive:

- A particular strength of GOAT is its assessment of scenarios for the street network, POIs, and buildings.
- GOAT identifies shortcomings in walking and cycling infrastructure.
- The instrument is powerful when assessing the number of residents with access to a particular amenity.
- Different accessibility measures provide diverse options to improve accessibility. Isochrones and multi-isochrones effectively capture the accessibility of one specific location or one district. The gravity-based accessibility heatmap provides an area-wide understanding of accessibility, thus helping identify areas that are underserved by a specific amenity and areas with shortcomings in their walking and cycling infrastructure.
- The customization of travel speeds and the additional routing modes (e.g., barrier-free and pedelec) are beneficial if a user group-specific picture of accessibility is needed.
- The additional spatial data integrated into GOAT (e.g., noise level and street view imagery) supplements the accessibility analyses. It provides additional layers of information for understanding the territory and local conditions.
- Users generally trusted the results of the analyses. Therefore, they welcomed the instrument's openness and transparency.
- A comprehensive visualization facilitates the use of the tool to effectively communicate with political decision-makers.

Negative:

- Due to the complexity of wayfinding in the urban context and limited data availability, the routing algorithm does not include all factors influencing walking and cycling travel times.
- Individual and temporal accessibility components are only prototypically implemented. In addition, factors such as comfort or safety are not included in the analyses.
- As an accessibility instrument, the GOAT cannot predict mobility behavior (e.g., pedestrian flows), which was often requested by the practitioners.

- Location planning from the perspective of service providers (e.g., mobility services and retail) might require more customized accessibility measures to properly assess the demand for a specific service.
- Stronger integration with existing GIS is needed to avoid technological silos.
- An open access provision of the tool might cause conflicts with sensitive data.

8.3.2 Usability assessment

GOAT was designed as an instruments that is easy and intuitive to use compared to classical desktop GIS. During the different workshops, GOAT was employed mainly by users who had not used other GIS software before. Most users familiarized themselves with the tool's core functionality after a short introduction supported by written and video tutorials. Furthermore, GOAT is not a mature software, and there are still significant shortcomings in terms of its usability. The positive and negative aspects of the tool's usability are summarized below.

Positive:

- The user interface is easier to use than classical desktop GIS. Therefore, users are equipped with a comparatively complex model, that can be operated after approximately one day of training.
- The practice appreciated the map's interactivity, the possibility to dynamically change the analyzed POI category and the fast calculation times of GOAT.
- More users can experience accessibility analyses, allowing individuals who are not tech-savvy to perform elaborated calculations.
- Scenarios and their effects on accessibility can be developed and compared easily.
- Users save significant time when using GOAT to perform the analyses compared to classical desktop GIS. More efficient workflows can translate into cost savings and more opportunities to use accessibility analyses in practice.

Negative:

- The familiarization with GOAT still takes too long, and the provided training material is insufficient.
- The limitations of the accessibility model were often not understood despite the project's open source nature.
- Not all functions are intuitive, and their purpose is not always clear.
- GOAT is too complex to be used by citizens, who are also not the target group.
- There are still several bugs that affect user experience.

8.3.3 Summary - tool assessment

GOAT is a useful addition to the landscape of accessibility instruments. Its strength is its integration of a comparatively easy user interface and with powerful yet straightforward accessibility measures. In addition, the tool's uniqueness is its high interactivity and the ability to evaluate scenarios. However, the instrument does not meet all expectations of the planning practice. Overall, it requires more mature user interface, stronger integration with existing GIS software, and better indicators. Moreover, the tool does not sufficiently teach the theoretical background of the accessibility concept and its limitations. Thus, there is the risk that the analyses could be misinterpreted or misused. However, with ongoing development the instrument has the potential to meet more needs of the planning practice. As a starting point it is suggested to follow the future development path sketched in Chapter 9.2. Finally, it can be concluded that GOAT provides useful support in answering real-world planning questions. Whether meeting the practitioner's requirements always contributes to the wider vision of sustainable urban and transport planning requires further discussion.

8.4 Main goal

Development of an open source, interactive, and transferable accessibility instrument for planning local accessibility by active mobility.

The presented accessibility instrument GOAT, aims to fill the gap described above (see Chapter 8.1). While the requirements are relevant for a wide range of instruments, the presented tool development geared toward active mobility and local accessibility. The tool architecture and characteristics are described in this section. Technically, GOAT is a WebGIS designed after the classic server-client architecture of the web (see Figure 6.3). Based on the categorization of the different accessibility instruments components (see Chapter 8.1.1), the tool architecture can be as follows:

- **Data store:** The architecture's core component is a spatially enabled PostgreSQL/-PostGIS database. Therefore, the data is organized in tables following the object-relational structure. In addition, the use of JSON as the key-value format allows greater flexibility when unstructured and nested data is saved.

- **Routing:** A fork of the pgRouting database extension (GOAT-Community, 2020a) is used as a routing library. The solution provides great flexibility, as the routing network is dynamically built for the calculation. The dynamic creation of the network graph is particularly relevant for the on-the-fly scenario building functionality.

- **Spatial operations:** Almost all spatial functions are performed using the PostGIS library and are written in SQL and PL/pgSQL. Only a few selected functions, like data conversion, are done using Python and libraries such as Geopandas.

- **Non-spatial operations:** Besides selected data import and export functions, which are done using Python, all non-spatial operations are programmed using SQL and PL/pgSQL.

- **Middleware:** An API written in Python is used as middleware. The API is a thin layer because most analytical functions and business logic happen in stored database procedures written in PL/pgSQL. Therefore, the API primarily communicates the accessibility measures and geospatial layers from the database to the client. The data is communicated using the GeoJSON, GeoBuf, and Vector tile format. While the GeoJSON and GeoBuf format is used for the dynamic layers, the Vector tile format is used for static layers.

- **User interface:** As a web application the user interface is developed as a single-page map application. Therefore, the frontend is developed with Javascript using the framework Vue.js and the library Openlayers.

The PostgreSQL/PostGIS database forms the backbone of the application. This technology is known for its maturity and wide usage in the open source community. As a web application, GOAT is deployed on cloud servers using Docker and Kubernetes. Further technical details are discussed in Chapter 5.

8.4.1 Tool characteristics

As described in Chapter 2.1, accessibility is composed of four components. The initial stages of the development, aimed to incorporate all four accessibility components. However, there are numerous ways and degrees to which the temporal and individual components of accessibility can be included in the analyses. Due to the complexity of the individual and temporal components, the focus soon shifted toward the transport and land-use component. Accordingly, the temporal and individual components of accessibility were only incorporated in prototypes. Accessibility changes at different times of the day to different POIs were modeled in two student theses (Ben Hassine, 2019; Jehle, 2020). The lack of available data on the opening hours of the different POIs was the main reason the feature was not developed further. In addition, the individual accessibility component was implemented by defining different routing profiles (e.g., elderly, wheelchair). Furthermore, the walking and cycling speeds can be adjusted for the travel time isochrones in GOAT. Though, this flexibility does not capture the often high differences between measured and self-reported accessibility (McCormack et al., 2008; Ryan & Pereira, 2021).

During the development process of GOAT, it was discovered that the increasing complexity of incorporating the individual accessibility component might interfere with the instrument's ease of use (see Chapter 8.3). GOAT uses contour-based and gravity-based accessibility measures (see Chapter 5) for implementing the most frequently used accessibility measures. A modified Gaussian function is used as an impedance function for the gravity-based accessibility measure. Due to the complexity of adequately calibrating the sensitivity parameters, users can choose from a range of predetermined variables for the different POIs. In addition to the accessibility measures, different spatial data (e.g., land-use, noise levels and cycling accidents) is integrated into the tool. Therefore, users have additional information to understand the territory and assess the quality of a space.

With the deliverable of GOAT (GOAT-Community, 2021c), the author provided an accessibility instrument with the following tool characteristics: open source, interactive, transferable, and focused on active mobility. Accordingly, it can be stated that the main goal was achieved. While the tool was successfully developed, characteristics such as interactivity or transferability are difficult to measure. In the following, each of the characteristics is discussed independently on a qualitative basis:

- **Open source:** GOAT is licensed under the GNU General Public License v3.0, a commonly used open source license. It allows free use and modification of the software as long as changes are released open source. The advantages of the open source software were described in Chapters 5 and 8.3. In the case of GOAT, the long-term success of the open source provision remains to be demonstrated. Especially if enough resources can be raised to avoid under-investment for the ongoing development and maintenance.
- **Interactivity:** The tool is interactive because it allows users to compute accessibility measures in real-time and visualize a range of spatial data. It also allows users to dynamically compute scenarios and visualize changes in accessibility. Furthermore, users can change the style of many layers and export the results. Although interactivity is subjective, the perfect degree of interactivity for a specific purpose cannot be predefined by the developer alone. The application of GOAT and its use by practitioners indicates that the interactive calculation provided by the tool is welcomed (see Chapters 7.6 and 8.3)
- **Transferable:** The application of GOAT demonstrated that the instrument is transferable to various study areas (see Chapter 4.2). However, in theory, almost every accessibility instrument is transferable to other study areas. Accordingly, GOAT is designed to be quickly transferable by building on frequently available data and integrating data preparation scripts (see Chapter 8.2). Despite the transfer of the tool to numerous municipalities, the focus of this project was on case studies in Germany. Therefore, its transferability to more international case studies should be investigated.
- **Active mobility:** GOAT supports the transport modes of walking and cycling. In addition, offers an experimental routing mode for wheelchair users and pedelecs. These transport modes fall under the category of active mobility. In addition, the analysis units are street-scale, grid-scale, and district-scale, thus matching the resolution needed to analyze local accessibility (see Chapter 5). One particular challenge is the computation of realistic travel times for each mode. The walking and cycling networks are mainly based on automobile networks and therefore use the street centerline instead of a separate network (see Chapter 5). In addition, other transport modes belong to the group of active mobility (e.g., skateboards) and different forms of micro-mobility, such as electric scooters, which might be relevant when analyzing local accessibility. The routing algorithm could be expanded to additional transport modes, but further calibration is required.

8.4.2 Summary - main goal

The research project could not address all challenges in the development and application of accessibility instruments. Furthermore, it should be noted that the proposed tool is only one of many other possible solutions. Nevertheless, the presented instrument is a unique contribution to the landscape of accessibility instruments. The tool is flexible, scalable, and transferable to different study contexts by design. It also reacts to the main challenges accessibility instruments face. Aside from theoretically matching the development needs, only long-term testing and real-world application by practitioners can establish its usefulness in practice.

Chapter 9

Conclusions

A novel accessibility instrument GOAT, was developed, applied, and tested in numerous case studies in this dissertation. From the beginning, it aimed to go beyond the development of a prototype and initiate a long-term open source project. Moreover, three research questions were answered to facilitate, validate and share the experience with the researchers and the development community.

9.1 Limitations

Each research paper (see Chapters 5, 6.5 and 7.6) discussed its limitations; however, a couple of overarching limitations of this dissertation are presented in this section. This project started with the assumption that a new accessibility instrument in active mobility and local accessibility was needed. Past research revealed dissatisfaction with existing instruments. However, this finding does not necessarily mean that a new accessibility instrument is needed but that existing ones could be improved instead.

In addition, the idea for the tool development was inherited from my own master's thesis. Despite the early literature review and testing of existing tools, the development of GOAT was started before a complete picture of the tool landscape was available. It can be argued that a complete overview might be impossible to achieve due to the numerous developments. It should be acknowledges that the capabilities of early versions of the tool and the technical expertise influenced the requirements established for GOAT. However, it was decided to follow an iterative process, which incrementally incorporated new findings from the literature, practitioner feedback, and experiences into the tool's design.

This process also had its limitations. Several conclusions on the usefulness are based on yet few case studies and the author's subjective experience. Furthermore, the tool development, particularly the data management strategies (see Chapter 8.2), was heavily influenced by local data availability. The presented instrument is only one of many possible solutions to the shortcomings of existing accessibility instruments.

The precise usefulness of GOAT cannot be easily answered (see Chapter 8.3). Although the evaluation was based on neutral feedback from various individuals, the author is self-assessing its own development and research. However, the involvement of additional researchers and discussion of the results with the broad community provided useful opportunities for self-reflection. Therefore, it can be argued that the results are valid, but additional case studies and further examination by additional researchers are required to prove the findings.

9.2 Future development path and research needs

Numerous future development directions were identified through the involvement of practitioners, continuous exchange with other developers and researchers, and observations from the literature. Additionally, the appearance of new data sets and technologies can stimulate new development directions. Concrete feature requests (see Table 5.5) were identified through user involvement. Furthermore, the bugs and feature requests are collected on the platform Github (GOAT-Community, 2021c). The following list contains several relevant aspects for accessibility instruments in general and offers suggestions of how GOAT should be developed further. The current trends and possible integration in the GOAT are described for each topic.

Realistic walking and cycling networks: Like most accessibility instruments with a walking and cycling mode, the routing network in GOAT is based on OSM. Generally, the OSM street network is considered relatively complete worldwide, particularly in densely populated areas (Barrington-Leigh & Millard-Ball, 2017). However, its completeness is primarily true for the network used by cars. Cyclists and pedestrians typically move alongside their dedicated infrastructure. While the OSM schema allows users to map individual sidewalks or cycleways and sidewalk attributes in many cases this mapping convention is not followed. Accordingly, a mix of separately drawn paths as sidewalks or cycleways and streets drawn for cars, representing the street centerline, is used for the routing implementation. However, the use of street centerlines instead of sidewalks as routing networks can cause significant differences in travel times for pedestrians (Van Eggermond & Erath, 2015). These differences might occur because the various types of street crossings cannot be appropriately modeled in a network of street centerlines. In addition, important quality parameters such as width, smoothness, or curbs typically missing even in densely mapped contexts such as German cities (Mobasheri et al., 2015).
Besides the need for ongoing improvements of OSM, exploring other methods for deriving a sidewalk and cycleway network from the available OSM data and potentially enriching it with additional data is suggested. In GOAT sidewalks were already computed using an offset geometry from the street centerline (Jehle, 2020; Plan4Better GmbH, 2021c). However, the results have not yet been used for routing. Similar strategies were adopted by Naumann and Kovalyov (2017) for routing. Furthermore, through deep learning methods and remote sensing, the availability of sidewalks can be detected from aerial and street view images (Ning et al., 2021).
Another approach conceives streets as areas and models them using polygons instead of lines. Although there are proposals in the OSM community (OpenStreetMap Community, 2021a; 2021b) to model street areas, it remains challenging to map them through manual methods. So far, little adoption of mapping street as areas has been observed. Overall, the presented enhancements for the routing network are essential to making the routing more realistic and customizable for different user groups (e.g.,

wheelchair users, the visually impaired or the elderly).

