Technische Universität München

Evaluating walking accessibility and equity to essential services with and without competition using the interactive accessibility instrument GOAT

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Abstract

The planning for sustainable, urban transport has received increased interest since the COVID-19 pandemic. Concepts such as the 15-minute city in Paris or the 20-minute neighbourhoods in Portland are viewed as role models for cities around the world. They seek to improve the conditions for active transport modes to reduce the use of cars. However, there is often limited knowledge about the conditions for walking and cycling and a lack of tools to properly assess current situations and the impacts of new planning principles. Accessibility instruments such as GOAT can serve as important tools to improve knowledge on active transport and facilitate the implementation sustainable urban planning concepts.

The thesis used GOAT to assess the walking accessibility to essential services in Munich. The assessment of accessibility heatmaps was coupled with horizontal and vertical equity analysis. For the equity analyses, a combination of sufficientarian and egalitarian equity measures was chosen. Sufficientarian concerns were measured with the share of the population within thresholds of twenty minutes and ten minutes of at least one amenity. Egalitarian concerns were measured with the Lorenz Curve and Gini Coefficient (horizontal equity) and correlation analysis (vertical equity). For the vertical equity analysis, the population was compared based on origin and households based on presence of children and parental status. Furthermore, an accessibility measure that includes competition effects was implemented in GOAT to assess accessibility more realistically.

The thesis has shown that amenities considered as basic (e.g., kindergartens, primary schools), were found distributed relatively equal among Munich's population, irrespective of the equity measure and travel time thresholds. However, more specialised amenities (e.g., organic supermarkets, gynaecologists) showed higher degrees of inequity across all measures. Germans without migration background and households without children had slightly better access than Germans with migration background, foreigners, and households with children. Even though, accessibility heatmaps revealed largely different patterns, no differences in the Gini Coefficients were found between measures with and without competition. Correlation coefficients decreased across all population groups.

The study highlighted the need for multi-criteria analysis to assess spatial patterns properly. Further research needs to be conducted to assess the relationships between measure with and without competition and their impacts on different types of equity analysis.

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List of Abbreviations

AI	Accessibility instrument
CUM	Cumulative opportunities measure
GIS	Geographic Information System
GOAT	Geo Open Accessibility Tool
LaSie	Langfristige Siedlungsentwicklung
OGC	Open Geospatial Consortium
OSM	OpenStreetMap
POI	Point of interest
PSS	Planning support system
SQL	Structured Query Language
TUM	Technical University of Munich
WFS	Web Feature Service
WMS	Web Map Service
2SFCA	Two step floating catchment area

1. Introduction

The COVID-19 pandemic has not only challenged healthcare systems worldwide, but also urban transport. Remote work, fears of infection in public transport, and travel restrictions have led to an increased interest in local mobility by active transport modes (Dunning & Nurse, 2021). Cities around the world have tried to deal with the new demand by setting up pop-up bike lanes, parklets, and 'summer streets', reallocating space from cars to active transport (Bliss, 2020). But while such measures are often seen as temporary, the pandemic can serve as a starting point for the long-term conversion to more sustainable and resilient urban transport systems (Hunter et al., 2021).

Planning concepts such as the 15-minute city or the 20-minute neighbourhood can serve as the basis for such a long-term conversion (Moreno, Allam, Chabaud, Gall, & Pratlong, 2021). They focus on providing local accessibility by active transport instead of mobility by car and, thus, can be seen as examples of the shift from mobility planning to accessibility planning (Da Capasso Silva, King, & Lemar, 2020). The growing interest in local accessibility makes it necessary to create new planning support tools that help to put the theory into practice (Pajares, Büttner, Jehle, Nichols, & Wulfhorst, 2021). Decision-makers and planners need support to identify areas with deficient access and find suitable solutions to improve local accessibility.

Even though cities such as Portland and companies such as HERE have created their own tools for the evaluation of local accessibility concepts, there is still a gap in the application of accessibility tools (Pajares et al., 2021). One tool that seeks to bridge this gap is the Geo Open Accessibility Tool (GOAT) which has been developed at the Technical University of Munich (TUM). It is an interactive, open-source accessibility instrument (AI) that enables users to calculate and visualise accessibility by foot or bicycle to a wide variety of amenities (Pajares et al., 2021). GOAT already includes a number of different measures but population data and the interplay between supply and demand, which is often seen as an important part of an accessibility measure (Geurs & van Wee, 2004), are not fully included yet.

This thesis seeks to achieve two goals. Firstly, an accessibility analysis will be caried out with GOAT for one study area. This will not only include an analysis of spatial patterns, but also of the distribution of accessibility among the population and different socio-demographic groups. Secondly, the thesis seeks to improve the inclusion of supply and demand in GOAT's accessibility measurement and its application to the study area. The City of Munich will serve as the study area. Reducing private vehicle usage and improving neighbourhood mobility have been important planning goals of the City of Munich for many years and, thus, an assessment of Munich's current situation will give insights whether access is, in fact, achieved. The focus of the accessibility analysis will be on essential services (e.g., education, healthcare).

This thesis seeks to answer the following research questions:

(1) Which areas in Munich have deficient levels of walking accessibility? Are there differences between different amenity types?
(2) Is the walking accessibility in Munich distributed equitably/equally? Are there differences between different amenity types?
(3) Are there correlations between accessibility levels and socio-economic as well as demographic factors?
(4) How can competition effects and socio-demographic data be incorporated into GOAT to assess accessibility, and levels of supply and demand more realistically? Are there differences in the results for accessibility measures with and without competition?

As a basis for the analysis, chapter 2 will feature a literature review on accessibility and equity as well as an introduction to GOAT. Based on this review the methodology of the study will be introduced in chapter 3. Chapter 4 will give background information about the study area, Munich. The procedures for the data acquisition and handling will be presented in chapter 5. In chapter 6, the results will be presented and discussed. Lastly, conclusions for future research and the development of GOAT will be drawn in the last chapter.

2. Literature review

2.1. Accessibility

As noted in the introduction, concepts such as the 15-minute city can be seen as examples of a shift from mobility planning to accessibility planning. Thus, these two planning principles will be distinguished at the beginning (chapter 2.1.1), before a definition of accessibility will be presented (chapter 2.1.2), measures of accessibility discussed (chapter 2.1.3), and the term ‘accessibility instruments’ introduced (chapter 2.1.4).

2.1.1. From mobility planning to accessibility planning

To better understand the difference between mobility planning and accessibility planning, it is useful to think about the actual purpose of travelling. The majority of the population does not travel for the sake of travelling, but instead because they want to reach destinations where they can participate in activities (Bertolini, Le Clercq, & Kapoen, 2005). The real demand is, thus, not travelling, but the participation in activities at certain locations. Being mobile is not an end in itself, but a means to the end of having access to destinations, i.e. accessibility (Coppola & Papa, 2013).

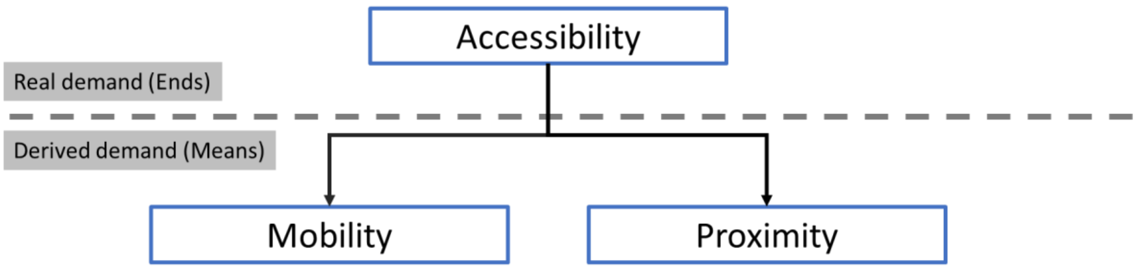


Figure 1 Relationship between accessibility, mobility, and proximity
Source Adapted from Silva & Larsson, 2019, p. 696

As figure 1 shows, there are, however, two variables that affect accessibility: *mobility* and *proximity*. Mobility planning has focused primarily on the mean of mobility, for example by building new roads and expanding existing roads. The private car became the focus of transport planning because its faster travel speeds promised increased access to destinations. However, the increase in accessibility by private cars led to a decrease in accessibility by proximity because destinations moved to locations further away from peoples’ homes. This had a negative impact on transport modes that require proximity, such as walking and cycling, and led to a modal shift from active transport modes to private vehicles (Handy, 2005).

As concerns for sustainability in the transport sector increased, the negative impacts of the increased use of private cars (e.g., noise pollution, greenhouse gas emissions) have led policymakers and planning practitioners to rethink planning practice and to place a greater emphasis on sustainable transport modes). Accessibility planning is often seen as a paradigm that can capture this shift in planning practice (Curtis, Scheurer, & Burke, 2013). Acknowledging that mobility as well as proximity are both relevant, planners have started to distinguish between *local accessibility* and *regional accessibility* (Handy, 1992). While the later should be achieved by public transport, the former should be achieved by walking and cycling.

Concepts such as the 20-minute neighbourhood and the 15-minute city can be seen as implementations of local accessibility. They aim to encourage active transport because of its many positive effects, for example on public health (Pucher & Dijkstra, 2003) and the climate (Rissel, 2009). The concepts often differ in their details but are similar to the extent that certain basic amenities such as grocery shops, doctors and pharmacies, childcare facilities and schools as well as recreational facilities should be accessible within short distances by foot or bicycle (see figure 2).

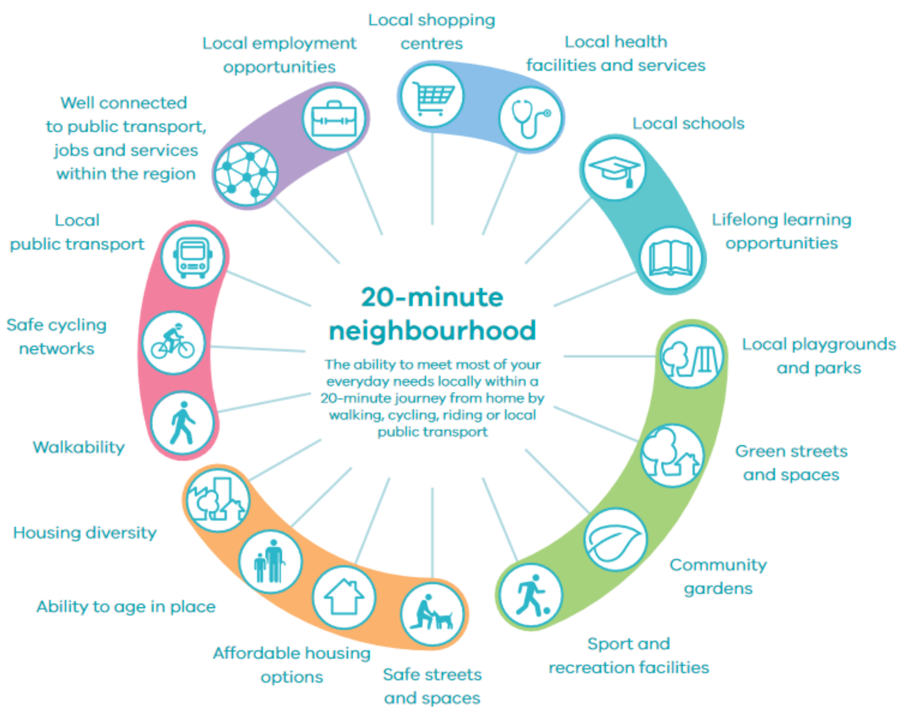


Figure 2 *Features of a 20-minute neighbourhood according to the City of Melbourne*
Source *"PLANMELBOURNE 2017-2050 // Plan Melbourne 2017-2050," 2017*

Even though proximity and mobility are important parts of achieving the goal of accessibility, the concept of accessibility is more complex and has more facets than just mobility and proximity.

2.1.2. Defining accessibility and its components

Accessibility has been defined in various ways since Walter G. Hansen famously defined it as "*the potential of opportunities for interaction*" (Hansen, 1959, p. 73). A definition that makes different facets of accessibility more explicit was proposed by Karst Geurs and Bert van Wee in their seminal paper "Accessibility evaluation of land-use and transport strategies: review and research directions" (Geurs & van Wee, 2004). According to Geurs and van Wee accessibility is

"the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)." (Geurs & van Wee, 2004, p. 128)

Their definition makes it clear that accessibility is a result of different components that interact with each other. In total they identified four components: a land-use component, a transport component, an individual component, and a temporal component. Accessibility is, thus, not only a function of distribution of origins and destinations, i.e. proximity, and the possibilities to move through space, i.e. mobility (see chapter 2.1.1), but also a function of individual capabilities and needs as well as temporal restrictions (see figure 3).

These components interact with and influence each other directly as well as indirectly. For example, the land-use component, which consists of the locations and characteristics of demand and opportunities, has an indirect influence on the transport system by setting origins and destinations for travel, i.e. the travel demand.

Based on the four components, every accessibility analysis can be characterised at least by the following questions:

1. What are the origins of trips? (e.g., home-based or work-based)
2. What are the destinations of trips? (e.g., shops or work-places)
3. Which transport mode(s) is(are) used? (e.g., walking or cycling)
4. Which group(s) of people is(are) examined? (e.g., children/elderly, men/women)
5. What time(s) of the day and year is(are) examined?

This illustrates the conceptual richness and complexity of the accessibility concept. To operationalise and measure accessibility, a multitude of factors have to be considered. As a consequence, there are numerous accessibility measures used in transport planning and research.

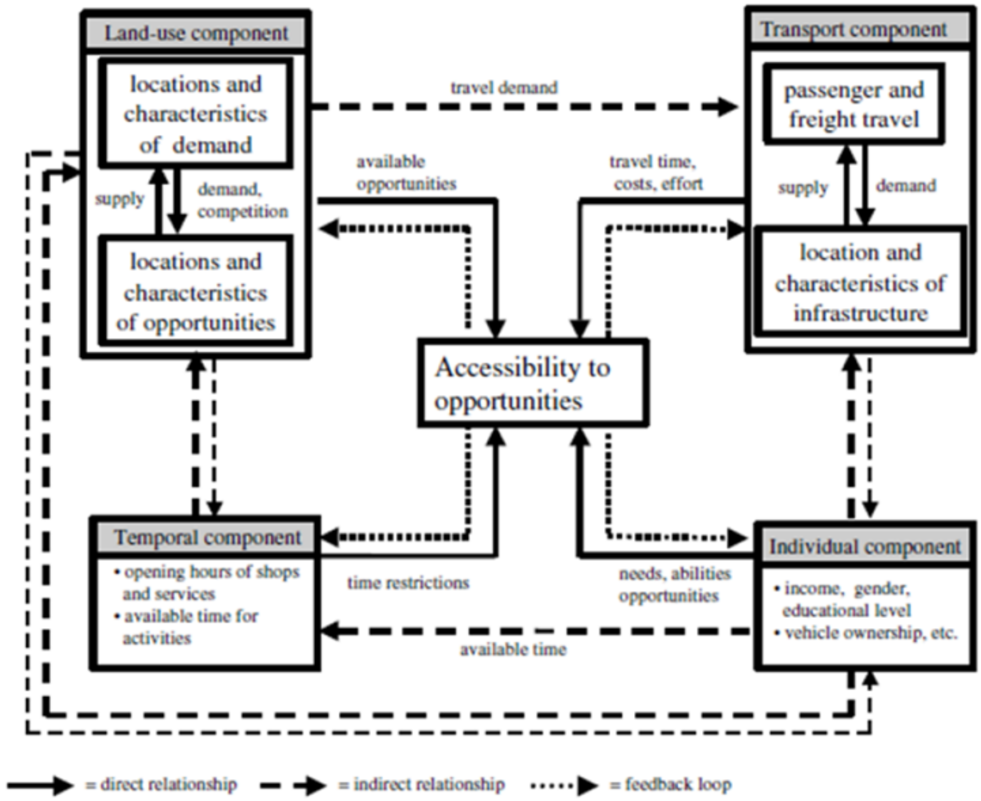


Figure 3 *The four components of accessibility and their interrelationships*
Source *Geurs & van Wee, 2004, p. 129*

2.1.3. Accessibility measures

Accessibility measures are used to quantify the level of accessibility numerically and are the basis for visual representation, usually in the form of maps. Different accessibility measures focus on different aspects of accessibility and often lead to different results (Geurs, 2018). Before the various accessibility measures are discussed, it is helpful to understand how an ideal accessibility measure is constructed.

Characteristics of an ideal accessibility measure

Geurs and van Wee (2004, pp. 130–131)have proposed a number of criteria for an 'ideal' accessibility measure. According to them, an ideal accessibility measure should

1. take all four components and their elements into account,
2. be sensitive to the location of the supply and demand for opportunities and the competition effects arising from the comparison of supply and demand,
3. "be sensitive to temporal constraints of opportunities" (p. 130),
4. "take individual needs, abilities and opportunities into account" (p. 130).

They also listed a number of behaviours that should be expected from any good accessibility measure if all other conditions remain constant (Geurs & van Wee, 2004, p. 130):

1. Accessibility should increase(decrease) if the service level (travel time, cost, effort) for a transport mode increases(decreases).
2. Accessibility should increase(decrease) if the number of opportunities increases(decreases).
3. Accessibility should increase(decrease) if the demand for an opportunity decreases(increases).
4. Accessibility of an individual/a group should not be affected by opportunities in which the individual/the group cannot participate.
5. Accessibility by a transport mode should not increase for people who are not able to use this transport mode.

As the review of the accessibility measure will show, the four criteria and five expected behaviours are seldom achieved by accessibility measures.

General overview

Mainly following their distinction between the four components, Geurs and van Wee have grouped accessibility measures into four families: infrastructure-based measures, location-based measures, person-based measures, and utility-based measures.

Infrastructure-based measures are often used in transport planning because they are more or less solely focused on the characteristics of the transport component. Typical measures are, for example, network connectivity indicators, e.g. the number of nodes that can be reached from one node in a network, or access cost indicators, that measure the travel impedance (time, distance, cost etc.) from one area to all other areas (see Geurs, 2018). The main drawback of infrastructure-based measures is their negligence of the land-use component. Thus, they are not responsive to changes in the land-use system. They only give limited information about accessibility as it is understood in the definition given above.

Location-based measures assess the level of accessibility for locations at origins and/or destinations. Three measures are typically used: connectivity measures, cumulative opportunity measures (CUM), and gravity-based measures. Connectivity measures simply calculate the impedance (time, distance, cost etc.) between an origin and, for example, the closest destination. CUMs, by contrast, count the number of opportunities (e.g., number of shops or number of work-places) within a given impedance. Lastly, gravity-based measures are a combination of the first two measures. They are calculated by weighing the attractiveness of a destination by applying a so-called “distance decay function” (often a negative exponential function or a gaussian function) which reduces the attractiveness of a destination with growing distance. The accessibility at an origin is then calculated as the sum of all weighted opportunities within reach (see figure 4).

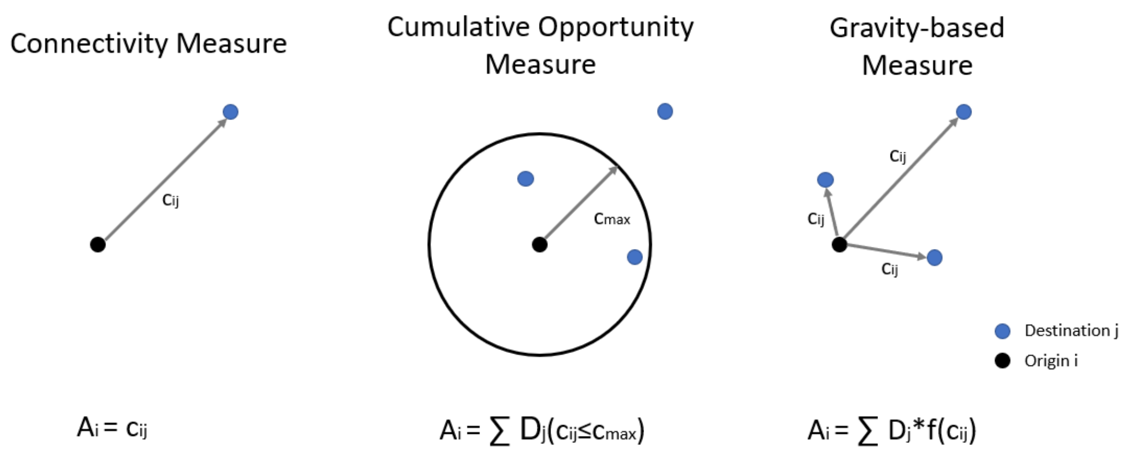


Figure 4 Visualisation of location-based accessibility measures and their calculation

Person-based measures evaluate accessibility from the perspective of an individual person and take the individuals time and monetary budgets as well as their wants and needs into account. Their computation, interpretation and communication are quite difficult (Geurs & van Wee, 2004, pp. 134–135); hence they won't be covered in detail here.

Utility-based measures are also more difficult to measure than infrastructure- and location-based measures. They try to measure the utility (benefits minus costs) derived from the access to destinations based on an individual's travel choices. Usually, the results are expressed in monetary terms which makes utility-based measures attractive for the application in cost-benefit analysis (Geurs, 2018).

Accessibility measures with competition

As mentioned at the beginning of this chapter, an ideal accessibility measure should be sensitive to demand at origins and supply at destinations as well as the confrontation between the two, i.e. competition. In accessibility research, and especially geographical health research, the so-called two step floating catchment area (2SFCA) method is among the most common competition measures (Paez, Higgins, & Vivona, 2019).

The 2SFCA was first introduced in 1982 by Alun Joseph and Peter Bantock (Joseph & Bantock, 1982) and has been used in many studies as a measure for accessibility under competition. It was used, for example, to measure the accessibility to jobs (Shen, 1998), urban services (Kelobonye, Zhou, McCarney, & Xia, 2020), or general practitioners (Joseph & Bantock, 1982). It is based on the gravity-based accessibility measure and its calculation consists of two steps, as the name already suggests:

$$A_i = \sum_j \frac{S_j \times f(c_{ij})}{D_j}$$

$$D_j = \sum_k P_k \times f(c_{kj})$$

with A_i = Accessibility at origin i
S_j = Supply at location j
$f(c_{ij})/f(c_{kj})$ = impedance between origin and destination
D_j = Demand potential at destination j
P_k = Population at competing origins k

Firstly, the demand potential D_j for every destination j is calculated as the sum of the population P_k in the competing origins k with access to the destination weighted by the impedance function $f(c_{kj})$. Secondly, the accessibility A_i for all origins i is calculated by dividing the supply potential at the destination, e.g. capacity C_j weighted by the impedance between origin and destination $f(c_{ij})$, by the demand potential of the destination and then adding the results for every origin.

2.1.4. Accessibility Instruments

As the phrase ‘shift from mobility planning to accessibility planning’ indicates, accessibility planning is not yet the norm in transport planning. In fact, accessibility researchers have lamented for years that there is an implementation gap between the knowledge on accessibility in research and its actual use in planning practice. Among the reasons for this gap reported in the literature are a lack of understanding among planning practitioners and decisionmakers as well as the lack of institutionalised guidelines and policies (Silva & Larsson, 2018).

Accessibility Instruments (AIs) are seen as an important cornerstone in overcoming this implementation gap (Silva, Bertolini, te Brömmelstroet, Milakis, & Papa, 2017). AIs are a special form of planning support systems (PSS) whose aim is the provision of explicit knowledge on accessibility, for example in the form of maps, to planners, researchers, policymakers, and also the public (Papa, Coppola, Angiello, & Carpentieri, 2017). Just like PSSs in general, AIs are geo-information-based tools that are usually built on a geographic information system (GIS) and/or a (geo)spatial database in combination with webserver applications for geospatial data, such as GeoServer .

2.2. GOAT

Since the analysis will be carried out with the accessibility instrument GOAT, this chapter will give some background information on GOAT's technical architecture, functionalities, and its possibilities for accessibility analysis.

2.2.1. Technical architecture

GOAT is a so-called WebGIS-application. It is based on a client-server-architecture and can be accessed through a web browser (see figure 5). GOAT is installed on a local hard drive by downloading it from its GitHub repository (https://github.com/goat-community/goat). The individual components of GOAT (database, website etc.) are run via the virtual machine *Docker*. After the installation process, a spatial database is set up on the server-side that consists of a *PostgreSQL*-database with the extension *PostGIS* to enable spatial operations. The data is transmitted to the client by *GeoServer* via the OGC-standards WFS (WebFeaturesService) and WMS (WebMapService). Visualisation in the browser and interaction with the client is facilitated via *css, javascript, OpenLayers* and *Vue*. Most functionalities for the handling of the data within the database are written in *python* (Pl/Python) and *spatial SQL* (Pl/pgSQL).

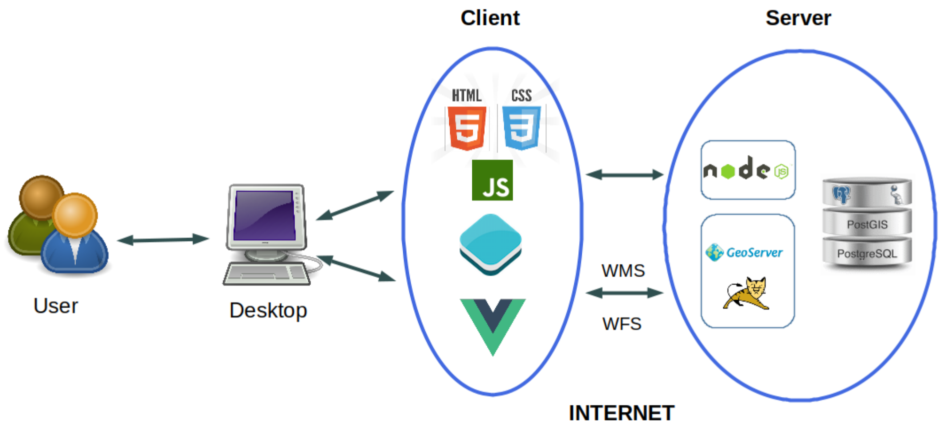


Figure 5 The client-server architecture of GOAT
Source Open-accessibility, 2021

Data

One notable feature of GOAT is its focus on open data. Particularly, GOAT makes extensive use of OpenStreetMap (OSM) data. The downloading of the OSM-data is automated and can, theoretically, be performed for any area worldwide because of OSM's standardized data structure. The only required input is a shapefile which contains the study area (*study_area.shp*). GOAT will then automatically download the OSM-data during the setup and extract the relevant information into separate tables (for example, POIs (Points of interest), land-use, buildings, ways). Even though this process is convenient and easily transferable, data quality and data accuracy can be problematic. Because OSM-data is maintained by volunteers, it is often outdated or incomplete. Accordingly, the data should be collected onsite before the setup or compared to official data sources to ensure its quality and accuracy. GOAT is also able to disaggregate population data automatically to the residential buildings that were extracted from the OSM-data. The population data must be added to the data folder before the database set-up as a shapefile (*census.shp*).

2.2.2. Accessibility measurement with GOAT

Currently, GOAT is able to model accessibility for the modes walking and cycling. GOAT also enables users to create scenarios, such as the building of new links in a network or the creation of new apartment buildings. So far, GOAT offers three distinct methods for the evaluation of accessibility: travel-time isochrones, a local accessibility heatmap, and the comparison of the accessibility heatmap and population densities.

The calculation of travel time isochrones can be performed in the browser by setting a starting point on the map. The travel-time isochrone will be displayed on the map and a box that contains information on reached population and POIs will be displayed as a pop-up window within the map. The travel time isochrone is a form of the cumulative opportunity measure (see chapter 2.1.3). If no POI is selected, it will return only the number of people within the isochrone. The user can set travel times from one to 20 minutes, speeds from one to 25 km/h, and the number of isochrones that will be calculated from one to four. An example is displayed in figure 6.

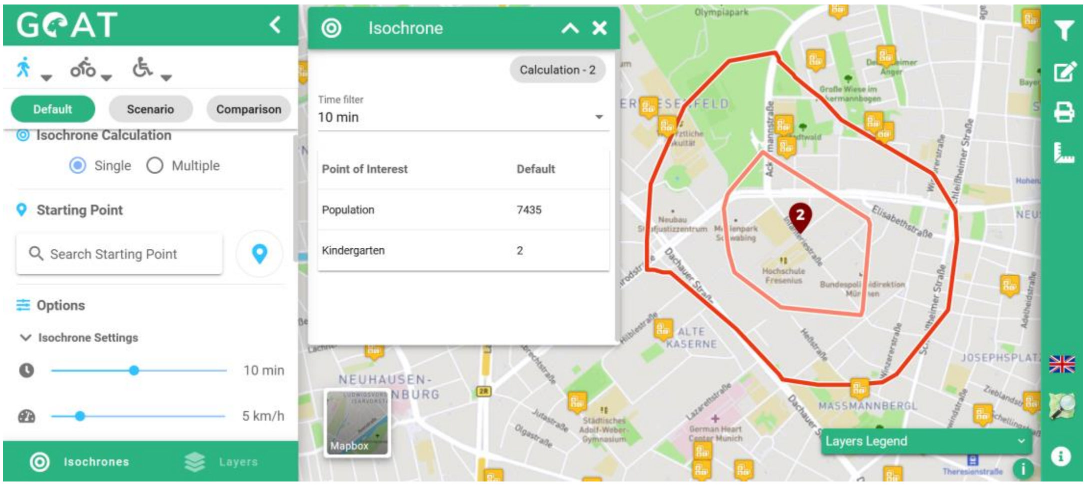


Figure 6 *Example of a travel time isochrone in GOAT*
Source *Screenshot taken from GOAT*

The *Local Accessibility* calculation produces a gravity-based accessibility measure for every cell of a pre-defined grid. The study area is divided into hexagonal grid-cells and for every grid-cell the accessibility to the selected amenities is calculated. The results are displayed as a heatmap with different colours indicating the level of accessibility based on the grouping into quintiles (dark red = no accessibility, dark green = highest quintile) (see figure 7).

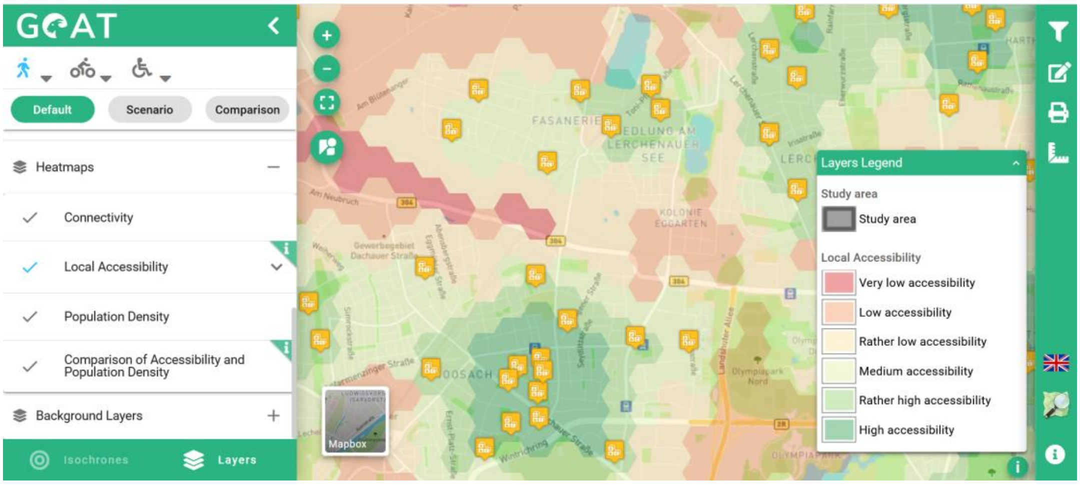


Figure 7 Example of an accessibility heatmap in GOAT
Source Screenshot taken from GOAT

Lastly, GOAT also offers a comparison between the gravity-based accessibility measure and the population density. If a grid is within the same quintile for both the accessibility and the population density, it is considered to be balanced (displayed in yellow on the map). If the accessibility is higher than the density it is grouped into high or rather high accessibility surplus (displayed in dark or light blue respectively).