Multi-modal extension: It was frequently requested that GOAT include accessibility analyses for other modes of travel, particularly public transport and cars. While this dissertation focused on active mobility and local accessibility, it acknowledges the need to include other modes of transport. Therefore, additional accessibility measures and public transport benchmarks could enrich the analyses. Covering public transport would also facilitate to analyze regional accessibility analyses and comparing accessibility by different modes of transport. This extension would make GOAT suitable to be used for more diverse planning questions and situations. In the last several years, multi-modal routing engines have seen significant progress. Among others OpenTripPlanner (Community OpenTripPlanner, 2021), Valhalla (Valhalla Community, 2022), and R5 (Conveyal, 2022a) are frequently used open source multi-modal routing engines.
While public transport schedules were difficult to obtain for many German cities, since 2020, the data has been published as open data for the whole country (Brosi, 2021). Therefore, the greatest challenge might be allowing interactive scenario building for the multi-modal calculation from a technical perspective. The routing developed for GOAT with its dynamic network-building approach cannot be extended without significantly increasing computation time for larger routing networks. Therefore, developing a new routing solution that works outside the database and retains at least parts of the network in its memory is suggested. Loading the routing graph each time from the database should be avoided. Furthermore, it should be explored if existing muti- and intermodal public transport routing engines can be used instead of developing an own solution.

Integration of further opportunity data sets: Diverse opportunity data sets are integrated into GOAT, particularly different sets of POIs and population data. However, users requested the integration of additional data. The most frequently mentioned one was employment data to measure the job accessibility. However, at least in Germany, this data is difficult to get on the needed resolution. One solution could be disaggregating data sourced on the level of municipalities or traffic zones. Furthermore, users frequently requested the integration of socio-demographic attributes as well as population numbers. Thus, it is suggested to extend the developed population disaggregation procedure and explore if it could benefit from common techniques used in population synthesis (Farooq et al., 2013; A. Moreno & Moeckel, 2018; Müller & Axhausen, 2011). Concerning POIs, users requested the integration of additional data on health care, sports, and green spaces. Green spaces were integrated prototypically, but data on green spaces was not always easily accessible. OSM data on green spaces is often inconsistent and public data usually neglects private green spaces (Ludwig et al., 2021). Remote sensing data often lacks the necessary spatial resolution and cannot differentiate between public and private green spaces (Ludwig et al., 2021). Therefore, fusing different data sets could be promising. Accordingly, Ludwig et al. (2021) fused Sentinel-2 imagery with OSM, yielding an overall accuracy of 95%. Besides the data availability, the computation of travel times to and from green spaces might be less trivial than expected. As green spaces are usually polygons, it must be determined whether the green space has specific access points or can be accessed from all sides. In addition, the incorporation of specialized indicators measuring green space accessibility might be necessary.

Validated gravity-based local accessibility measure: As described in Chapter 8.4.1, the currently implemented gravity-based accessibility measure for walking has sensitivity parameters that are not calibrated for the different POIs as suggested in literature (Geurs & van Eck, 2001; Handy & Niemeier, 1997; Iacono et al., 2008). Instead, users can select the sensitivity parameter that suits them best based on their experience. Previous research has indicated that the acceptable travel times to walk to different public transport stops vary based on the type of service (e.g., bus, tram, or metro) (Sarker et al., 2019). Defining acceptable travel times for all POIs and translating them to appropriate sensitivity parameters is challenging. Furthermore, the sensitivity variables might vary between study contexts and population groups (see Chapter 2.2). For the German context, it is suggested to explore the raw data of the mobility household survey "Mobilität in Deutschland" (Nobis & Kuhnimhof, 2018) and supplement missing categories with findings from the literature. Similarly, questionnaires on the acceptable travel times to the different POIs should be conducted.
In addition, thresholds should be defined that categorize the computed gravity-based accessibility into one of the categories from low to high. The currently implemented quantiles could be computed based on a more extensive data set that uses varying spatial typologies to determine suitable thresholds. The first step in this direction was realized in Viertler's master's thesis (Viertler, 2020). Finally, the ultimate goal could be to develop an aggregated "15-Minute City index", which incorporates diverse destinations and allows easy calibration of local study contexts.

Spatio-temporal analyses: Accessibility significantly varies between different times of the day. Past studies have calculated temporal changes in accessibility due to changes in the transport network for both public transport and cars (Boisjoly & El-Geneidy, 2016; Moya-Gómez & Geurs, 2020; Stępniak & Goliszek, 2017). Furthermore, variations in the opportunity data were conducted. For example temporal variations in job densities (Boisjoly & El-Geneidy, 2016) and the availability of grocery stores (Widener et al., 2017) during the day were studied. Furthermore, a prototypical safe-night routing mode that accounted for street illumination was developed for GOAT (Jehle, 2020). Temporal changes in accessibility for different POIs considering opening hours were also computed (Ben Hassine, 2019; Jehle, 2020). Besides variations in the transport network and POIs, Järv et al. (2018) came up with accessibility analyses accounting for the temporal dynamics in the distribution of people throughout day. The temporal variations were computed based on mobile phone data (Järv et al., 2018).
The increasing availability of data could make spatio-temporal analyses more feasible for practice applications. It must also be considered that the spatio-temporal analyses would make tools such as GOAT more complex. In particular, mobile phone data for dynamic populations furthermore could make the tool more expensive to apply. Furthermore, whether concrete planning questions would benefit from spatio-temporal analyses remains unclear. The workshops with the planning practitioners revealed an interest in particular for spatio-temporal analyses for public transport. Beyond the need for ongoing development in this area, it is recommended that the interest and willing-

ness of practice to pay for such analyses is explored in more detail.

Walking flows: Accessibility analyses are limited in predicting mobility behavior. When presenting the tool GOAT to different practitioners, the first expectation was often that the tool should be capable of computing pedestrian flows. The users wanted more that the computation of accessibility measures; they also wanted to know how many people were likely to use a path at any given time. This wish was not unexpected. given that traffic volumes are a common indicator produced by macroscopic transport models. While it is feasible to integrate the capabilities of a transport model, especially for walking and cycling, into GOAT other options should be explored.
The author developed a prototype indicator to identify the most popular routes toward a particular point of interest. The author developed a prototype indicator during a hackathon (Plan4Better GmbH, 2021a) to identify the most popular routes toward a particular point of interest. The development was integrated with the help of another software developer (GOAT-Community, 2022a). The algorithm computes the shortest paths from all residential or workplace locations within a specific catchment area towards a particular destination. The different routes are overlayed in the following map where each route is weighted by the number of persons at the specific starting location. For example Figure 9.1 shows potential pedestrian streams for school children to a selected primary school in Freiburg. Therefore, the indicator provide a valuable starting point for further development.

Figure 9.1: Potential pedestrian flows to primary schools for home-based trips of 6-10-year-old children

Space Syntax provides a series of methods to analyze spatial relations, and the toolkit has been actively used and developed since the 1970s (van Nes & Yamu, 2021). Using Space Syntax among others using axial lines, the main street axis can be identified (van Nes & Yamu, 2021). Furthermore, examples have combined the methodology with accessibility analyses (Ståhle et al., 2005) and agent-based models (Omer & Kaplan, 2017). Another interesting method to identify desired pedestrian paths is the Ant Road Planner (Khodnenko et al., 2018; Smirnov & Gurevich, 2021) developed to design convenient path networks in local neighborhoods. The mentioned examples show the potential to expand accessibility instruments by additional indicators and methods that would shed light on pedestrians' actual or potential use of street spaces.

Integration with existing GIS: Currently GOAT is primarily a technological silo for its users. Despite its ability to import scenarios and export selected calculations, it cannot be integrated easily with existing GIS used. A more powerful integration into existing GIS software is suggested to better integrate existing workflows and databases. For example, by opening APIs according to the standards like WMS and WFS from the Open Geo Spatial Consortium (OGC) (Website OGC, 2022), the different layers and indicators could be integrated into a wide range of existing software. Meanwhile, better integration into existing desktop GIS could be achieved by its integration as a software plugin. It is suggested that a GOAT plugin for QGIS be developed, that allows the direct integration of some of the analyses into the widely used and open desktop GIS.

Built-in documentation: GOAT users frequently requested better documentation of the provided indicators and data. Despite the documentation and tutorials on the project website, users had difficulty finding the relevant sections. Therefore, it is suggested to embed the instructions for using the tool and its indicators into the tool itself. Ideally, GOAT teaches accessibility to practitioners and communicates the potentials and limitations of accessibility. More accessible documentation provides greater transparency and reduces the risk of becoming a black box.

Data strategies: The data supply for accessibility instruments could present an ongoing challenge despite the increased availability of open and new data sets. There are three main paths in terms of data strategies. First, the development of data preparation and fusion steps should be continued. The semi-automatic and automatic refinement of data significantly improved the quality of available data sets.
Second, there is significant potential in using new data sets from remote and social sensing. Remote sensing benefits from improvements in machine learning methods and the increasing availability of very high-resolution satellite imagery. With social sensing, the increasing volumes of big data produced by individuals with devices such as smartphones could be utilized to better understand spatial relations (Liu et al., 2015).
Finally, active contribution to OSM should be continued. The development of methodologies such as the mapping mode in GOAT could improve the effectiveness of collecting data. Moreover, a stronger involvement in the GOAT project and other projects is suggested to strengthen exchange with the OSM community.

The presented future directions are numerous but not complete. At the same time, for the development of GOAT, maintaining and improving the existing features should be prioritized first. Users already recognized the significant potential of GOAT's existing features, but a broader practical application would require a higher maturity of the developed software. Furthermore, the tool's usability still needs improvement, as the user workshops revealed (see Chapter 7.6). Therefore, it is suggested that continuous user tests be conducted, especially if new features are added or existing functions are modified. In this context mockups and prototypes could be used to test different versions of possible changes to the user interface before the actual implementation. Other methods such as session recordings or card sorting could be used to further test the existing and upcoming changes to the user interface. Furthermore, it is suggested to experiment with testing methods that involve eye-tracking. It would also be enriching to explore how cognitive science methods could help in assess and improve the application's usability. It must be ensured that GOAT is appropriately managed as an open source project by enhancing the developer documentation and easing the collaboration of the project.

9.3 Final reflections

This dissertation began with the motivation of contributing to more sustainable development in cities and regions. Despite its success in developing a novel instrument and applying it to real-world planning contexts, it is impossible to say or quantify if the presented research has impacted the sustainability of cities and regions in this study. The slow pace by which changes in the urban and transport system are realized forecloses the immediate success of PSS. The successful development produced a valuable contribution by addressing common challenges for accessibility instruments. Overall, the development was received with positive feedback from practice, and some of the studied municipalities' planned long-term use of GOAT are positive signals that the instrument can actively make a difference. Overall, it can be concluded that a straightforward change of reality through the development of a tool as shown in Figure 1.1 is not realistic. Instead, a more realistic process could be the one shown in Figure 9.2.

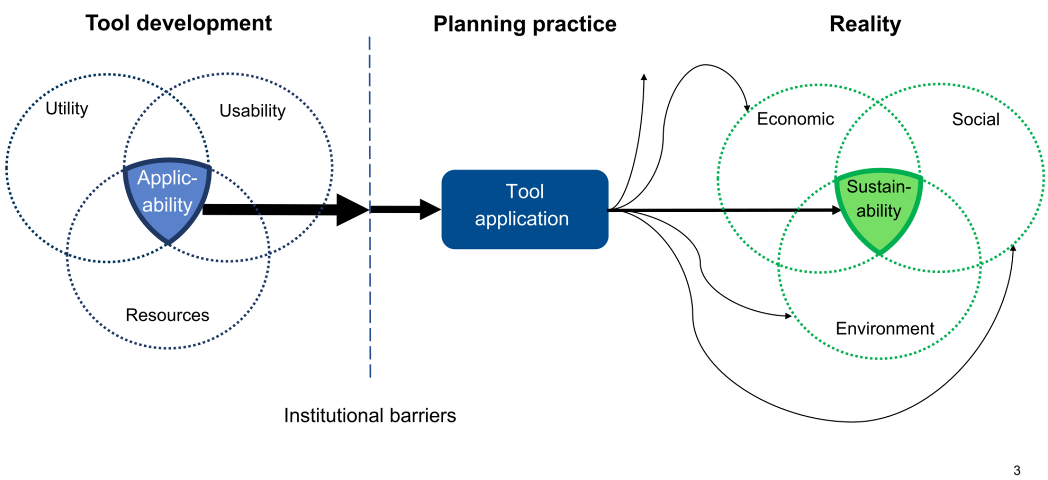

Figure 9.2: Accessibility instruments as a contribution to sustainable development

An applicable accessibility instrument defined by its utility, usability, and required resources still needs to maneuver around potential institutional barriers before being actively applied by the planning practice. Furthermore, even if applied in practice, whether the tool is used to plan sustainable, is still a question. While these reflections might be frustrating at first sight, they should instead encourage upcoming research to focus on addressing the bigger picture. For future development, ongoing exchange with the planning practice should be strengthened to guarantee that the real-world requirements are met. Furthermore, tool developers should actively communicate accessibility and ensure that planning with accessibility instruments contributes to sustainable development.

This thesis aimed to contributed closing the implementation gap in the field of accessibility instruments. It is hoped that the pragmatic development will demonstrate its long-term usefulness, while the interaction with practice facilitated priceless mutual learning and prepared the ground for new adventures.

Bibliography

Accessibility Research Group at the University of Helsinki. (2020a). Mapple Analyst - Helsinki Region. Retrieved November 4, 2020, from https://www.mapple.fi/

Accessibility Research Group at the University of Helsinki. (2020b). Website Accessibility Research Group. Retrieved November 4, 2020, from https://blogs.helsinki.fi/accessibility/

Akiyama, Y., Takada, H., & Shibasaki, R. (2013). Development of Micropopulation Census through Disaggregation of National Population Census. *conference papers*, 31.