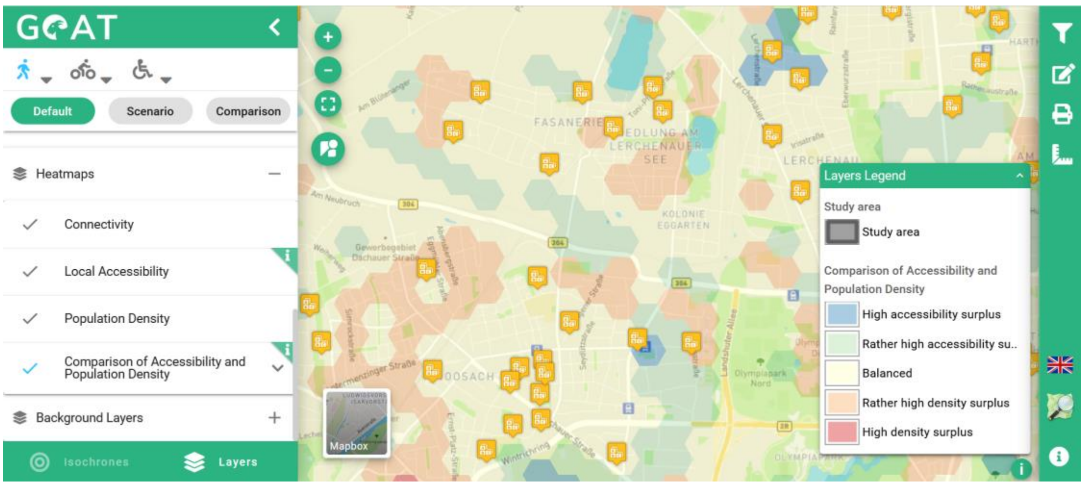


Figure 8 Example for the comparison of accessibility and population density with GOAT
Source Screenshot taken from GOAT

If the density is higher than the accessibility it is grouped into high or rather high density surplus (displayed in red or orange respectively) (see figure 8).

All accessibility measurements can also be performed from a database administration tool and the results saved within separate tables for further analysis.

So far, these measures don’t entirely fulfil the criteria for “ideal” accessibility measures. Even though the comparison between accessibility and population density gives some comparison between supply and demand, it does not really reflect competition effects. Integrating supply and demand into the analysis will be one task of this thesis. Furthermore, solely looking at the accessibility values calculated for grid-cells (or any other spatial feature) might lead to a ‘fetishism of space’. Actually, the people who have access to destination should be at the heart of the analysis and not the space from which they have access. In recent years, considerations on the fairness of the distribution of accessibility among the population, often referred to as spatial equity (Ashik, Mim, & Neema, 2020) or equitable accessibility (Lucas, van Wee, & Maat, 2016) have increasingly become guiding principles for accessibility analysis.

2.3. Equity

Like accessibility, equity is a concept that can be defined and measured in multiple, often opposing, ways. In chapter 2.3.1, the term ‘equity’ will be clarified, and a variety of common definitions introduced. Subsequently, ways to measure equity and the relationship between equity and accessibility will be explored.

2.3.1. Defining (spatial) equity

‘Equity’ is a term that has preoccupied human-beings at least since antiquity. It is closely linked to the terms ‘justice’ and ‘fairness’, and often used interchangeably with ‘equality’ (Carleton & Porter, 2018). While there are schools of thought that equate equity with equality (i.e. egalitarians), both concepts need to be clearly distinguished. Drawing on its relation to justice, equity is often viewed as synonymous to *distributive justice* (Pereira, Schwanen, & Banister, 2017). Following this usage, questions of equity are related to the justness/fairness of the distribution of goods, wealth, services etc., in contrast to *procedural justice*, which is the fairness/justness of processes, and *substantive justice*, which deals with legal rights and entitlements (Pereira et al., 2017).

When equity concerns are used in spatial/geographical analysis, the term ‘spatial equity’ is often used. In the literature, the question has been raised whether spatial equity is a specific form of equity (*content*) or an application of one type of equity to the spatial domain (*context*). Pirie (1983) has argued that spatial justice/equity is the application of the distributive justice to the spatial domain and, thus, only differs in its context from other applications of distributive justice. In fact, Pirie (1983) sees spatial equity as dealing with the question how opportunities are distributed in space. Spatial equity is, thus, closely related to accessibility. Accordingly, spatial equity will be understood in this thesis as the question of the justness of the distribution of accessibility.

2.3.2. What is a just distribution?

There are different views on what constitutes a just distribution. A common view is the already mentioned *egalitarianism*. According to egalitarianism a distribution is just if it is equal (strong egalitarianism), i.e. every person has the same amount of the distributed good, or as equal as possible (weak egalitarianism) . An opposing view to egalitarianism is the concept of *sufficientarianism*, according to which a distribution is just if all people are at least above a certain minimum threshold (Lucas et al., 2016). Another famous family of ethical theories on equity is *utilitarianism*. For utilitarianists, a distribution is just when it maximizes the total utility (benefits minus costs) of a population (Pereira et al., 2017). Lastly, there are also *needs-based* approaches, that see a distribution as just if it matches the need of the population (Whitehead, L Pearson, Lawrenson, & Atatoa-Carr, 2019).[1]

All these view on equity have certain problems. Egalitarianism faces the problem that perfect equality is impossible to achieve in transport planning (Martens & Golub, 24 and 2011). Sufficientarianism, by contrast, faces the problem that the definition of a ‘sufficient level’ is often arbitrary and, thus, prone to subjectivity (Pereira et al., 2017). Utilitarianism is often criticised, because situations in which individuals that are already well off benefit more than individuals who are worse off must be preferred if they maximize the total welfare (Pereira et al., 2017). Needs-based approaches also face the problem that the quantification and definition of needs is often not trivial and grounded in subjective judgements.

Because of the shortcoming of the different theories of equity, it is useful to combine different ones within an equity analysis (Lucas et al., 2016). This ensures that the equity analysis is not – or to a lesser degree – affected by subjective preferences for certain ethical theories. Of course, the choice of an ethical theory behind an equity analysis also goes hand-in-hand with the choice of a measurement technique.

[1] There are numerous other justice theories that won’t be covered in depth within this chapter. For example, Pereira, Schwanen, and Banister (2017) also discuss *Libertarianism*, the view that individual rights are more important than aggregate welfare, *Intuitionism*, the view that the fairness of distribution should always be evaluated context dependent without a guiding theory, and *Rawls’ Egalitarianism*, the view that a fair distribution should be as equal as possible and maximize the position of the least advantaged groups.

2.3.3. Measuring equity

Different ethical theories require different measurement techniques. In this chapter (at least) one common measure will be introduced for every theory. This chapter will also address which accessibility measures are suitable for equity analysis with GOAT. Utilitarian equity measures will be neglected, since GOAT does not feature an utilitarian accessibility measure.

Egalitarianism

The most common way to measure equity from an egalitarian perspective can be found in Lorenz Curve and, associated with it, the Gini Index (Lucas et al., 2016). The Lorenz Curve is a visualisation of the cumulative distribution of a variable across the cumulative share of the population. The cumulative share of the population is plotted on the x-axis and the corresponding cumulative share of the variable is plotted on the y-axis. In case of perfect equality, the Lorenz Curve would be a straight line, the line of equality. The distribution is more unequal if the Lorenz Curve is further away from the line of equality. The equality of the distribution can also be expressed by a single index, the Gini Index. The Gini Index is calculated by dividing the area between the Lorenz Curve and the line of equality by the maximum possible area below the line of equality. A value of 0 indicates perfect equality. A value of 1 indicates perfect inequality (one person owns everything). A distribution is more equal when the value is closer to zero. Because the construction of the Lorenz Curve requires values that are zero or greater than zero, it cannot be performed with utility-based accessibility measures.

Sufficientarianism

For the sufficientarian measurement, usually the share of people above a certain threshold is defined (Lucas et al., 2016). The aim is that 100 % of the population are above the pre-defined threshold. The definition of the threshold is usually based on policy goals or actual travel behaviour. For example, when analysing the 15-minute city, the share of people with access to destinations within 15 minutes would be counted. The calculation is fairly easy and can be performed with all types of accessibility measures.

Needs-based

Needs-based theories are most often measured by conducting a so-called gap-analysis (Carleton & Porter, 2018). A needs-gap-analysis compares the distribution of accessibility with the distribution of the population, identifying areas that deviate from an ideal ratio of access-to-need. The gap-analysis is mainly done visually, and the results are presented in maps. It can be performed with all accessibility measures. Needs-/demand-based considerations can also be integrated directly into the accessibility measure by including competition effects (see chapter 2.1.3). If accessibility measures themselves include such considerations, egalitarian and sufficientarian considerations can be combined with needs-/demand-based considerations. An overview of the different measures is presented in table 1.

Table 1 *Theories of distributive justice and their respective measures*

Theory	Accessibility measure(s)	Common equity measure(s)	Pro/Con
Egalitarianism	Infrastructure-based, Location-based, Person-based	Lorenz Curve and Gini Coefficient	+ Easy to interpret Easy comparison between different areas and amenities - No spatial component
Sufficientarianism	All measures	Share of population above threshold	+ Easy to interpret Easy comparison between different areas and amenities - No spatial component (but mapping is possible) "Right" threshold is often difficult to define
Needs-based	All measures	Gap analysis	+ Population characteristics considered Spatial component considered - Aggregation might hide information

2.3.4. Horizontal and vertical equity

A last thought must be given on the question of how different population groups are integrated into the analysis. The justness of a spatial distribution cannot be separated from questions of social justice in regard to different population groups (Carleton & Porter, 2018). Two possibilities are often referred to in the literature: *horizontal equity* and *vertical equity*.

Horizontal equity is used to describe equity considerations that do not look at the differences between individuals or groups of individuals, but instead treat *everybody as equal* (Carleton & Porter, 2018; Litman, 2021). Horizontal equity is often used to describe equity analyses that consider the total population. However, an analysis that assesses the equity between men would also be considered an analysis of horizontal equity, since all men are treated as equals.

Vertical equity, by contrast, is used when different individuals or groups of individuals are compared to each other. For example, a comparison of the accessibility for men and women would be considered as an analysis of vertical equity. Vertical equity is regularly used to compare advantaged and disadvantaged groups. In a transport- and accessibility-related equity analysis, vertical equity is often divided into *socio-economic equity* and *equity in mobility* based on different reasons for transport disadvantages (Carleton & Porter, 2018; Litman, 2021; see figure 9). Socio-economic equity compares groups based on characteristics such as gender, ethnicity, income, or employment status. Equity in mobility is used to describe comparisons based on factors such as car availability, disability, age, or the possession of a driver's license. Considerations of vertical equity are especially relevant for needs-based equity analysis because different population segments often have different needs and abilities (Whitehead, Pearson, Lawrenson, & Atatoa-Carr 2019, p. 3-4).

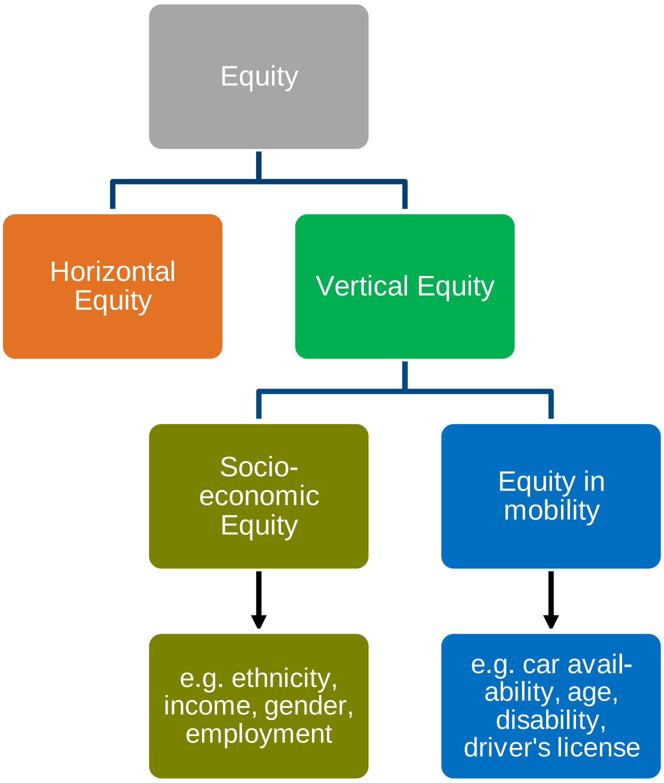


Figure 9 Overview of different types of equity

Even though most equity measures can be applied to a horizontal as well as vertical equity analysis, vertical equity analysis is often performed with specific measures. One specific method, is correlation analysis (Truelove, 1993). It can show how accessibility values correlate with the distribution of the population and whether higher numbers for certain population groups are aligned with higher values of accessibility . A comprehensive equity analysis should incorporate horizontal as well as vertical equity concerns.

2.4. Conclusion of the literature review

The literature review has shown that GOAT supplies its users with different accessibility measures. However, the competition effects arising from the confrontation of supply and demand are not yet integrated. Because GOAT uses a gravity-based accessibility measure, the 2SFCA method is a suitable measure for accessibility in the case of competition. Furthermore, an analysis of accessibility must not only consider the spatial distribution of accessibility but also the spatial distribution of the population. Measures based on different concepts of equity as well as horizontal and vertical equity perspectives should be incorporated into an analysis to ensure that it reveals actual disparities among the population and between different socio-economic groups. GOAT is especially suited for equity analysis based on egalitarian, sufficientarian, and needs-based approaches. In the following section, the methods to answer the research questions will be presented.

3. Methodology

This chapter will introduce the methodology adopted on the basis of the literature review and used to answer the research questions. Firstly, the research questions and the respective measures to answer them will be presented briefly. Then, the different methods will be discussed in more detail.

3.1. Research questions and overview of methodology

This thesis will evaluate accessibility and spatial equity for home-based trips to essential services by the mode of walking. Time of the day and year will not be considered. The vertical equity analysis will be based on socio-economic differences that will be defined based on risks of poverty in Munich (chapter 4.6).

The methodology of this thesis was chosen to answer the following research questions (see introduction):

(1) Which areas in Munich have deficient levels of walking accessibility? Are there differences between different amenity types?
(2) Is the walking accessibility in Munich distributed equally? Are there differences between different amenity types?
(3) Are there correlations between accessibility levels and socio-economic as well as demographic factors?
(4) How can competition effects and socio-demographic data be incorporated into GOAT to assess accessibility, and levels of supply and demand more realistically? Are there differences in the results for accessibility measures with and without competition?

To answer the first question, maps and box plots will be used to produce graphic and numeric representations of accessibility. The calculated accessibility values will serve as the basis for the equity analysis. The second questions will be answered by applying sufficientarian (share of the population above threshold) and egalitarian equity measures (Lorenz Curve and Gini Coefficientt). The vertical, socio-economic equity analysis will be based on a comparison of the shares of the population in the socio-economic groups and a comparison of the correlation coefficients. Lastly, the fourth research questions will be answered by applying the methods of the first three questions to the accessibility measure with competition and comparing the results to the measure without competition. Figure 10 presents an overview of the methodology.

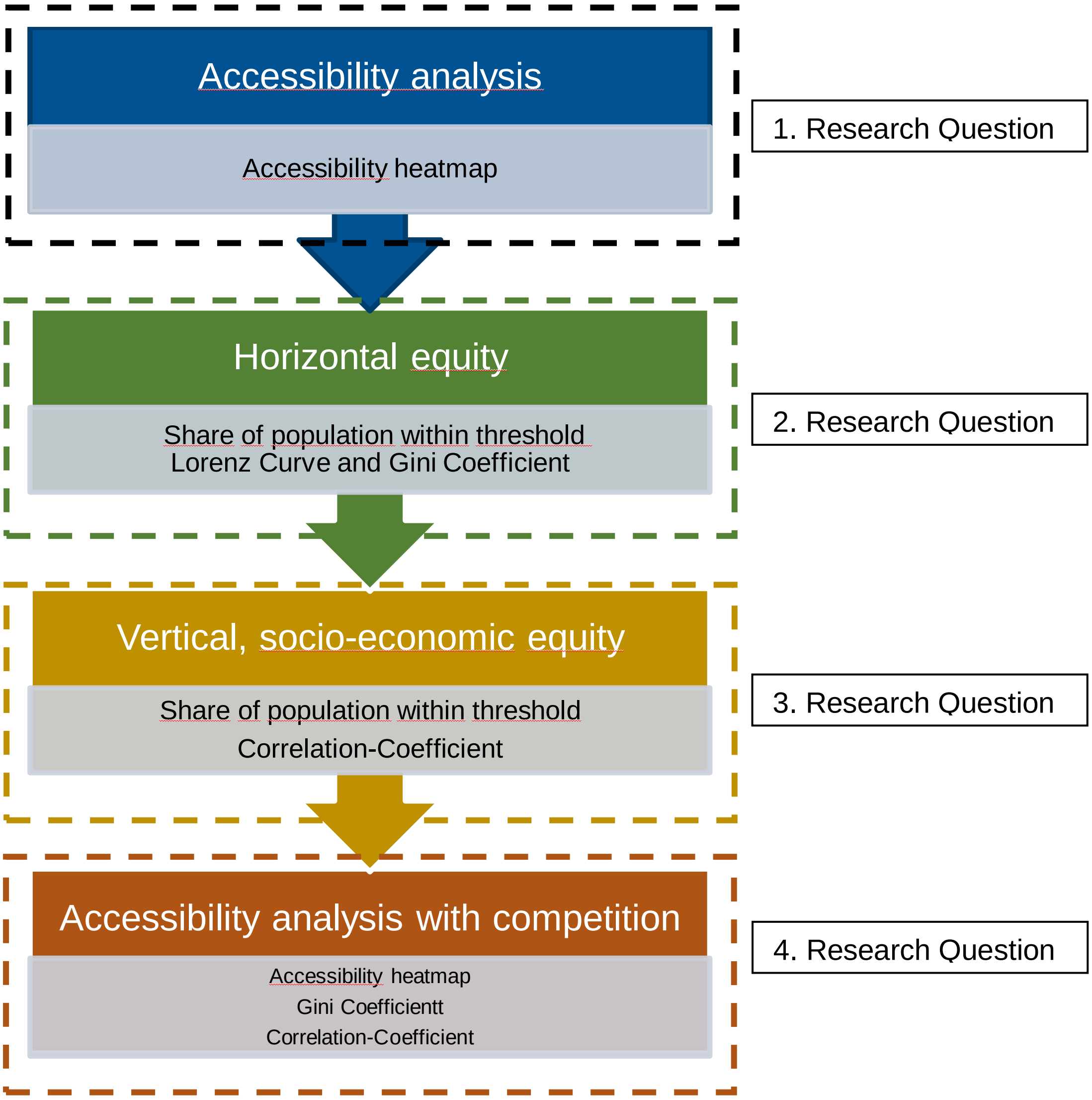


Figure 10 Overview of the methodology

Before the individual methods are presented, it is necessary to define the essential services that will be considered for the accessibility analysis.

3.2. Definition of essential services

It was already mentioned in chapter 2.1.1 that the provision of certain essential services within walking distance is one goal of the 15-minute-/20-minute-concepts. Doctors, pharmacies, schools, childcare institutions, and grocery shops were mentioned as potential essential services in such concepts. Essential services are also defined as part of the so-called *Landesentwicklungspläne* (land development plans) in Germany. *Landesentwicklungspläne* are based on the *Zentrenkonzept* (centre-concept) which defines a hierarchy of different centres for a whole federal state. For each type of centre, amenities are defined that should be accessible by the population. The lowest level in the hierarchy consists of so-called *Grundzentren* (basic centres). The definition of the essential services that should be accessible in basic centres is different for every federal state, however common amenities and categories can be identified (see Ministerium des Inneren und für Sport Rheinland-Pfalz, 2008; Verordnung über das Landesentwicklungsprogramm Bayern (LEP), 2020; Wirtschaftsministerium Baden-Württemberg, 2002). These are illustrated in figure 11. Amenities in cursive are considered as less important.

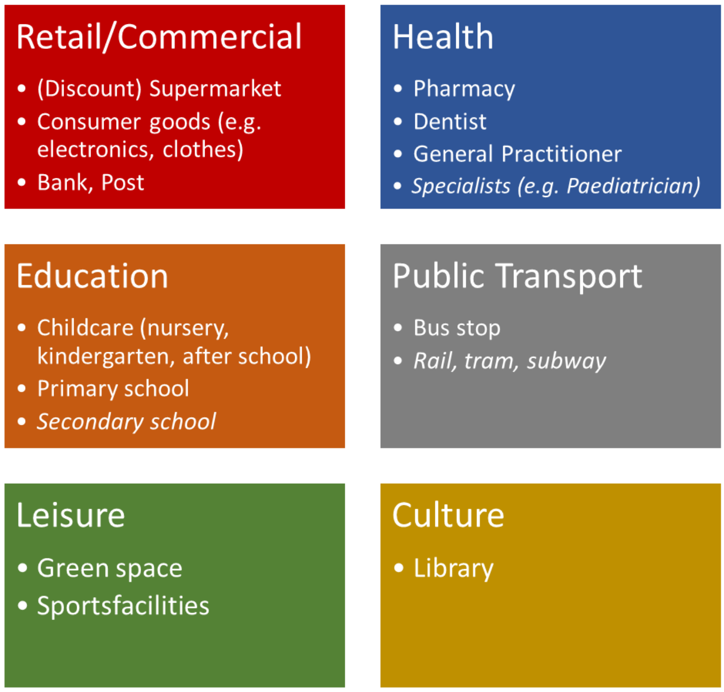


Figure 11 Essential services according to the Landesentwicklungspläne

This study will focus on the categories of health, education, public transport, and food retailing/grocery shops (i.e. (discount) supermarkets). As specialists in the category of ‘health’, paediatricians and gynaecologists will be included. In the category of ‘education’, all major types of secondary schools in Bavaria (Haupt-/Mittelschule, Realschule, and Gymnasium) will be considered.

3.3. Accessibility calculation and assessment

The basis for the accessibility assessment as well as the equity analysis is GOAT’s gravity-based accessibility measure. The competition-adjusted accessibility measure will be used for further analysis of nurseries and kindergartens. The calculation of these two measures and their visualisation will be presented in the following chapters.

3.3.1. Gravity-based accessibility without competition

The gravity-based accessibility measure is the basis for the local accessibility calculation and the accessibility heatmap in GOAT. It calculates the accessibility A for every origin i to all destinations O_j that can be reached within a certain threshold. The default threshold is 20 minutes. The centres of a hexagonal grid, covering the study area, are used as origins. The destinations are the amenities chosen for the calculation (e.g., supermarkets). The measure's principle is illustrated in figure 12.

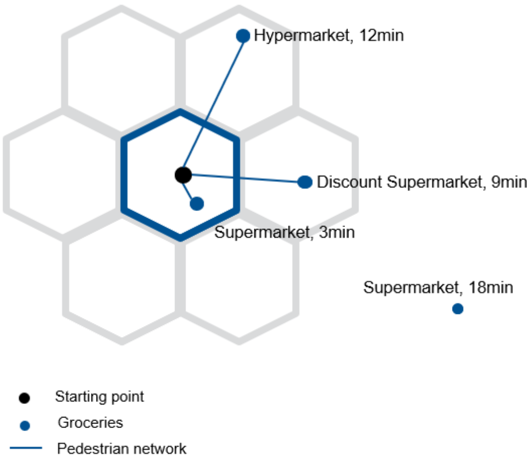


Figure 12 Principle of the gravity-based accessibility index in GOAT

The accessibility value A_i at an origin i is then calculated with the following formula:

$$A_i = \sum_j O_j \times f(t_{ij}) \times 10{,}000$$

with: $f(t_{ij}) = e^{\left(-t_{ij}^2/\beta\right)}$

The accessibility at an origin is the sum of the accessibility values to all destinations j. The accessibility value is calculated by multiplying the value O_j with the impedance function $f(t_{ij})$ and a factor of 10,000. The value of O_j is '1' if the destination is within the threshold and '0' if it is outside of the threshold. The impedance function $f(t_{ij})$ takes values between 1 (t_{ij} = 0) and 0 based on the travel time t_{ij} between origin and destination. Because the accessibility value is multiplied by a factor of 10,000 the maximum value for one opportunity at destination j is 10,000. The accessibility values are never negative and between zero and infinity. Higher values indicate a higher level of accessibility.

The impedance function's sensitivity to travel times depends on the values of the β-parameter. Lower values lead to a steeper decline in the impedance function (see figure 14) and to lower accessibility values at farther destinations, because the attractiveness of destinations declines quicker with growing distance. Predefined β-parameters in GOAT range from 150,000 to 450,000. They are stored in the *variable_container* table, which is created during the setup by the *goat_config.yaml* file. It is also possible to assign an additional weight (integer values from 1 to 10) to the amenities that will change the value of O_j for destinations within the threshold, accordingly.

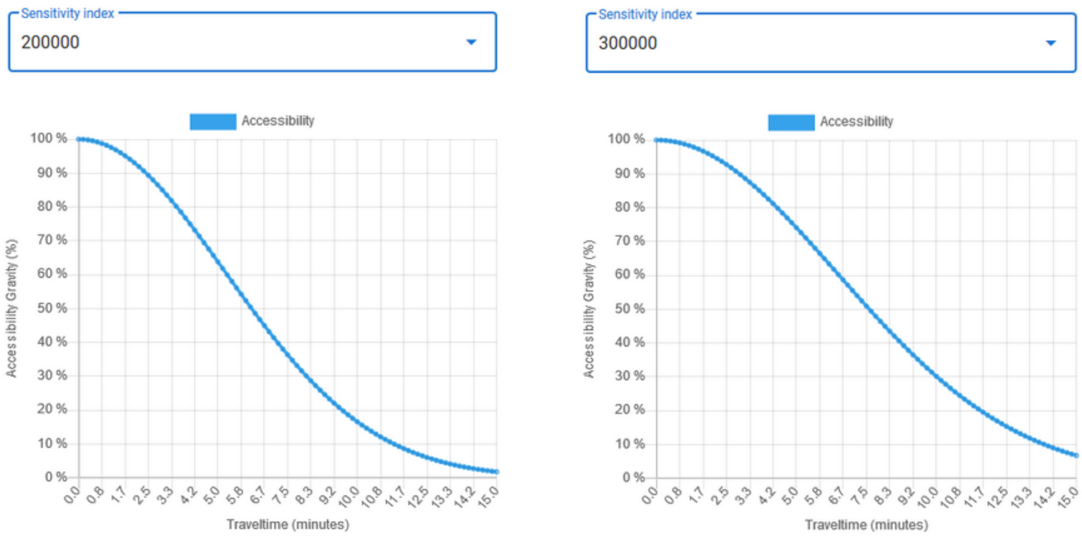


Figure 13 *Comparison between two impedance functions with different sensitivity parameters*

The sensitivity parameters need to be adjusted for the different amenity types based on actual travel data (Iacono, Krizek, & El-Geneidy, 2010). This will be done in chapter 5.3 of this thesis.

The accessibility calculation is implemented in GOAT's spatial database with the SQL-function *heatmap_dynamic.* The function requires information about the selected amenities, the value of the sensitivity index, and the weight. This information is inserted into the function in json format. Information about the mode of walking and the scenario must also be provided. The function takes the following form when called in the database:

```
heatmap_dynamic('{"nursery":{"sensitity":550000,"weight":1}}'::jsonb,'default',0)
```

The basis for the calculation is the table *reached_POIs_heatmap* which is precalculated during the setup of GOAT and stored in the database. It contains the accessibility values from every point of interest (poi) to all cells of the grid that are within 20 minutes.

3.3.2. Gravity-based accessibility with competition (2SFCA)

As mentioned in the literature review, the 2SFCA method is derived from the gravity-based accessibility measure. It does not only take the accessibility between origin i and destination j into account, but also the total population that has access from competing origins k to the destination as well as the capacity at destination j. The principle of the 2SFCA is depicted in figure 14.

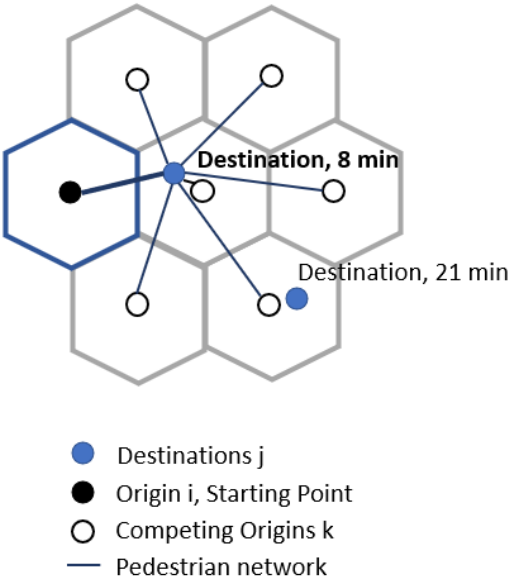


Figure 14 Principle of the 2SFCA method in GOAT

The formulas for the 2SFCA (see chapter 2.1.3) were adjusted to fit with GOAT's gravity-based measure:

$$A_i = \sum_j \frac{O_j \times C_j \times f(t_{ij})}{D_j}$$

$$D_j = \sum_k P_k \times f(t_{kj})$$

with A_i = Accessibility at origin i
O_j = Opportunity value at destination j
C_j = Capacity/smupply at destination j
$f(t_{ij})/f(t_{kj})$ = impedance between origin and destination
D_j = Demand potential at destination j
P_k = Population at competing origins k

The calculation was done in the spatial database with the SQL-function *heatmap_dynamic_population*. The function first calculates the demand potential D for every destination j. The demand potential is the sum of the population at grid cells k, where such are within the threshold, multiplied by the impedance function between the grid cell and the destination. In a second step, the accessibility is calculated for every grid cell, analogous to the calculation for the simple gravity-based heatmap. However, the accessibility value is multiplied by the capacity at the respective destination and divided by the demand potential to that destination. The resulting values are greater than zero but mostly remain below ten. A value of 1 indicates perfect balance between supply and demand from an origin's perspective. Values above 1 indicate a higher supply than demand and, values below 1 indicate lower supply than demand.

To include the supply at POIs, the capacity column was added to the *pois* table in GOAT by altering the *pois.SQL* file, which is executed during the database setup. The values from the key 'capacity' in the tag column were inserted into the newly created capacity-column. It should be noted that the capacity key often holds values that are not numeric. Values with letters or special signs had to be excluded during the setup which probably leads to a loss of information. For all POIs where the capacity is null, the capacity was set to '1' to ensure that the competition calculation works properly.

The population data was included by adding a new column to the *grid_heatmap* table which contains an array of integer values. The array contains the values for the different user groups (e.g., population, under 3 years, 3 to 5 years etc.). These values are accessed in the *heatmap_dynamic_population* function in a similar way to the sensitivity values by adding a new key value pair to the json that contains the amenity, the sensitivity, and the weight. The function can be accessed from the database in the following way:

```
heatmap_dynamic_population('{"nursery":{"sensitity":550000,"weight":1,
”userGroup”:”Under 3 years”}}'::jsonb,'default',0)
```

Like the sensitivity parameters, the values of the key-value-pair "userGroup" have to be predefined in the *variable_container*-table. They were added to the *goat_config.yaml*-file, which creates the *variable_container* during the setup. A new dropdown menu was also added to the browser menu from which the user group of interest can be chosen.

Because the inclusion of competition effects requires more extensive data, calculations will only be made for a few selected amenity types, namely nurseries and kindergartens.