Aloi, A., Alonso, B., Benavente, J., Cordera, R., Echániz, E., González, F., Ladisa, C., Lezama-Romanelli, R., López-Parra, Á., Mazzei, V., Perrucci, L., Prieto-Quintana, D., Rodríguez, A., & Sañudo, R. (2020). Effects of the COVID-19 Lockdown on Urban Mobility: Empirical Evidence from the City of Santander (Spain). *Sustainability*, *12*(9), 3870. https://doi.org/10.3390/su12093870

Analytics, C. (2017). *The Ultimate Technical Guide to UrbanFootprint* (tech. rep.). Calthorpe Analytics. Berkley. https://urbanfootprint.com/wp-content/uploads/2017/11/UrbanFootprint-Technical-Guide-v2-3.pdf

Appleyard, B. (2015). New methods to measure the built environment for human-scale travel research: Individual access corridor (IAC) analytics to better understand sustainable active travel choices. *JOURNAL OF TRANSPORT AND LAND USE*, 25. https://doi.org/https://doi.org/10.5198/jtlu.2015.786

Barrington-Leigh, C., & Millard-Ball, A. (2017). The world's user-generated road map is more than 80% complete. *PLOS ONE*, *12*(8), e0180698. https://doi.org/10.1371/journal.pone.0180698

Basemap Ltd. (2022). TRACC Travel Time analysis. Retrieved April 14, 2022, from https://www.basemap.co.uk/tracc/

Bast, H., Storandt, S., & Weidner, S. (2015). Fine-grained population estimation. *Proceedings of the 23rd SIGSPATIAL International Conference on Advances in Geographic Information Systems*, 1–10. https://doi.org/10.1145/2820783.2820828

Batista e Silva, F., Gallego, J., & Lavalle, C. (2013). A high-resolution population grid map for Europe [Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17445647.2013.764 *Journal of Maps*, *9*(1), 16–28. https://doi.org/10.1080/17445647.2013.764830

Bayerisches Landesamt für Statistik. (2015). *Statistische Berichte - Einwohnerzahlen am 31. Dezember 2011* (tech. rep.). Fürth. https://www.statistik.bayern.de/mam/produkte/veroffentlichungen/statistische_berichte/a1200c_201144_41736.pdf

Bayerisches Landesamt für Statistik. (2021). *Statistische Berichte - Einwohnerzahlen am 31. Dezember 2020* (tech. rep.). Fürth. https://www.statistik.bayern.de/mam/produkte/veroffentlichungen/statistische_berichte/a1200c_202044.pdf

Beck, M. J., & Hensher, D. A. (2020). Insights into the impact of COVID-19 on household travel and activities in Australia – The early days of easing restrictions. *Transport Policy*, *99*, 95–119. https://doi.org/10.1016/j.tranpol.2020.08.004

Beckman, R. J., Baggerly, K. A., & McKay, M. D. (1996). Creating synthetic baseline populations. *Transportation Research Part A: Policy and Practice*, *30*(6), 415–429. https://doi.org/10.1016/0965-8564(96)00004-3

Ben Hassine, E. (2019). Bachelorarbeit: Modellierung der fußläufigen Erreichbarkeit im Tagesverlauf.

Ben-Akiva, M., & Stevan R., L. (1979). Disaggregate travel and mobility choice models and measures of accessibility. Hensher, D.A., Sopher, P.R. (Eds.)

Bertolini, L., le Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: A conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy*, *12*(3), 207–220. https://doi.org/10.1016/j.tranpol.2005.01.006

Bertolini, L., & Silva, C. (2019). Bridging the Implementation Gap. *Designing Accessibility Instruments* (1st). Routledge.

Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Gopal, A., Srour, I., & Weston, L. (2002). *Development of an Urban Accessibility Index: Formulations, Aggregation, and Application* (tech. rep.). Texas Department of Transportation. Austin. https://ctr.utexas.edu/wp-content/uploads/pubs/4938_4.pdf

BMDV. (2022). BMDV - Entwicklung eines offenen und interaktiven Erreichbarkeitstools für den Fuß- und Radverkehr auf Basis von Open Data - Geo Open Accessibility Tool (GOAT). Retrieved January 5, 2022, from https://www.bmvi.de/SharedDocs/DE/Artikel/DG/mfund-projekte/GOAT.html

Boisjoly, G., & El-Geneidy, A. (2016). Daily fluctuations in transit and job availability: A comparative assessment of time-sensitive accessibility measures. *Journal of Transport Geography*, *52*, 73–81. https://doi.org/10.1016/j.jtrangeo.2016.03.004

Boisjoly, G., & El-Geneidy, A. M. (2017a). How to get there? A critical assessment of accessibility objectives and indicators in metropolitan transportation plans. *Transport Policy*, *55*, 38–50. https://doi.org/10.1016/j.tranpol.2016.12.011

Boisjoly, G., & El-Geneidy, A. M. (2017b). The insider: A planners' perspective on accessibility. *Journal of Transport Geography*, *64*, 33–43. https://doi.org/10.1016/j.jtrangeo.2017.08.006

Bracken, I., & Martin, D. (1989). The Generation of Spatial Population Distributions from Census Centroid Data [Publisher: SAGE Publications Ltd]. *Environment and Planning A: Economy and Space*, *21*(4), 537–543. https://doi.org/10.1068/a210537

Bracken, I. (1991). A Surface Model Approach to Small Area Population Estimation [Publisher: Liverpool University Press]. *The Town Planning Review*, *62*(2), 225–237. Retrieved December 8, 2020, from https://www.jstor.org/stable/40113020

Britannica, The Editors of Encyclopaedia. (2019). "transportation". https://www.britannica.com/technology/transportation-technology.

Brosi, P. (2021). GTFS.DE - GTFS für Deutschland. Retrieved January 7, 2022, from https://gtfs.de/

Buehler, R., Pucher, J., Gerike, R., & Götschi, T. (2017). Reducing car dependence in the heart of Europe: Lessons from Germany, Austria, and Switzerland. *Transport Reviews*, *37*(1), 4–28. https://doi.org/10.1080/01441647.2016.1177799

Bundesinstitut für Bau-, S. u. R. (i. B. f. B. u. R. ((2019). *Methodische Weiterentwicklungen der Erreichbarkeitsanalysen des BBSR* (tech. rep.). Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR). Bonn. https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/bbsr-online/2019/bbsr-online-09-2019-dl.pdf?__blob=publicationFile&v=3

Büttner, B. (2016). *Consequences of sharp increases in mobility costs on accessibility* (Dissertation). Technische Universität München. München.

Büttner, B., Ji, C., & Wulfhorst, G. (2019). TUM Accessibility Atlas: A Tool for Research and Practice. *Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices* (p. 504). Routledge.

Büttner, B., Kinigadner, J., Ji, C., Wright, B., & Wulfhorst, G. (2018). The TUM Accessibility Atlas: Visualizing Spatial and Socioeconomic Disparities in Accessibility to Support Regional Land-Use and Transport Planning. *Networks and Spatial Economics*, *18*(2), 385–414. https://doi.org/10.1007/s11067-017-9378-6

C40 Cities. (2020). *C40 Mayors' Agenda For a Green and just recovery* (tech. rep.). C40 Cities. https://c40-production-images.s3.amazonaws.com/other_uploads/images/2093_C40_Cities_%282020%29_Mayors_Agenda_for_a_Green_and_Just_Recovery.original.pdf?1594824518

Caset, F., Vale, D. S., & Viana, C. M. (2018). Correction to: Measuring the Accessibility of Railway Stations in the Brussels Regional Express Network: A Node-Place Modeling Approach. *Networks and Spatial Economics*, *18*(3), 531–531. https://doi.org/10.1007/s11067-018-9420-3

Center for Neighborhood Technology. (2020). Website AllTransit. Retrieved November 4, 2020, from https://alltransit.cnt.org/

Charreire, H., Weber, C., Chaix, B., Salze, P., Casey, R., Banos, A., Badariotti, D., Kesse-Guyot, E., Hercberg, S., Simon, C., & Oppert, J.-M. (2012). Identifying built environmental patterns using cluster analysis and GIS: Relationships with walking, cycling and body mass index in French adults, 11. https://doi.org/10.1186/1479-5868-9-59

Chen, H., Wu, B., Yu, B., Chen, Z., Wu, Q., Lian, T., Wang, C., Li, Q., & Wu, J. (2021). A New Method for Building-Level Population Estimation by Integrating LiDAR, Nighttime Light, and POI Data [Publisher: Science Partner Journal]. *Journal of Remote Sensing*, *2021*. https://doi.org/10.34133/2021/9803796

Chesbrough, H. W. (2003). *Open innovation: The new imperative for creating and profiting from technology*. Harvard Business School Press.

Choi, Y., Seo, M. J., & Oh, S. H. (2016). Walkability analysis of Busan's urban residential zones [Number: 6]. *KSCE Journal of Civil Engineering*, *20*(6), 2535–2547. https://doi.org/10.1007/s12205-015-0331-2

Citilabs. (2020). Website Sugar Access - Citilabs. Retrieved November 3, 2020, from https://www.citilabs.com/software/sugar/sugar-access/

Community OpenTripPlanner. (2021). OpenTripPlanner Project. Retrieved December 23, 2021, from https://github.com/opentripplanner
Conveyal. (2022a). Conveyal R5 Routing Engine [original-date: 2015-10-22T13:23:49Z]. Retrieved January 7, 2022, from https://github.com/conveyal/r5
Conveyal. (2022b). Conveyal User Manual. Retrieved November 24, 2020, from https://docs.conveyal.com/
Conveyal. (2022c). Github Conveyal. Retrieved November 24, 2020, from https://github.com/conveyal
Conveyal. (2022d). Website Conveyal. Retrieved November 24, 2020, from https://www.conveyal.com
Couclelis, H. (2000). From Sustainable Transportation to Sustainable Accessibility: Can We Avoid a New Tragedy of the Commons? In D. G. Janelle & D. C. Hodge (Eds.), *Information, Place, and Cyberspace* (pp. 341–356). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-04027-0_20
Crnjak, V. (2020). Github vjeranc/pgrouting [original-date: 2020-05-30T08:01:41Z]. Retrieved November 1, 2020, from https://github.com/vjeranc/pgrouting
Curtis, C., & Scheuer, J. (2019). The SNAMUTS Accessibility Tool in Action: Case Study Adelaide, Australia. *Designing Accessibility Instruments: Lessons on their useability for integrated land use and transport planning practices*. Routledge.
Curtis, C., & Scheurer, J. (2012). Benchmarking public transport accessibility in Australasian cities, 22.
D'Haese, S., Gheysen, F., De Bourdeaudhuij, I., Deforche, B., Van Dyck, D., & Cardon, G. (2016). The moderating effect of psychosocial factors in the relation between neighborhood walkability and children's physical activity [Number: 1]. *International Journal of Behavioral Nutrition and Physical Activity*, *13*(1), 128. https://doi.org/10.1186/s12966-016-0452-0
Dhanani, A., Tarkhanyan, L., & Vaughan, L. (2017). Estimating pedestrian demand for active transport evaluation and planning. *Transportation Research Part A: Policy and Practice*, *103*, 54–69. https://doi.org/10.1016/j.tra.2017.05.020
Diepolder, S. (2020). Bachelorarbeit: Entwicklung eines absoluten Erreichbarkeitsindex für die Nahmobilität.
Dijkstra, E. W. (1959). A Note on Two Problems in Connexion with Graphs, 3. https://doi.org/https://doi.org/10.1007/BF01386390
Dunning, R., & Nurse, A. (2020). Viewpoint The surprising availability of cycling and walking infrastructure through COVID-19, 7. https://doi.org/https://doi.org/10.3828/tpr.2020.35
Dutch Ministry of Infrastructure and Water Management. (2020). Website Mobiliteitsscan [Last Modified: 2020-02-03]. Retrieved November 4, 2020, from https://mobiliteitsscan-info.nl/
Eicher, C. L., & Brewer, C. A. (2001). Dasymetric Mapping and Areal Interpolation: Implementation and Evaluation [Publisher: Taylor & Francis _eprint: https://doi.org/10.1559/15230400178 *Cartography and Geographic Information Science*, *28*(2), 125–138. https://doi.org/10.1559/152304001782173727
El-Geneidy, A., & Levinson, D. (2006). *Access to Destinations: Development of Accessibility Measures* (Final report MN/RC-2006-16). Minnesota Department of

Transportation. Minnesota. https://conservancy.umn.edu/bitstream/handle/11299/638/200616.pdf?sequence=1&isAllowed=y

ESRI. (2020). Job Accessibility | Maps We Love - Esri UK & Ireland. Retrieved November 24, 2020, from https://www.esriuk.com/en-gb/maps-we-love/gallery/job-accessibility

European Comission. (2020). OPEN SOURCE SOFTWARE STRATEGY 2020 – 2023 Think Open. https://ec.europa.eu/info/sites/default/files/en_ec_open_source_strategy_2020-2023.pdf

European Environment Agency. (2020). The first and last mile - the key to sustainable urban transport. Retrieved November 7, 2020, from https://www.eea.europa.eu/publications/the-first-and-last-mile

European Platform on Mobility Management. (2020). TEMS - The EPOMM Modal Split Tool. Retrieved November 3, 2020, from http://www.epomm.eu/tems/

European Union, Copernicus Land Monitoring Service, & European Environment Agency (EEA). (2018). Urban Atlas 2018 — Copernicus Land Monitoring Service. Retrieved June 23, 2021, from https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018

Farooq, B., Bierlaire, M., Hurtubia, R., & Flötteröd, G. (2013). Simulation based population synthesis. *Transportation Research Part B: Methodological*, *58*, 243–263. https://doi.org/10.1016/j.trb.2013.09.012

Federal Office for Building and Regional Planning. (2020). Website Bundesamt für Bauwesen und Raumordnung. Retrieved November 3, 2020, from https://www.bbsr.bund.de/BBSR/DE/forschung/raumbeobachtung/Komponenten/Erreichbarkeitsmodell/erreichbarkeitsmodell.html

FGSV. (2014). *Hinweise zur Nahmobilität: Strategien zur Stärkung des nichtmotorisierten Verkehrs auf Quartiers- und Ortsteilebene* [OCLC: 985731032]. FGSV Verl.