3.3.3. Visualizing accessibility

The results of the accessibility calculations will be presented in the form of heatmaps. The accessibility heatmaps will be created with GOAT. The visualisation of the gravity-based accessibility measure is based on the *heatmap_gravity* function. It groups the grids into quintiles based on the results of the *heatmap_dynamic* function (see chapter 3.3.1). The same inputs as for the *heatmap_dynamic* function are required. The result is a map which shows the grids in six different colours according to their level of accessibility. Dark red indicates areas without access. Dark green indicates areas with high access (see figure 15).

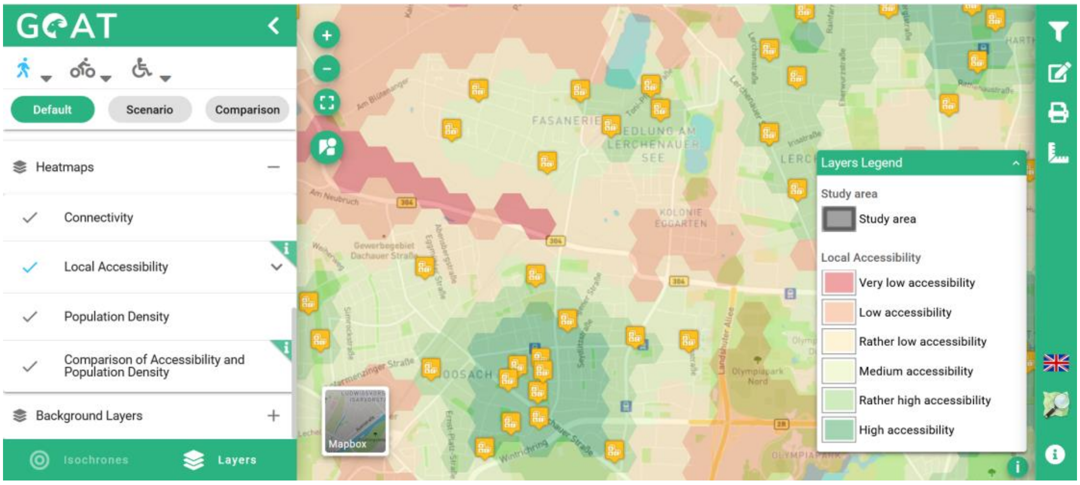


Figure 15 *Example of an accessibility heatmap in GOAT*
Source *Screenshot taken from GOAT*

The results for the competition measure can be visualised in the same way. The *heatmap_competition* function was created, which works identically to the *heamtpap_gravity* function but takes the results of the *heatmap_dynamic_population* function as an input instead.

3.4. Horizontal equity

3.4.1. Share of population within threshold

To measure equity under sufficientarianism one of the most common measure is the share of the population within a certain threshold (see chapter 2.3.3). Because GOAT uses a threshold for the accessibility calculation (see chapter 3.3.1), the population within the threshold can be calculated by adding the population of the grids k with an accessibility index greater than zero. The sum of the population within the threshold is then divided by the sum of the total population. The result will be multiplied by 100 to receive percentages. The calculation is fairly simple:

$$share\ of\ population\ within\ threshold = \frac{\sum_{j=1}^{k} population_j\ (Ai_j > 0)}{\sum_{j=1}^{n} population_j} \times 100\ [\%]$$

However, the choice of a threshold is quite difficult. Threshold can be chosen positively according to “*revealed levels* of participation” (Lucas et al., 2016, p. 482) or normatively according to the “*opportunity* to participate*” (Lucas et al., 2016, p. 482)*. Often, values between 500 metres and 1,000 metres are chosen normatively. The City of Munich sets limits at 600 metres (~7.5 minutes) for grocery shops and 750 metres (~9.4 minutes) for childcare institutions (Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2016). As a compromise, two different threshold will be used: the 20-minute threshold of GOAT and a 10-minute threshold. The results will be presented in tables that show the share of the population with access to the different amenity types according to the three thresholds (see table 2).

Table 2 Example table for population shares within different thresholds

Public Transport	**Share of population within...**	
Amenity Type	**20 minutes**	**10 minutes**
Bus Stop	99.9%	98.9%
Tram Stop	59.6%	42.8%
Subway Station	77.0%	55.3%
Rail Station	53.9%	19.8%

The calculation of the shares was implemented with python (Jupyter Notebook) in the script *equity_sufficientarianism.ipynb*. For the calculation, the accessibility and population data were saved in separate tables in GOAT's database. The data was accessed directly from the database via python's psycopg2-module and manipulated with the pandas-module. For the calculations numpy was used. The visualisation was created with Microsoft Excel.

3.4.2. Lorenz Curve and Gini Coefficient

To measure equity from an egalitarian perspective, the Lorenz Curve and the Gini Coefficient will be used. The Lorenz Curve is a graphic representation of the distribution of an attribute, in this case accessibility, over the population. The construction of the Lorenz Curve requires value pairs where every value is greater or equal to zero (non-negative). To construct the Lorenz Curve the values of the attribute must be arranged in ascending order. Based on this ordered arrangement, the cumulative share of the population is plotted on the x-axis and the cumulative share of accessibility on the y-axis. For every point i the x- and y-value can be calculated with (p = population, a = accessibility, n = number of value pairs) (formula adapted from Schira, 2009, p. 67):

$$x_i = 100 \times \sum_{j=1}^{i} \frac{p_j}{\sum_{j=1}^{n} p_j}$$

$$y_i = 100 \times \sum_{j=1}^{i} \frac{p_j * a_j}{\sum_{j=1}^{n} p_j * a_j}$$

The value pairs are then plotted into a coordinate system and connected by straight lines. Because the Lorenz Curve is plotted by connecting the value pairs, it is actually not a curve but a polygon chain. It is always convex (Schira, 2009, p. 69). The Lorenz Curve must be compared to the line of equality which is a straight line at a 45 degree angle to both axes (see figure 16). The Lorenz Curve is identical to the line of equality when the attribute is distributed perfectly equal among the population. At every point on the Lorenz Curve the x and y value would be identical, which means that the share of population would be equal to the share of the distributed attribute. The Lorenz Curve is always below or equal to the line of equality.

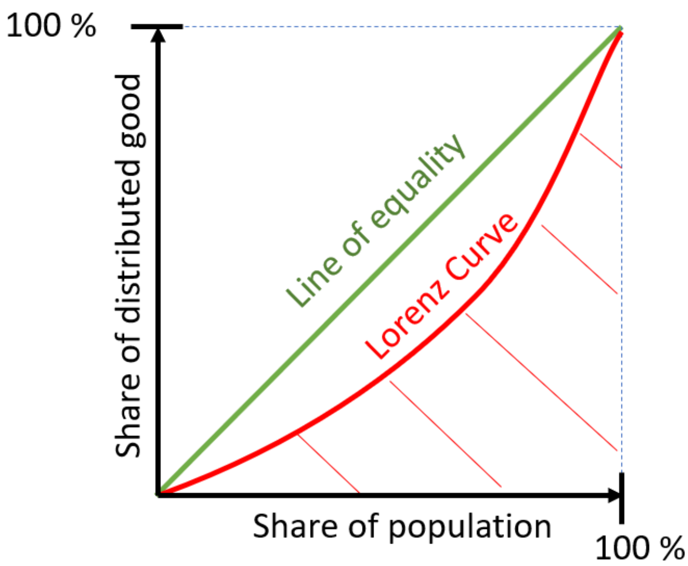


Figure 16 Example of a Lorenz Curve

Based on the Lorenz Curve, the Gini Coefficient can be calculated. The Gini Coefficient is a numerical, normalized measure of the equality of a distribution. It is calculated by dividing the area between the Lorenz Curve and the line of equality by the maximum possible area between the line of equality and the Lorenz Curve. A Gini Coefficient of 0 indicates complete equality. A Gini Coefficient of 1 indicates complete inequality (Schira, 2009, pp. 73–75).

$$0 \leq GINI \leq 1$$

To calculate the Gini Coefficient, both axes are normalised to a maximum value of ‘1’ instead of taking the percentages. Consequently, the maximum area under the line of equality is ½ (½*1*1). The maximum possible area between the line of equality and the Lorenz Curve CA_{max} can be calculated by subtracting the minimum possible area under the Lorenz Curve (1/(2*n)) from ½. Because the Lorenz Curve is constructed as a polygon chain, the area under the Lorenz Curve can be calculated by adding the areas between the individual points of the polygon chain. These areas are all trapezoids. By using the formula for the calculation of the area of trapezoids, the area between the Lorenz Curve and the line of absolute equality can be calculated as follows:

$$CA = \frac{1}{2} - \sum_{j=1}^{k} \frac{1}{2}(y_{j-1} + y_j) \times (x_j - x_{j-1})$$

$$CA_{max} = \frac{1}{2} - \frac{1}{2n} = \frac{n-1}{2n}$$

$$GINI := \frac{CA}{CA_{max}} = CA \times \frac{2n}{n-1}$$

The Gini Coefficients for the amenities in each category will be compared to each other and presented in tables. The Gini Coefficients are grouped into five groups: highly equal, rather equal, rather unequal, highly unequal, and severely unequal. They will be displayed in different colours to highlight the differences (see table 3).

Table 3 Evaluation and visualisation of Gini Coefficients

Amenity	Gini Coefficient
Highly equal	0.00 – 0.14
Rather equal	0.15 – 0.29
Rather unequal	0.30 – 0.44
Highly unequal	0.45 – 0.59
Severely unequal	0.60 – 1.00

The calculation of the Gini Coefficient and visualisation of the Lorenz Curve were implemented with python (Jupyter Notebook) in the script *equity_lorenz_and_gini.ipynb*. For the calculation, the accessibility and population data were saved in separate tables in GOAT's database. The data was accessed directly from the database via python's psycopg2 module and manipulated with the pandas module. Numpy was used for the calculation and matplotlib for the visualisation.

3.5. Vertical socio-economic equity

While horizontal equity treats everybody as equal, vertical equity compares different population groups. An analysis based on vertical socio-economic equity compares groups based on socio-economic characteristics such as gender or household income. The idea is that groups that are socio-economically disadvantaged or at risk of social exclusion shouldn't be disadvantaged spatially (see chapter 2.3.4). The socio-economic groups for the analysis will be determined based on the risk of poverty in Munich (see section 4.6).

3.5.1. Share of population within threshold

Just as in the horizontal equity analysis, the share of the population within a threshold can be used as an indicator for sufficientarianism from a vertical equity perspective. It shows whether certain population segments have less access to destinations, are at risk of exclusion from participation in activities and have to rely on other modes of transport to reach destinations.

The share of the population within a threshold will be calculated and presented for the different socio-demographic groups as for horizontal equity (see chapter 3.4.2 and table 4). The calculations was implemented with the script *equity_sufficientarianism_vertical.ipynb*.

Table 4 Example of a table for the evaluation of vertical equity from a sufficientarian perspective

Grocery Shops	Grocery Shop		Supermarket		Discount Supermarket		Organic Supermarket	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
Household w/o children	98.7%	89.2%	97.9%	80.0%	95.8%	70.2%	77.3%	41.2%
Household with children	98.2%	86.4%	97.1%	76.0%	94.4%	65.2%	72.9%	34.9%
Household single parent	98.6%	88.1%	97.6%	78.3%	95.1%	67.3%	72.7%	35.6%
Household two parent	98.1%	86.0%	97.0%	75.4%	94.3%	64.7%	72.9%	34.8%

3.5.2. Correlation coefficient

An egalitarian equity assessment for vertical equity could make use of the Lorenz Curve and the Gini Coefficient as well. The Gini Coefficient would then be a measure of the equality within a socio-demographic group and a comparison of Gini Coefficients would reveal whether the accessibility distribution within one group is more equitable than the distribution for another group. However, this would give no comparison of the differences in the absolute values for each group and the relationship between the presence of groups and accessibility values. Because of this the Lorenz Curve and the Gini Coefficient won't be used to assess egalitarianism from a vertical equity perspective. Instead, linear correlation coefficients will be used.

Linear correlation coefficients are measures of the relationship between two variables. They assume that the relationship between both variables is linear, i.e. it can be described by a straight line. If this assumption is not met, non-linear correlation coefficients have to be used. Most common linear correlation coefficients take values from -1 to +1. Negative values indicate a negative relationship, i.e. if one variable increases(decreases), the other variable decreases(increases). Positive values indicate a positive relationship, i.e. if one variable increases(decreases), the other variable increases(decreases) as well. Values closer to -1 or +1 indicate a higher correlation, i.e. a stronger relationship between both variables. A value of zero indicates that no correlation is present (Schira, 2009, pp. 94–96).

The most common linear correlation coefficient is the Pearson-Coefficient, also called the Pearson r. The Pearson r is calculated by dividing the covariance of two variables by the product of their standard deviations, s. The covariance, c_{xy}, is the arithmetic mean of the products of the deviations of the individual values from their respective mean value. The calculations are listed below (all formulas adapted from Schira, 2009):

$$s = +\sqrt{\frac{1}{n} \times \sum_{j=1}^{n} \left(x_j - x_{mean}\right)^2}$$

$$c_{xy} = \frac{1}{n} \times \sum_{j=1}^{n} \left(x_j - x_{mean}\right)\left(y_j - y_{mean}\right)$$

$$r_{xy} = \frac{c_{xy}}{s_x \times s_y}$$

Values over +0.5, respectively below -0.5, are usually seen as “high” correlations. While values between +0.3 and +0.5, respectively between -0.3 and -0.5, are seen as “medium” correlations. Values between 0.1 and 0.3 and -0.1 and -0.3 are seen as “low” correlations (Schäfer, 2016, p. 101). The correlations can also be visualised with scatter plots where all value pairs are plotted. Figure 17 depicts different scatter plots and their respective correlation coefficients. Scatter plots also reveal whether a correlation is in fact linear (Schäfer, 2016, p. 101).

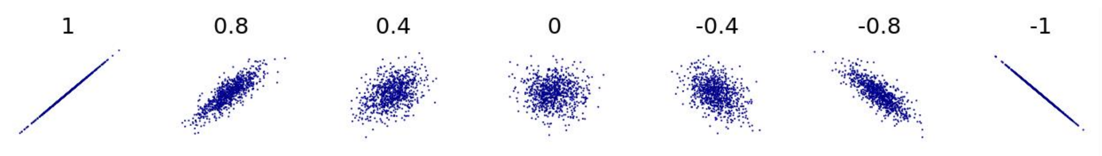


Figure 17 Different scatter plots and their respective Pearson coefficients

The results can also be visualised in so-called heatmaps. Heatmaps are tables in which the value of each cell is the correlation coefficient between the variables in the respective row and column. The cells then receive a colour based on the value. A higher correlation will have a darker colour. Negative and positive values have different colours (see figure 18).

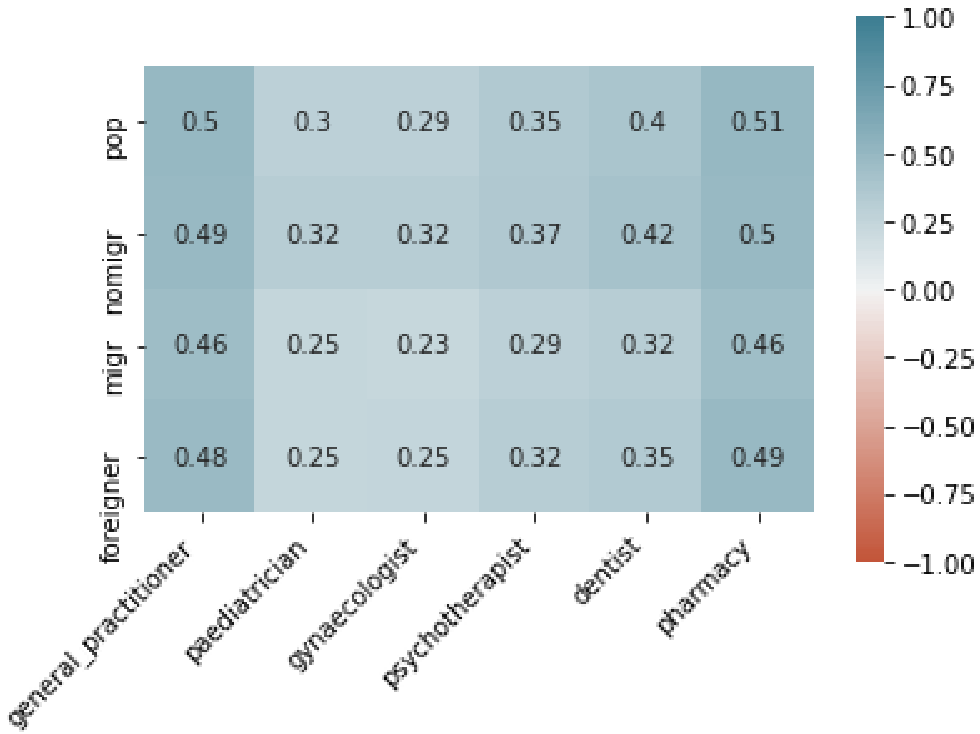


Figure 18 Example of a correlation coefficient heatmap

In this thesis, heatmaps will be provided in the text body and scatter plots in the appendix.

The calculation of the correlation coefficients and their visualisation were done in python (Jupyter Notebook) in the script *equity_correlation_heatmap.ipynb* and *equity_correlation_scatter.ipynb*. For the calculation, the accessibility and population data were saved in separate tables in GOAT's database. The data was accessed directly from the database via python's psycopg2 module and manipulated with the pandas module. For the calculations numpy was used and for the visualisation seaborn and matplotlib.

The calculations for all parts of the analysis will be based on the grid cells of GOAT's *grid_heatmap*-layer since accessibility values are calculated specifically on this level. This means that population numbers have to be (dis)aggregated to this unit as well. However, no large scale aggregations have to be computed for the analysis (for example to district levels). Such aggregations often result in data loss and distortions of the actual results (Omer, 2006).

4. Study area

The study area of this thesis is Munich. It was also the location for which GOAT was first developed. To better understand and interpret the results of the accessibility and equity analysis, it is crucial to have knowledge of the population (chapter 4.1.), land use (chapter 4,2), transport (chapter 4.3), and planning principles in Munich (chapter 4.4). This chapter will also introduce the results of existing analysis on the provision of essential services (chapter 4.5) and disadvantaged groups in Munich (chapter 4.6)

4.1. Population

Munich is Bavaria's most populous city and the third most populous city in Germany with approximately 1,562,096 inhabitants in 834,542 households as of 31 December 2020 (Statistisches Amt der Landeshauptstadt München, 2021; Statistisches Amt der Landeshauptstadt München, n.d.c). Because of its relatively small size, about 310 square kilometres, Munich is the most densely populated city in Germany with a population density of about 4,800 inhabitants per square kilometre (Statistisches Bundesamt, 2020). However, the population density is distributed unequally across the city as shown in figure 19. The densest areas are located in the city centre and adjacent areas, while peripheral areas are less densely populated.

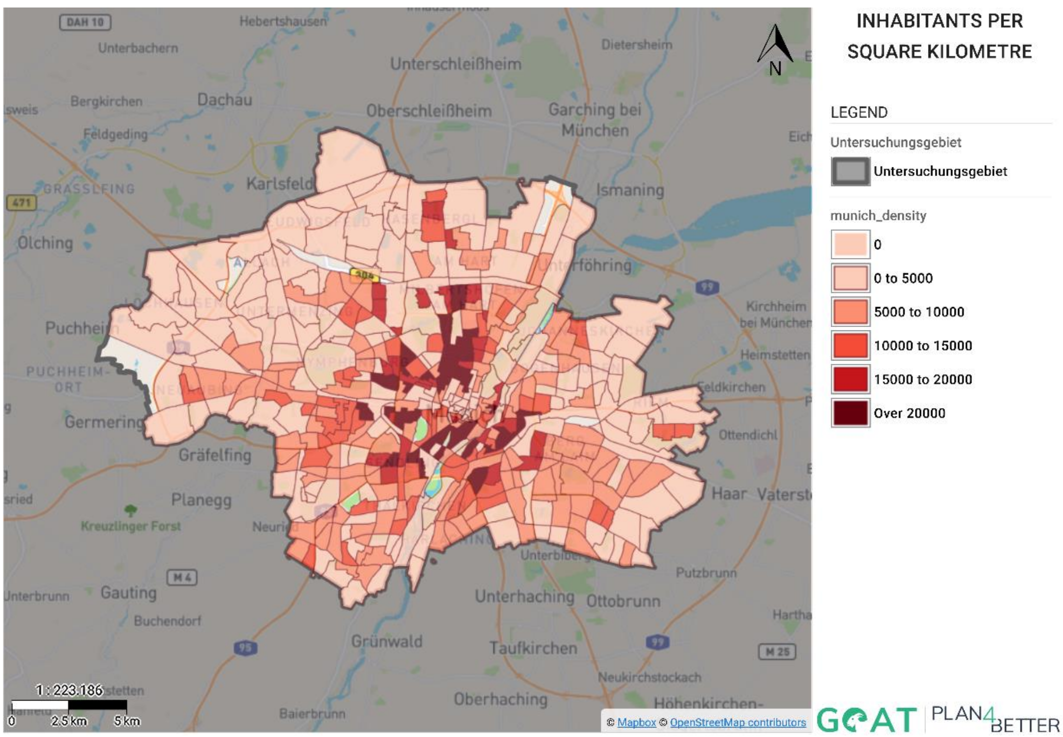


Figure 19 Population density in Munich

It can be expected that the population and the densities will further increase in the future. Munich has seen large growth in recent years. While around 1,387,000 people lived inside the municipality's boundaries in the year 2000, this number has increased by around 200.000 to 1,562,000 inhabitants (2020) over 20 years. Recent projections by the City of Munich see additional growth of around 250,000 people, a rise of 16 %, through 2040 (Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2019).

4.2. Land use

As figure 20 shows, the majority of Munich's area is covered by residential areas. Larger green areas and areas for agriculture are located in the north, west, north-east, and south-east. Commercial areas are spread across the city with notable concentrations around the Euroindustriepark in the northern part of the city. Notable green spaces for sports and leisure are located along the Isar river, especially the "Englischer Garten" north of the city centre, at Nymphenburg Castle in the western part of the city and at the Olympiapark in the north-west. In general, the land use in Munich reflects the high population density and shows relatively equal distributions of green spaces and commercial areas across the city.

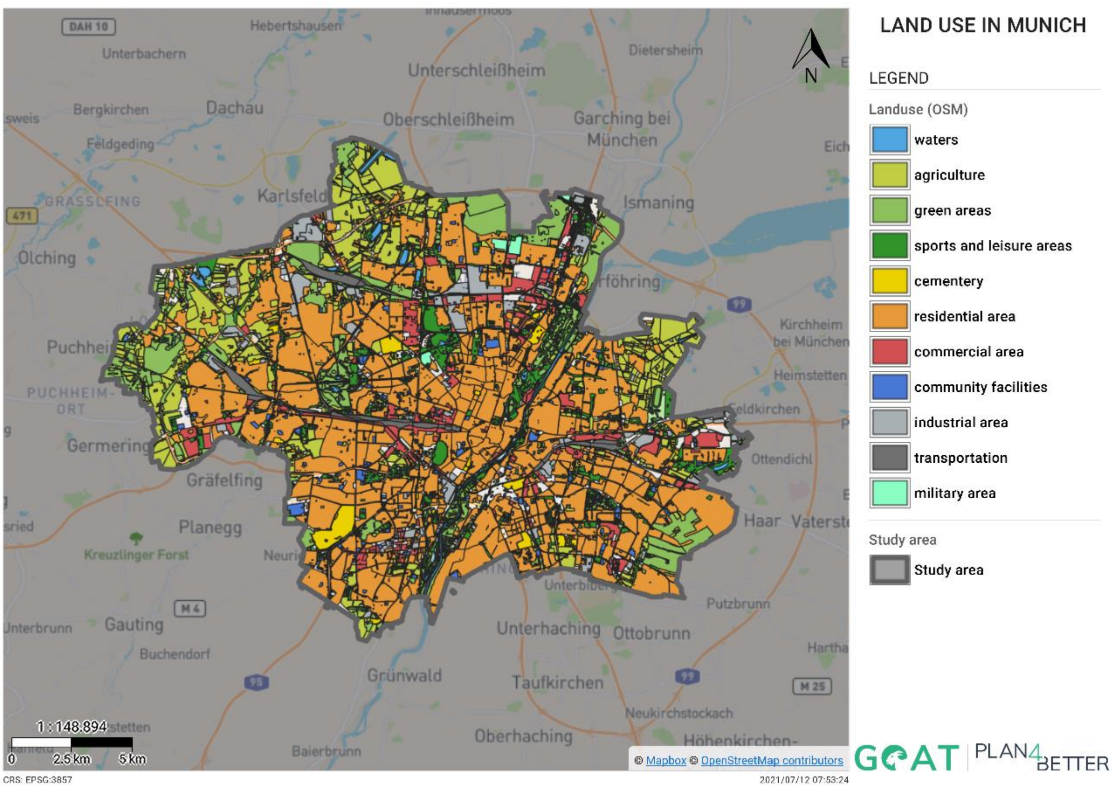


Figure 20 Land use in Munich based on OSM data

4.3. Transport

Roughly two thirds of all trips in Munich are made with sustainable transport modes (walking, cycling, public transport). Compared to other German cities with more than one million inhabitants, Munich has slightly higher shares of trips made by bike or public transport but lower walking shares (see figure 21).

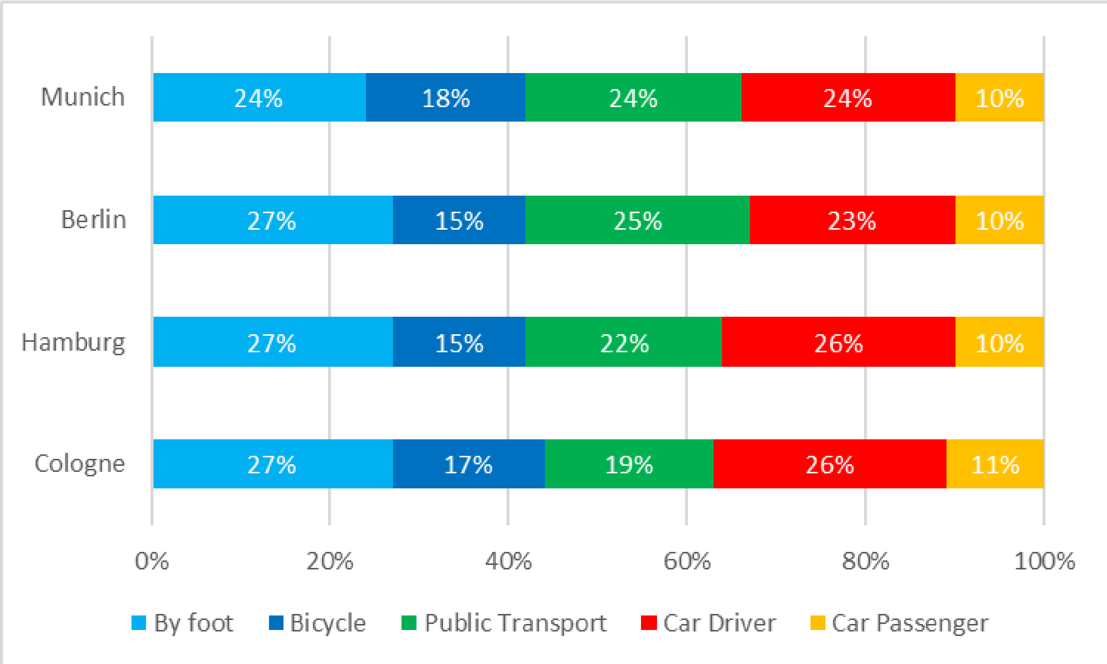


Figure 21 *Modal split of selected German cities*
Source *Own visualisation based on Follmer & Belz, 2019, p. 9*

The shares of transport modes diverge largely within the city. Between 74 and 80 % of all trips are made with sustainable transport modes in the central districts of Altstadt-Lehel, Ludwigsvorstadt-Isarvorstadt, and Maxvorstadt. By contrast, around 50 % of all trips are made with private cars in peripheral districts such as Allach-Untermenzing. Aubing-Lochhausen-Langwied (both in the west), and Trudering-Riem (in the east). The share of trips by foot ranges from 32 % (Ludwigsvorstadt-Isarvorstadt) to 16 % (Allach-Untermenzing). Higher shares of trips by foot are observed in the city's most central districts (see figure 22). Accordingly, higher shares of trips by car are observed in peripheral districts.

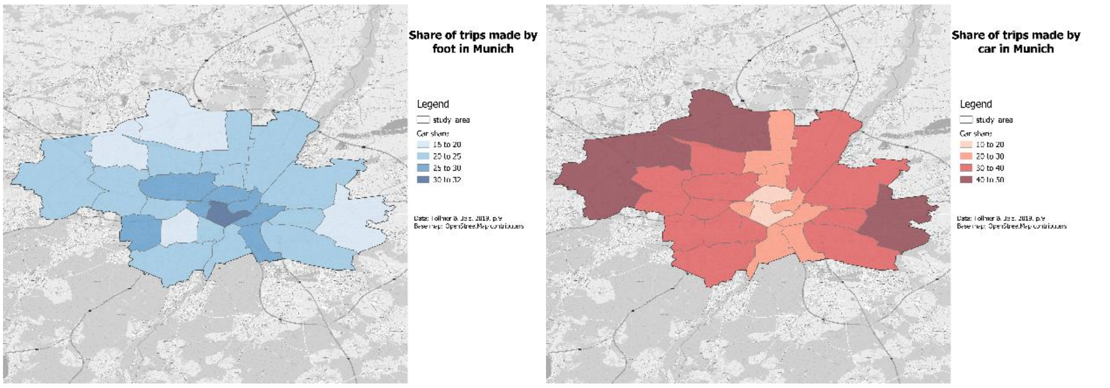


Figure 22 *Share of trips by foot and car in Munich*
Source *Visualisation with GOAT based on Follmer & Belz, 2019, p. 9.*

4.4. Urban and transport planning principles and guidelines

Continuing population growth and the need for more sustainable transport are also reflected in current urban and transport planning guidelines.

Langfristige Siedlungsentwicklung (LaSie)

To cope with the growing demand for housing space, the City of Munich has adopted three strategies to create new housing which were integrated into the *Langfristige Siedlungsentwicklung* (LaSie; long-term urban development). The LaSie comprises three strategies: the redensification of urban areas that were developed from the 1950s to the 1980s, the conversion of industrial areas and business parks to mixed-uses, and the development of new housing at the outskirts of the city (such as Freiham in the west and Unterföhring in the north-east) (Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2011). These new developments are likely to improve accessibility in Munich because densities will be increased, mixed uses encouraged, and currently underdeveloped areas developed. The new urban developments will also have an influence on one of Munich's guiding principles of urban planning: the *Zentrenkonzept* (centre concept).

Zentrenkonzept

The *Zentrenkonzept*, which was first introduced in 1975, is one of the guiding principles of urban planning in Munich. Its aim is the maintenance, improvement, and expansion of Munich's polycentric structure for the supply with goods and services. The main focus is on stores for daily needs. Among the motivations to pursue a polycentric urban structure are the reduction of trips by car and the promotion of a city of short trips (*Stadt der kurzen Wege*) (Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2020). A goal is that at least one grocery shop should be accessible within 600 metres (~ 7 minutes 30 seconds) of walking distance from one’s home (Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2020, p. 10).

The *Zentrenkonzept* defines different types of centres, namely: the city centre (*Innenstadt*), district centres (*Stadtteilzentren*), neighbourhood centres (*Quartierszentren*), and close-range centres (*Nahbereichszentren*). There are, besides the city centre, 15 district centres, 17 neighbourhood centres, and 90 close-range centres. Another two district centres as well as two neighbourhood centres are planned. These plans correspond to the urban development laid out by the LaSie. The locations of the centres, except the close-range centres, are presented in figure 23.

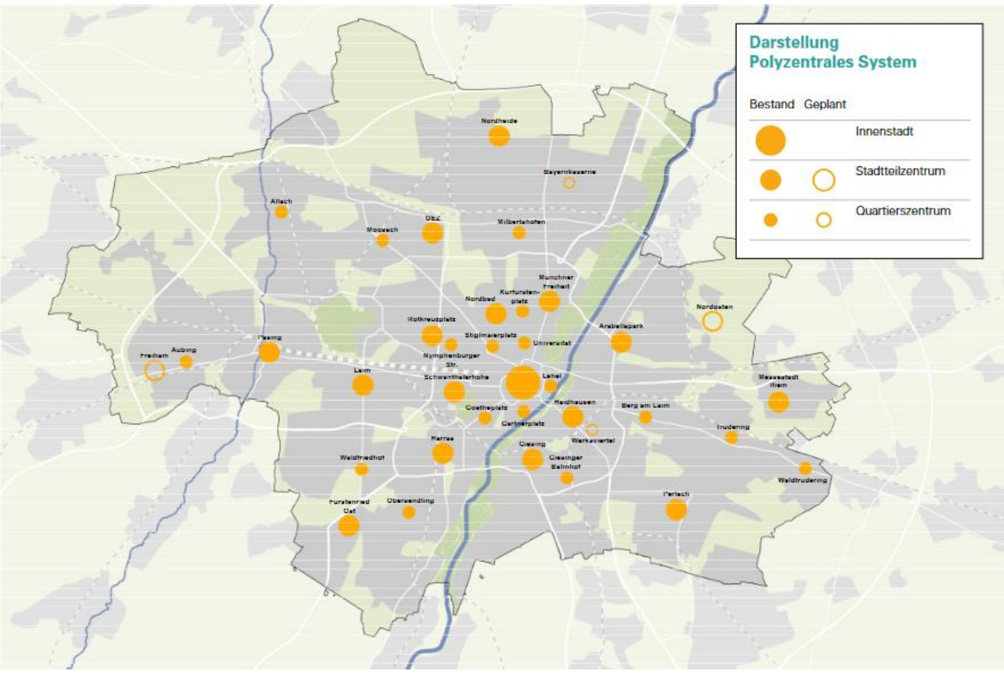


Figure 23 *Centres in Munich according to the centre concept*
Source *Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2020, p. 3*

While close-range centres are primarily focused on the provision of daily goods, neighbourhood centres and, especially, district centres should also provide access to more specialised shops as well as (public) services to achieve a mix of uses (Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2020, p. 23). Accordingly, higher values of accessibility around these centres should be expected in the accessibility analysis.

Mobilitätsplan – Modellstadt 2030

Besides these urban planning principles, the City of Munich is currently working on the development of a *Mobilitätsplan* (mobility plan) that should replace the old *Verkehrsentwicklungsplan* (transport development plan). Parallel to the development of the mobility plan, the project *Modellstadt 2030* (model city 2030) was initiated. Results from the model city project should also serve as a basis for the mobility plan (Referat für Stadtplanung und Bauordnung Stadtentwicklungsplanung PLAN HA I/3, 2020).

The participants in the model city have defined six key tools to improve mobility in Munich, among them neighbourhood mobility and active mobility, as well as four indicators, including accessibility, for the evaluation of strategies. Conditions for walking should be improved by a redesign and redistribution of urban space in favour of walking and cycling (Inzell Initiative, 2018).

4.5. Provision of essential services

Besides planning guidelines and strategies that seek the improvement of accessibility and active transport, the City of Munich regularly monitors the provision of essential services in Munich.

Münchner Stadtteilstudie

The *Münchner Stadtteilstudie* observes the distribution of socio-economic characteristics and selected essential services across the city. The 475 *Stadtbezirksteilviertel*, which are a statistical unit that consists of no more than 99 blocks, are the spatial unit of analysis. For the last Stadtteilstudie in 2015, the access to grocery shops and nurseries/kindergartens was examined. As a measure of access to grocery shops, the share of the population within 600 metres and the share of the population older than 64 within 300 metres of a grocery shop were combined. Areas with an access below average are mainly located at the city's periphery (see figure 24).

The access to nurseries and kindergartens ismeasured with the so-called ABZ-model. ABZ is an akronym for "Angebots-Bedarfs-Zuordnung" (supply-demand allocation). The ABZ-model works similar to the competition-based accessibility index. It creates catchment areas for both supply (e.g nurseries) and demand (e.g., children under the age of 3) locations. The demand is then distributed iteratively to the supply within its catchment, until there is no supply available or the whole demand is distributed. For catchment areas of 750 metres, the analysis has revealed that underserved areas are mainly located at the periphery, but also in larger areas closer to the city centre (e.g., Berg am Laim 14; see figure 25).

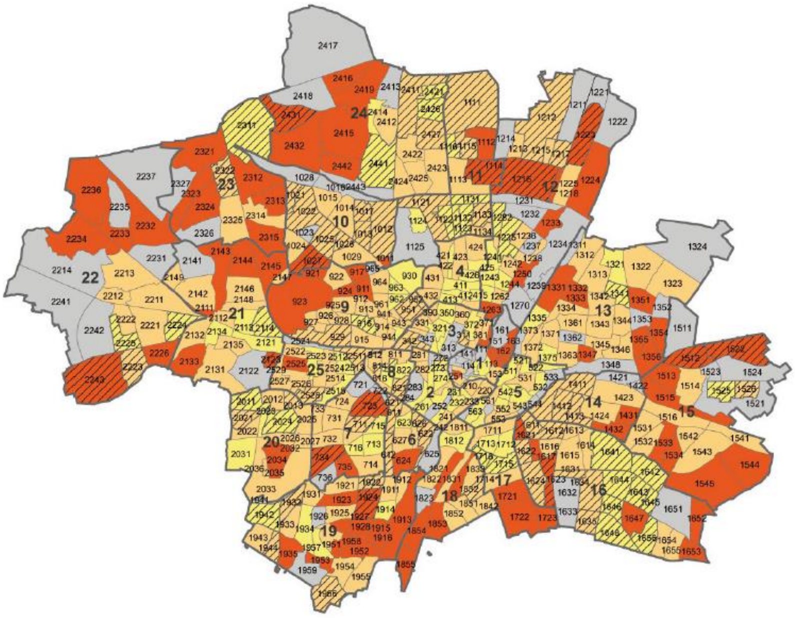


Figure 24 *Access to grocery shops in Munich*
Source *Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2016, p. 20*
Explanation *red = areas with below average access, orange = areas with average access, yellow = areas with above average access*

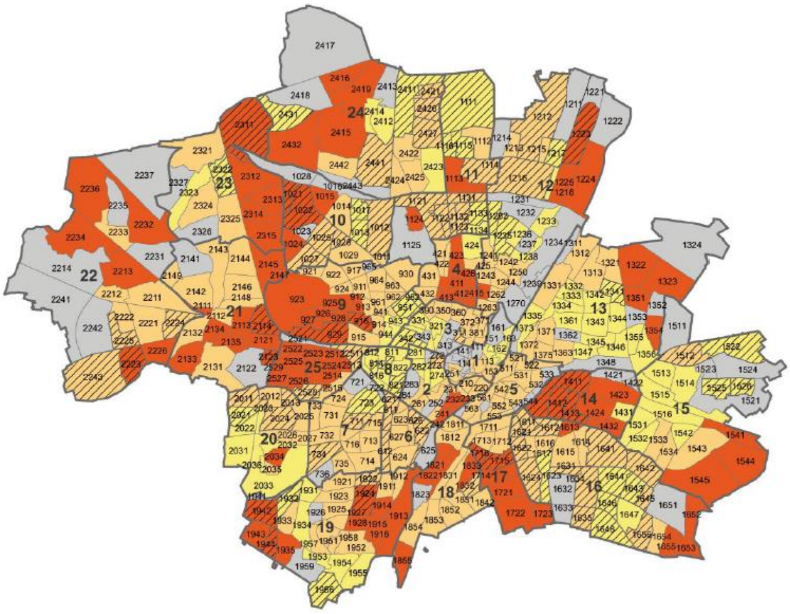


Figure 25 *Combined level of provision of kindergartens and nurseries in Munich*
Source *Landeshauptstadt München, Referat für Stadtplanung und Bauordnung, 2016, p. 29*
Explanation *red = areas with below average provision, orange = areas with average provision, yellow = areas with above average provision*

Monitoring of basic health services

Besides these accessibility analyses, the City of Munich also publishes data on the provision of basic health services (e.g., pharmacies, general practitioners, dentists) across the districts. To compare the provision between the districts, the population per amenity is calculated. This reveals large disparities between the different districts. While the central district Altstadt-Lehel has 34 inhabitants per doctor (Statistisches Amt der Landeshauptstadt München, n.d.b) and 845 inhabitants per pharmacy (Statistisches Amt der Landeshauptstadt München, n.d.a), the peripheral district Feldmoching-Hasenbergl has 1,411 inhabitants per doctor (Statistisches Amt der Landeshauptstadt München, n.d.b) and 6,897 inhabitants per pharmacy (Statistisches Amt der Landeshauptstadt München, n.d.a).

Based on the findings of the *Stadtteilstudie* and the statistical monitoring of pharmacies and doctors, it can be expected that accessibility will largely differ between central and peripheral areas.

4.6. Socio-economically disadvantaged population groups

Lastly, it must be discussed which groups are socio-economically disadvantaged. This will serve as a basis for the vertical equity analysis. In 2017, the last *Münchner Armutsbericht* (Munich's report on poverty) was published. It found that almost 270.000 people in Munich live in poverty of which around 130,000 receive assistance through social benefits. People in poverty have less than 60 % of the average (net equivalent) income at their disposal (Landeshauptstadt München Sozialreferat, 2017, p. 7). The following relationships between poverty and socio-demographic variables were found:

1. Households with single parents are on average the poorest while households of couples without children and households with two parents are among the richest (Landeshauptstadt München Sozialreferat, 2017, p. 23).
2. Foreigners are on average poorer than Germans with and without a migration background. Germans with a migration background are on average poorer than Germans without a migration background (Landeshauptstadt München Sozialreferat, 2017, p. 25).
3. Elderly (65 or older) and young adults (18 to 24) are on average poorer than adults (25 to 64) (Landeshauptstadt München Sozialreferat, 2017, p. 26).

Because data on the distribution of young adults could not be obtained, household status (without children, single parent, two parent) and origin (German without migration background, German with migration background, foreign) were chosen as socio-demographic characteristics for the vertical equity analysis. Data was provided by the City of Munich's statistical office on the level of the *Stadtbezirksteilviertel*.

Of the roughly 1,562,000 people living in Munich, around 446,000 (29 %) are foreigners, i.e. they don't have a German passport. 17 % of Munich's population are Germans with a migration background, i.e. they are German citizens but themselves or at least one of their parents were not born with German citizenship. Foreigners are relatively evenly distributed across the city. By contrast, large numbers of Germans with a migration background live in a few selected areas (e.g., Hasenbergl in the north, Neuperlach in the south-east, Messestadt-Riem in the east) (see figure 26).

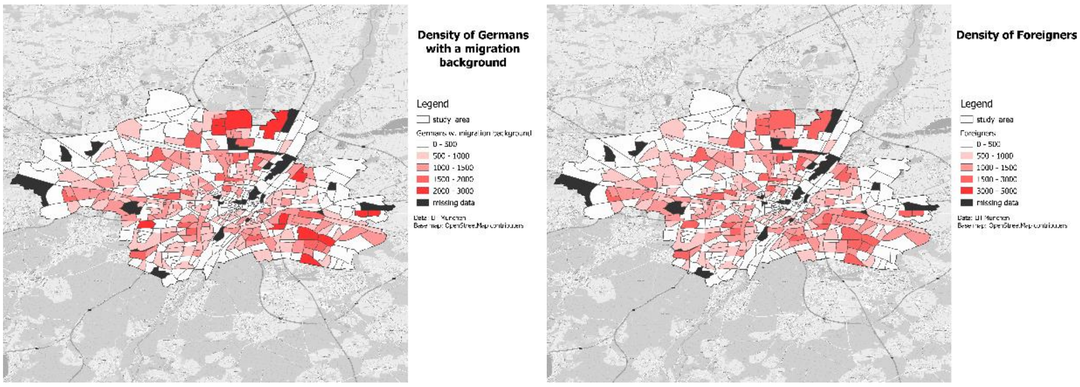


Figure 26 *Share of foreign population (left) and Germans with a migration back ground (right) in Munich*

The majority of the 834,000 households in Munich, about 82 %, are without children. Households with children make up only 18 % of all households and households with a single parent only 3.2 %. Households with single parents are, thus, only a small group compared to households with two parents which make up 82 % of all households with children. Figure 27 shows the distribution of single-parent and two-parent households.

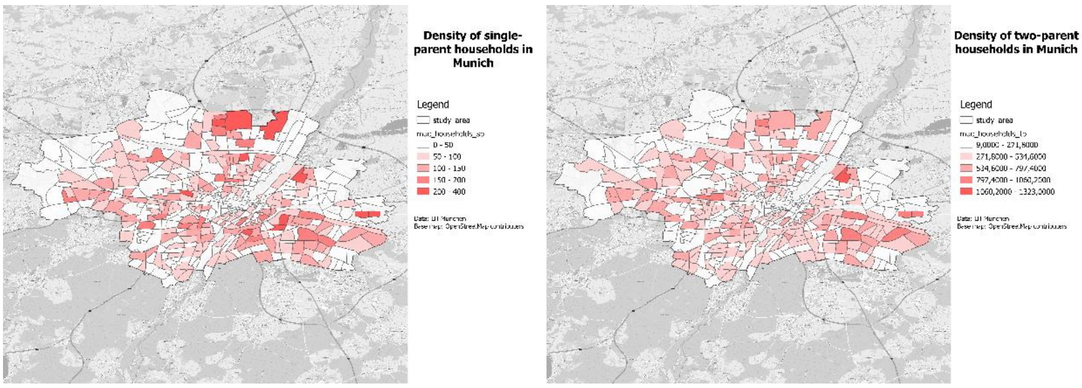


Figure 27 *Density of single-parent (left) and two-parent (right) households*

5. Data collection and preparation

The accessibility and equity analysis require the collection and preparation of different data, namely:

1. Points of interest (locations and capacities)
2. Socio-demographic data
3. Travel data for the adjustment of the impedance function

The data acquisition, data preparation, and implementation in GOAT will be presented in the following sections for each data type.

5.1. Points of interest

Points of interest are stored in GOAT in the *pois*-table which is created during the setup with the SQL-script *pois.SQL* from the downloaded raw OSM-database. The most important columns are ‘gid’, ‘amenity’, ‘geom’, and ‘tags’. The column ‘gid’ serves as the primary key and holds a unique integer number for every POI. The amenity-type is stored in the ‘amenity’-column. Additional information about POIs (e.g., capacity, speciality of doctors, address) is stored in the tags-column as key-value-pairs.

5.1.1. Method to check data accuracy

To ensure realistic results of the accessibility and equity analysis, the data stored in the pois table had to be assessed for completeness and accuracy. Because of the large amount of POIs and the size of the study area, the common procedure of collecting and verifying data by foot or by bike was not feasible for all POIs. Instead, data from official data sources was used to assess the quality of the data (see figure 28).

If the difference between the number of POIs found in the secondary source and the number of POIs in GOAT/OSM was less than ten percent, the OSM-data was kept and updated/reviewed with the data of the secondary sources as a guide for on-site visits. If the difference between the number of POIs in the two different sources was greater than ten percent, the OSM-data was replaced with data from a reliable secondary source. The OSM data for all amenity types was dated from the 20 March 2021.

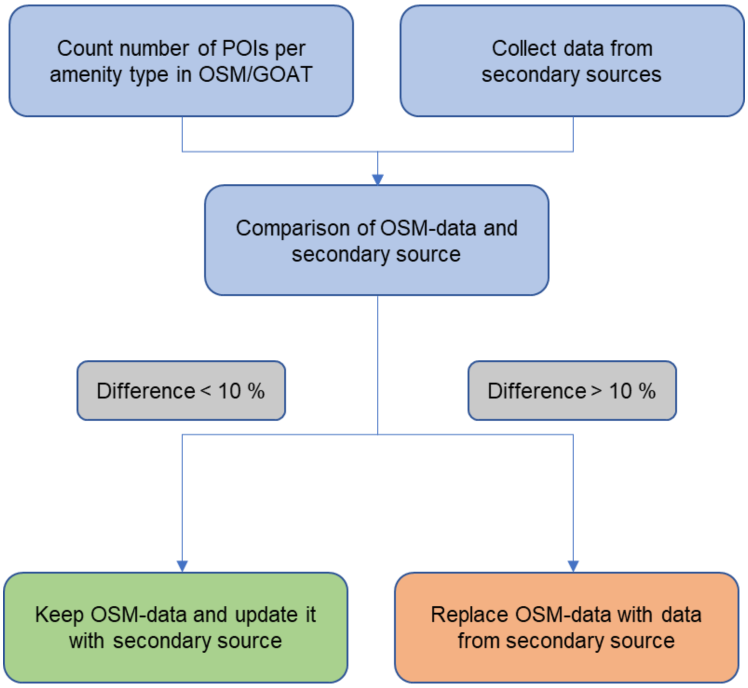


Figure 28 *Procedure of data collection for POIs*

5.1.2. Data accuracy

Education

Data for the amenities in the category 'education was collected from the "Bayerische Landesamt für Statistik" (statistical office of the free state of Bavaria). It publishes data on the number of schools and childcare institutions for the municipalities in Bavaria annually. Table 5 shows the comparison between the two data sources.

Table 5 *Comparison between POIs in OSM/GOAT and in secondary sources for amenities in the category of 'education'*

<table>
<tr><th>Education</th><th>POIs in OSM/GOAT</th><th colspan="2">POIs in secondary source</th><th>Secondary source</th></tr>
<tr><td>Nursery</td><td>98</td><td>36</td><td rowspan="3">794 mixed groups</td><td rowspan="3">Bayerisches Landesamt für Statistik, 2020b</td></tr>
<tr><td>Kindergarten</td><td>650</td><td>459</td></tr>
<tr><td>After-school</td><td>Does not exist in GOAT</td><td>159</td></tr>
<tr><td>Grundschule ("primary_school")</td><td>128</td><td colspan="2">156
(including 22 private)</td><td rowspan="4">Bayerisches Landesamt für Statistik, 2020a</td></tr>
<tr><td>Hauptschule</td><td rowspan="3">secondary_school: 129</td><td colspan="2">58
(including 14 private)</td></tr>
<tr><td>Realschule</td><td colspan="2">37
(including 14 private)</td></tr>
<tr><td>Gymnasium</td><td colspan="2">56
(including 16 private)</td></tr>
</table>

Childcare institutions are mapped with 'amenity = kindergarten'. In GOAT, nurseries and kindergartens are distinguished based on the maximum and minimum age of a POI (OSM-tags: min_age and max_age). After-school care is not yet integrated into GOAT.

The comparison reveals problems between the mapping of these amenity types in OSM and their latter usage in GOAT. At the moment, nurseries and kindergarten are distinguished during the setup of GOAT by the maximum and minimum age that is tagged in OSM. However, the clear distinction between nursery, kindergarten, and also after-school care cannot be easily drawn. The official data shows that 794 of the 1,448 child-care facilities have mixed age groups. This could be represented in OSM by adding the tags ‘nursery’, ‘preschool’, or ‘after_school’ to the amenity ‘kindergarten’. However, this has been seldom done so far.

Schools face a similar problem. So far, there is no tag to distinguish the different types of German secondary schools in OSM. GOAT used to distinguish the different types based on the names of school, because they often include references to the school type. This practice, however, can lead to wrong or lost data. As a consequence, German schools can be included in GOAT by adding data from https://jedeschule.de/schulen/ in a separate table called *custom_pois_no_fushion*. The data from jedeschule.de is, however, also not complete and thus, another source had to be used.

Health

The data accuracy check for the amenities in the category health revealed large disparities for doctors and a relative high accuracy for pharmacies (see table 6).

Table 6 Comparison between POIs in OSM/GOAT and in secondary sources for amenities in the category of ‘health’

Health	POIs in OSM/GOAT	POIs in secondary source	Secondary source
Pharmacy	349	350	Statistisches Amt der Landeshauptstadt München, n.d.a
Dentist	192	1,766	Statistisches Amt der Landeshauptstadt München, n.d.d
General practitioner	Categories do not exist in GOAT yet; doctors: 501	1,165 (910 offices) (including “hausärtzliche Internisten”)	Statistisches Amt der Landeshauptstadt München, n.d.b
Gynaecologist		354 (285 offices)	
Paediatrician		157 (124 offices)	

Grocery shops

Supermarkets, discounters, and organic supermarkets where chosen as a measure of local supply. It could be argued that organic supermarkets should be excluded from the analysis because of they specifically target wealthier population segments and thus are not accessible to population groups which are at risk of poverty, because they lack financial resources. Organic supermarkets will thus be viewed as an equal substitute to regular supermarkets/discounters in this study.

Because a city-wide on-street review would have not been feasible in a timely manner, supermarkets, discounters, and organic supermarkets were by collecting data from the websites of the biggest chains, comparing them to the OSM-data, and checking all the POIs that were either only mapped in OSM or only listed on a brand-website. POIs that did not belong to a specific brand were also reviewed on-site. Furthermore, convenience stores were excluded from being counted as organic in the pois.sql file, as well as the chains “Hermannsdorfer Landmetzgereien” and “Vitalia Reformhaus”, since they are not supermarkets.

Table 7 *Comparison between POIs in OSM/GOAT and in secondary sources for amenities in the category of ‘grocery shops’*

Grocery shops	**POIs in OSM/GOAT**	**POIs in secondary source**	**Secondary source**
Supermarket	211 (+ 45 independent markets)	210	EDEKA ZENTRALE Stiftung & Co. KG, 2021; Feneberg Lebensmittel GmbH, 2021; nahkauf, 2021; REWE Markt GmbH, 2021
Discount Supermarket	192	188	Aldi Süd, 2021; Lidl, 2021; Netto Marken-Discount, 2021; NORMA Lebensmittelfilialbetrieb Stiftung & Co. KG, 2021; PENNY Markt GmbH, 2021
Hypermarket	13	14	AEZ Frische aus Leidenschaft, 2021: HIT Handelsgruppe GmbH & Co. KG, 2021; Kaufland, 2021; real GmbH, 2021; V-MARKT, 2021
Organic Supermarket	53 (+ 36 independent markets)	54	Alnatura Produktions- und Handels GmbH, 2021; basic AG, 2021; biokultur - Dein Biomarkt, 2021; dennree GmbH, 2021; VollCorner Biomarkt, 2021

Public Transport

The POIs in the category ‘transport’ were compared to data from the Münchner Verkehrsgesellschaft mbH (MVG) and the maps of the stations of the Münchner Verkehrsverbund (MVV). OSM showed a high accuracy of the data, only missing some bus stops. However, the reason for the missing bus stops could also be that the MVG counts bus stops in neighbouring municipalities as well. The data in the category of ‘public transport’ was, thus, deemed to be complete.

Table 8 Comparison between POIs in OSM/GOAT and in secondary sources for amenities in the category of ‘public transport’

<table>
<tr><th>Public Transport</th><th>POIs in OSM/GOAT</th><th>POIs in secondary source</th><th>Secondary source</th></tr>
<tr><td>Bus Stop</td><td>1,005</td><td>1,036</td><td rowspan="3">Münchner Verkehrsgesellschaft mbH [MVG], 2020</td></tr>
<tr><td>Tram Stop</td><td>172</td><td>172 (excluding 2 stops in Grünwald)</td></tr>
<tr><td>Subway Entrances</td><td>93</td><td>93 (excluding duplicates and stations in Garching)</td></tr>
<tr><td>Rail Stations</td><td>43 (excluding duplicates)</td><td>43</td><td>MVV GmbH, 2021</td></tr>
</table>

5.1.3. Data collection/acquisition

Education

Because the OSM data is not compatible with the needed categorisations for both kindergartens and schools, data was acquired from different data sources and the OSM-data in the *pois*-table replaced with the newly acquired data. Data for childcare institutions was collected from the City of Munich’s *Kitafinder*-website, which lists all childcare institutions which are open to the public (and also some private). The kitafinder is maintained by the City of Munich’s department for education and sports (“Referat für Bildung und Sport”). The data can be downloaded from the website’s sourcecode as a json file (see figure 29).

The json-file was transformed into csv. The table already includes complete information on the names, addresses, and coordinates of the POIs. However, there is no consistent information about the age groups and capacities. The information about the age groups and the capacities per age group was taken from statistical data that is published for the 25 Stadtbezirke annually (München, 2021). For some institutions, no information was available in the data by the City of Munich. In this case, the information was taken from the website. The data was then added manually to the csv-table in accordance with OSM tags (capacity, capacity:nursery, capacity:kindergarten, capacity:after_school). The table was then and saved as a shapefile with QGIS and loaded into the database.

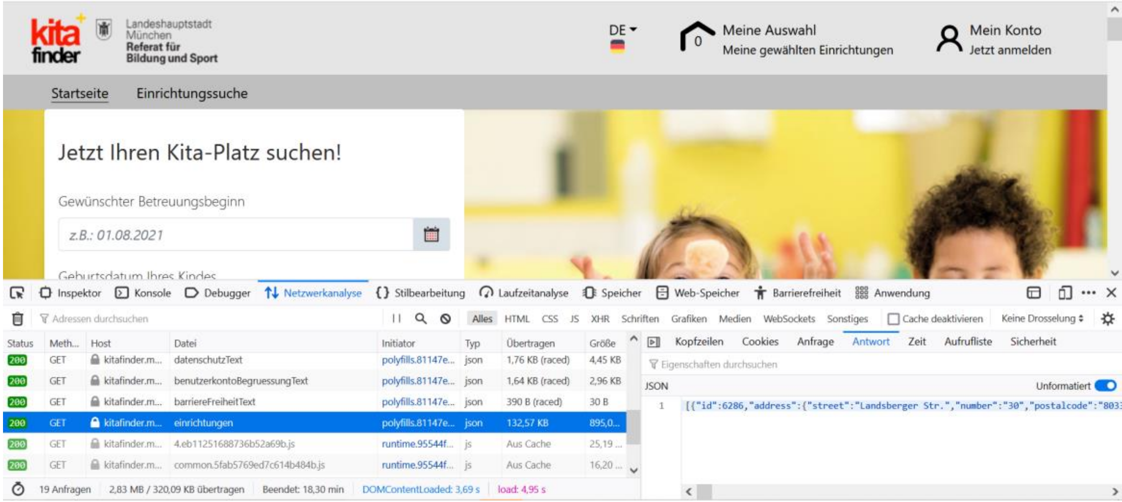


Figure 29 *Collection of the child care data*
Source *https://kitafinder.muenchen.de/elternportal/de/*

The data for the schools was taken from the Bavarian State Ministry of Education's school search tool. The results of the search can be downloaded as a csv-file directly from the browser (see figure 30).

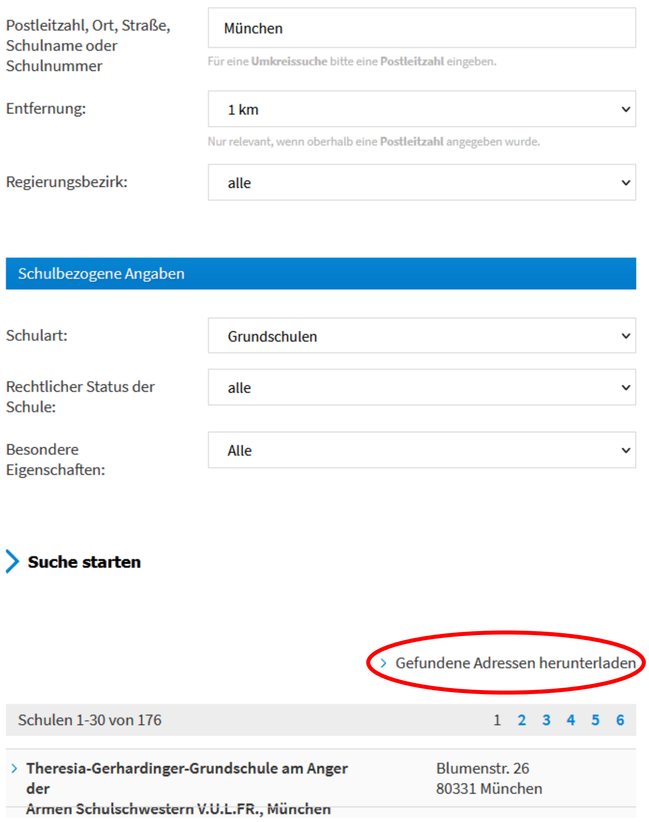


Figure 30 *Collection of the school data*
Source *https://www.km.bayern.de/schueler/schulsuche.html*

It includes information on the name, school type, and address. Because it does not include coordinates, the coordinates were added with a python script that uses the module geopy to geocode the coordinates with OSM's Nominatim based on the addresses. The resulting table was stored as csv and turned into a shapefile with QGIS.

Doctors

The data for doctors was collected with a web scraper (*doctors_scraper.ipynb*) from the website of the *Kassenärztliche Vereinigung Bayerns* (https://dienste.kvb.de/arztsuche/app/einfacheSuche.htm). The data holds information on the type of doctors, name, and address. Based on the addresses the coordinates were then geocoded with the script *doctors_geocoding.ipynb* based on Nominatim. The table was then turned into a shapfile with QGis.

Dentists

The data for dentists was collected from the website of the *Bayerische Landeszahnärzte Kammer*. As with the kindergartens, the data can be collected directly from the source code of the website as a json file (see figure 31). The collected table has information on names and addresses of the dentist. The locations of the dentists were, again, geocoded based on their addresses with the script *dentist.geocond.ipynb.*

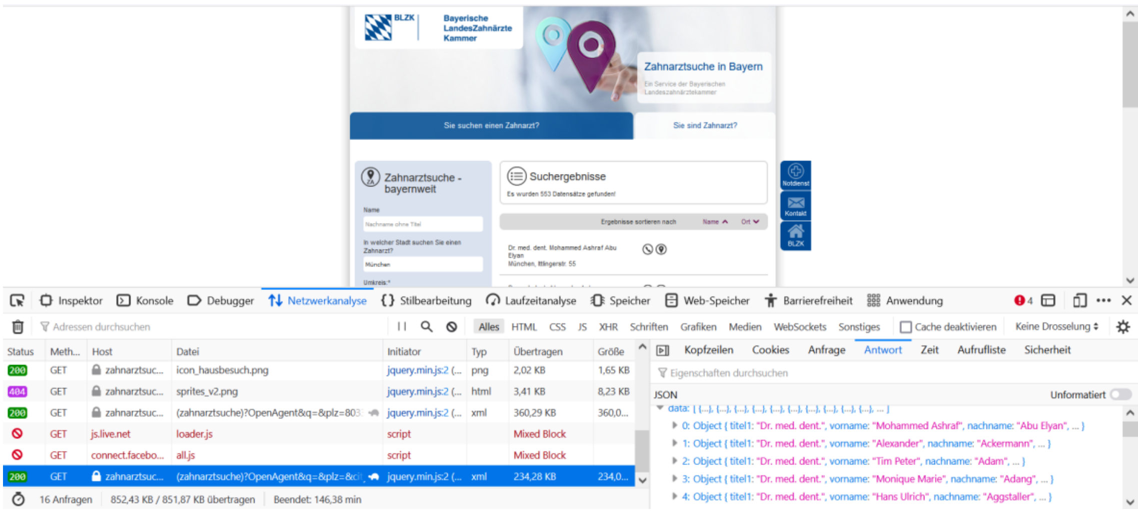


Figure 31 *Collection of the dentist data*

Pharmacies/Grocery shops/Public Transport

Pharmacies, grocery shops, and public transport fulfilled the data accuracy criterion and were, thus, mapped in OSM. However, no source of all public transport stops was found that could be compared to the stops in OSM and, thus, no additional data was collected.