Flügel, S., Hulleberg, N., Fyhri, A., Weber, C., & Ævarsson, G. (2019). Empirical speed models for cycling in the Oslo road network. *Transportation*, *46*(4), 1395–1419. https://doi.org/10.1007/s11116-017-9841-8

Follmer, R., & Belz, J. (2019). *Mobilität in Deutschland – MiD Kurzreport Stadt München, Münchner Umland und MVV-Verbundraum.* (tech. rep.). Studie von infas, DLR, IVT und infas 360 im Auftrag des Bundesministers für Verkehr und digitale Infrastruktur (FE-Nr. 70.904/15). Bonn, Berlin. www.mobilitaet-in-deutschland.de

Footprint, U. (2020). Website Urban Footprint. Retrieved November 3, 2020, from https://urbanfootprint.com/

Forster, B. C. (1985). An examination of some problems and solutions in monitoring urban areas from satellite platforms [Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/01431168508948430]. *International Journal of Remote Sensing*, *6*(1), 139–151. https://doi.org/10.1080/01431168508948430

Frantz, D., Schug, F., Okujeni, A., Navacchi, C., Wagner, W., van der Linden, S., & Hostert, P. (2021). National-scale mapping of building height using Sentinel-1 and Sentinel-2 time series. *Remote Sensing of Environment*, *252*, 112128. https://doi.org/10.1016/j.rse.2020.112128

Free Software Foundation e.V. (2021). Public Money, Public Code. Retrieved December 24, 2021, from https://publiccode.eu/

Galton, F. (1881). On the Construction of Isochronic Passage-Charts. *Proceedings of the Royal Geographical Society and Monthly Record of Geography*, *3*(11), 657. https://doi.org/10.2307/1800138

Garb, J. L., Cromley, R. G., & Wait, R. B. (2007). Estimating Populations at Risk for Disaster Preparedness and Response [Publisher: De Gruyter Section: Journal of Homeland Security and Emergency Management]. *Journal of Homeland Security and Emergency Management*, *4*(1). https://doi.org/10.2202/1547-7355.1280

Geertman, S. (2006). Potentials for Planning Support: A Planning-Conceptual Approach. *Environment and Planning B: Planning and Design*, *33*(6), 863–880. https://doi.org/10.1068/b31129

Geertman, S., Allan, A., Pettit, C., & Stillwell, J. (2017a). Chapter 1 Introduction to 'Planning Support Science for Smarter Urban Futures' [doi: 10.1007/978-3-319-57819-4_1]. *Planning Support Science for Smarter Urban Futures* (pp. 1–19). Springer.

Geertman, S., Allan, A., Pettit, C., & Stillwell, J. (2017b). *Planning Support Science for Smarter Urban Futures*. Springer Nature.

Geertman, S., & Stillwell, J. (2020). Planning support science: Developments and challenges. *Urban Analytics and City Science*, *47*(8), 1326–1342. https://doi.org/10.1177/2399808320936277

Geertman, S., Stillwell, J., & Toppen, F. (2013). Introduction to 'Planning Support Systems for Sustainable Urban Development' [10.1007/978-3-642-37533-0_1]. *Planning Support Systems for Sustainable Urban Development*. Springer.

Geisser, P., & Lenk, S. (2017). *Grau, Grün und Blau – die Bodennutzung in München* (tech. rep.). Statistisches Amt der Landeshauptstadt München. München. https://www.muenchen.de/rathaus/dam/jcr%3A93314652-5c20-4bea-b303-f2eb3160526a/MueSta_4_17_Grau%2CGruen%2520und%2520Blau_die%2520Bodennutzung%2520in%2520Muenchen.pdf

Geofabrik. (2020). Geofabrik Download Server. Retrieved November 4, 2020, from http://download.geofabrik.de/

Geofabrik GmbH Karlsruhe. (2021). GeoFabrik. Retrieved June 23, 2021, from http://www.geofabrik.de/

Geurs, K., & van Eck, R. (2001). *Accessibility measures: Review and applications* (tech. rep. RIVM Report 408505 006). http://www.rivm.nl/bibliotheek/rapporten/408505006.pdf

Geurs, K., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, *12*(2), 127–140. https://doi.org/10.1016/j.jtrangeo.2003.10.005

Geurs, K., & Wee, B. (2013). Accessibility: Perspectives, measures and applications. *Accessibility: Perspectives, measures and applications. In B. van Wee, J. A. Annema, & D. Banister (Eds.), The transport system and transport policy: An introduction (pp. 207-226).* (pp. 207–226). Edward Elgar.

Giduthuri, V. K. (2015). Sustainable Urban Mobility: Challenges, Initiatives and Planning. *Current Urban Studies*, *03*(03), 261–265. https://doi.org/10.4236/cus.2015.33022

GOAT-Community. (2020a). Goat-community/pgrouting [original-date: 2020-08-14T12:35:02Z]. Retrieved July 24, 2021, from https://github.com/goat-community/pgrouting

GOAT-Community. (2020b). State of the map poster GOAT - Plan sustainable cities with GOAT and OSM data. https://2020.stateofthemap.org/posters/poster-goat.pdf

GOAT-Community. (2021a). Data Preparation. Retrieved August 25, 2021, from https://www.open-accessibility.org/docs/data_preparation/

GOAT-Community. (2021b). GOAT Population Source Code [original-date: 2018-09-30T11:09:17Z]. Retrieved July 4, 2021, from https://github.com/goat-community/goat/tree/hackathon/app/database/data_preparation/SQL/population

GOAT-Community. (2021c). GOAT Repository [original-date: 2018-09-30T11:09:17Z]. Retrieved July 4, 2021, from https://github.com/goat-community/goat

GOAT-Community. (2021d). GOAT Repository [original-date: 2018-09-30T11:09:17Z]. Retrieved July 4, 2021, from https://github.com/goat-community/goat

GOAT-Community. (2021e). Homepage Open Accessibility. Retrieved August 10, 2021, from https://open-accessibility.org/

GOAT-Community. (2022a). Algorithm potential pedestrian streams [original-date: 2018-09-30T11:09:17Z]. Retrieved January 8, 2022, from https://github.com/goat-community/goat/blob/b69a57e9a0b419389425bc84a7d3824889782134/app/database/database_functions/walkability/potential_flows_v2.sql

GOAT-Community. (2022b). Github-Account GOAT-Community. Retrieved August 11, 2021, from https://github.com/goat-community

Goodchild, M., & Lam, N. S.-N. (1980). Areal interpolation: A variant of the traditional spatial problem. *Geo-Processing*, *1*, 29–312.

Gorrini, A., & Bandini, S. (2019). Elderly Walkability Index through GIS: Towards Advanced AI-based Simulation Models. *CEUR Workshop Proceedings*, *2333*, 67–82.

Gould, P. (1969). Spatial Diffusion Commission on College Geography. (Association of American Geographers - Washington, DC). https://files.eric.ed.gov/fulltext/ED120029.pdf

Graser, A. (2016). Integrating Open Spaces into OpenStreetMap Routing Graphs for Realistic Crossing Behaviour in Pedestrian Navigation. *GI_Forum*, *4*(1), 217–230. https://doi.org/10.1553/giscience2016_01_s217

Grudin, J. (1992). Utility and usability: Research issues and development contexts. *Interacting with Computers*, *4*(2), 209–217. https://doi.org/10.1016/0953-5438(92)90005-Z

Hackl, R., Raffler, C., Friesenecker, M., Kramar, H., Kalasek, R., Soteropoulos, A., Wolf-Eberl, S., Posch, P., & Tomschy, R. (2019). Promoting active mobility: Evidence-based decision-making using statistical models. *Journal of Transport Geography*, *80*, 102541. https://doi.org/10.1016/j.jtrangeo.2019.102541

Hägerstrand, T. (1970). What about people in Regional Science? *Papers of the Regional Science Association*, *24*(1), 6–21. https://doi.org/10.1007/BF01936872

Hahmann, S., Miksch, J., Resch, B., Lauer, J., & Zipf, A. (2018). Routing through open spaces – A performance comparison of algorithms. *Geo-spatial Information Science*, *21*(3), 247–256. https://doi.org/10.1080/10095020.2017.1399675

Haklay, M., & Tobón, C. (2003). Usability evaluation and PPGIS: Towards a user-centred design approach. *International Journal of Geographical Information Science*, *17*(6), 577–592. https://doi.org/10.1080/1365881031000114107

Hall, C. M., & Ram, Y. (2018). Walk score® and its potential contribution to the study of active transport and walkability: A critical and systematic review. *Transportation Research Part D: Transport and Environment*, *61*, 310–324. https://doi.org/10.1016/j.trd.2017.12.018

Hamburg, M. (2017). *Leitprojekt Regionale Erreichbarkeitsanalysen - Abschlussbericht und Erreichbarkeitsatlas* (tech. rep.). Metropolregion Hamburg. Hamburg.

Hamburg, M. (2020). Geoportal der Metropolregion Hamburg. Retrieved November 4, 2020, from http://geoportal.metropolregion.hamburg.de/mrh_erreichbarkeitsanalysen/

Handy, S. (1993). Regional Versus Local Accessibility: Implications for Nonwork Travel. Retrieved June 4, 2022, from https://escholarship.org/uc/item/2z79q67d

Handy, S. (2002). Accessibility- vs. mobility-enhancing strategies for addressing automobile dependence in the U.S., 34. https://escholarship.org/content/qt5kn4s4pb/qt5kn4s4pb.pdf?t=krnetj

Handy, S. (2020). Is accessibility an idea whose time has finally come? *Transportation Research Part D: Transport and Environment*, *83*, 102319. https://doi.org/10.1016/j.trd.2020.102319

Handy, S., & Niemeier, D. A. (1997). Measuring Accessibility: An Exploration of Issues and Alternatives. *Environment and Planning A: Economy and Space*, *29*(7), 1175–1194. https://doi.org/10.1068/a291175

Hanekamp, G. (2021). *Evaluate the Walking AccessibilitytoPublic Transport inMunich and Atlanta Using Accessibility Tools* (Study Project).

Hansen, W. (1959). *Accessibility & Residential Growth* (Doctoral dissertation). Massachusets Institute of Technology (MIT).

Harris, B. (1989). Beyond Geographic Information Systems. *Journal of the American Planning Association*, *55*(1), 85–90. https://doi.org/10.1080/01944368908975408

Higgins, C. D. (2019). Accessibility Toolbox for R and ArcGIS. *Findings*, 8416. https://doi.org/10.32866/8416

Hofstee, P., Islam, M., & Ltd, G. (2004). Disaggregation of Census Districts: Better Population Information for Urban Risk Management, 6.

Huang, Z., Ottens, H., & Masser, I. (2007). A Doubly Weighted Approach to Urban Data Disaggregation in GIS: A Case Study of Wuhan, China [_eprint: https://onlinelibrary.wiley.com/doi/pdf/1 9671.2007.01041.x]. *Transactions in GIS*, *11*(2), 197–211. https://doi.org/https://doi.org/10.1111/j.1467-9671.2007.01041.x

Hull, A., Bertolini, L., & Silva, C. (2012). *Accessibility Instruments for Planning Practice* [OCLC: 1025996720]. Heriot-Watt University ; Porto : Departament of Geography Planning; International Development Studies Faculty of Engineering of Oporto University ; Amsterdam :

Humberto, M., Pizzol, B., Moura, F., Giannotti, M., & de Lucca-Silveira, M. P. (2020). Investigating the Mobility Capabilities and Functionings in Accessing Schools Through Walking: A Quantitative Assessment of Public and Private Schools in São Paulo (Brazil) [Number: 2]. *Journal of Human Development and Capabilities*, *21*(2), 183–204. https://doi.org/10.1080/19452829.2020.1745163

Iacono, M., Krizek, K., & El-Geneidy, A. (2008). *Access to Destinations: How Close is Close Enough? Estimating Accurate Distance Decay Functions for Multiple Modes and Different Purposes* (tech. rep.). Minnesota Department of Transportation. https://hdl.handle.net/11299/151329

Iacono, M., Krizek, K. J., & El-Geneidy, A. (2010). Measuring non-motorized accessibility: Issues, alternatives, and execution. *Journal of Transport Geography*, *18*(1), 133–140. https://doi.org/10.1016/j.jtrangeo.2009.02.002

IEA. (2021). *Global EV Outlook 2021* (tech. rep.). IEA. Paris. https://www.iea.org/reports/global-ev-outlook-2021

Ingram, D. (1971). The concept of accessibility: A search for an operational form. *Regional Studies*, *5*(2), 101–107. https://doi.org/10.1080/09595237100185131

ISO. (2018). ISO 9241-11:2018(en), Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts. Retrieved October 31, 2021, from https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-2:v1:en

ITDP. (2018). *Pedestrians First - Tools for a walkable city* (tech. rep.). Institute for Transportation and Development Policy. New York. Retrieved November 23, 2020, from https://www.itdp.org/publication/walkability-tool/

ITDP. (2020). Github Pedestriansfirst [original-date: 2019-11-08T19:41:56Z]. Retrieved November 23, 2020, from https://github.com/ITDP/pedestriansfirst

Ivanov, G. (2021). Master thesis : Development of novel data fusion strategies and walkability indicators using the interactive accessibility instrument GOAT in San Pedro Garza García (Mexico).

Jain, D., & Tiwari, G. (2017). Population disaggregation to capture short trips – Vishakhapatnam, India. *Computers, Environment and Urban Systems*, *62*, 7–18. https://doi.org/10.1016/j.compenvurbsys.2016.10.003

Järv, O., Tenkanen, H., Salonen, M., Ahas, R., & Toivonen, T. (2018). Dynamic cities: Location-based accessibility modelling as a function of time. *Applied Geography*, *95*, 101–110. https://doi.org/10.1016/j.apgeog.2018.04.009

Jehle, U. (2020). Master thesis: Incorporating the four accessibility components into an interactive accessibility instrument.