Pharmacies in OSM were compared to pharmacies listed on muenchen.de. A web scrapper was written to collect the data from muenchen.de (*pharmacy_scraper.ipynb*). The data from muenchen.de and OpenStreetMap were then compared manually in QGis and

POIs that were only in one of the two sources, either in OSM or on muenchen.de, were collected in an excel sheet. For grocery shops the same procedure was chosen. The data in OSM was compared to the data on the websites (see sources in table 7). All independent markets were also collected in the excel sheet. The result was a list of 53 pharmacies, 6 discount supermarkets, 48 supermarkets, and 34 organic supermarkets. For 87 POIs, no action had to be taken, because OSM data was more accurate than the secondary data or already up to date. For grocery shops, origin values (e.g., Asian, African) were often missing (10 times).

5.1.4. Implementation in GOAT

The data that was collected from secondary sources was merged into the table *pois_custom_full_fusion* in the database. This table was then inserted into the pois table of GOAT with an additional script in the *pois.sql* file. It will replace all existing POIs in GOAT's pois table which belong to the same amenity as the pois in the *pois_custom_full_fusion* table and are within the study area. The POIs from *pois_custom_full_fusion* are then filled into the *pois* table. The data collected through on-street mapping was automatically loaded into GOAT's database with a new setup.

5.2. Socio-Demographic Data

5.2.1. Data acquisition

The socio-demographic data was acquired from the City of Munich's statistical office ("Statistisches Amt") in the form of excel sheets. Data on the distribution of households by presence of children and parental status (children, no children, single-parent, two-parent) and the distribution of population by origin (German with a migration background, German without a migration background, foreigner) is used for the vertical equity analysis. Data on the distribution of age groups (e.g., younger than 3 years, 3 to 5 years) is used to calculate the demand for the competition measure. The data is dated to January 1st 2021. The excel sheets contain the absolute values of population on the level of the 477 Stadtbezirksteilviertel, which are the smallest statistical unit of analysis in Munich above the level of building blocks. Because of data privacy, values of five or less were not shown and instead replaced with a dot.

5.2.2. Implementation in GOAT

Because the data was transferred in excel files that and was not machine readable, the data had to be cleaned first. The dots symbolizing values under five were replaced with '999999', because non-numerical values would lead to problems during later calculations. The socio-economic data was grouped into three tables: *muc_origin*, *muc_age*, and *muc_households*. Based on the absolute values in the columns, the shares were calculated in excel.

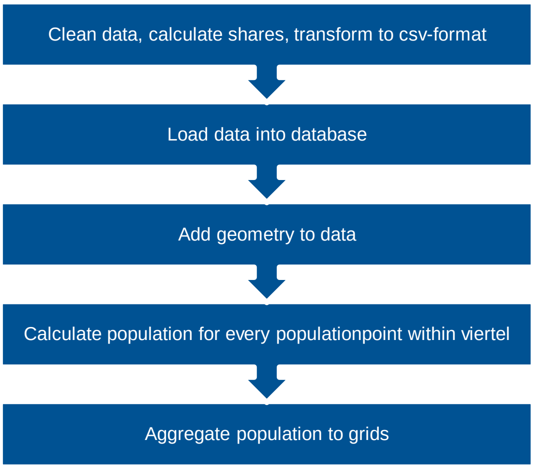


Figure 32 Process of the implementation of the socio-demographic data

The data was then transformed to csv-files and loaded into the database. Geometries were added to each table with the file *muc_stadtbezirksteilviertel.shp*. The tables were then used to calculate the values for the different socio-demographic groups on the level of the population points stored in the table *population*. It was assumed that the shares are distributed equally within every Stadtbezirksteilviertel. The population of every population point was multiplied with the respective shares of the socio-demographic groups and the results stored in separate columns. The values were then aggregated to the grids and a separate table *grid_population* was created. The values for age and origin from the *grid_population* column were then inserted as arrays into the newly created *userGroup*-column of the *grid_heatmap* for the use in competition calculations.

To deal with the data regarding the household composition, households were added to GOAT with the functions *census_household.sql, household_disagregation.sql, household_distribution.sql* that were adapted from the respective function for the creation of the *population* table. However, the households were not disaggregated to new developments. Thus, the location of household and population data does not overlap completely.

5.3. Impedance/Distance-Decay Function

Also, the β-parameter of the impedance function for the accessibility calculation has to be adjusted. As mentioned before, GOAT's impedance function is a modified gaussian function which takes values from 1 to 0, decreasing with growing distance between origin and destination. Accordingly, POIs close to the origin have higher accessibility values. A lower β-parameter will lead to a steeper decline of the impedance function and thus to a larger weighting of destinations close to the origin (see figure XY). β-parameters implemented in GOAT are multiples of 50,000 and range from 150,000 to 450,000.

5.3.1. Data acquisition

The β-parameter can be set either normatively or positively based on travel behaviour. Usually, the β-parameter is adjusted by fitting a curve to data provided in travel diaries (Iacono, Krizek, & El-Geneidy, 2008). It is assumed that actual travel behaviour reflects people's preferences. Ideally, individual travel data is provided for each trip purpose.

For the City of Munich, travel data was taken from the study 'Mobilität in Deutschland 2017' (Deutsches Zentrum für Luft- und Raumfahrt e.V. [DLR], 2020). The password to access the regional data for Munich was provided by the mobility office of the City of Munich. Travel data was available for daily goods (e.g., grocery shops), services (e.g., pharmacies and doctors), and education (e.g., schools and kindergartens). For the amenities in the category transport no data was available. Accordingly, the default β-parameter of 300.000 was used. The data was fitted to the share of walking trips per distance. The distances were converted to seconds to comply with GOAT's impedance over travel time. The impedance function can, thus, be understood as the likelihood of making a trip by foot.

5.3.2. Results of curve fitting

The impedance function can be fit to the travel data with the non-linear least squares regression (Schira, 2009, pp. 120–122). The quality of the fitting is assessed with the r^2-value. The r^2-value is the squared correlation coefficient (Schäfer, 2016, pp. 195–196). r^2-values range from 0 to 1, with values closer to 1 indicating a better fit.

As a comparison to GOAT's modified gaussian impedance function, also the negative exponential and the modified negative exponential function have been fitted to the travel data:

$$Negative\ exponantial: f_{ij} = e^{-\beta * t_{ij}}$$

$$Modified\ negative\ exponential: f_{ij} = \alpha * e^{-\beta * t_{ij}}$$

They are widely used alternatives to the modified gaussian (Iacono et al., 2008; Vale & Pereira, 2017). The results are presented in figure 33.

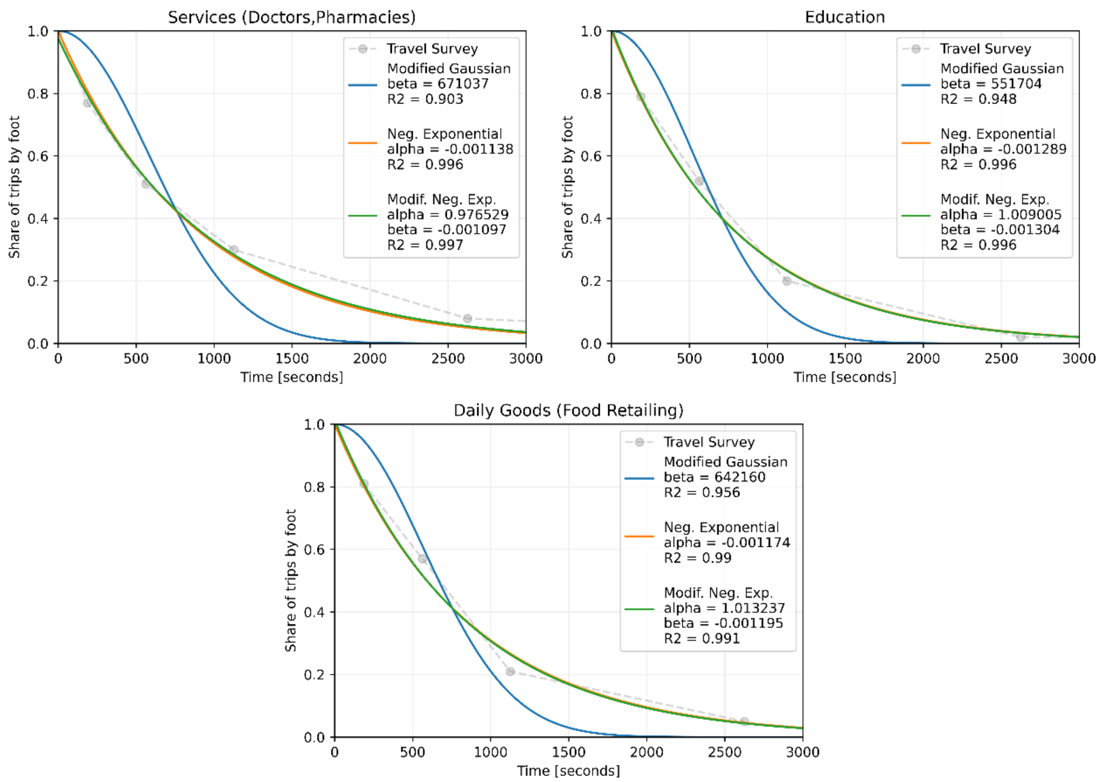


Figure 33 *Results of the fitting of the distance decay function*

Overall, the negative exponential functions showed better fit to the travel data, even though R-values for the modified gaussian function also were relatively close to 1. The β-parameters for the modified gaussian function varied between 551,704 and 671,037 and are considerably larger than the values currently used in GOAT. Even though, the negative exponential functions had a better fit to the data, the modified gaussian was kept so the results can be easier compared to other studies with GOAT. The β-parameters were rounded to the closest multiple of 50,000, 550,000 for education and 650,000 for grocery shops and doctors/pharmacies, to be consistent with existing parameters in GOAT.

5.3.3. Implementation in GOAT

The additional sensitivities were added in the *goat_config.yaml* file to the table '*variable_container*'. These additional sensitivities will be added automatically during the setup of GOAT and the corresponding accessibility indices will be calculated during the heatmap-setup. The values were also added to *HeatmapOptions.vue* so they can be used for the creation of accessibility heatmaps in the GOAT interface.

6. Results and discussion

This chapter contains a presentation and discussion of the results for the four categories of basic need, i.e. education, health, grocery shops, and public transport. Firstly, the accessibility analysis based on the accessibility maps is addressed. In the text, only the map for the combined accessibility to all amenities of one category will be shown. The maps for the individual amenities can be found in the appendix (appendices B to E). The accessibility analysis is followed by the horizontal equity analysis with the population shares above the thresholds and the Lorenz Curves/ Gini Coefficients. Lastly, the vertical equity analysis follows for each category. After the results of the categories have been discussed, the findings from the comparison of accessibility with and without competition are presented.

6.1. Education

6.1.1. Accessibility analysis

The combined accessibility map for the amenities in the category ‘education’ shows that most areas that are considered as having very low or low accessibility are located in unpopulated areas (see figure 34). Populated areas with low accessibility can be found

- in the west in Gern, Ober- and Untermenzing,
- in the north in Am Hart and Lerchenau,
- in the north-east in Daglfing and Riem,
- in the east in Waldtrudering, Waldperlach, and Gartenstadt-Trudering,
- and in the south in Solln, Harlaching, and Fasangarten.

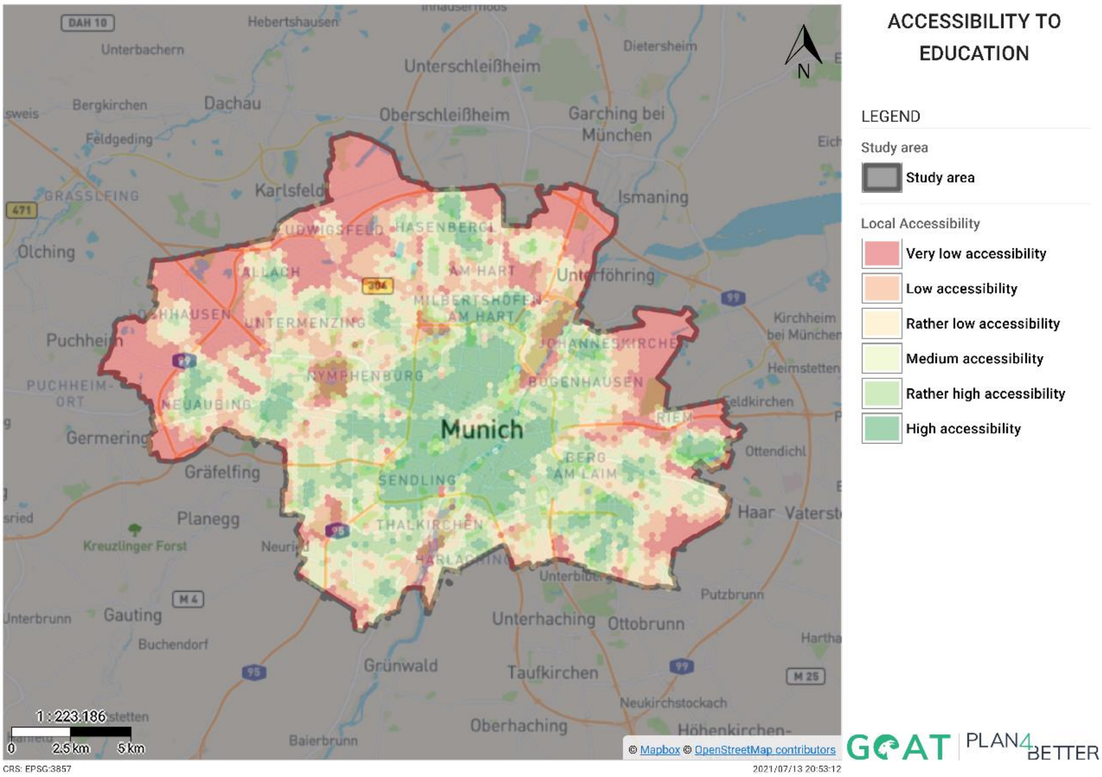


Figure 34 Map of the combined accessibility to amenities in the category 'education'

6.1.2. Horizontal equity

Share of population within thresholds

The analysis according to the sufficiantarian criteria, shows that at least one amenity of every type is accessible to the majority of the population within 20 minutes (see table 9). Almost all inhabitants in Munich have access to at least one kindergarten, nursery, after-school, and *Grundschule*. The access to secondary schools is less equally distributed. More than two-thirds of the population don't have walking access to the highest level of secondary education, the Gymnasium, even though most children attend it after elementary school today. The good access to Haupt-/Mittelschulen reflects their former function as the main secondary school (hence they were called "*Volksschulen*", i.e. people's schools).

Table 9 Share of population with access to amenities in the category of 'education'

Education	Share of population within...	
Amenity Type	**20 minutes**	**10 minutes**
Nursery	99.6%	94.9%
Kindergarten	99.7%	97.3%
After School Care	98.2%	79.8%
Grundschule	96.8%	65.9%
Haupt-/Mittelschule	72.1%	28.1%
Realschule	49.8%	16.9%
Gymnasium	62.9%	20.6%

Lorenz Curve and Gini Coefficient

The Lorenz Curves for the amenities grouped in the education category reveal almost no (childcare and primary schools) to only slight inequalities (secondary schools). As expected, the curves for the three types of secondary schools are farther from the line of absolute equality than the curves for early childhood and primary education. The access to *Gymnasien*, the highest level of secondary education, is the most unequally distributed among all amenity types. The pairs of elementary schools and kindergartens, nurseries and after-school facilities, as well as *Hauptschulen* and *Realschulen* have similar distributions of access among the population. *Grundschulen* and kindergartens have an almost equal distribution.

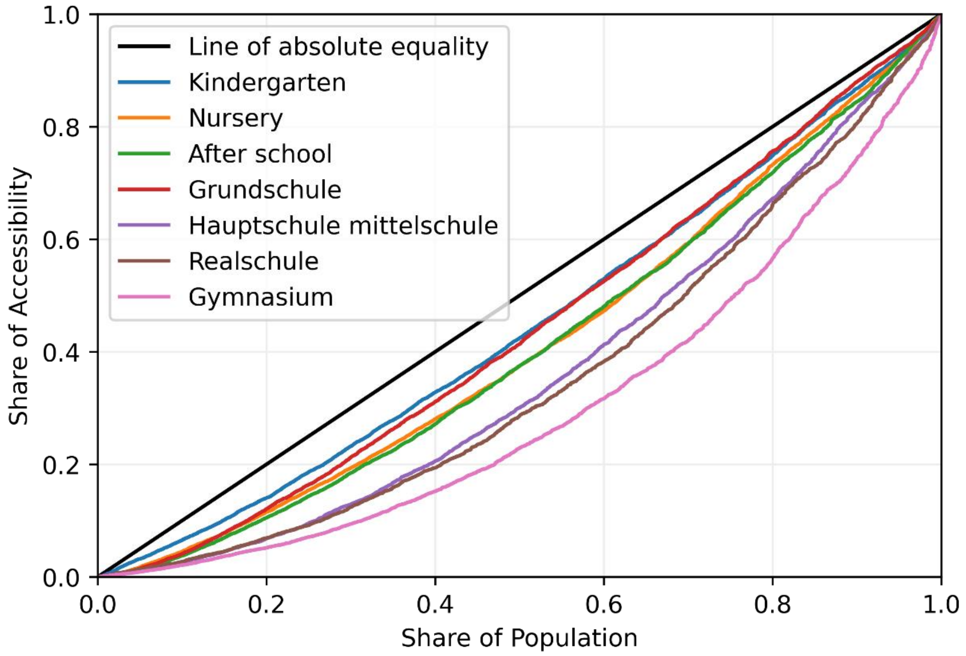


Figure 35 Lorenz Curves for the amenities in the category of 'education'

This is also reflected in the respective Gini Coefficients. *Gymnasien* have the worst score with 0.39 (rather unequal), while kindergartens have the best score with 0.11 (highly equal). *Grundschulen* also have a highly equal score of 0.12. Nurseries and after-schools are very close together at 0.17 and 0.18, respectively, as well as *Haupt-/Mittelschulen* and *Realschulen* at 0.27 and 0.29, respectively.

Table 10 Gini Coefficients for the amenities in the category of 'education'

Amenity Type	Gini Coefficient
Kindergarten	0.11
Nursery	0.17
After-School	0.18
Grundschule	0.12
Haupt-/Mittelschule	0.27
Realschule	0.29
Gymnasium	0.39

6.1.3. Vertical equity

For the vertical equity analysis of the amenities in the category of 'education, only the basic amenities (nursery, kindergarten, after-school care, *Grundschule*) were considered.

Vertical socio-economic equity based on origin of population

The distributions remain relatively equal across the population and households for both thresholds (see table 11). Germans with migration background have slightly better access to all amenities. However, the level of access within the 10-minute threshold is still high among all groups.

Table 11 Share of population by origin with access to amenities in the category of 'edu cation'

Education	Nursery		Kindergarten		After-School Care		Grundschule	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
German w/o migration	99.6%	94.6%	99.6%	97.2%	98.3%	79.1%	96.7%	64.9%
German with migration	99.7%	95.4%	99.8%	97.7%	98.8%	81.4%	97.7%	67.7%
Foreigner	99.7%	95.5%	99.8%	97.5%	98.7%	81.0%	97.4%	67.3%

The correlation coefficients reveal higher correlations for all amenity types, except *Realschulen*, between the level of accessibility and Germans without a migration background (see figure 36). For nurseries and kindergartens, there is even a high correlation between the population density of Germans without a migration background and accessibility. The correlation between the density of population groups and accessibility levels are on a high medium level, while the correlation to secondary schools is on a low level. For foreigners and Germans with a migration background, there is no correlation with the accessibility to *Gymnasien*. As expected, the correlation is always positive, i.e. the accessibility increases with higher density.

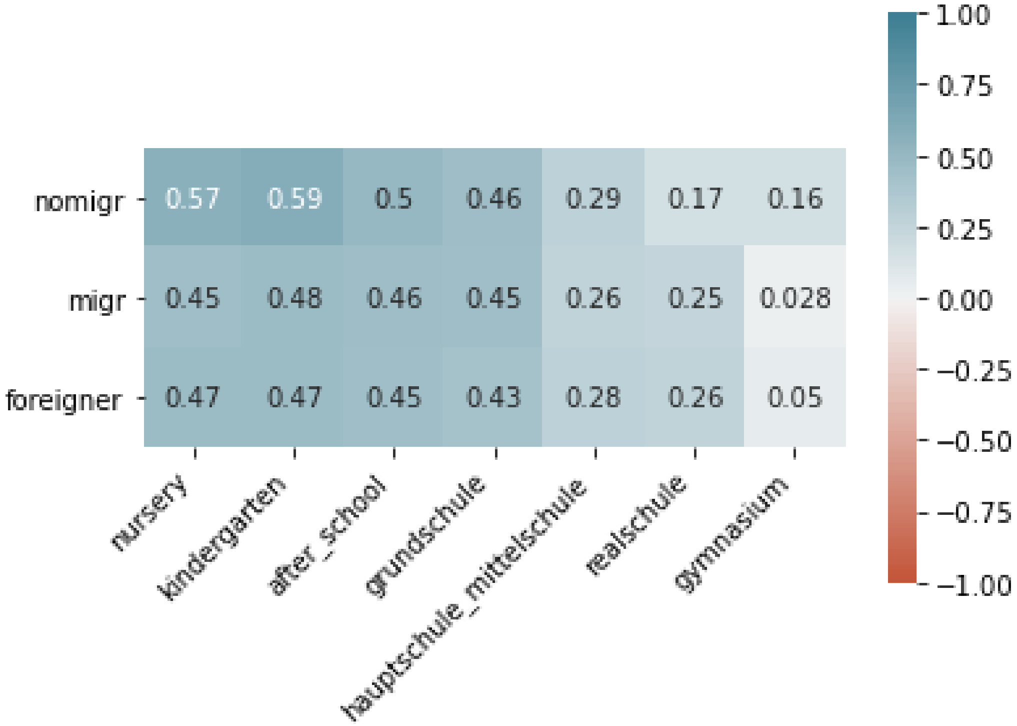


Figure 36 *Correlation heatmap for amenities in the category of 'education' and population by origin*

Explanation *nomigr = Germans w/o a migration background, migr = Germans with a migrat ion background*

Vertical socio-economic equity based on household composition

The comparison between households based on their composition, reveals that households without children have a slightly better access than households with children. Single-parent households, in turn, have better access than two-parent households. The share of population with access remains high for both thresholds, even though after-school care and *Grundschulen* experience sharper drops in access (see table 12). However, almost all households have access to the basic education services irrespective of the household composition.

Table 12 Share of households by children and parental status with access to amenities in the category of 'education'

Education	Nursery		Kindergarten		After-School Care		Grundschule	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
Household w/o children	99.8%	95.8%	99.9%	98.0%	98.5%	81.7%	97.4%	68.2%
Household with children	99.7%	94.7%	99.8%	97.4%	98.1%	79.0%	96.7%	65.2%
Household single parent	99.8%	95.6%	99.8%	97.7%	98.4%	80.9%	97.2%	66.9%
Household two parent	99.7%	94.5%	99.8%	97.3%	98.0%	78.5%	96.6%	64.7%

The comparison between the correlation coefficients for all household types reveals that households without children have higher correlations than households with children. Also for the different household types, the correlation is always positive and medium to high for the essential services. The correlation coefficients between the number of single-parent households and accessibility are slightly above the levels of two-parent households for all amenities.

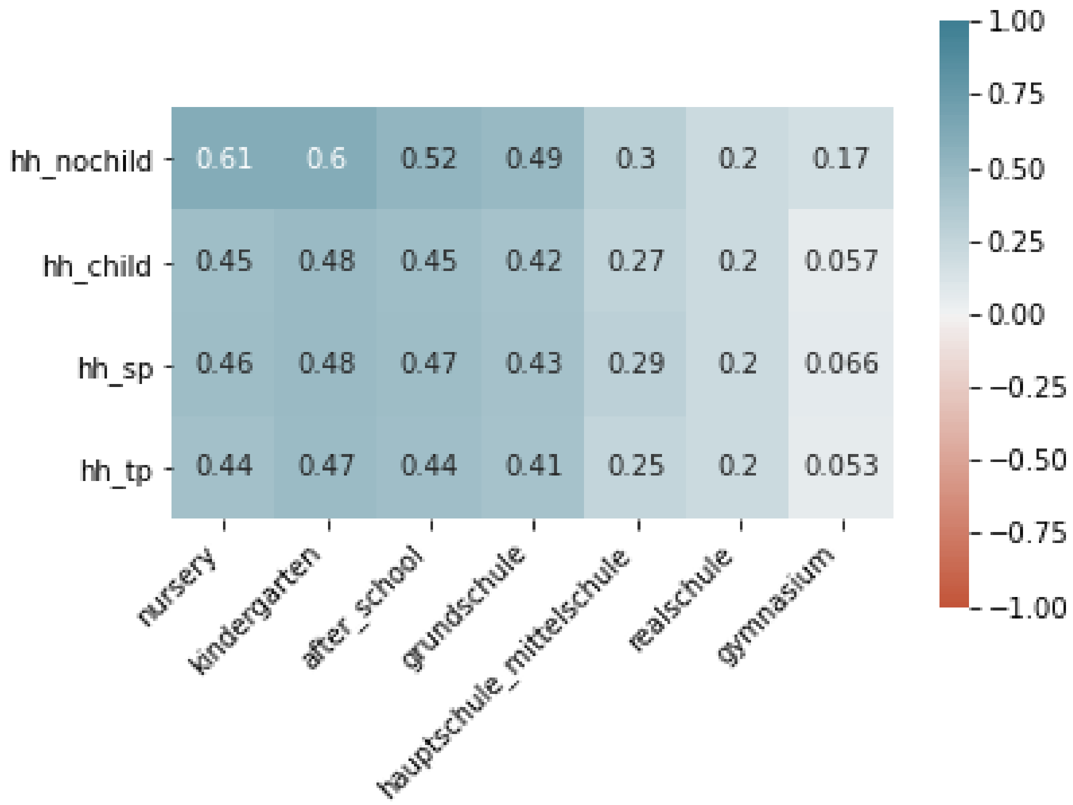


Figure 37	*Correlation heatmap for amenities in the category of 'education' and households by children and parental status*
Explanat	*hh_nochild = households without children, hh_child = households with children hh_sp = single-parent households, hh_tp = two-parent households*

6.2. Health

6.2.1. Accessibility analysis

The accessibility heatmap for the amenities in the category of 'health' reveals similar patterns to the map for the category of 'education', however with larger levels of low accessibility in populated areas. The areas that are mostly very low, low, or rather low are:

- in the west: Lochhausen, Pipping, (Neu-)Langwied, Gern, Ober- and Untermenzing,
- in the north/northwest: Ludwigsfeld, Am Hart and Lerchenau,
- in the northeast: Daglfing, Riem, Messestadt-Riem
- in the east: in Waldtrudering, Waldperlach, and Gartenstadt-Trudering,
- and in the south: Großhadern, Obersendling, Thalkirchen, Harlaching, and Fasangarten.

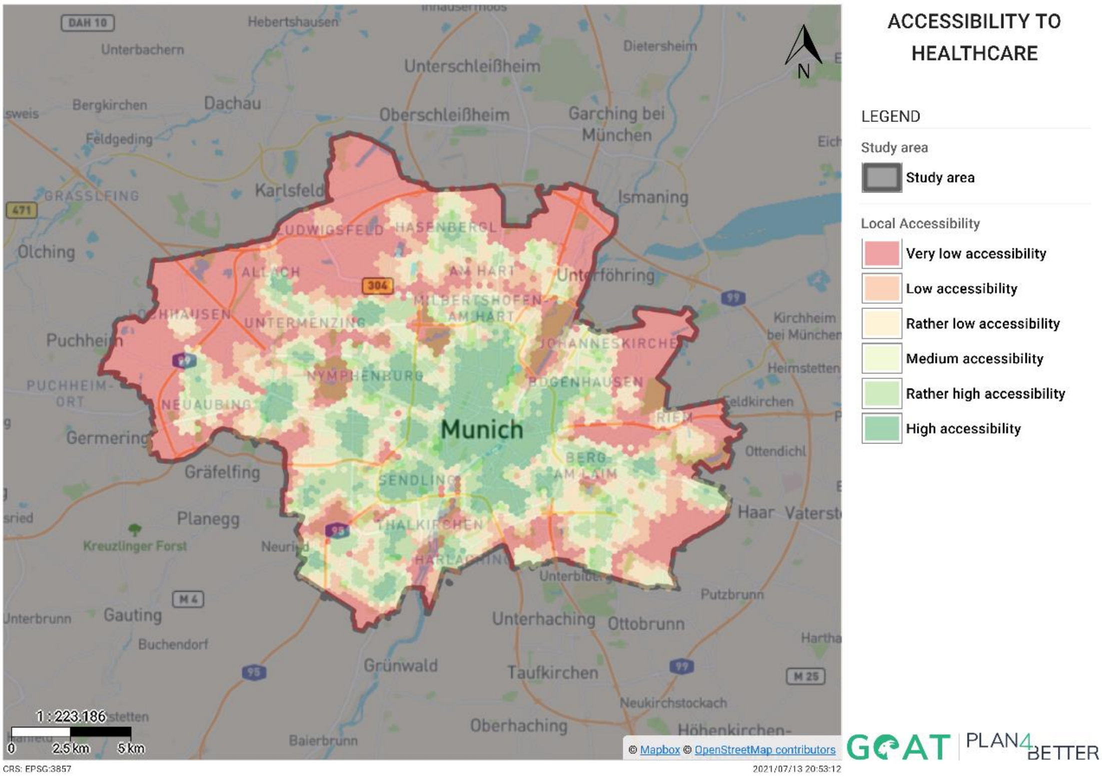


Figure 38 Map of the combined accessibility to amenities in the category of 'health'

6.2.2. Horizontal equity

Share of population within threshold

The comparison of the shares of the population that have access to the different amenity types reveals disparities between the essential services (pharmacy, dentist, general practitioner) and the extended essential services (paediatrician, gynaecologist). Even though, the difference between access within 20 minutes is not large, it increases sharply with the 10-minute threshold. The share of the population within 10 minutes of a paediatrician drops by almost 50 %. However, also the population with access to dentists and pharmacies decreases more sharply with the 10-minute threshold than the access to general practitioners. Based on the 20-minute threshold, the access would be judged to be far better and more equitable. The 10-minute threshold reveals large disparities in the provision of specialist doctors, since around 50 % of the population does not have sufficient walking access based on this threshold.

Table 13 Share of population with access to amenities in the category of 'health'

Health	Share of population within...	
Amenity Type	**20 minutes**	**10 minutes**
Pharmacy	98.0%	82.8%
Dentist	96.4%	76.4%
General Practitioner	98.9%	88.7%
Paediatrician	89.2%	46.8%
Gynaecologist	88.0%	54.1%

Lorenz Curve and Gini Coefficient

Interestingly, the huge difference in the provision of paediatricians would not be noticed as much when comparing the Lorenz Curves of the different amenities. The distribution of the absolute level of accessibility to paediatricians is almost equal to pharmacies and general practitioners (see figure 39). This reflects the relatively equal distribution of paediatricians that can be seen on the respective accessibility map (see appendix C). Gynaecologists, by contrast, have by far the most unequal distribution. The bottom 20 % of the population experiences less than 60 % of the total accessibility. Dentists lie in the middle between the gynaecologists and the more equally distributed pharmacies, general practitioners, and paediatricians.