Jiang, H., Geertman, S., & Witte, P. (2020). Avoiding the planning support system pitfalls? What smart governance can learn from the planning support system implementation gap. *Environment and Planning B: Urban Analytics and City Science*, *47*(8), 1343–1360. https://doi.org/10.1177/2399808320934824

Kahlmeier, S., Boig, E. A., Castro, A., Smeds, E., Benvenuti, F., Eriksson, U., Iacorossi, F., Nieuwenhuijsen, M. J., Panis, L. I., Rojas-Rueda, D., Wegener, S., & de Nazelle, A. (2021). Assessing the Policy Environment for Active Mobility in Cities—Development and Feasibility of the PASTA Cycling and Walking Policy Environment Score. *International Journal of Environmental Research and Public Health*, *18*(3), 986. https://doi.org/10.3390/ijerph18030986

Kahlmeier, S., Götschi, T., Cavill, N., Castro Fernandez, A., Brand, C., Rojas Rueda, D., Woodcock, J., Kelly, P., Lieb, C., Oja, P., Foster, C., Rutter, H., & Racioppi, F. (2017). Health economic assessment tool (HEAT) for walking and for cycling. methods and user guide on physical activity, air pollution, injuries and carbon impact assessments [Publisher: World Health Organization, Regional Office for Europe]. https://doi.org/10.5167/UZH-151107

Kang, C.-D. (2015). The effects of spatial accessibility and centrality to land use on walking in Seoul, Korea. *Cities*, *46*, 94–103. https://doi.org/10.1016/j.cities.2015.05.006

Kang, J., Körner, M., Wang, Y., Taubenböck, H., & Zhu, X. X. (2018). Building instance classification using street view images. *ISPRS Journal of Photogrammetry and Remote Sensing*, *145*, 44–59. https://doi.org/10.1016/j.isprsjprs.2018.02.006

Khodnenko, I., Kudinov, S., & Smirnov, E. (2018). Walking distance estimation using multi-agent simulation of pedestrian flows. *Procedia Computer Science*, *136*, 489–498. https://doi.org/10.1016/j.procs.2018.08.256

Kinigadner, J. H. (2020). *Carbon-based accessibility analysis* (Dissertation). Technische Universität München. München.

Kliemann, L., & Sanders, P. (Eds.). (2016). *Algorithm Engineering: Selected Results and Surveys* (Vol. 9220). Springer International Publishing. https://doi.org/10.1007/978-3-319-49487-6

Klosterman, R. E. (1997). Planning Support Systems: A New Perspective on Computer-Aided Planning. *Journal of Planning Education and Research*, *17*(1), 45–54. https://doi.org/10.1177/0739456X9701700105

Koenig, J. G. (1980). Indicators of urban accessibility: Theory and application. *Transportation*, *9*(2), 145–172. https://doi.org/10.1007/BF00167128

Korsaa, M., Olesen, R., & Vinter, O. (2002). *Iterative Software Development, A Practical View* (Abridged version). Software Technology Forum. Hørsholm (Denmark). http://www.ottovinter.dk/df-16a.pdf

Koszowski, C., Gerike, R., Hubrich, S., Götschi, T., Pohle, M., & Wittwer, R. (2019a). Active Mobility: Bringing Together Transport Planning, Urban Planning, and Public Health. In B. Müller & G. Meyer (Eds.), *Towards User-Centric Transport in Europe: Challenges, Solutions and Collaborations* (pp. 149–171). Springer International Publishing. https://doi.org/10.1007/978-3-319-99756-8_11

Koszowski, C., Gerike, R., Hubrich, S., Götschi, T., Pohle, M., & Wittwer, R. (2019b). Active Mobility: Bringing Together Transport Planning, Urban Planning, and Public Health. In B. Müller & G. Meyer (Eds.), *Towards User-Centric Transport in Europe* (pp. 149–171). Springer International Publishing. https://doi.org/10.1007/978-3-319-99756-8_11

Kwan, M.-P. (1998). Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework. *Geographical Analysis*, *30*(3), 191–216. https://doi.org/10.1111/j.1538-4632.1998.tb00396.x

Landesamt für Digitalisierung Breitband und Vermessung. (n.d.). Bayerische Vermessungsverwaltung - Produkte - ALKIS/Katasterauszüge - Hausumringe. Retrieved June 26, 2021, from https://www.ldbv.bayern.de/produkte/kataster/hausumringe.html

Landesamt für Digitalisierung Breitband und Vermessung. (2020). Bayerische Vermessungsverwaltung - Produkte - ATKIS Basis-DLM. Retrieved June 26, 2021, from https://www.ldbv.bayern.de/produkte/atkis-basis-dlm.html

Langford, M., Unwin, D., & Maguire, D. (1990). *Generating improved population density maps in an integrated GIS*.

Larman, C., & Basili, V. (2003). Iterative and Incremental Development: A Brief History. *Computer*, *36*, 47–56. https://doi.org/10.1109/MC.2003.1204375

Laverty, A. A., Millett, C., Majeed, A., & Vamos, E. P. (2020). COVID-19 presents opportunities and threats to transport and health. *Journal of the Royal Society of Medicine*, *113*(7), 251–254. https://doi.org/10.1177/0141076820938997

Leao, S. Z., Huynh, N., Taylor, A., Pettit, C., & Perez, P. (2017). Chapter 22 Evolution of a Synthetic Population and Its Daily Mobility Patterns Under Spatial Strategies for Urban Growth [doi: 10.1007/978-3-319-57819-4_22]. *Planning Support Science for Smarter Urban Futures* (pp. 399–417). Springer.

Levine, J. (2019). Accessibility as the Foundation for Transport and Land-Use Planning Practice. *Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices* (1st, p. 17). Routledge.

Levine, J., Grengs, J., Shen, Q., & Shen, Q. (2012). Does Accessibility Require Density or Speed?: A Comparison of *Fast* Versus *Close* in Getting Where You Want to Go in U.S. Metropolitan Regions. *Journal of the American Planning Association*, *78*(2), 157–172. https://doi.org/10.1080/01944363.2012.677119

Li, M., Koks, E., Taubenböck, H., & van Vliet, J. (2020). Continental-scale mapping and analysis of 3D building structure. *Remote Sensing of Environment*, *245*, 111859. https://doi.org/10.1016/j.rse.2020.111859

Li, X., Zhou, Y., Gong, P., Seto, K. C., & Clinton, N. (2020). Developing a method to estimate building height from Sentinel-1 data. *Remote Sensing of Environment*, *240*, 111705. https://doi.org/10.1016/j.rse.2020.111705

Liu, Y., Liu, X., Gao, S., Gong, L., Kang, C., Zhi, Y., Chi, G., & Shi, L. (2015). Social Sensing: A New Approach to Understanding Our Socioeconomic Environments. *Annals of the Association of American Geographers*, *105*(3), 512–530. https://doi.org/10.1080/00045608.2015.1018773

Ltd, B. (2020). Transforming Travel Time Analysis - Basemap. Retrieved November 3, 2020, from https://www.basemap.co.uk/

Lu, Z., Im, J., Rhee, J., & Hodgson, M. (2014). Building type classification using spatial and landscape attributes derived from LiDAR remote sensing data. *Landscape and Urban Planning*, *130*, 134–148. https://doi.org/10.1016/j.landurbplan.2014.07.005

Ludwig, C., Hecht, R., Lautenbach, S., Schorcht, M., & Zipf, A. (2021). Mapping Public Urban Green Spaces Based on OpenStreetMap and Sentinel-2 Imagery Using Belief Functions. *ISPRS International Journal of Geo-Information*, *10*(4), 251. https://doi.org/10.3390/ijgi10040251

Luque-Martın, I., & Pfeffer, K. (2020). Limitations and potential of panning support systems application in planning in Southern Spain: Bridging academia and practice. *Handbook of Planning Support Science*.

Majk Shkurti. (2022). Github Majk Shkurti. Retrieved June 21, 2022, from https://github.com/majkshkurti

Mapbox. (2016). Concaveman - A very fast 2D concave hull algorithm in JavaScript (generates a general outline of a point set). [original-date: 2016-02-10T11:30:34Z]. Retrieved November 1, 2020, from https://github.com/mapbox/concaveman

Massachusetts Institute of Technology. (2020). Website CoAXs. Retrieved November 24, 2020, from http://coaxs.scripts.mit.edu/home/

McCormack, G. R., Cerin, E., Leslie, E., Du Toit, L., & Owen, N. (2008). Objective Versus Perceived Walking Distances to Destinations: Correspondence and Predictive Validity. *Environment and Behavior*, *40*(3), 401–425. https://doi.org/10.1177/0013916507300560

Meng, L., Allan, A., & Somenahalli, S. (2017). Chapter 15 Investigating Theoretical Development for Integrated Transport and Land Use Modelling Systems [doi: 10.1007/978-3-319-57819-4_15]. *Planning Support Science for Smarter Urban Futures* (pp. 263–278). Springer.

Mennis, J. (2003). Generating Surface Models of Population Using Dasymetric Mapping [Publisher: Routledge _eprint: https://www.tandfonline.com/doi/pdf/10.1111/0033-0124.10042]. *The Professional Geographer*, *55*(1), 31–42. https://doi.org/10.1111/0033-0124.10042

Mennis, J. (2009). Dasymetric Mapping for Estimating Population in Small Areas [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1749-8198.2009.00220.x]. *Geography Compass*, *3*(2), 727–745. https://doi.org/https://doi.org/10.1111/j.1749-8198.2009.00220.x

Meyer, M. D., & Miller, E. J. (1984). Urban Transportation Planning: A decision-oriented approach. Retrieved November 28, 2021, from https://trid.trb.org/view/207171

mitTransportAnalys. (2020). Github mitTransportAnalys. Retrieved November 24, 2020, from https://github.com/mitTransportAnalyst

Mobasheri, A., Bakillah, M., Rousell, A., Hahmann, S., & Zipf, A. (2015). On the completeness of sidewalk information in OpenStreetMap, a case study of Germany, 3.

Moeckel, R., Spiekermann, K., & Wegener, M. (2003). Creating a Synthetic Population, 18.

Monteiro, J., Martins, B., Murrieta-Flores, P., & Pires, J. M. (2019). Spatial Disaggregation of Historical Census Data Leveraging Multiple Sources of Ancillary Information [Number: 8 Publisher: Multidisciplinary Digital Publishing Institute]. *ISPRS International Journal of Geo-Information*, *8*(8), 327. https://doi.org/10.3390/ijgi8080327

Monteiro, J., Martins, B., & Pires, J. M. (2018). A hybrid approach for the spatial disaggregation of socio-economic indicators. *International Journal of Data Science and Analytics*, *5*(2), 189–211. https://doi.org/10.1007/s41060-017-0080-z

Moreno, A., & Moeckel, R. (2018). Population Synthesis Handling Three Geographical Resolutions. *ISPRS International Journal of Geo-Information*, *7*(5), 174. https://doi.org/10.3390/ijgi7050174

Moreno, C., Allam, Z., Chabaud, D., Gall, C., & Pratlong, F. (2021). Introducing the “15-Minute City”: Sustainability, Resilience and Place Identity in Future Post-Pandemic Cities. *Smart Cities*, *4*(1), 93–111. https://doi.org/10.3390/smartcities4010006

Moya-Gómez, B., & Geurs, K. (2020). The spatial–temporal dynamics in job accessibility by car in the Netherlands during the crisis. *Regional Studies*, *54*(4), 527–538. https://doi.org/10.1080/00343404.2018.1538554

Müller, K., & Axhausen, K. W. (2011). Hierarchical IPF: Generating a synthetic population for Switzerland, 22.

Munichways. (2021). Website Munichways. Retrieved September 25, 2021, from https://www.munichways.de/

Munir, H., Linåker, J., Wnuk, K., Runeson, P., & Regnell, B. (2018). Open innovation using open source tools: A case study at Sony Mobile. *Empirical Software Engineering*, *23*(1), 186–223. https://doi.org/10.1007/s10664-017-9511-7

Munoz Nieto, R. L. (2020). Master thesis: Walking accessibility, equity and travel behavior assessment in Bogotá-Colombia using an interactive accessibility instrument.

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., & Jaedicke, C. (2006). Global landslide and avalanche hotspots. *Landslides*, *3*(2), 159–173. https://doi.org/10.1007/s10346-006-0036-1

Naumann, S., & Kovalyov, M. Y. (2017). Pedestrian Route Search Based on OpenStreetMap. In G. Sierpiński (Ed.), *Intelligent Transport Systems and Travel Behaviour* (pp. 87–96). Springer International Publishing. https://doi.org/10.1007/978-3-319-43991-4_8

Nebiyou, N., Yin, S., & Li, M. (2016). *The Metropolitan Chicago Accessibility Explorer* (tech. rep.). University of Illinois at Chicago. Chicago. http://urbanaccessibility.com/accessibility/final_report.pdf

Nielsen, J. (1994). *Usability Engineering* [Google-Books-ID: 95As2OF67f0C]. Morgan Kaufmann.

Ning, H., Ye, X., Chen, Z., Liu, T., & Cao, T. (2021). Sidewalk extraction using aerial and street view images. *Environment and Planning B: Urban Analytics and City Science*, 239980832199581. https://doi.org/10.1177/2399808321995817

Nobis, C., & Kuhnimhof, T. (2018). *Mobilität in Deutschland 2017 - Ergebnisbericht* (Ergebnisbericht Mobilität in Deutschland - MiD Ergebnisbericht). Studie von infas, DLR, IVT und infas 360 im Auftrag des Bundesministers für Verkehr und digitale Infrastruktur (FE-Nr. 70.904/15). Bonn, Berlin. www.mobilitaet-in-deutschland.de

Nourian, P., Rezvani, S., Valeckaite, K., & Sariyildiz, S. (2018). Modelling walking and cycling accessibility and mobility: The effect of network configuration and occupancy on spatial dynamics of active mobility. *Smart and Sustainable Built Environment*, *7*(1), 101–116. https://doi.org/10.1108/SASBE-10-2017-0058

Oki, T., & Osaragi, T. (2017). Chapter 25 Urban Improvement Policies for Reducing Human Damage in a Large Earthquake by Using Wide-Area Evacuation Simulation Incorporating Rescue and Firefighting by Local Residents [doi: 10.1007/978-3-319-57819-4_25]. *Planning Support Science for Smarter Urban Futures* (pp. 449–468). Springer.

Omer, I., & Kaplan, N. (2017). Using space syntax and agent-based approaches for modeling pedestrian volume at the urban scale. *Computers, Environment and Urban Systems*, *64*, 57–67. https://doi.org/10.1016/j.compenvurbsys.2017.01.007

Open Geospatial Consortium. (2022). The Home of Location Technology Innovation and Collaboration | OGC. Retrieved April 16, 2022, from https://www.ogc.org/

Openshaw, S. (1981). The modifiable areal unit problem [Publisher: Routledge and Kegan Paul, Andover]. *Quantitative geography: a British view*, 60–69. Retrieved January 7, 2021, from https://ci.nii.ac.jp/naid/10003011548/

OpenStreetMap Community. (2020). Overpass API User's Manual. Retrieved November 4, 2020, from https://dev.overpass-api.de/overpass-doc/en/

OpenStreetMap Community. (2021a). Key:area:highway – OpenStreetMap Wiki. Retrieved January 7, 2022, from https://wiki.openstreetmap.org/wiki/Key:area:highway

OpenStreetMap Community. (2021b). Proposed features/Street area – OpenStreetMap Wiki. Retrieved January 7, 2022, from https://wiki.openstreetmap.org/wiki/Proposed_features/Street_area

OpenStreetMap Foundation. (2021). Stats – OpenStreetMap Wiki. Retrieved December 31, 2021, from https://wiki.openstreetmap.org/wiki/Stats

Osaragi, T., & Noriaki, H. (2017). Chapter 5 A Decision Support System for Fighting Multiple Fires in Urban Areas Caused by Large Earthquakes [doi: DOI 10.1007/978-3-319-57819-4_5]. *Planning Support Science for Smarter Urban Futures* (pp. 77–93). Springer.

Páez, A., Scott, D. M., & Morency, C. (2012). Measuring accessibility: Positive and normative implementations of various accessibility indicators. *Journal of Transport Geography*, *25*, 141–153. https://doi.org/10.1016/j.jtrangeo.2012.03.016

Pajares, E. (2017). Master Thesis: Development of an interactive accessibility web-tool on the neighborhood level for the city of Munich.

Pajares, E. (2019). Development of an interactive web application for accessibility modelling on the neighborhood level. *Transportation Research Procedia*, *41*, 621–624. https://doi.org/10.1016/j.trpro.2019.09.111

Pajares, E., Büttner, B., Jehle, U., Nichols, A., & Wulfhorst, G. (2021). Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility. *Journal of Transport Geography*, *93*, 103080. https://doi.org/10.1016/j.jtrangeo.2021.103080

Pajares, E., Muñoz Nieto, R., Meng, L., & Wulfhorst, G. (2021). Population Disaggregation on the Building Level Based on Outdated Census Data. *ISPRS International Journal of Geo-Information*, *10*(10), 662. https://doi.org/10.3390/ijgi10100662

Papa, E., Silva, C., te Brömmelstroet, M., & Hull, A. (2015). Accessibility instruments for planning practice: A review of European experiences. *The Journal of Transport and Land Use*, *9*(3), 57–75. https://doi.org/10.5198/jtlu.2015.585

Park, J.-S., & Oh, S.-J. (2011). A New Concave Hull Algorithm and Concaveness Measure for n-dimensional Datasets, 14. https://doi.org/https://doi.org/10.6688/JISE.2012.28.3.10

Penck, A. (1889). Isochronenkarte der österreichisch-ungarischen Monarchie.

Peter, M. (2017). *Bedienhinweise - Das Erreichbarkeitsportalder Metropolregion Hamburg* (tech. rep.). Technische Universität Hamburg. Hamburg. https://www.daten-hamburg.de/zz_sonstiges/MRH/erreichbarkeitsanalysen/bedienungshinweise.pdf

Pettit, C., Biermann, S., Pelizaroc, C., & Bakelmun, A. (2020). A Data-Driven Approach to Exploring Future Land Use and Transport Scenarios: The Online What If? Tool. *Journal of Urban Technology*, *27*(2), 21–44. https://doi.org/10.1080/10630732.2020.1739503

pgRouting Community. (2022). pgRouting Project — Open Source Routing Library. Retrieved November 1, 2020, from https://pgrouting.org/

Plan4Better GmbH. (2021a). Hackathon: Development of a Walkability Index | Plan4Better. Retrieved January 8, 2022, from https://plan4better.de/en/posts/2021-04-06-walkability-index/

Plan4Better GmbH. (2021b). Homepage Plan4Better GmbH. Retrieved August 11, 2021, from https://plan4better.de/

Plan4Better GmbH. (2021c). Project WALKIE successfully completed | Plan4Better. Retrieved January 7, 2022, from https://plan4better.de/en/posts/2021-08-06-walkie/

Plan4Better GmbH. (2021d). Technical Architecture GOAT. Retrieved July 2, 2021, from https://plan4better.de/docs/technicalarchitecture/

Pozoukidou, G., & Chatziyiannaki, Z. (2021). 15-Minute City: Decomposing the New Urban Planning Eutopia. *Sustainability*, *13*(928), 25. https://doi.org/https://doi.org/10.3390/su13020928

Prahalad, C., & Ramaswamy, V. (2004). Co-creation experiences: The next practice in value creation. *Journal of Interactive Marketing*, *18*(3), 5–14. https://doi.org/10.1002/dir.20015

Qiu, Y., Zhao, X., Fan, D., & Li, S. (2019). Geospatial Disaggregation of Population Data in Supporting SDG Assessments: A Case Study from Deqing County, China [Number: 8 Publisher: Multidisciplinary Digital Publishing Institute]. *ISPRS International Journal of Geo-Information*, *8*(8), 356. https://doi.org/10.3390/ijgi8080356

Rauch, S., Taubenböck, H., Knopp, C., & Rauh, J. (2021). Risk and space: Modelling the accessibility of stroke centers using day- & nighttime population distribution and different transportation scenarios. *International Journal of Health Geographics*, *20*(1), 31. https://doi.org/10.1186/s12942-021-00284-y

Rode, P. (2013). Trends and Challenges: Global Urbanisation and Urban Mobility [Series Title: Lecture Notes in Mobility]. In Institute for Mobility Research (Ed.), *Megacity Mobility Culture* (pp. 3–21). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-34735-1_1

Rosina, K., Silva, F. B. e., Vizcaino, P., Herrera, M. M., Freire, S., & Schiavina, M. (2020). Increasing the detail of European land use/cover data by combining heterogeneous data sets. *International Journal of Digital Earth*, *13*(5), 602–626. https://doi.org/10.1080/17538947.2018.1550119

Russo, P., Lanzilotti, R., Costabile, M., & Pettit, C. (2017). Towards satisfying practitioners in using Planning Support Systems. *Computers, Environment, and Urban Systems*, *67*, 9–20. https://doi.org/https://doi.org/10.1016/j.compenvurbsys.2017.08.009

Ryan, J., & Pereira, R. H. (2021). What are we missing when we measure accessibility? Comparing calculated and self-reported accounts among older people. *Journal of Transport Geography*, *93*, 103086. https://doi.org/10.1016/j.jtrangeo.2021.103086

Sarker, R. I., Mailer, M., & Sikder, S. K. (2019). Walking to a public transport station: Empirical evidence on willingness and acceptance in Munich, Germany. *Smart and Sustainable Built Environment*, *9*(1), 38–53. https://doi.org/10.1108/SASBE-07-2017-0031

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J., & Gehlert, T. (2017). The German Naturalistic Cycling Study – Comparing cycling speed of riders of different e-bikes and conventional bicycles. *Safety Science*, *92*, 290–297. https://doi.org/10.1016/j.ssci.2015.07.027

Schott, M. (2020). Study project: Finding optimal locations for shared mobility stations.

Schug, F., Frantz, D., Linden, S. v. d., & Hostert, P. (2021). Gridded population mapping for Germany based on building density, height and type from Earth Observation data using census disaggregation and bottom-up estimates [Publisher: Public Library of Science]. *PLOS ONE*, *16*(3), e0249044. https://doi.org/10.1371/journal.pone.0249044

Score, W. (2021). Walk Score Methodology. Retrieved November 23, 2020, from https://www.walkscore.com/methodology.shtml

Silva, C. (2020). Accessibility at the local scale: How it constrains our ability to 'live locally'. *Handbook of Sustainable Transport* (pp. 333–342). Edward Elgar Publishing. https://doi.org/10.4337/9781789900477.00047

Silva, C., Bertolini, L., & Pinto, N. N. (Eds.). (2019). *Designing accessibility instruments: Lessons on their usability for integrated land use and transport planning practices*. Routledge, Taylor & Francis Group.

Silva, C., & Larsson, A. (2019). Is there such a thing as good enough accessibility? *Transportation Research Procedia*, *41*, 694–707. https://doi.org/10.1016/j.trpro.2019.09.118

Silva, C., & Altieri, M. (2022). Is regional accessibility undermining local accessibility? *Journal of Transport Geography*, *101*, 103336. https://doi.org/10.1016/j.jtrangeo.2022.103336

Silva, C., Bertolini, L., te Brömmelstroet, M., Milakis, D., & Papa, E. (2017). Accessibility instruments in planning practice: Bridging the implementation gap. *Transport Policy*, *53*, 135–145. https://doi.org/10.1016/j.tranpol.2016.09.006

Šimbera, J. (2020). Neighborhood features in geospatial machine learning: The case of population disaggregation [Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15230406.2019. *Cartography and Geographic Information Science*, *47*(1), 79–94. https://doi.org/10.1080/15230406.2019.1618201

Smirnov, E., & Gurevich, M. (2021). Ant Road Planner - Pedestrian simulator. Retrieved January 8, 2022, from https://antroadplanner.ru/

SNAMUTS. (2016). Spatial Network Analysis for Multi-modal Urban Transport Systems (SNAMUTS). Retrieved November 3, 2020, from http://www.snamuts.com/

Spiekermann, K., Wegener, M., Květoň, V., Marada, M., Schürmann, C., Biosca, O., Segui, A. U., Antikainen, H., Kotavaara, O., Rusanen, J., Bielańska, D., Fiorello, D., Komornicki, T., Rosik, P., & Stepniak, M. (2013). *TRACC Transport Accessibility at Regional/Local Scale and Patterns in Europe* (tech. rep.). Luxembourg.

Stadt München. (2018). *Wohnungsbauatlas für München und die Region* (tech. rep.). München. https://www.muenchen.de/rathaus/dam/jcr:7aa34193-f9d5-417a-9201-885a55ec20d8/LHM_Wohnungsbauatlas_web.pdf

Ståhle, A., Marcus, L., & Karlström, A. (2005). - Geographic Accessibility with Axial Lines in GIS, 13. https://www.diva-portal.org/smash/record.jsf?dswid=2842&pid=diva2%3A469861

Statistische Ämter des Bundes und der Länder. (2011). ZENSUS2011 - Bevölkerungs- und Wohnungszählung 2011 - Ergebnisse des Zensus 2011 zum Download - erweitert. Retrieved February 23, 2021, from https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html?nn=3065474

Statistische Ämter des Bundes und der Länder. (2021). Gemeindeverzeichnis | Statistikportal.de. Retrieved July 3, 2021, from http://www.statistikportal.de/de/gemeindeverzeichnis

Statistisches Bundesamt. (2021). Road transport: EU-wide carbon dioxide emissions have increased by 24% since 1990 - German Federal Statistical Office. Retrieved October 3, 2021, from https://www.destatis.de/Europa/EN/Topic/Environment-energy/CarbonDioxideRoadTransport.html

Stead, D., & Marshall, S. (2001). The Relationships between Urban Form and Travel Patterns. An International Review and Evaluation [Publisher: European Journal of Transport and Infrastructure Research]. *European Journal of Transport and Infrastructure Research*, Vol 1 No 2 (2001). https://doi.org/10.18757/EJTIR.2001.1.2.3497

Stępniak, M., & Goliszek, S. (2017). Spatio-Temporal Variation of Accessibility by Public Transport—The Equity Perspective. In I. Ivan, A. Singleton, J. Horák, & T. Inspektor (Eds.), *The Rise of Big Spatial Data* (pp. 241–261). Springer International Publishing. https://doi.org/10.1007/978-3-319-45123-7_18

Stewart, A. F., & Zegras, P. C. (2016). CoAXs: A Collaborative Accessibility-based Stakeholder Engagement System for communicating transport impacts. *Research in Transportation Economics*, *59*, 423–433. https://doi.org/10.1016/j.retrec.2016.07.016

te Brömmelstroet, M. (2010). Equip the warrior instead of manning the equipment: Land use and transport planning support in the Netherlands. *Journal of Transport and Land Use*, *3*(1). https://doi.org/10.5198/jtlu.v3i1.99

te Brömmelstroet, M. (2017). PSS are more user-friendly, but are they also increasingly useful? *Transportation Research Part A*, *104*, 11. https://doi.org/http://dx.doi.org/10.1016/j.tra.2016.05.012

te Brömmelstroet, M., & Bertolini, L. (2010). Integrating land use and transport knowledge in strategy-making. *Transportation*, *35*, 85–104. https://doi.org/10.1007/s11116-009-9221-0

te Brömmelstroet, M., Curtis, C., Larsson, A., & Milakis, D. (2016). Strengths and weaknesses of accessibility instruments in planning practice: Technological rules based on experiential workshops. *European Planning Studies*, *24*(6), 21. https://doi.org/10.1080/09654313.2015.1135231

te Brömmelstroet, M., Silva, C., & Bertolini, L. (2014). *Assessing usability of accessibility instruments* [OCLC: 883953178]. COST office ;

Tobler, W. R. (1970). A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography*, *46*, 234. https://doi.org/10.2307/143141

Transport for Greater Manchester. (2020). GM Accessibility Levels (GMAL). Retrieved November 4, 2020, from https://data.gov.uk/dataset/d9dfbf0a-3cd7-4b12-a39f-0ec717423ee4/gm-accessibility-levels-gmal

Transport for London. (2015). Assessing transport connectivity in London, 60. http://content.tfl.gov.uk/connectivity-assessment-guide.pdf

Transport for London. (2020a). WebCAT planning tool. Retrieved November 4, 2020, from https://www.tfl.gov.uk/info-for/urban-planning-and-construction/planning-with-webcat/webcat

Transport for London. (2020b). Website WebCAT - Planning with WebCAT. Retrieved November 4, 2020, from https://www.tfl.gov.uk/info-for/urban-planning-and-construction/planning-applications/planning-with-webcat

TUM - Chair of Urban Structure and Transport Planning. (2021). META-Accessibility. Retrieved December 4, 2021, from https://www.accessibilityplanning.eu//

UGENT. (2019). Website StationsRadar. Retrieved November 3, 2020, from https://stationsradar.ugent.be/

United Nations. (2019). *World Urbanization Prospects: The 2018 revision.* [OCLC: 1120698127]. UNITED NATIONS.