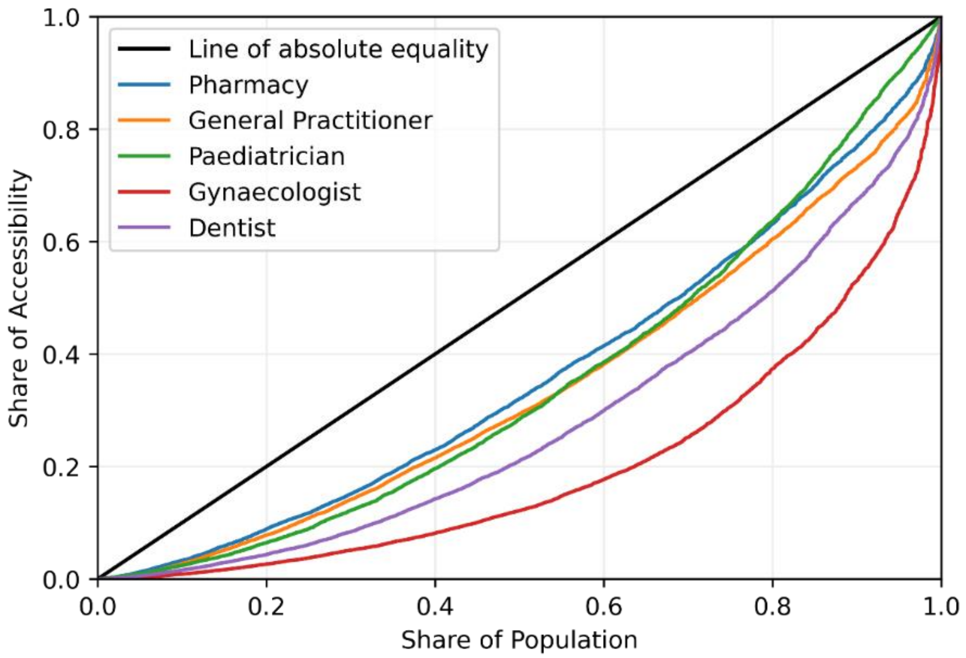


Figure 39 Lorenz Curves for the amenities in the category of 'health'

Overall, the distribution of the accessibility to the amenities in the 'health'-category is less equal than the distribution of amenities in the 'education'-category. The primary reason is the high concentration of doctors in the city centre (see chapter 4.5). This is also reflected by the respective Gini Coefficients which are all, except for pharmacies, categorized as rather unequal or even severely unequal (see table 14).

Table 14 Gini Coefficients for amenities in the category of 'health'

Amenity Type	Gini Coefficient
General Practitioner	0.32
Paediatrician	0.30
Gynaecologist	0.60
Dentist	0.44
Pharmacy	0.28

6.2.3. Vertical equity

Vertical socio-economic equity based on origin of population

The vertical equity analysis based on origin of the population reveals only minor differences between the different groups. The share of the population with access to the amenities within 20 minutes is almost equal for all population groups (between 88 % and 99 %). Slightly more Germans without a migration background have access to dentists, paediatricians, and gynaecologists within a 10-minute threshold. However, these differences lie between 3 to 1.4 percentage points. The access to the amenities can, thus, be deemed as equitable from a vertical equity perspective.

Table 15 Share of population by origin with access to amenities in the category of 'health'

Health	Pharmacy		Dentist		General Practitioner		Paediatrician		Gynaecologist	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
German w/o migration	97.7%	82.2%	96.3%	77.3%	98.7%	88.3%	88.8%	47.3%	88.2%	55.1%
German with migration	98.2%	82.9%	96.6%	75.0%	99.0%	88.8%	89.3%	45.9%	87.2%	52.1%
Foreigner	98.3%	84.2%	96.6%	75.3%	99.1%	89.6%	89.8%	46.1%	88.1%	53.1%

The comparison of the correlation coefficients, however, reveals greater differences between Germans with and without a migration background. Foreigners perform slightly better than Germans without a migration background. The correlation coefficients for Germans without a migration background indicate medium correlations while the correlation coefficients for Germans with a migration background indicate only low correlations. All correlations are positive. One exception is the correlation coefficient between Germans with a migration background and the accessibility to gynaecologist. A higher number of Germans with a migration background in an area does not indicate greater accessibility to gynaecologists. This reflects the highly unequal distribution of gynaecologists which are mainly located in the city centre. Germans with a migration background, on the other hand, mainly live in more peripheral areas (see chapter 4.6).

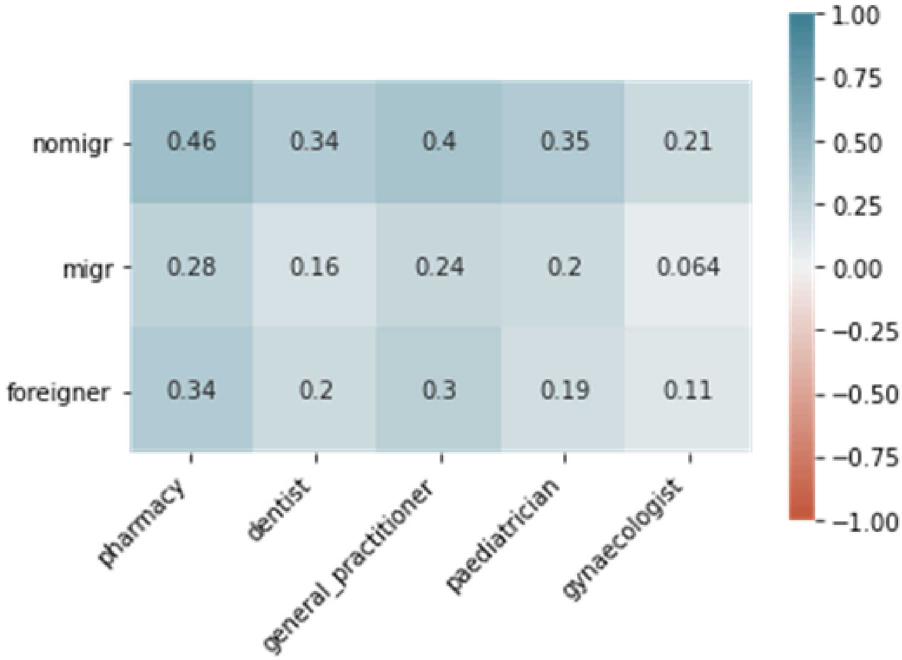


Figure 40 *Correlation heatmap for amenities in the category of ‘health’ and population by origin*

Explanat *nomigr = Germans w/o a migration background, migr = Germans with a migra tion background*

Vertical socio-economic equity based on household composition

The comparison of households based on their composition also reveals moderate disparities. Overall, more households without children have access to health-amenities within the 10-minute threshold than households with children. The 20-minute threshold reveals almost no differences, except for paediatricians and gynaecologists. Slightly more single parent than two-parent households have access to the amenities.

Table 16 *Share of households by children and parental status with access to amenities in the category of ‘health’*

Health	Pharmacy		Dentist		General Practitioner		Paediatrician		Gynaecologist	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
Household w/o children	98.5%	85.9%	97.3%	79.8%	99.2%	90.9%	91.0%	48.8%	90.3%	57.6%
Household with children	97.8%	81.6%	96.2%	74.8%	98.8%	87.9%	88.2%	45.6%	87.0%	52.0%
Household single parent	98.3%	83.6%	97.0%	76.2%	99.1%	89.2%	90.0%	46.9%	88.1%	53.1%
Household two parent	97.7%	81.1%	96.0%	74.5%	98.8%	87.6%	87.8%	45.3%	86.8%	51.8%

Using a correlation analysis for comparing absolute accessibility values and the number of households in every category, shows a higher positive correlation for households without children for every amenity. Except for gynaecologists, all correlation coefficients indicate a medium level of positive correlation between the number of households without children and the level of accessibility. The presence of households with children is only mildly correlated with higher levels of accessibility. There are only minor differences between the Pearson coefficients for single-parent households and two-parent households.

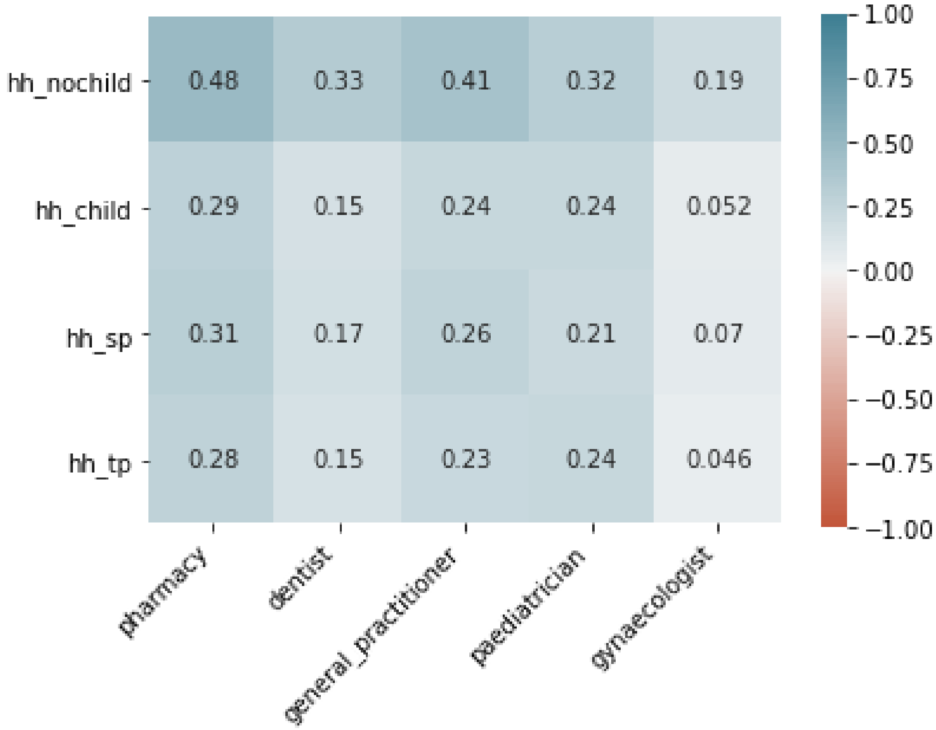


Figure 41 *Correlation heatmap for amenities in the category of 'health' and households by children and parental status*

Explanat *hh_nochild = households without children, hh_child = households with children hh_sp = single-parent households, hh_tp = two-parent households*

6.3. Grocery shops

6.3.1. Accessibility analysis

The combined accessibility to all grocery shops can be seen in figure 42. Again, the accessibility is highly concentrated in the city centre and the adjacent districts (Schwabing, Sendling, Giesing etc.). Larger areas with low levels of accessibility are mainly located in the not-developed areas in the west, north-west, north-east, and south-east. There are also some smaller areas with low levels of access

- in the north/northwest: Ludwigsfeld, Am Hart, and Lerchenau
- in the west: Lochhausen, Aubing, Pipping, (Neu-)Langwied, Gern, Obermenzing
- in the northeast: Bogenhausen, Riem, Daglfing, Messestadt-Riem

- in the east: Waldtrudering, Waldperlach,
- in the south: Fasangarten, Harlaching, Großhadern

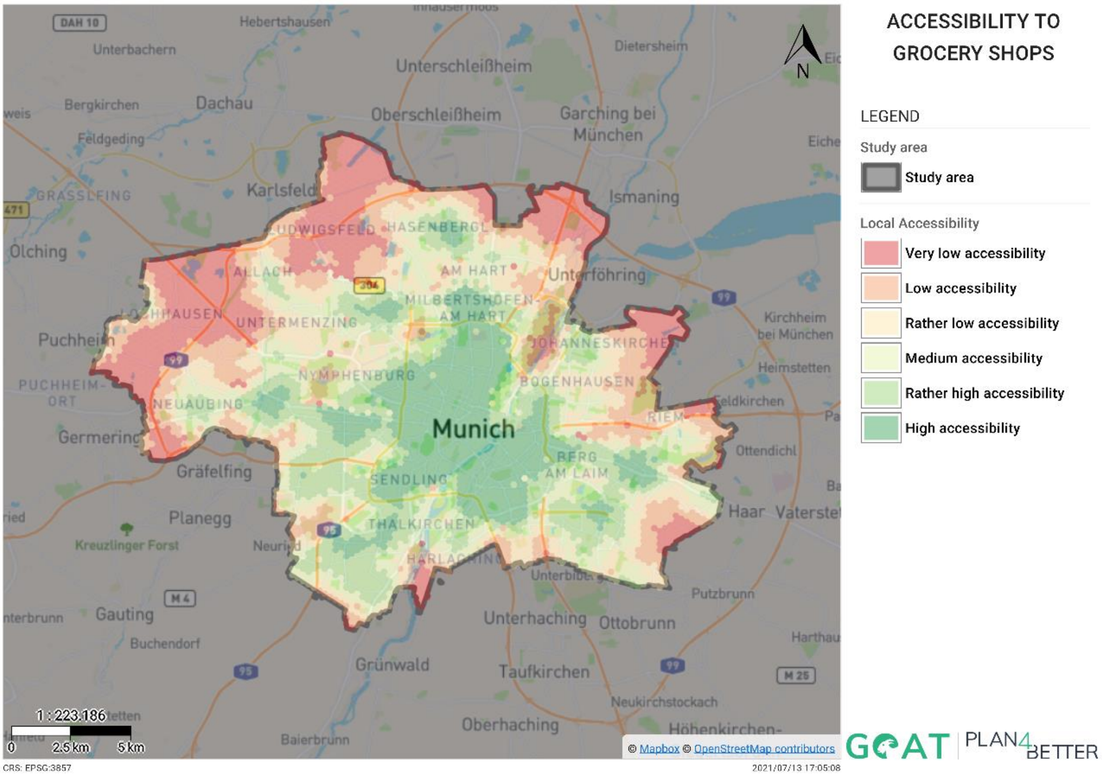


Figure 42 *Map of the combined accessibility for amenities in the category of 'grocery shops'*

6.3.2. Horizontal equity

Share of population within thresholds

Besides the individual amenities, an aggregate value for all grocery shops, except organic supermarkets, was calculated, because supermarkets and discount supermarkets fulfil the same function and are, thus, substitutes. As expected, the share of the population with access to organic supermarkets is far below the shares for the other amenities. The access to any kind of grocery shop drops only slightly from a 20 to a 10-minute threshold. From a sufficientarian point of view, the access to supermarkets or discount supermarkets can be judged as relatively equitable while the access to organic supermarkets shows large inequalities, which is, of course, a result of their low numbers.

Table 17 Share of population with access to amenities in the category of 'grocery shops'

Grocery Shop	Share of population within...	
Amenity Type	**20 minutes**	**10 minutes**
Grocery Shops	98.2%	87.4%
Supermarket	97.3%	77.4%
Discount Supermarket	94.9%	67.3%
Organic Supermarket	74.5%	37.8%

Lorenz Curve and Gini Coefficient

The Lorenz Curves of the grocery shops show relativly equal distributions across all amenity types. Supermarkets and discount supermarkets are more equally distributed than organic supermarkets. The bottom 40 % of the population with access to an organic supermarket within 20 minutes have 20 % of the accessibility, while the bottom 40 % with access to a (discount) supermarket within 20 minutes have about 25 % of the accessibility.

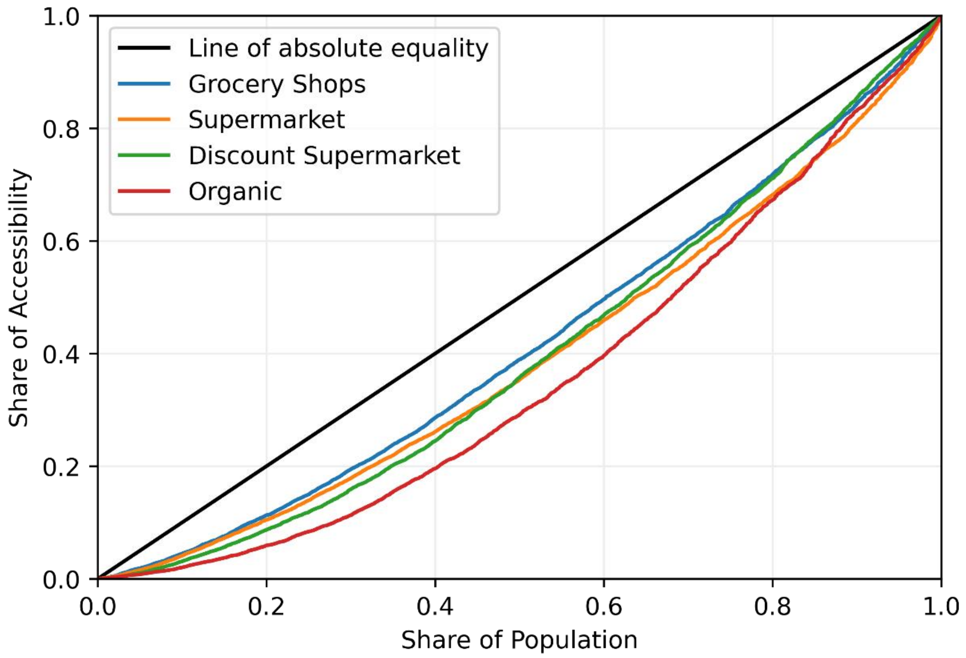


Figure 43 Lorenz Curve for amenities in the category of 'grocery shops'

The Gini Coefficients reflect the visual representation. Supermarkets and discount supermarkets are close together and more equally distributed with Gini Coefficients of 0.21 and 0.20, respectively. Organic supermarkets have a Gini Coefficient of 0.28. All distributions can be categorized as relatively equal based on the Gini Coefficients.

Table 18 *Gini Coefficients for amenities in the category of 'grocery shops'*

Amenity Type	Gini Coefficient
Grocery Shops Combined	0.17
Supermarket	0.21
Discount Supermarket	0.20
Organic	0.28

6.3.3. Vertical equity

Vertical socio-economic equity based on origin of population

From a sufficientarian perspective, the access to grocery shops is distributed relatively equally for population groups based on their origin. The share of Germans with a migration background and foreigners with access to (discount) supermarkets is marginally higher than that of Germans without a migration background within a 10-minute threshold. In turn, more Germans without a migration background have access to organic supermarkets, irrespective of the threshold. The higher share of Germans without a migration background with access to organic supermarkets might reveal a substitution of regular supermarkets for population groups with higher income.

Table 19 *Share of population by origin with access to amenities in the category of 'gro cery shops'*

Grocery Shops	Grocery Shop		Supermarket		Discount Supermarket		Organic Supermarket	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
German w/o migration	98.1%	86.5%	97.2%	76.9%	94.4%	65.4%	76.4%	40.0%
German with migration	98.7%	88.7%	97.7%	78.4%	95.6%	68.7%	71.9%	34.6%
Foreigner	98.6%	89.2%	97.6%	78.5%	96.2%	71.2%	72.3%	35.7%

The analysis of the correlation between population figures and the level of accessibility reveals higher correlation coefficients for Germans without a migration background and foreigners than for Germans with a migration background. Overall, all correlations are positive on a medium to high level, with the exception of values for Germans with a migration background/foreigners and organic supermarkets. A reason for the more equal correlation coefficients might be the lower concentration of supermarkets in the city centre compared to other amenities, for example doctors.

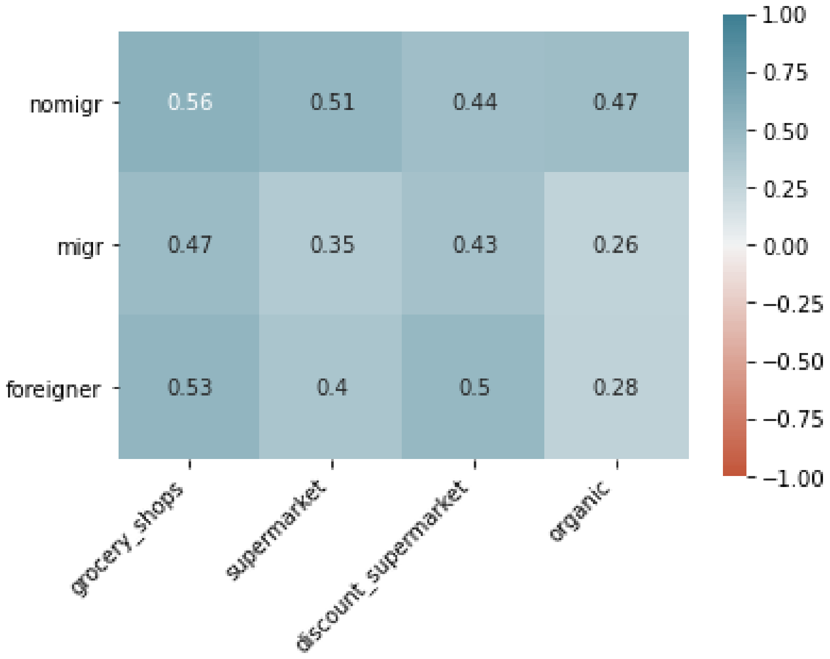


Figure 44 *Correlation heatmap for amenities in the category of 'grocery shops' and population by origin*

Explanation *nomigr = Germans w/o a migration background, migr = Germans with a migration Background,*

Vertical socio-economic equity based on household composition

The vertical equity analysis based on household composition reveals similar results. The 20-minute threshold reveals almost no differences between the different types of households. However, a higher share of households without children has access to any type of grocery shop within ten minutes than households with children. The largest disparity can, again, be found for organic supermarkets, to which 41.2 % of all households without children have access within ten minutes, while the same is true for only 34.9 % of households with children. Across all amenities, the share of single-parent households with access within the thresholds is almost equal to or above the share of two-parent households.

Table 20 *Share of households by children and parental status with access to amenities in the category of 'grocery shops'*

Grocery Shops	Grocery Shop		Supermarket		Discount Supermarket		Organic Supermarket	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
Household w/o children	98.7%	89.2%	97.9%	80.0%	95.8%	70.2%	77.3%	41.2%
Household with children	98.2%	86.4%	97.1%	76.0%	94.4%	65.2%	72.9%	34.9%
Household single parent	98.6%	88.1%	97.6%	78.3%	95.1%	67.3%	72.7%	35.6%
Household two parent	98.1%	86.0%	97.0%	75.4%	94.3%	64.7%	72.9%	34.8%

The correlation heatmap illustrates, yet again, that the number of households without children is more strongly positively correlated with higher absolute numbers of accessibility than the number of households with children (figure 45). Most correlation coefficients indicate medium to high correlation between the household-density and levels of accessibility. Differences between single-parent households and two-parent households are marginal across the amenity types.

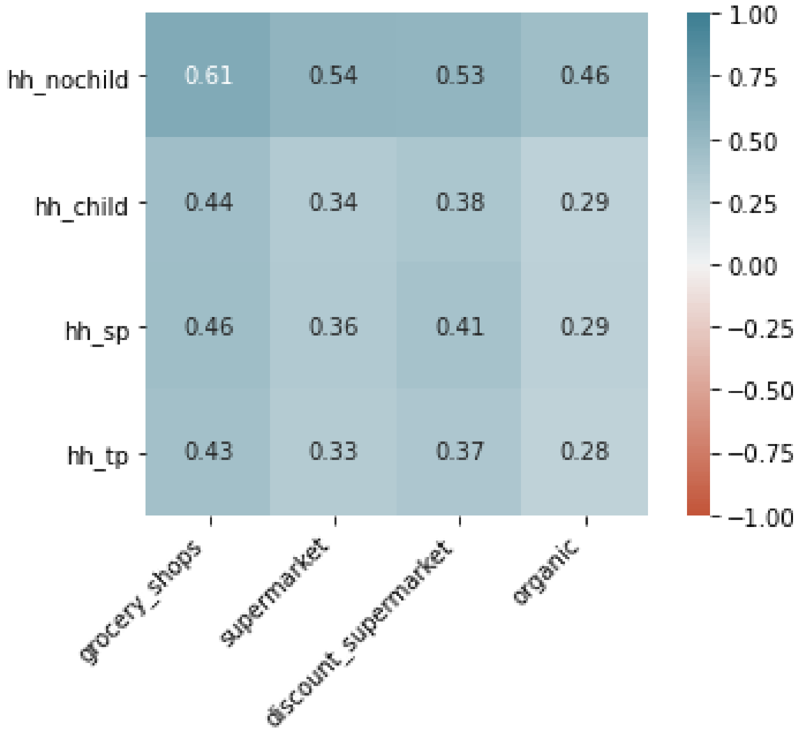


Figure 45 *Correlation heatmap for amenities in the category of 'grocery shops' and households by children and parental status*

Explanation *hh_nochild = households without children, hh_child = households with children hh_sp = single-parent households, hh_tp = two-parent households*

6.4. Public transport

6.4.1. Accessibility analysis

The combined accessibility heatmap for the amenities in the category of 'public transport' shows quite a different picture than the heatmaps for the other categories. There are only a few areas with very low accessibility, i.e. no accessibility at all. In fact, this reflects the good coverage of Munich with bus stops (see map for bus stops in appendix E). However, the following areas stand out because of their lower accessibility values:

- In the west: Pipping/(Neu-)Langwied,
- In the north: Ludwigsfeld, Fasanerie, Lerchenau
- In the north-east: Daglfing
- In the east: parts of Waldperlach and Waldtrudering

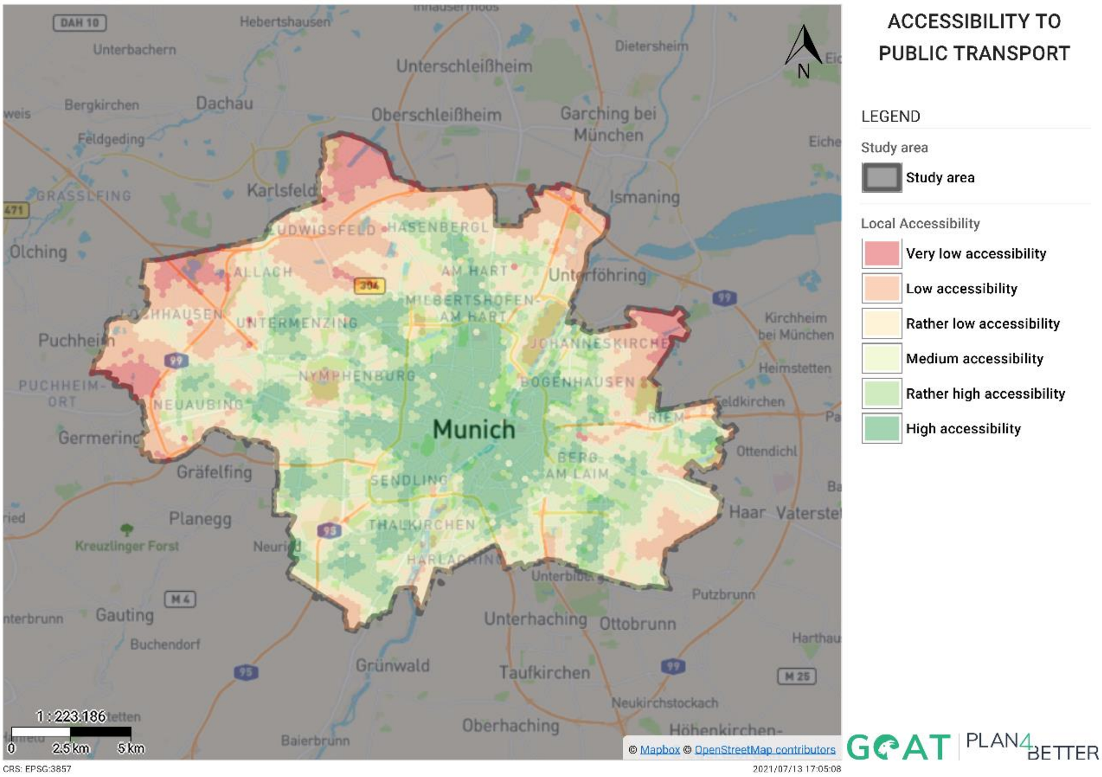


Figure 46 Map of the combined accessibility to amenities in the category 'public transport'

6.4.2. Horizontal equity

Share of population with amenity within thresholds

From a sufficientarian perspective, the shares of the essential amenity of bus stops is highly positive. Even within a 10-minute threshold, almost the whole population is able to reach at least one bus stop. The high access to the subway system is quite surprising since it does not cover most parts of Munich's western area. However, this reflects the subway systems construction and expansion in accordance with the building of new housing, for example in the Messestadt Riem and Neuperlach, and its coverage of almost all parts of the city's most densely populated districts in the city centre. Tram stops are also accessible to a majority of the population within 20 minutes and also show good access within 10 minutes. By contrast, there is a huge dip for rail stations between the 20-minute and the 10-minute threshold. This could indicate that areas around rail stations are less densely populated.

Table 21 *Shares of population with access to amenities in the category of 'public transport'*

Public Transport	**Share of population within...**	
Amenity Type	**20 minutes**	**10 minutes**
Bus Stop	99.9%	98.9%
Tram Stop	59.6%	42.8%
Subway Station	77.0%	55.3%
Rail Station	53.9%	19.8%

Lorenz Curve and Gini Coefficient

The Egalitarian equity analysis reveals similar results to the sufficientarian analysis. Bus stops are distributed almost equally. Tram stops and subway stations are distributed rather unequally with the bottom 60 % of the population receiving around 40 % of the accessibility. Rail stations show the highest level of inequality. The bottom 60 % of the population within the 20-minute threshold only have 20 % of the accessibility, while the top 20 % have more than 50 %. In total, the faster, rail-based public transport modes (tram, subway, rail) are distributed less equaly than busses.

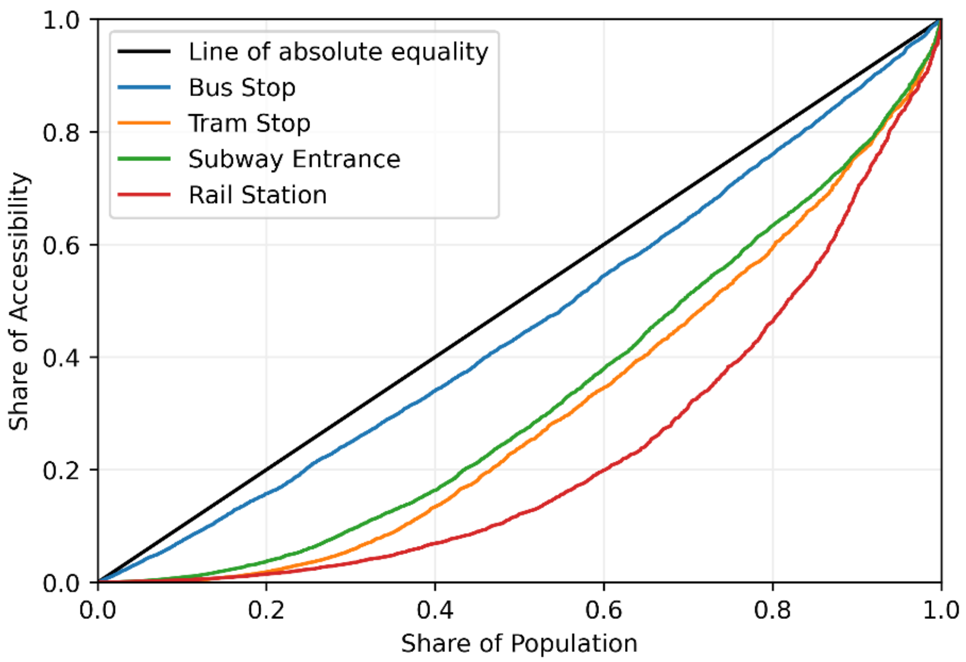


Figure 47 *Lorenz Curve for the amenities in the category of 'public transport'*

Accordingly, the Gini Coefficient for bus stops indicates a highly equal distribution, while tram stops and subway stations are distributed rather unequally. The Gini Coefficient for rail stations shows the highly unequal distribution.

Table 22 Gini Coefficients for amenities in the category of 'public transport'

Amenity Type	Gini Coefficient
Bus stop	0.09
Tram stop	0.39
Subway station	0.34
Rail station	0.53

6.4.3. Vertical equity

Share of population within threshold

The comparison of different user groups based on their access to the amenities within certain thresholds reveals almost no differences. Tram stops are slightly distributed in favour of Germans without a migration background and foreigners, while access to subway stations is slightly better for Germans with a migration background and foreigners than Germans without a migration background. Bus stops are distributed almost equally across the different population groups.

Table 23 Share of population by origin with access to amenities in the category of 'pub lic transport'

Public Transport	Bus Stop		Tram Stop		Subway Station		Rail Station	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
German w/o migration	99.9%	98.8%	60.7%	44.1%	75.2%	54.2%	54.6%	19.4%
German with migration	99.9%	99.0%	57.0%	39.8%	78.4%	55.4%	53.0%	19.5%
Foreigner	99.9%	99.0%	58.8%	41.5%	80.2%	58.0%	53.5%	20.8%

Larger disparities are seen for the distribution among households. Households without children have significantly higher access to tram stops and subway stations, beating households with children by almost 8 % for both amenity types. Two-parent households have the lowest access to these two amenity types. Single-parent households perform better than the households with children in general and, accordingly, two-parent households.

Table 24 Share of households by children and parental status with access to amenities in the category of 'public transport'

Public Transport	Bus Stop		Tram Stop		Subway Station		Rail Station	
Threshold	20 min	10 min	20 min	10 min	20 min	10 min	20 min	10 min
Household w/o children	100.0%	99.1%	63.9%	47.2%	80.2%	59.8%	53.9%	19.3%
Household with children	100.0%	99.0%	56.6%	39.2%	74.3%	52.3%	53.9%	19.1%
Household single parent	100.0%	99.1%	59.2%	41.3%	78.0%	55.8%	53.8%	18.9%
Household two parent	99.9%	99.0%	56.0%	38.7%	73.5%	51.5%	53.9%	19.1%

Correlation with accessibility values

The correlation between the absolute values of population groups and the respective accessibility values shows higher positive correlations for Germans without a migration background (see table 48). Foreigners also have higher Pearson coefficients than Germans with a migration background. However, the correlation coefficients only indicate low (0.1-0.3) to medium (0.3-0.5) correlations for bus stops, tram stops, and subway stations. Bus stops, again, have almost equal values across all groups. For rail stations, no correlation between accessibility and population numbers was found. This echoes the findings of the other measures that areas in proximity to rail stations are only sparsely populated. All correlation coefficients are positive which reflects the hypothesis that population density and accessibility values are correlated positively.

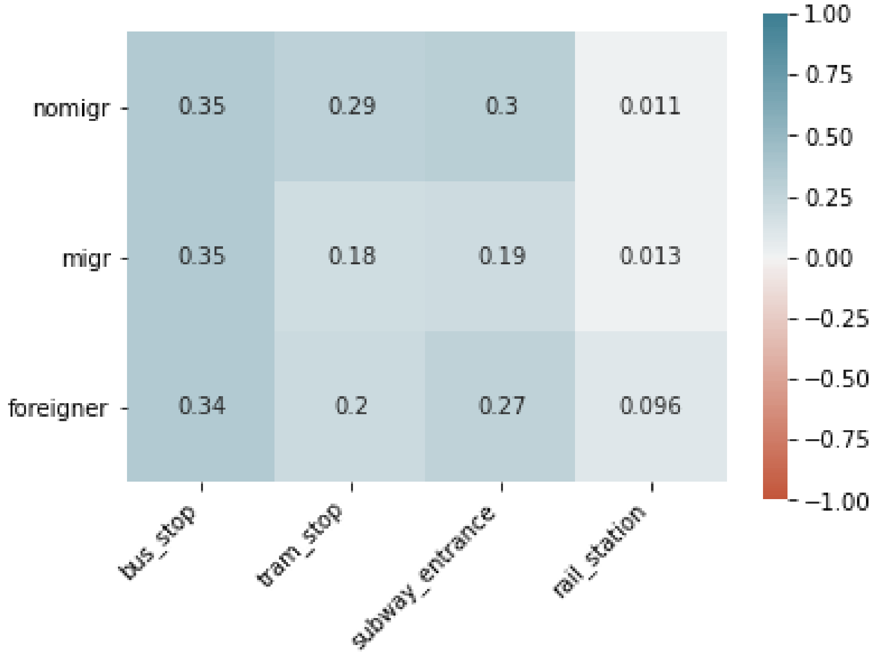


Figure 48 *Correlation heatmap for amenities in the category of 'public transport' and population by origin*

Explanation *nomigr = Germans w/o a migration background, migr = Germans with a migra tion background*

Similar results can be observed for the correlation between the accessibility values and the household compositions. For rail stations, there is again no correlation between the population numbers and the accessibility. The Pearson coefficient for bus stops is almost identical among all groups, reflecting the broad distribution across the city. The higher correlation coefficients of households with children to tram stops and subway stations reflects the higher values observed in the shares of population with access to these amenities for both thresholds.

In total, households without children show higher levels of accessibility to all . However, single-parent households perform equal to or slightly better, depending on the measure, than two-parent households. Except for subway stations, the differences between households with and without children are greater than the differences between single-parent households and two-parent households.

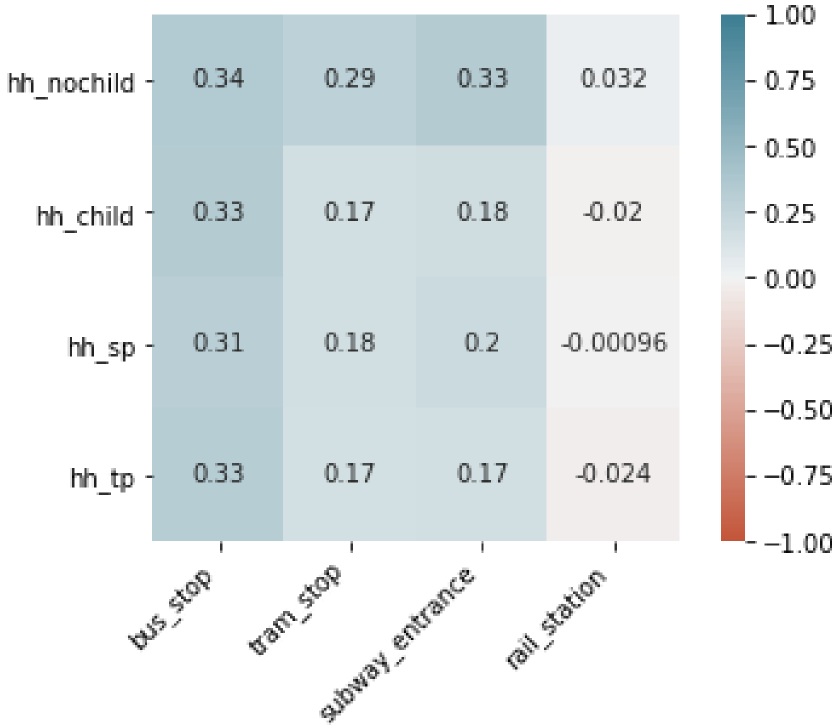


Figure 49 *Correlation heatmap for amenities in the category of 'public transport' and households by children and parental status*

Explanation *hh_nochild = households without children, hh_child = households with children hh_sp = single-parent households, hh_tp = two-parent households*

6.5. Comparison of accessibility with and without competition

This chapter will present the comparison of the accessibility and equity analyses with and without competition for nurseries and kindergartens. Because only about 55 % of all children under the age of three are attending a nursery (Landeshauptstadt München, Referat für Bildung und Sport, 2018, p. 20), the demand potential was multiplied with a factor of 0.6 for the competition calculation to nurseries in the *heatmap_dynamic_population* function.

Accessibility maps

The accessibility heatmaps for the accessibility to nurseries (figure 50) and kindergartens (figure 51) with and without competition show very diverse spatial patterns. While the accessibility without competition is highly concentrated in the central districts, accessibility with competition is distributed more evenly across the city.

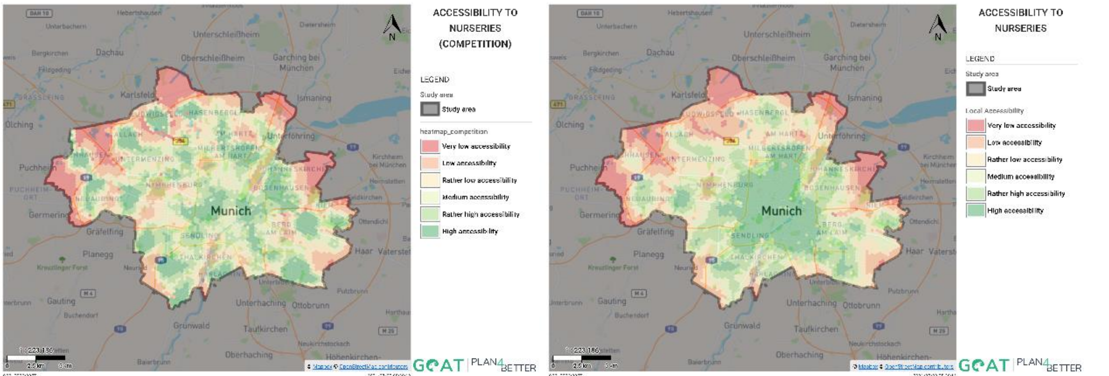


Figure 50 *Comparison of heatmaps for accessibility to nurseries with competition (left) and without competition (right)*

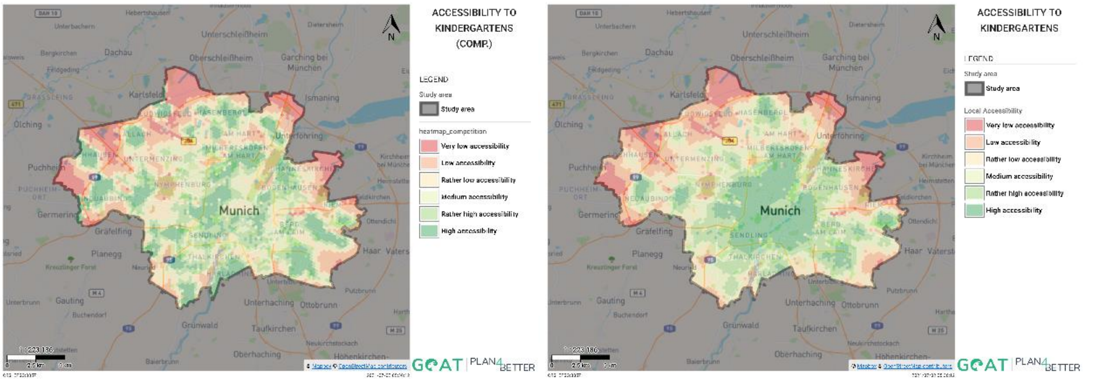


Figure 51 *Comparison of heatmaps for accessibility to kindergartens with competition (left) and without competition (right)*

It can also be observed that areas having no access in the accessibility measures without competition, also have no access in the accessibility measure with competition.

One problem of the accessibility measure with competition was observed at a municipality border (close to Freiham) where a kindergarten with a relatively high capacity of 75 is in a neighbouring town (Germering). Because there is almost no population within the grid cells on Munich's side of the border, the competition calculations resulted in extremely high values of up to 130. This is more than 30 times higher than the maximum value for nurseries (4.79). The extreme values were excluded for the further analysis, accordingly. The mean value was 0.91 for kindergartens and 0.68 for nurseries. The median was 0.93 for kindergartens and 0.64 for nurseries.

Gini Coefficients

Even though, the measures with and without competition demonstrated very different spatial patterns, their Gini Coefficients are almost identical (see table 25). The Gini Coefficient for the accessibility to kindergartens without competition is 0.11 and for accessibility to kindergartens with competition 0.07. For nurseries, the Gini Coefficient with competition is slightly higher (0.20) than without competition (0.17).

Table 25 Comparison of the Gini Coefficients for accessibility to kindergartens and nurseries with and without competition

Amenity Type	Gini Coefficient
Kindergarten w/o comp.	0.11
Kindergarten w. comp.	0.07
Nursery w/o comp.	0.17
Nursery w. comp.	0.20

Correlation coefficients

Correlation coefficients, by contrast, differ largely between the measures with and without competition. Correlation coefficients of nurseries based on the accessibility measure with competition are significantly lower and only show low or no correlations between the population numbers and higher accessibility values. The correlation coefficients of the accessibility values with competition for kindergartens are higher than for nurseries, but still significantly lower than for the accessibility measures without competition. This result should be expected because the accessibility value is less sensitive to the density of opportunities at a location.

In contrast to the accessibility measure without competition, the accessibility measure with competition shows no advantage in accessibility for economically better off groups such as Germans without migration background and households without children. Germans without migration and foreigners have higher correlations coefficients for nurseries (0.14 and 0.15 respectively) and kindergartens (0.32 and 0.29 respectively) than Germans without migration background (0.099 and 0.25 respectively) (see figure 52).

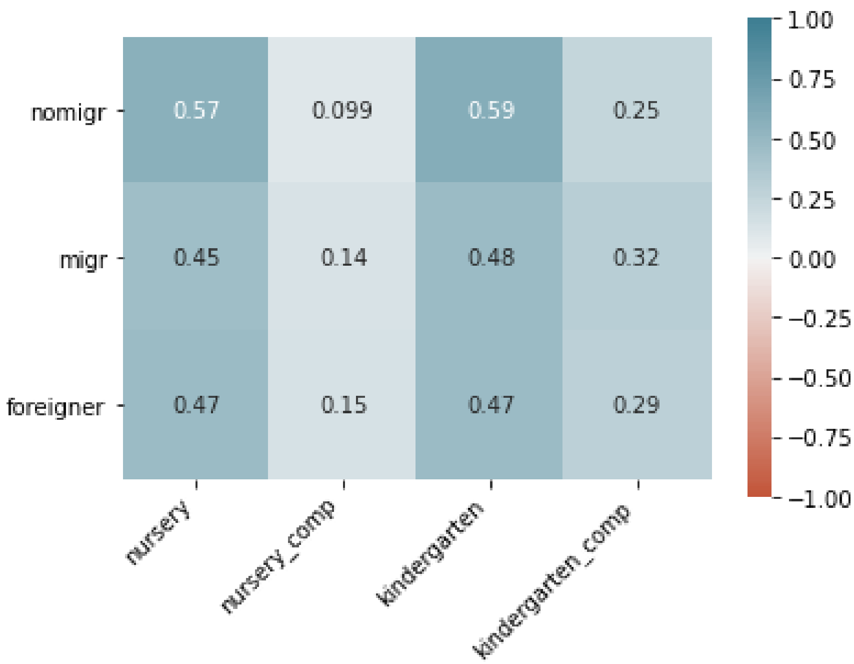


Figure 52 *Correlation heatmap for amenities in the category of 'public transport', population by origin, and accessibility measures with and without competition*

Explanation *nomigr = Germans w/o a migration background, migr = Germans with a migra tion Background*

For the comparison between households based on the presence of children and parental status, almost no differences can be observed for the accessibility with competition. While households without children performed significantly better than single-parent households for nurseries (0.6 and 0.46 respectively) and kindergartens (0.6 and 0.48 respectively) without competition, there is almost no difference between the values for the accessibility measure with competition (nurseries: 0.12 to 0.11; kindergartens 0.26 to 0.27). Single-parent households, again, perform slightly better than two-parent households.

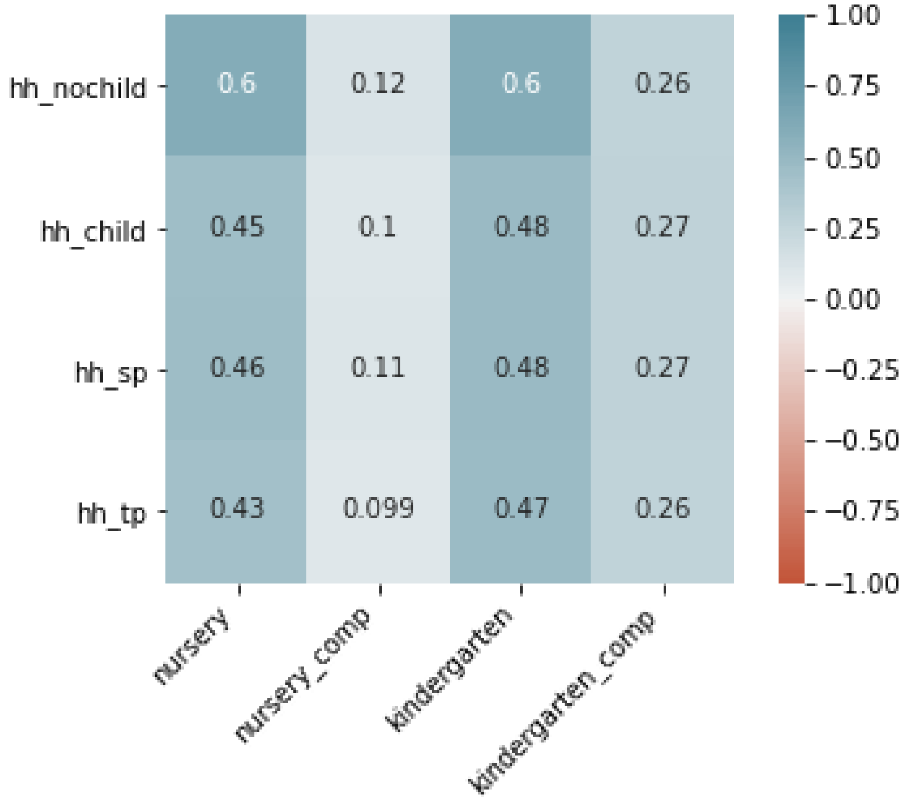


Figure 53 *Correlation heatmap for amenities in the category of 'public transport', households with children and parental status and accessibility measures with and without competition*

Explanation *hh_nochild = households without children, hh_child = households with children, hh_sp = single-parent households, hh_tp = two-parent households*

7. Conclusion

7.1. Findings of the thesis

This thesis has applied a multi-criteria accessibility and equity analysis to Munich. Also, a new, competition-based accessibility measure was developed in GOAT. Based on the results and discussions section, the four research questions (see chapter 1 and chapter 3.1) can be answered.

Firstly, the accessibility analysis has shown that areas with very low accessibility are mostly located in undeveloped areas at Munich's periphery. There are a number of areas in developed areas that have low accessibility values for most of the amenity categories, namely:

- In the west: Lochhausen, Pipping, (Neu-) Langwied, Gern, Unter- and Obermenzing
- In the northwest: Ludwigsfeld
- In the north: Fasanerie, Lerchenau, Am Hart
- In the northeast: Daglfing, Riem
- In the east: Waldperlach, Waldtrudering, Gartenstadt-Trudering
- In the south: Fasangarten, Harlaching, Solln

From a perspective of horizontal equity, The results showed higher inequities for amenities that are more specialised (e.g., rail stations, organic supermarkets, gynaecologists, Gymnasien), while amenities considered as 'basic' (e.g., kindergartens, pharmacies, general practitioners) were accessible by a larger share of the population and also had more equal distributions across the population. Specialised amenities were especially sensitive to differences in the threshold chosen for the sufficientarian analysis. Inequity was higher for the 10-minute threshold. High inequalities were observed for amenities in the category 'health'. Based on the Gini Coefficient, only pharmacies were characterised as being distributed rather equally. This reflects the results of the population per doctor ratios published by the City of Munich (see chapter 4.5).

From a vertical equity perspective, the sufficientarian analysis revealed only minor differences between different socio-economic groups for the 20-minute threshold. With the 10-minute threshold, inequity increased for some amenities. However, households without children and Germans without a migration background have higher correlation coefficients for almost any amenity than households with children, irrespective of parental status, and Germans with a migration background and foreigners. Households with single parents had slightly higher correlations coefficients for most amenities than households with two parents. This is likely a result of self-selection, since two-parent households have, on average, a higher income and can afford to move to residential areas with lower densities and, accordingly, lower accessibility.

Lastly, the comparison between the results for the accessibility measure without competition and the accessibility measure with competition demonstrated the effects of the inclusion of supply and demand. The accessibility heatmap provided quite different spatial patterns. While the measure without competition resulted in a concentration of higher accessibility values in the central districts, the measure with competition showed more equally distributed pattern. This did, however, not result greater differences between the horizontal equity analysis with the Lorenz Curve and Gini Coefficient. By contrast, the results of the correlation analysis with competition differ very much from the results of the analysis without competition. Competition measures only revealed low correlations between the number of people/households within a grid and the accessibility value. The differences between socio-demographic groups also diminished. The correlations found for kindergartens were significantly higher than the correlations for nurseries.

However, some limitations of the study also need to be adressed. First, the disaggregation of households did not match the population disaggregation, because households were not disaggregated to newly developed areas. This might have led to differences in the results for the vertical equity analysis. Secondly, for the disaggregation of the socio-demographic groups it was assumed that the distribution of these groups is the same for all population points within one *Stadtbezirksteilviertel*. However, even within one *Stadtbezirksviertel* the distribution might vary from building to building. Thirdly, the assessment of the competition effects might be biased because of an inflation of demand and/or supply (Paez et al., 2019), i.e. the demand or supply seem greater than they actually are.

7.2. Recommendations for future research and developments

The thesis has provided a basis for future research by applying a multi-criteria approach to the analysis of spatial (in) equities and further statistical analysis could be applied to analyse the interrelation between different equity and accessibility measures. Especially, the comparison of accessibility measurement with and without competition and their relation to equity concerns need further investigation. For example, it could be analysed whether the almost identical Gini Coefficients of the distribution of nurseries and kindergarten for measure with and without competition can also be found for other types of amenities that are less equally distributed. Another interesting application of the competition measures would be its comparison to results that are achieved by the City of Munich’s ABZ model. The ABZ model assigns the demand iteratively to the supply and, thus, does not suffer from the problem of inflation of demand/supply, because every person can only access one destination and every destination can only give each of its places to only one person.

Especially, the question of data quality needs to be addressed in future developments of GOAT. The review of the data accuracy of the POIs (chapter 5.1.1) revealed large differences between the OSM data and the data from official sources for many amenities. Amenities that are easily visible either because of their size or their exposed position, like pharmacies and supermarkets, have had relatively good accuracy. Amenities that are more difficult to find by on street survey, such as doctors, were mapped relatively poorly. Also, the problem of the incompatibility of the tags to define different types of schools and the missing additional information (e.g., capacity, doctor speciality) for most amenities pose a problem. The integration of more data from official data sources, for example for schools and kindergartens, seems the best way to solve these problems for larger areas.

Another area of interest should be the definition of the impedance function and the sensitivity parameter. In this thesis, the fitting to observed travel data revealed better fit for negative exponential functions and also higher sensitivity parameters for the modified Gaussian function than currently implemented in GOAT. This echoes the results of previous analyses with GOAT (Nieto, 2020). Further research needs to be conducted to solve the question which impedance function and which sensitivity parameters are the best to describe people’s perception of the attractiveness of destinations.

Appendices

Appendix A: List of altered and added scripts/files

All files are available at: https://github.com/SeisenB/goat/tree/development.

Altered files

Table 26 Altered files

app\database\data_preparation\SQL
pois.sql
census.sql
app\client\public\static
app-conf.json
app\client\public\static\layer-styles\translations
translations.json
app\client\src\components\layers\filter
HeatmapOptions.vue
app\client\src\locales
de.json
en.json
app\config
goat_config.yaml

Added files

Table 27 Added files

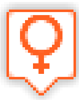
app\database\data_preparation\SQL
census_household.sql
household_disagregation.sql
household_distribution. sql (needs to be run manually)

grid_population.sql
app\database\database_functions\heatmap
heatmap_dynamic_population.sql
heatmap_competition.sql
grid_access.sql (needs to be run manually)
app\client\public\static\layer-styles\styles
heatmap_competition.json

Added POIs

All markers taken from: https://mapicons.mapsmarker.com/markers/. Toolbar icons are saved at app\client\src\pois. Map icons are saved at app\client\public\img\pois-map.

Table 28 Added POIs

	Toolbar Icon	**Map Icon Accessible**	**Map Icon not Accessible**
After-school			
General Practitioner			
Gynaecologist			
Paediatrician			
Psychotherapist			

Added layers

Table 29 Added layers

app\database\database_functions\layers_api	app\client\public\static\layer-styles\styles
age_14_under.sql	age_14_under.json
age_15_64.sql	age_15_64.json
age_65_over.sql	age_65_over.json
hh_single_parent.sql	hh_single_parent.json
hh_two_parent.sql	hh_two_parent.json
hh_with_children.sql	hh_with_children.json
hh_without_children.sql	hh_without_children.json
modeshare_bike.sql	modeshare_bike.json
modeshare_car.sql	modeshare_car.json
modeshare_put.sql	modeshare_put.json
modeshare_umweltverbund.sql	modeshare_umweltverbund.json
modeshare_walking.sql	modeshare_walking.json
munich_density.sql	munich_density.json
munich_zentren.sql	munich_zentren.json
origin_foreigner.sql	origin_foreigner.json
origin_with_migration.sql	origin_with_migration.json
origin_without_migration.sql	origin_without_migration.json

Statistical analysis

Table 30 Scripts for statistical analysis

app\database\statistics
equity_correlation_heatmap.ipynb
eqioty_correlation_heatmap_comp.ipynb

equity_correlation_scatter.ipynb
equity_lorenz_and_gini.ipynb
equity_lorenz_and_gini_comp.ipynb
equity_sufficientarianism.ipynb
equity_sufficientarianism_vertical.ipynb

Data collection

Table 31 Scripts for data collection

app\database\data_collection
dentist_geocoding.ipynb
doctors_geocoding.ipynb
doctors_scraper.ipynb
impedance_function.ipynb
pharmacies_geocoding.ipynb
pharmacy_scraper.ipynb
schools_geocoding.ipynb