University of Illinois at Chicago. (2020). Metropolitan Chicago Accessibility Explorer. Retrieved November 24, 2020, from http://urbanaccessibility.com/

University of Minnesota. (2018). Access Across America | Accessibility Observatory at the University of Minnesota. Retrieved November 4, 2020, from http://access.umn.edu/research/america/

University of Rostock. (2021). Availability of official geodata | OpenGeoEdu. Retrieved July 15, 2021, from https://learn.opengeoedu.de/en/opendata/vorlesung/offene-geodaten/amtliche-geodaten

UrbanRural SOLUTIONS. (2019). Der Daseinsvorsorgeatlas Niedersachsen - Kurzinformation zum digitalen Planungstool, 6. Retrieved November 3, 2020, from http://www.vsl.tu-harburg.de/urbanruralsolutions/UR-Daseinsvorsorgeatlas-Niedersachsen.pdf

UrbanRural Solutions. (2020). Website UrbanRural Solutions. Retrieved November 3, 2020, from http://www.vsl.tu-harburg.de/urbanruralsolutions/Projekt

U.S. Department of Housing and Urban Development. (2020). Location Affordability Index v.3. Retrieved November 24, 2020, from https://hudgis-hud.opendata.arcgis.com/datasets/location-affordability-index-v-3/data?geometry=-xx0.270,38.x07,-x05.225,38.859

US EPA. (2014). Smart Location Mapping. Retrieved November 4, 2020, from https://www.epa.gov/smartgrowth/smart-location-mapping

Vale, D. S., & Pereira, M. (2017). The influence of the impedance function on gravity-based pedestrian accessibility measures: A comparative analysis. *Environment and Planning B: Urban Analytics and City Science*, *44*(4), 740–763. https://doi.org/10.1177/0265813516641685

Valhalla Community. (2022). Valhalla/valhalla [original-date: 2016-01-19T19:42:29Z]. Retrieved January 7, 2022, from https://github.com/valhalla/valhalla

Van Eggermond, M. A., & Erath, A. (2015). Pedestrian and transit accessibility on a micro level: Results and challenges. *Journal of Transport and Land Use*. https://doi.org/10.5198/jtlu.2015.677

van Nes, A., & Yamu, C. (2021). *Introduction to Space Syntax in Urban Studies*. Springer International Publishing. https://doi.org/10.1007/978-3-030-59140-3

Venter, C. (2016). *Developing a Common Narrative on Urban Accessibility:* (tech. rep.). Brookings. Washington D.C.

Viertler, S. (2020). Master thesis: Development of a statistical standard for classifying distance-decay accessibility indices for walking.

Vonk, G., Geertman, S., & Schot, P. (2006). Usage of Planning Support Systems. In J. P. Leeuwen & H. J. P. Timmermans (Eds.), *Innovations in Design & Decision Support Systems in Architecture and Urban Planning* (pp. 263–274). Springer Netherlands. https://doi.org/10.1007/978-1-4020-5060-2_17

Wang, L., & Wu, C. (2010). Population estimation using remote sensing and GIS technologies. *International Journal of Remote Sensing*, *31*(21), 5569–5570. https://doi.org/10.1080/01431161.2010.496809

Website OGC. (2022). OGC Standards and Resources | OGC. Retrieved January 7, 2022, from https://www.ogc.org/standards

WHO. (2019). WHO | Air pollution. Retrieved October 1, 2019, from http://www.who.int/sustainable-development/transport/health-risks/air-pollution/en/

Widener, M. J., Minaker, L., Farber, S., Allen, J., Vitali, B., Coleman, P. C., & Cook, B. (2017). How do changes in the daily food and transportation environments affect grocery store accessibility? *Applied Geography*, *83*, 46–62. https://doi.org/10.1016/j.apgeog.2017.03.018

World Health Organization, Krug, E., Bettcher, D., Arnold, V., & Robinson, S. (2019). The role of cities in preventing noncommunicable diseases and road injuries [Place: Copenhagen Publisher: World Health Organization. Regional Office for Europe]. *Public health panorama*, *5*(2-3), 336–340. Retrieved June 4, 2022, from https://apps.who.int/iris/handle/10665/330102

Wright, J. K. (1936). A Method of Mapping Densities of Population: With Cape Cod as an Example [Publisher: [American Geographical Society, Wiley]]. *Geographical Review*, *26*(1), 103–110. https://doi.org/10.2307/209467

Wu, S.-s., Qiu, X., & Wang, L. (2005). Population Estimation Methods in GIS and Remote Sensing: A Review [Publisher: Taylor & Francis _eprint: https://doi.org/10.2747/1548-1603.42.1.80]. *GIScience & Remote Sensing*, *42*(1), 80–96. https://doi.org/10.2747/1548-1603.42.1.80

Wu, S.-s., Wang, L., & Qiu, X. (2008). Incorporating GIS Building Data and Census Housing Statistics for Sub-Block-Level Population Estimation. *The Professional Geographer*, *60*(1), 121–135. https://doi.org/10.1080/00330120701724251

Wulfhorst, G., Büttner, B., & Ji, C. (2017). The TUM Accessibility Atlas as a tool for supporting policies of sustainable mobility in metropolitan regions. *Transportation Research Part A: Policy and Practice*, *104*, 121–136. https://doi.org/10.1016/j.tra.2017.04.012

Wurman, R. S., RadicalMedia, & ESRI. (2020). Website Urban Observatory. Retrieved November 24, 2020, from https://www.urbanobservatory.org/

Xie, Y., Weng, A., & Weng, Q. (2015). Population Estimation of Urban Residential Communities Using Remotely Sensed Morphologic Data [Conference Name: IEEE Geoscience and Remote Sensing Letters]. *IEEE Geoscience and Remote Sensing Letters*, *12*(5), 1111–1115. https://doi.org/10.1109/LGRS.2014.2385597

z create labs GmbH. (2021). Website z creative labs. Retrieved February 23, 2021, from https://zcreativelabs.com/work/15-min-city-map/

z create labs GmbH, & Here. (2021). 15-Minute City Map. Retrieved February 23, 2021, from https://app.developer.here.com/15-min-city-map/

Zhang, J., Tan, P. Y., Zeng, H., & Zhang, Y. (2019). Walkability Assessment in a Rapidly Urbanizing City and Its Relationship with Residential Estate Value [Number: 8]. *Sustainability*, *11*(8), 2205. https://doi.org/10.3390/su11082205

Zhang, X., Hua, Q., & Zhang, L. (2016). Development and Application of a Planning Support System for Regional Spatial Functional Zoning Based on GIS. *Sustainability*, *8*(909), 1–17. https://doi.org/10.3390/su8090909

Zuckriegl, L. (2021). Master thesis: Bewertung des Nutzens eines interaktiven Erreichbarkeitsinstrumentes zur Erstellung eines Mobilitätskonzeptes in der Praxis.

Appendix A

Reviewed accessibility instruments

Tool	Country	Tool type	Scenario building	Access	Walking	Cycling	Public Transport	Car	Network OSM	Network Public	Network Proprietary	Opportu-nities - OSM	Opportu-nities Public	Opportu-nities Proprietary	Sources
SNAMUTS Spatial Network Analysis for Multimodal Urban Transport Systems	Australia	Desktop	yes	Closed			x		x	x			x		(Curtis & Scheuer, 2019; Curtis & Scheurer, 2012; SNAMUTS, 2016)
BBSR accessibility instrument	Germany	Desktop	yes	Closed			x	x		x			x		(Bundesinstitut für Bau-, 2019; Federal Office for Building and Regional Planning, 2020)
TUM Accessibility Atlas	Germany	Desktop	yes	Closed	x	x	x	x	x	x		x	x		(Büttner et al., 2019; Büttner et al., 2018; Wulfhorst et al., 2017)
Daseinsvor-sorgeatlas	Germany	Web	yes	Closed	x	x	x	x	x	x			x		(UrbanRural SOLUTIONS, 2019; UrbanRural Solutions, 2020)
TRACC	UK	Desktop, Web	yes	Closed	x	x	x	x		x	x		x	x	(Ltd, 2020; Spiekermann et al., 2013)
Sugar Access	USA	Desktop, Web	yes	Closed	x	x	x	x		x	x		x	x	(Citilabs, 2020)
Urban Footprint	USA	Web	yes	Closed	x		x		x	x			x	x	(Analytics, 2017; Footprint, 2020)
StationsRadar	Belgium	Web	no	Open Access	x	x	x	x	x	x		x	x		(Caset et al., 2018; UGENT, 2019)
Mapple Analyst	Finland	Web	no	Open Access	x	x	x	x	x	x			x		(Accessibility Research Group at the University of Helsinki, 2020a; 2020b)
Erreichbarkeitsportal	Germany	Web	no	Open Access	x	x	x	x	x	x		x	x	x	(Hamburg, 2017; 2020; Peter, 2017)
Mobiliteitsscan	Netherlands	Web	yes	Open Access		x	x	x		x			x		(Dutch Ministry of Infrastructure and Water Management, 2020)
GMAL Great Manchester Accessibility Levels	UK	Database, Desktop	no	Open Access	x		x			x			x		(Transport for Greater Manchester, 2020)
WebCAT Web-based Connectivity Assessment Toolkit	UK	Web	no	Open Access	x		x			x			x		(Transport for London, 2015; 2020a; 2020b)
Access to Jobs and Workers Via Transit Tool	USA	Database, Web	no	Open Access			x			x			x		(US EPA, 2014)
National Walkability Index	USA	Database, Web	no	Open Access	x					x	x		x		(US EPA, 2014)

Accessibility Observatory	USA	Web	no	Open Access	x	x	x	x	x	x	x		x		(University of Minnesota, 2018)
All Transit	USA	Web	no	Open Access			x			x			x		(Center for Neighborhood Technology, 2020)
Job accessibility maps	USA	Web	no	Open Access			x		x	x			x		(ESRI, 2020)
Metropolitan Chicago Accessibility Explorer	USA	Web	no	Open Access			x	x	x	x			x		(Nebiyou et al., 2016; University of Illinois at Chicago, 2020)
Urban Observatory	USA	Web	no	Open Access			x	x		x	x		x		(Wurman et al., 2020)
WalkScore	USA	Web	No	Open Access	x				x	x	x	x	x		(Hall & Ram, 2018; Score, 2021)
Location affordability index	USA	Database, Web	no	Open Source	x		x	x		x			x		(U.S. Department of Housing and Urban Development, 2020)
CoAXs Collaborative Access-based Stakeholder Engagement	USA	Web	yes	Open Source			x		x	x			x		(Massachusetts Institute of Technology, 2020; mitTransportAnalys, 2020)
Conveyal Analysis	USA	Web	yes	Open Source			x		x	x			x		(Conveyal, 2022b; 2022c; 2022d)
Pedestrians First	USA	Web	yes	Open Source	x				x			x	x		(ITDP, 2018; 2020)
15-Minute City Map	Switzerland	Web	no	Open Access	x			x			x			x	(z create labs GmbH, 2021; z create labs GmbH & Here, 2021)

Appendix B

Used software and programming languages

Software and programming languages	**Technical role**
PostgreSQL v12 / PostGIS v3	Spatial database as core of the application (Backend)
Custom pgRouting v2.6.11	Routing algorithm (Backend)
PLV8	Database extension to run Javascript (Backend)
Python v3.7	Automation and data preparation (Middleware, Backend)
Javascript (ES 6/7), HTML and CSS	Front-end programming languages (Client)
Vue v2.6, Vuex v3.1, Vuetify v2.0	Javascript and material design framework (Client)
Openlayers v6.1	Javascript library for web mapping (Client)
Docker, Docker Compose	Containerization software (DevOps)
Kubernetes	Software for container orchestration (DevOps)

Appendix C

Mapping table schema

Table Names Figures	Table Names SQL
Buildings Custom	buildings_custom
Buildings OSM	buildings_osm
Census Tracts	census
Census Tracts New Development	census_split_new_development
Fixed Population	fixed_population
Land-use Custom 1	landuse
Land-use Custom 2	landuse_additional
Land-use OSM	landuse_osm
Population	population
Residential Entrances	residential_addresses
Study Area	study_area
Updated Census Tracts	census_prepared

Appendix D

Table schema

Heatmap tables

reached_pois_heatmap	
id	int4
gid	int4
amenity	text
name	_int4
gridids	_int4
arr_cost	_int4
edge	int4
fraction	float8
accessibility_indices	_int4
userid	int4
scenario_id	int4

reached_edges_heatmap	
id	int4
edge	int8
gridids	_int4
start_cost	_int2
end_cost	_int2
userid	int4
scenario_id	int4
start_perc	float8
end_perc	float8
partial_edge	bool
geom	geometry

grid_ordered	
grid_id	int4
starting_points	_numeric
centroid	geometry
section_id	int8
id	int8
geom	geometry

compute_sections	
section_id	int4
geom	geometry

grid_heatmap	
grid_id	int4
area_isochrone	float8
percentile_area_isochrone	int2
population	int4
percentile_population	int2
geom	geometry

Isochrone tables

isochrones	
gid	int4
userid	int4
scenario_id	int4
id	int4
step	int4
speed	numeric
concavity	numeric
modus	varchar(20)
objectid	int4
parent_id	int4
population	int4
pois	text
sum_pois	text
starting_point	text
geom	geometry

area_isochrones_scenario	
gid	int4
grid_id	int4
area_isochrone	numeric
scenario_id	int4
geom	geometry

edges	
id	int4
edge	int4
cost	float8
start_cost	float8
end_cost	float8
objectid	int4
geom	geometry

starting_point_isochrones	
gid	int4
userid	int4
objectid	int4
number_calculation	int4
geom	geometry

multi_isochrones	
gid	int4
objectid	int4
coordinates	_numeric
userid	int4
id	int4
step	int4
speed	numeric
alphashape_parameter	numeric
modus	int4
parent_id	int4
routing_profile	text
population	jsonb
geom	geometry

Network tables

ways_userinput	
id	int8
class_id	int4
length_m	float8
name	text
source	int4
target	int4
one_way	int4
maxspeed_forward	int4
maxspeed_backward	int4
osm_id	int8
bicycle	text
foot	text
oneway	text
crossing	text
one_link_crossing	bool
crossing_delay_category	int2
bicycle_road	text
cycleway	text
highway	text
incline	text
incline_percent	int4
lanes	numeric
lit	text
lit_classified	text
parking	text
parking_lane_both	text
parking_lane_right	text
parking_lane_left	text
segregated	text
sidewalk	text
sidewalk_both_width	numeric
sidewalk_left_width	numeric
sidewalk_right_width	numeric
smoothness	text
surface	text
wheelchair	text
wheelchair_classified	text
width	numeric
s_imp	float8
rs_imp	float8
impedance_surface	numeric
death_end	int8
userid	int4
scenario_id	int4
original_id	int8
geom	geometry

ways	
id	int8
class_id	int4
length_m	float8
name	text
source	int4
target	int4
one_way	int4
maxspeed_forward	int4
maxspeed_backward	int4
osm_id	int8
bicycle	text
foot	text
oneway	text
crossing	text
one_link_crossing	bool
crossing_delay_category	int2
bicycle_road	text
cycleway	text
highway	text
incline	text
incline_percent	int4
lanes	numeric
lit	text
lit_classified	text
parking	text
parking_lane_both	text
parking_lane_right	text
parking_lane_left	text
segregated	text
sidewalk	text
sidewalk_both_width	numeric
sidewalk_left_width	numeric
sidewalk_right_width	numeric
smoothness	text
surface	text
wheelchair	text
wheelchair_classified	text
width	numeric
s_imp	float8
rs_imp	float8
impedance_surface	numeric
death_end	int8
geom	geometry

dem	
rid	int4
rast	raster
filename	text

ways_modified	
gid	int8
way_type	text
surface	text
wheelchair	text
lit	text
street_category	text
foot	text
bicycle	text
scenario_id	int4
original_id	int4
status	int4
edit_type	text
geom	geometry

ways_userinput_vertices_pgr	
id	int8
osm_id	int8
cnt	int4
class_ids	_int4
foot	_text
bicycle	_text
lit_classified	_text
wheelchair_classified	_text
death_end	bool
userid	int4
scenario_id	int4
geom	geometry

ways_vertices_pgr	
id	int8
osm_id	int8
cnt	int4
class_ids	_int4
foot	_text
bicycle	_text
lit_classified	_text
wheelchair_classified	_text
death_end	bool
geom	geometry

osm_way_classes	
class_id	int4
type_id	int4
name	text
priority	float8
default_maxspeed	int4

Point of interest tables

pois

gid	int4
osm_id	int8
origin_geometry	text
access	text
housenumber	text
amenity	text
origin	text
organic	text
denomination	text
brand	text
name	text
operator	text
public_transport	text
railway	text
religion	text
opening_hours	text
ref	text
tags	hstore
wheelchair	text
geom	geometry

pois_userinput

gid	int4
osm_id	int8
origin_geometry	text
access	text
housenumber	text
amenity	text
origin	text
organic	text
denomination	text
brand	text
name	text
operator	text
public_transport	text
railway	text
religion	text
opening_hours	text
ref	text
tags	hstore
wheelchair	text
userid	int4
scenario_id	int4
pois_modified_id	int4
geom	geometry

aois

gid	int4
osm_id	int8
origin_geometry	text
access	text
amenity	text
denomination	text
name	text
operator	text
opening_hours	text
ref	text
wheelchair	text
sport	text
tags	hstore
geom	geometry

pois_modified

gid	int4
name	text
amenity	text
opening_hours	text
scenario_id	int4
original_id	int4
wheelchair	text
geom	geometry

System tables

scenarios

scenario_id	int8
scenario_name	text
userid	int8
deleted_ways	_int8
deleted_pois	_int8
deleted_buildings	_int8
ways_heatmap_computed	bool

variable_container

identifier	varchar(100)
variable_simple	text
variable_array	_text
variable_object	jsonb

user_data

userid	int8

Population tables

population	
gid	int4
fixed_population	float8
population	float8
building_gid	int4
geom	geometry

population_userinput	
gid	int4
fixed_population	float8
population	float8
building_gid	int4
scenario_id	int4
buildings_modified_id	int4
geom	geometry

population_modified	
gid	int4
building_gid	int4
population	numeric
scenario_id	int4
geom	geometry

buildings	
gid	int4
osm_id	int4
building	text
amenity	text
residential_status	text
housenumber	text
street	text
building_levels	int2
building_levels_residential	int2
roof_levels	int2
height	float8
area	int4
gross_floor_area_residential	int4
geom	geometry

buildings_modified	
gid	int4
building	text
building_levels	numeric
building_levels_residential	numeric
gross_floor_area	int4
population	numeric
scenario_id	int4
original_id	int4
geom	geometry

study_area	
gid	int4
name	text
sum_pop	int4
default_building_levels	int2
default_roof_levels	int2
area	float8
geom	geometry

study_area_union	
gid	int4
geom	geometry

study_area_crop	
gid	int4
geom	geometry

census	
gid	int4
id	text
pop	float8
geom	geometry

Appendix E

Core variables in data configuration file

```
DATA_SOURCE:
  #"no_download" if you don't want to download OSM data automatically.
  ↪ Make sure that the file is called raw-osm.osm.pbf.
  OSM_DOWNLOAD_LINK:
  ↪ "https://download.geofabrik.de/europe/germany/bayern/oberbayern-latest.osm.pbf"
  BUFFER_BOUNDING_BOX: 0.045 #in degree (default: approx. 3km)
  EXTRACT_BBOX: "yes" #"yes" ==> Use study area as BBOX,"no_extract" ==>
  ↪ Import whole dump, "done" ==> Extract was already done

DATA_REFINEMENT_VARIABLES:
  #extrapolation ==> census.shp + landuse.shp needed as input
  #disaggregation ==> landuse.shp needed as input + high-resolution
  ↪ population input data + building data
  #distribution ==> landuse.sho need as input + high-resolution
  ↪ population input data
  #custom_population ==> population.shp custom population data needed
  POPULATION: "census_extrapolation"
  #"yes" if you want to add these layers
  ADDITIONAL_WALKABILITY_LAYERS: "no"
  OSM_MAPPING_FEATURE: "no"
  variable_container:
    heatmap_sensitivities:
    ↪ [150000,200000,250000,300000,350000,400000,450000]
    pois_one_entrance:
    ↪ ["kindergarten","nursery","primary_school","secondary_school",

    ↪ "grundschule","hauptschule","realschule","gymnasium","bar","biergarten","cafe",

    ↪ "fast_food","ice_cream","restaurant","theatre","cinema","library","nightclub",
```

```
↪ "recycling","car_sharing","bicycle_rental","cargo_bike","charging_station",
"taxi","hairdresser","atm","bank","dentist","doctors","pharmacy",

↪ "post_box","post_office","fuel","bakery","butcher","clothes","convenience",
"general","fashion","florist","greengrocer","kiosk","mall","shoes",
"sports","supermarket","health_food","discount_supermarket",
"hypermarket","international_supermarket","chemist","organic",
"marketplace","hotel","museum","hostel","guest_house","viewpoint",
"gallery","playground","discount_gym","gym","yoga"
]
pois_more_entrances:
↪ ["bus_stop","tram_stop","subway_entrance","rail_station",

↪ "community_sports_center","waterpark","park","forest","heath_scrub","lake",
"river"]
excluded_class_id_walking:
↪ [0,101,102,103,104,105,106,107,501,502,503,504,701,801]
categories_no_foot: ["use_sidepath","no"]
excluded_class_id_cycling:
↪ [0,101,102,103,104,105,106,107,501,502,503,504,701,801]
categories_no_bicycle: ["use_sidepath","no"]
categories_sidewalk_no_foot: ["separate"] #Used for visualization
↪ purpose only
max_length_links: '300'
custom_landuse_no_residents: ["AX_TagebauGrubeSteinbruch",
  "AX_SportFreizeitUndErholungsflaeche",
  "AX_FlaecheBesondererFunktionalerPraegung",
  "AX_BauwerkOderAnlageFuerSportFreizeitUndErholung",
  "AX_Halde",
  "AX_Friedhof",
  "AX_IndustrieUndGewerbeflaeche",
  "AX_Landwirtschaft",
  "AX_Wald",
  "AX_Gehoelz",
  "AX_Heide",
  "AX_Moor",
  "AX_Insel",
  "AX_Sumpf",
  "AX_UnlandVegetationsloseFlaeche",
  "AX_Vegetationsmerkmal",
  "AX_Bahnverkehr",
  "AX_Platz",
  "AX_Strassenverkehr",
  "AX_Flugverkehr",
  "AX_Fließgewaesser",
```

```
  "AX_Hafenbecken",
  "AX_StehendesGewaesser"
]
custom_landuse_with_residents_name: ["%seniorenheim%"]
custom_landuse_additional_no_residents: [
  "Water",
  "Permanent crops (vineyards, fruit trees, olive groves)",
  "Railways and associated land",
  "Herbaceous vegetation associations (natural grassland, moors...)",
  "Forests",
  "Sports and leisure facilities",
  "Other roads and associated land",
  "Green urban areas",
  "Arable land (annual crops)",
  "Fast transit roads and associated land",
  "Industrial, commercial, public, military and private units",
  "Mineral extraction and dump sites",
  "Pastures"
]
osm_landuse_no_residents:
↪  ["farmyard","construction","farmland","quarry","industrial","retail",
"commercial","forest","military",
"cemetery","landfill","allotments","recreation
↪  ground","railway","parking","grass","grassland","green","garages"]
aois_no_residents:
↪  ["forest","park","lake","river","forest","park","swimming_lake"]
#All buildings that can be potentially residential
building_types_potentially_residential: ["yes"]
#All buildings that are definitely residential
building_types_residential:
↪  ["apartments","bungalow","detached","dormitory","residential","house",
"terrace","home","semidetached_house"]
tourism_no_residents: ["zoo"]
amenity_no_residents:
↪  ["hospital","university","community_centre","school","kindergarten",
"recreation_ground","wood"]
default_building_levels: '3'
minimum_building_size_residential: '30'
census_minimum_number_new_buildings: '1'
average_gross_living_area: '50'
average_building_levels: '4'
average_roof_levels: '1'
average_height_per_level: '3.5'
wheelchair:
  smoothness_no: ["very_bad","horrible","very_horrible","impassable"]
  smoothness_limited: ['bad']
```

```
  surface_no:
   ↪  ['ground','grass','sand','dirt','unhewn_cobblestone','unpaved']
  surface_limited: ['gravel']
  highway_onstreet_yes: ['living_street']
  highway_onstreet_limited: ['residential','service']
lit:
  highway_yes: ['living_street','residential','secondary','tertiary']
  highway_no: ['track']
  surface_no: ['ground','gravel','unpaved','grass']
cycling_surface:
  paving_stones: '0.2'
  sett: '0.3'
  unhewn_cobblestone: '0.3'
  cobblestone: '0.3'
  pebblestone: '0.3'
  unpaved: '0.2'
  compacted: '0.05'
  fine_gravel: '0.05'
  gravel: '0.3'
  sand: '0.4'
  grass: '0.25'
  mud: '0.4'
cycling_smoothness:
  intermediate: '0.05'
  bad: '0.1'
  very_bad: '0.2'
  horrible: '0.3'
  very_horrible: '0.5'
cycling_crossings_delay:
  delay_1: 15
  delay_2: 30
compute_slope_impedance: "'no'"
##-----------------------------------Size limits for areas of
↪  interest------------------------------------##
## Limits the area to be displayed for certain amenities (like
↪  parks).
## The limits should be defined in square meters
areas_boundaries:
  parks:
    small: [2000]
    ##large: [300000]
  forest:
    small: [2000]
    ##large: [300000]
  heath:
    small: [0]
```

```
    ##large: [300000]

 ↪  ##-----------------------------------------------------------------------------
##-----------Definition for the reclassification of points of
 ↪  interest--------------------------------------##

 ↪  ##-----------------------------------------------------------------------------
##  Data structure: Amenity type -> Brand name -> Name variables
 ↪  (including variation of the brand name)
pois_search_conditions:
  chemist:
    dm: []
    rossmann: []
  supermarket:
    edeka: ['e center', 'edeka']
    rewe: ['rewe', 'rewe city']
  discount_supermarket:
    aldi: []
    lidl: []
    penny: []
    netto: []
    norma: []
  hypermarket:
    hit: []
    real: []
    kaufland: []
    v-markt: []
    marktkauf: []
  no_end_consumer_store:
    hamberger: []
    metro: []
  health_food:
    vitalia: []
    reformhaus: []
  operators_bicycle_rental: ['münchner verkehrs
   ↪  gesellschaft','münchner verkehrsgesellschaft','mvg']
  bank:
    sparkasse: ['kreissparkasse','sparkasse','stadtsparkasse']
    hypovereinsbank: ['hypo vereinsbank', 'hypovereinsbank']
    raiffeisenbank: ['raiffeisenbank', 'vr bank', 'vr-bank',
     ↪  'volksbank','volks', 'Münchner']
  fast_food:
    mcdonalds: ['mcdonald']
  nursery: ['krippe','kinderkrippe','kita']
  discount_gym:
```

```
    fitstar: ['fit-star','fit star']
    mcfit: []
    fitx: []
    cleverfit: ['clever fit','cleverfit']
    jumpersfitness: ['jumpers fitness']
  community_sport_centre: ['bezirkssportanlage']
```

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