Appendix B: Maps and scatter plots for amenities of the category education

Nursery

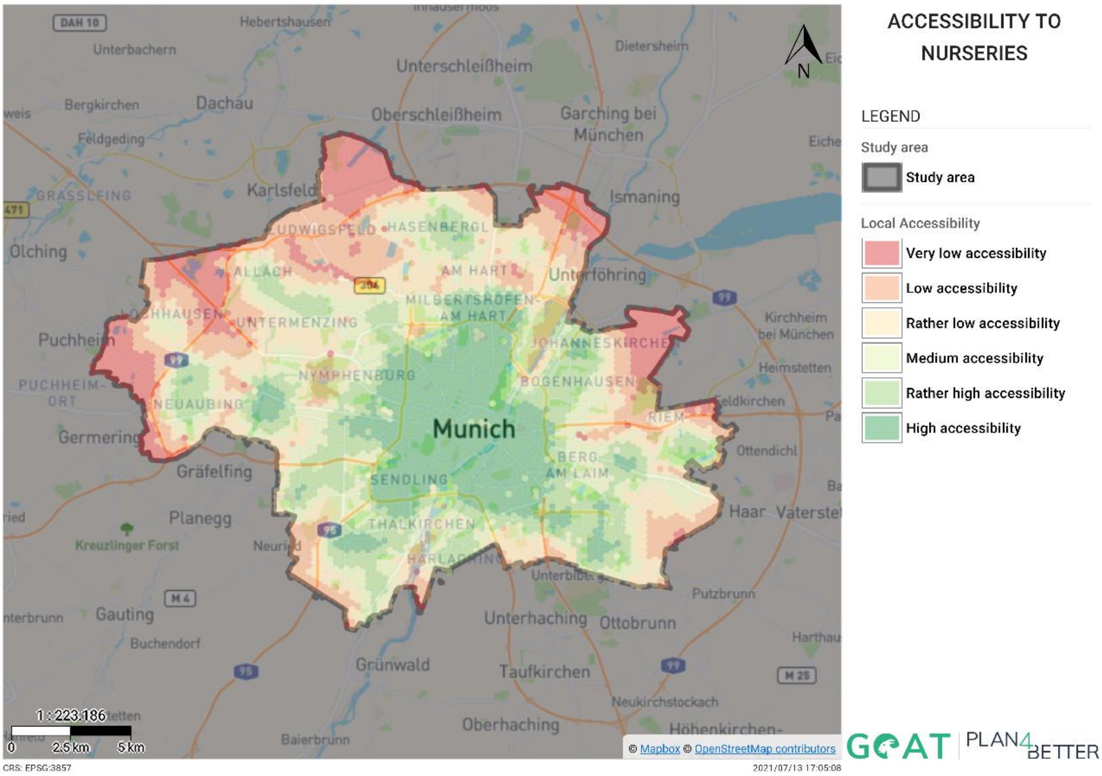


Figure 54 Heatmap for the accessibility to nurseries

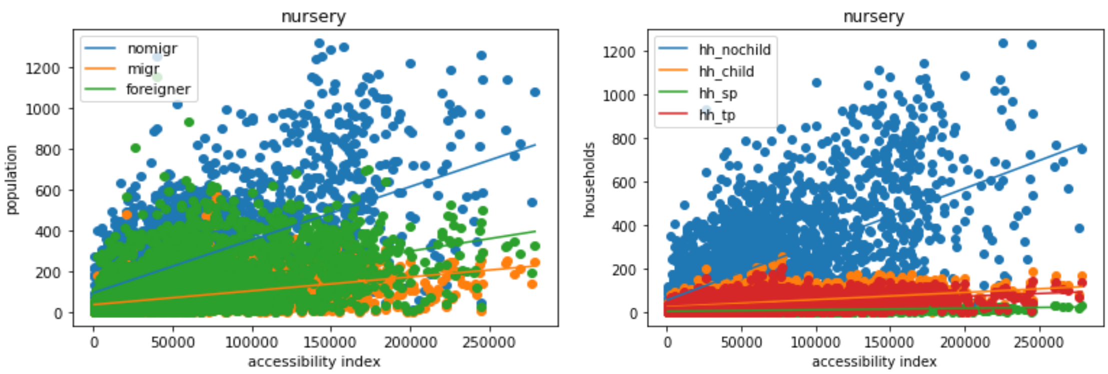


Figure 55 Scatter plots for nurseries and socio-demographic groups

Kindergartens

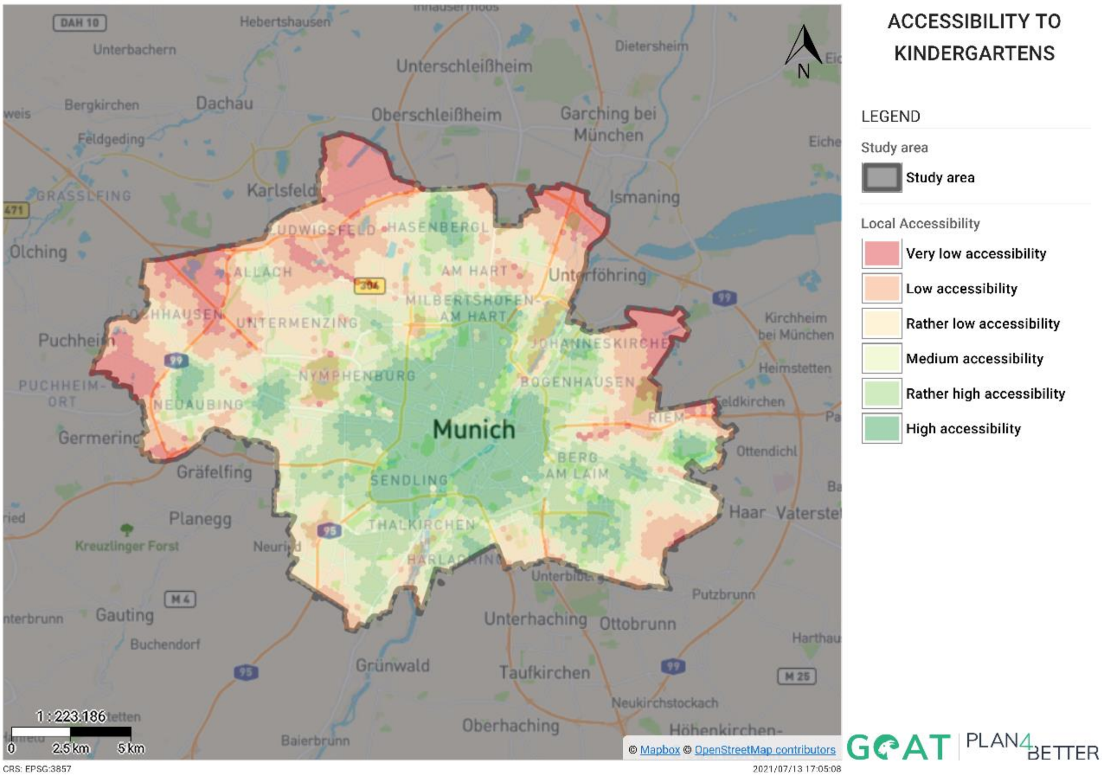


Figure 56 Heatmap for the accessibility to kindergartens

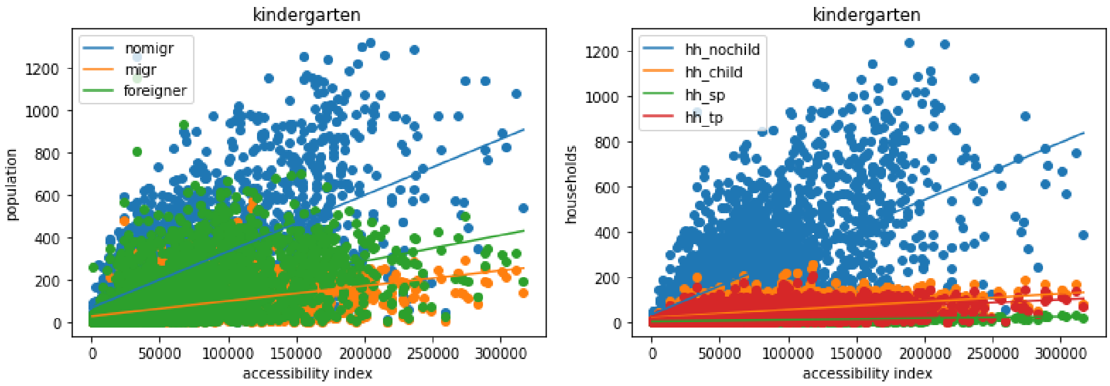


Figure 57 Scatter plots for kindergartens and socio-demographic groups

After-school care

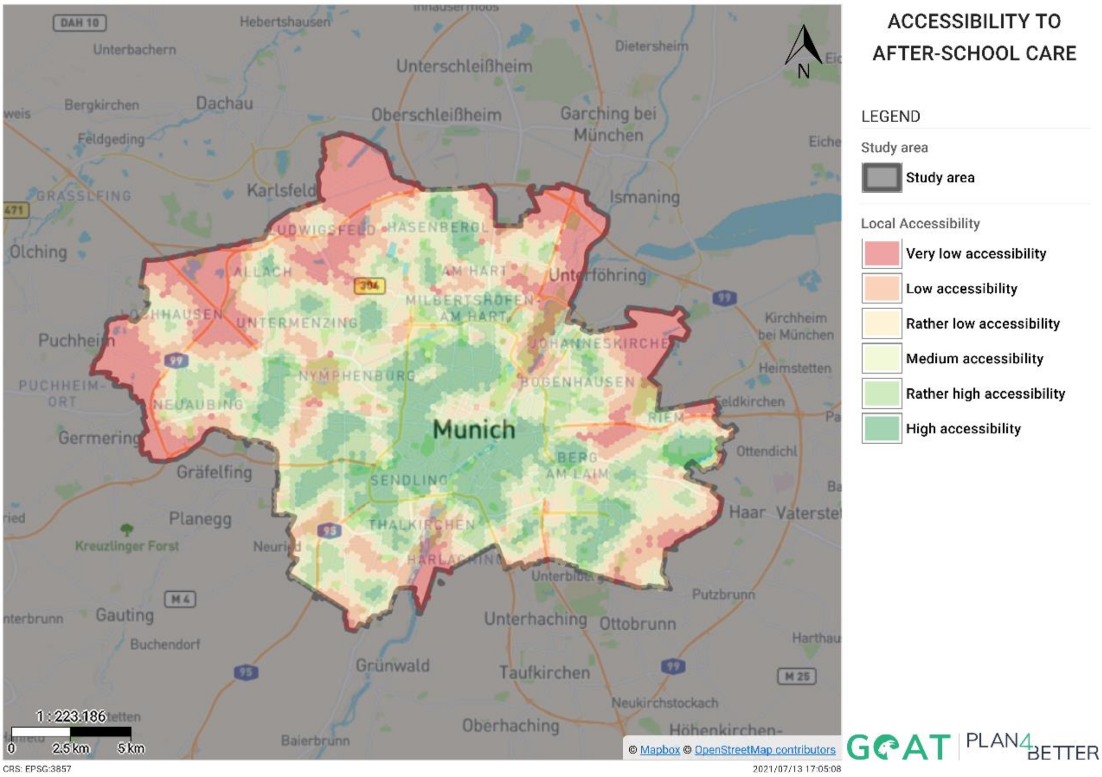


Figure 58 Heatmap for the accessibility to after-school care

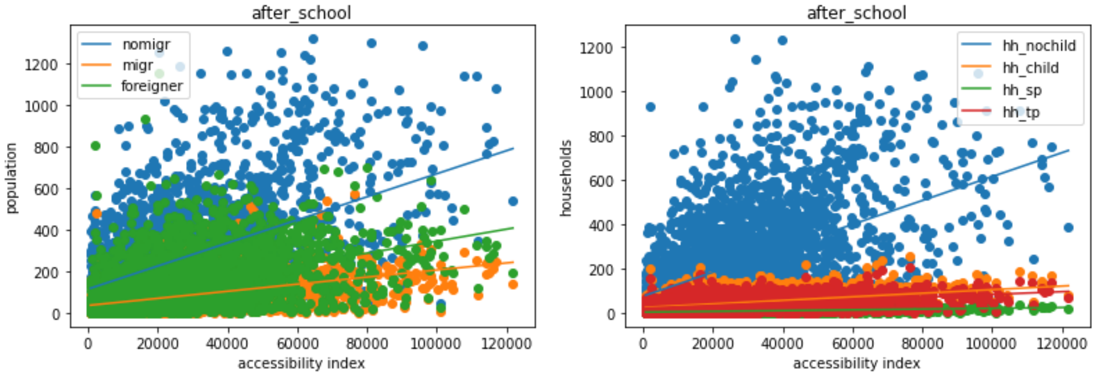


Figure 59 Scatter plots for after-school care and socio-demographic groups

Grundschule

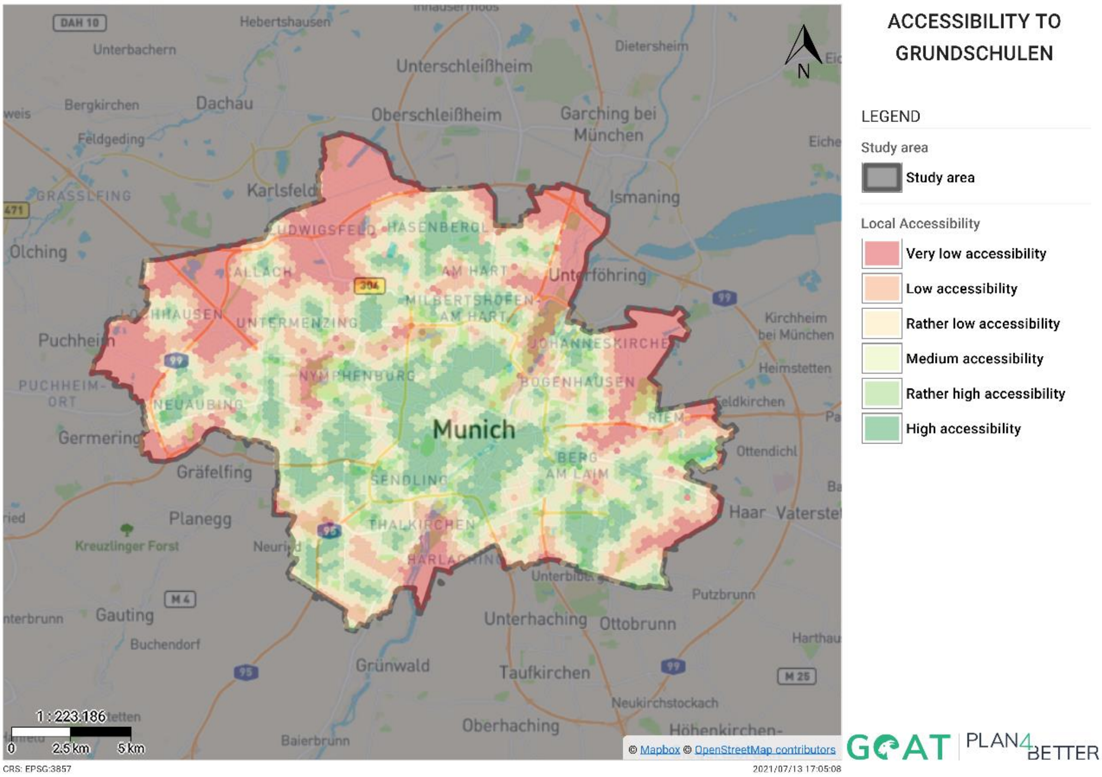


Figure 60 Heatmap for the accessibility to Grundschulen

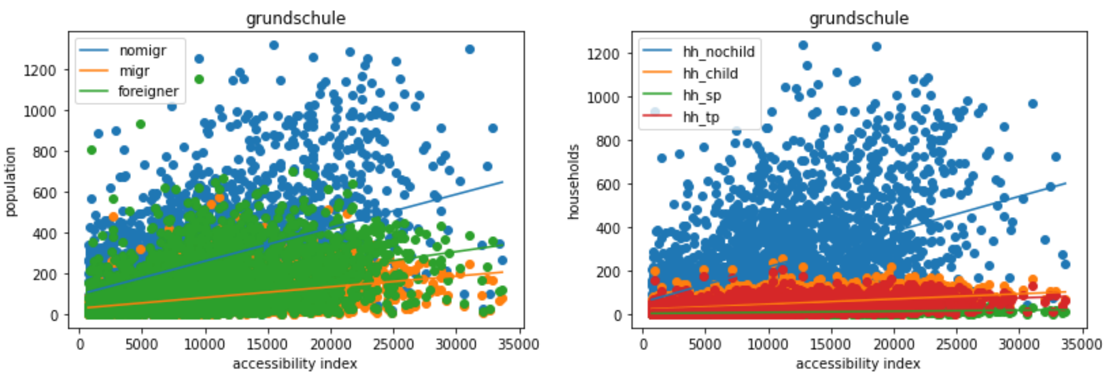


Figure 61 Scatter plots for Grundschulen and socio-demographic groups

Haupt-/Mittelschulen

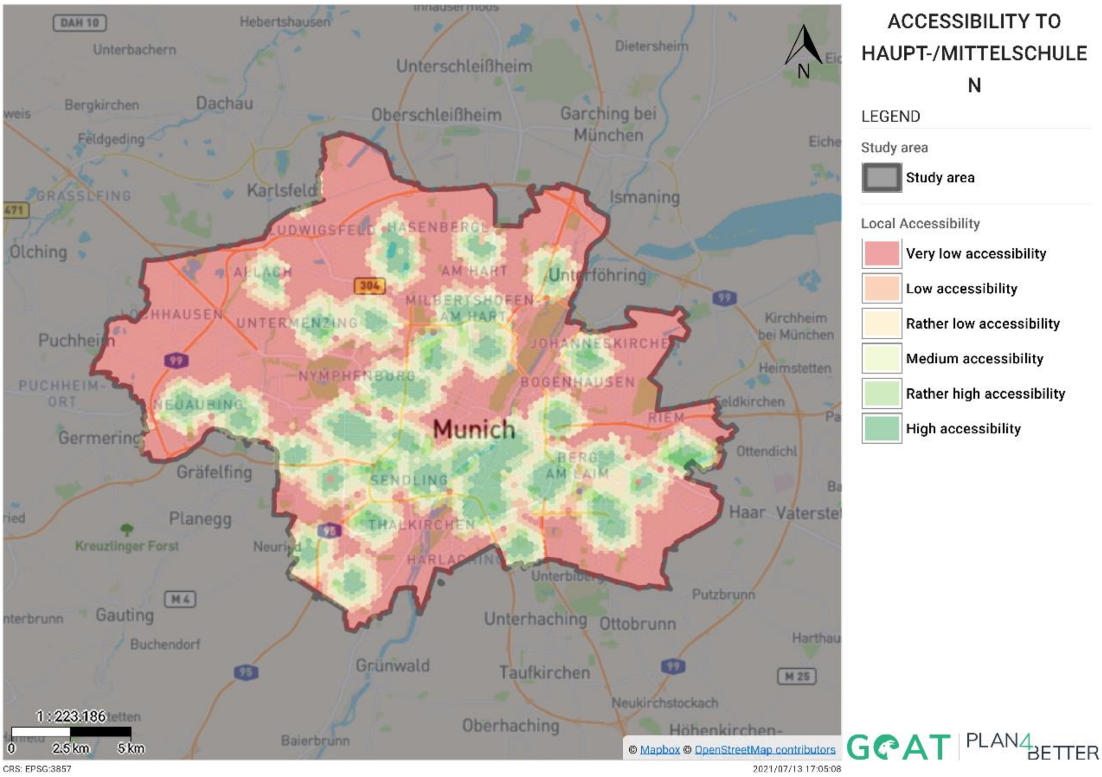


Figure 62 Heatmap for the accessibility to Haupt-/Mittelschulen

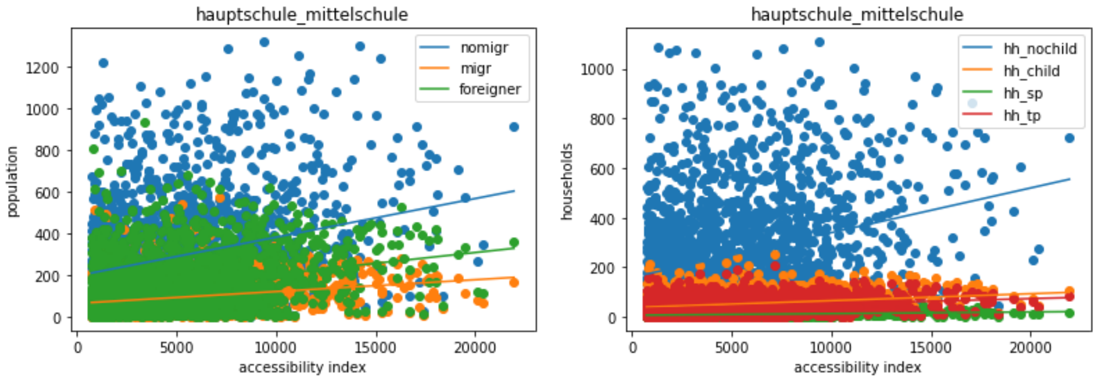


Figure 63 Scatter plots for Haupt-/Mittelschulen and socio-demographic groups

Realschulen

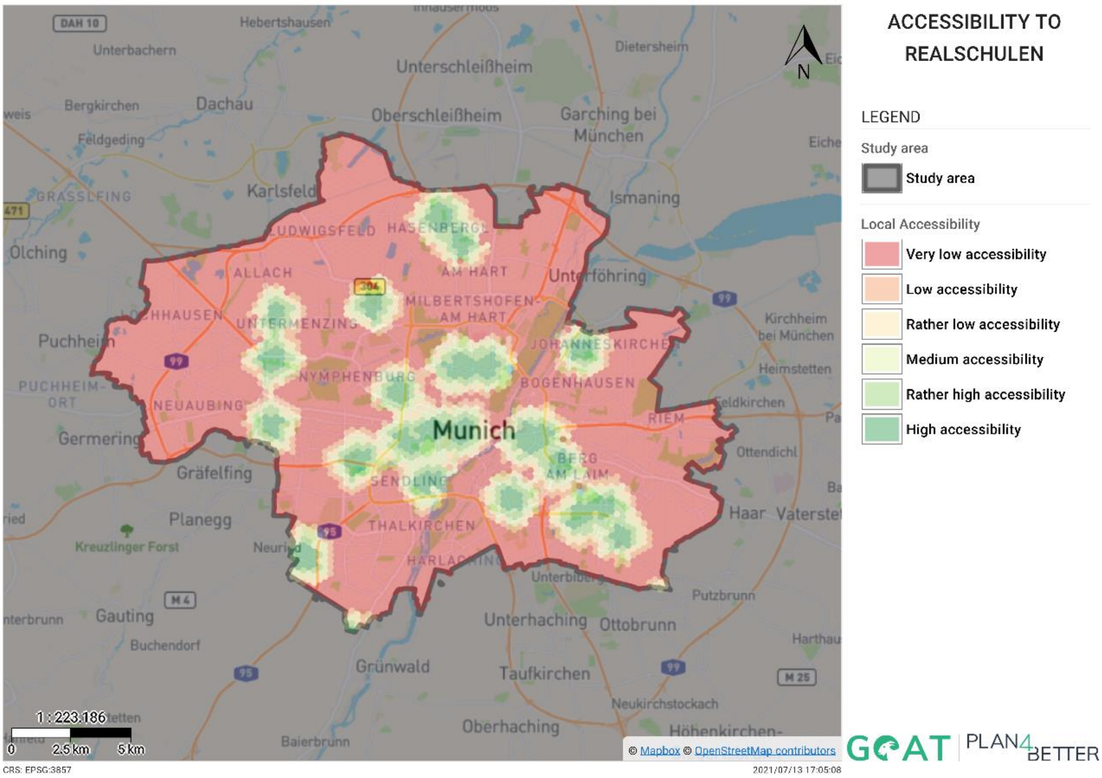


Figure 64 Heatmap for the accessibility to Realschulen

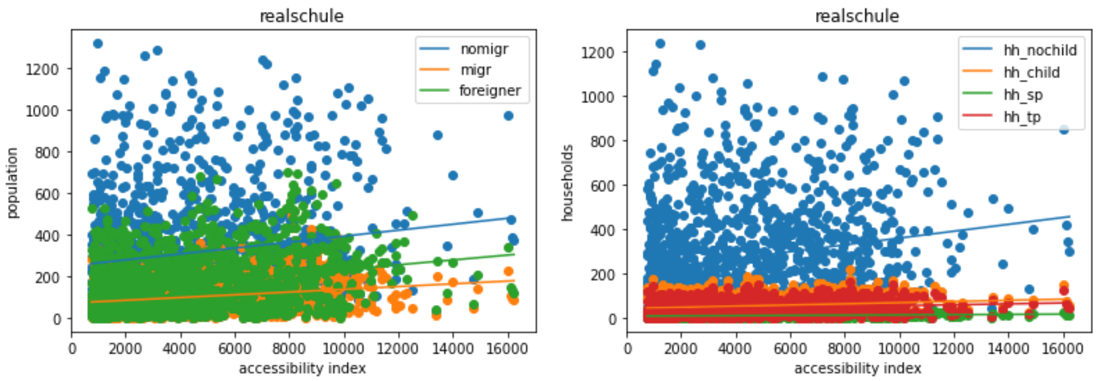


Figure 65 Scatter plots for Realschulen and socio-demographic groups

Gymnasien

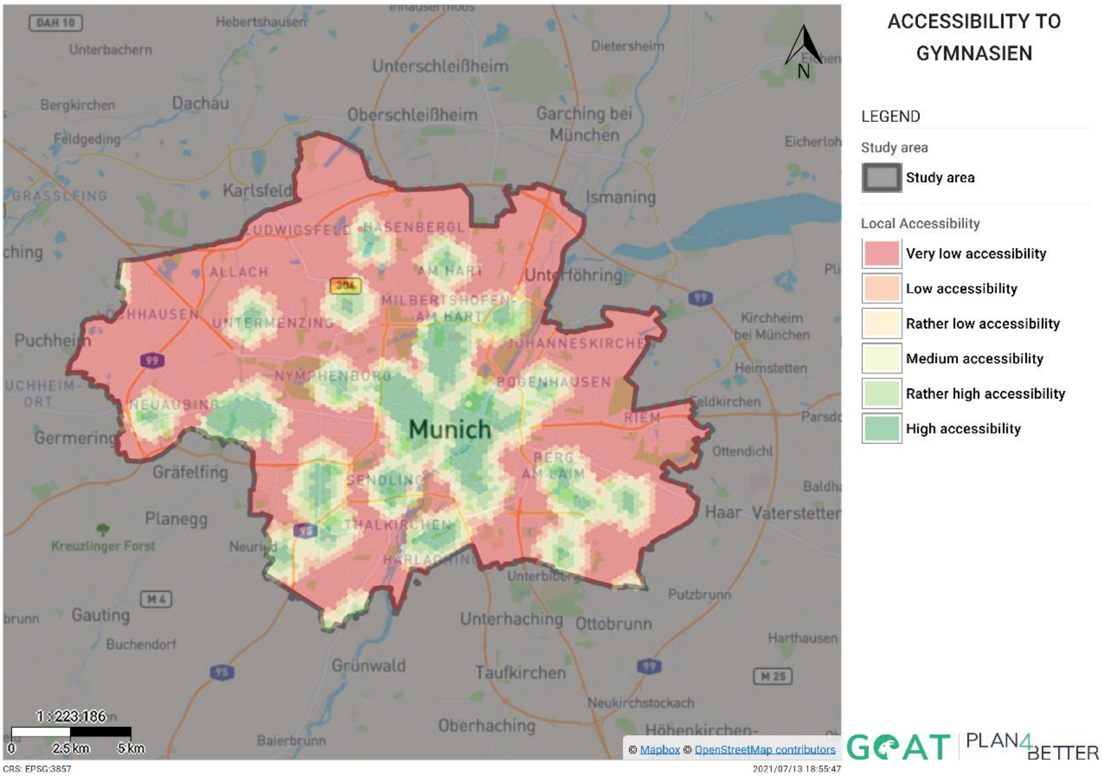


Figure 66 Heatmap for the accessibility to Gymnasien

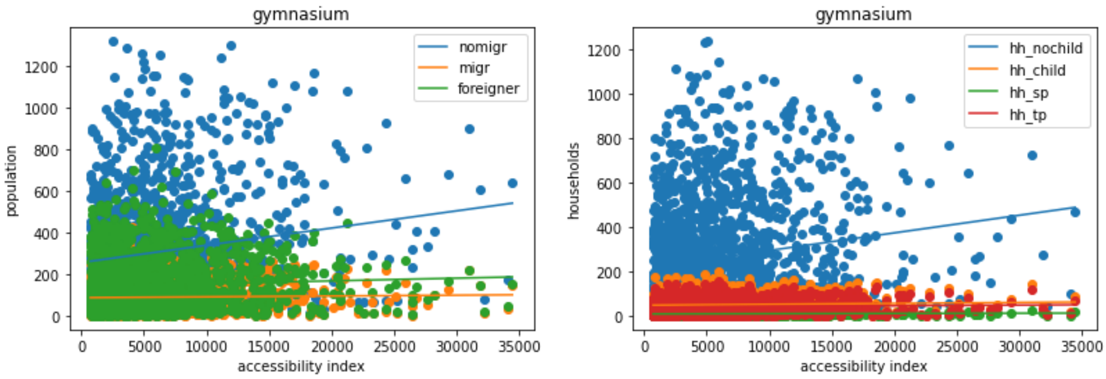


Figure 67 Scatter plots for Gymnasien and socio-demographic groups

Appendix C: Maps and scatter plots for amenities of the category health

Pharmacy

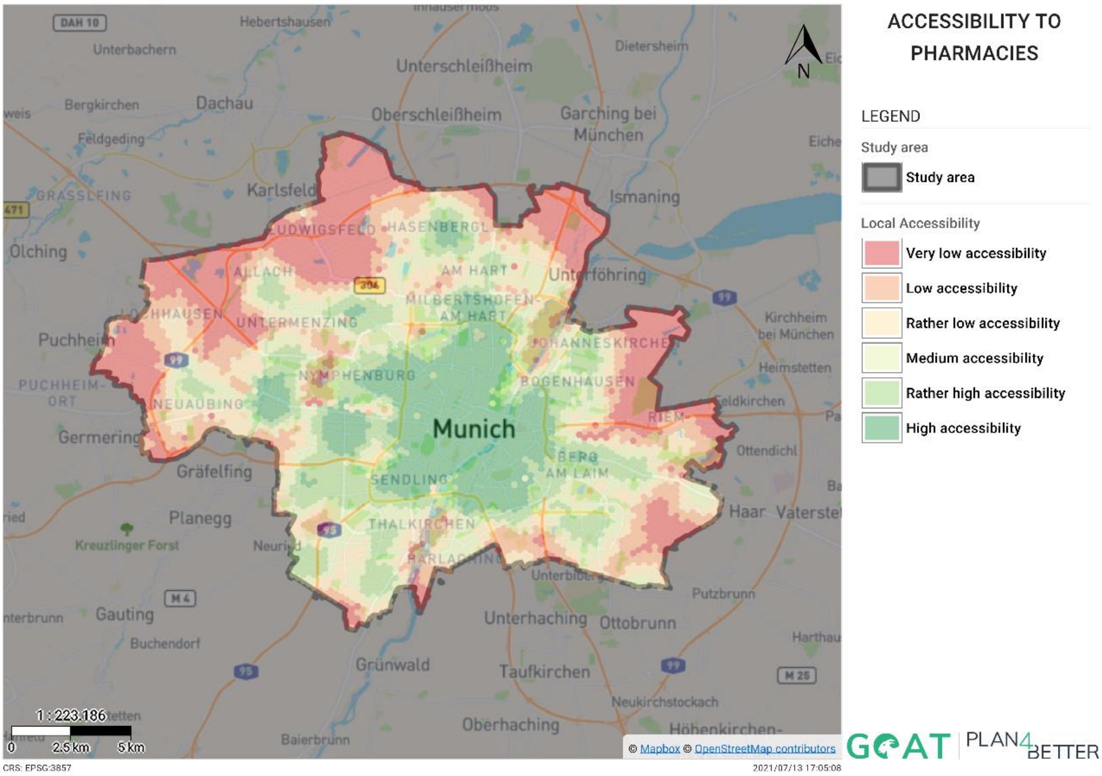


Figure 68 Heatmap for the accessibility to pharmacies

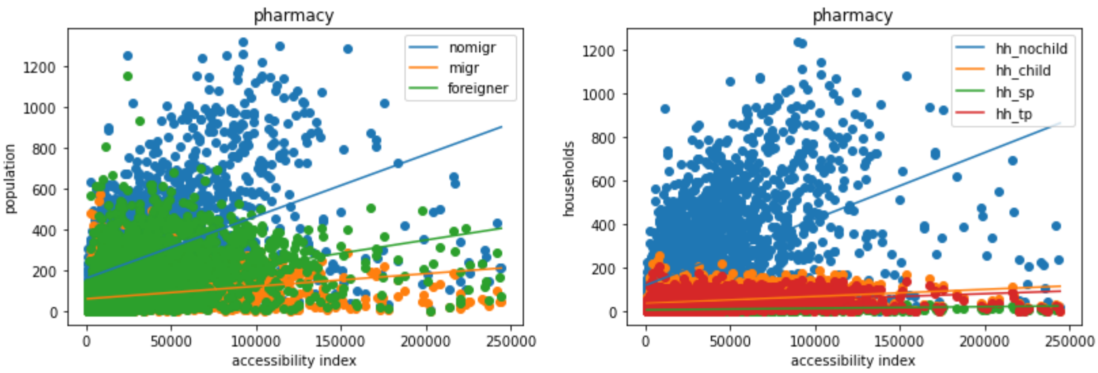


Figure 69 Scatter plots for pharmacies and socio-demographic groups

Dentist

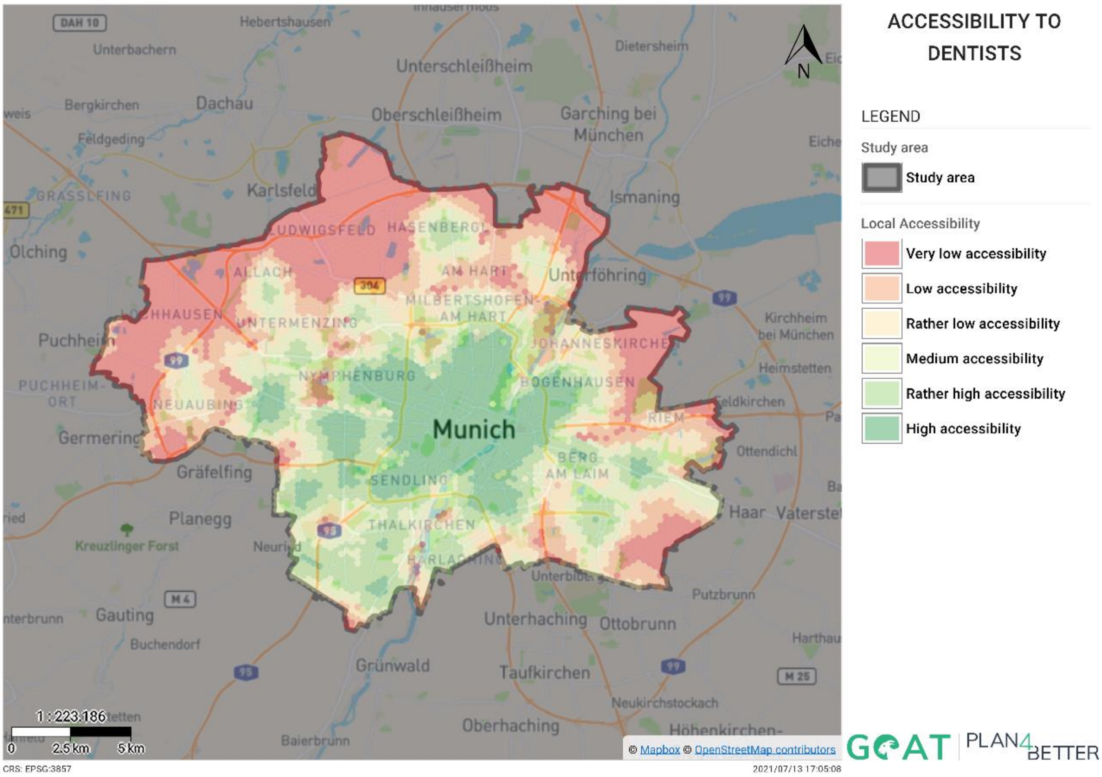


Figure 70 Heatmap for the accessibility to dentists

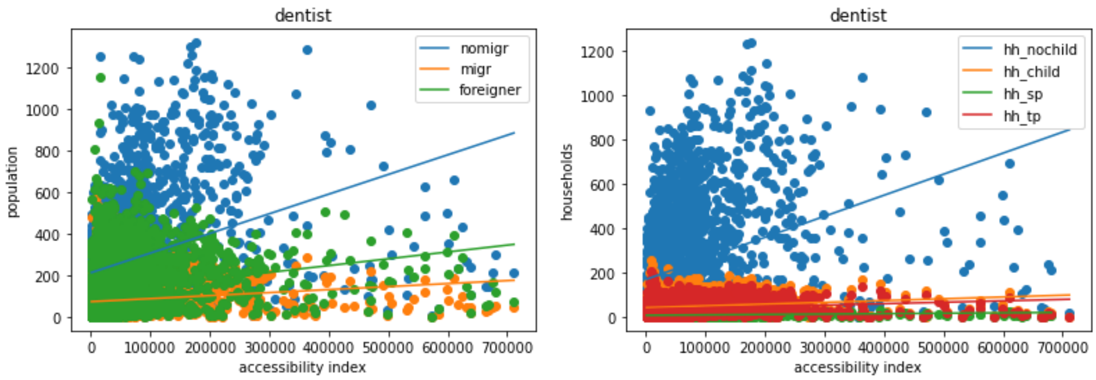


Figure 71 Scatter plots for dentists and socio-demographic groups

General practitioners

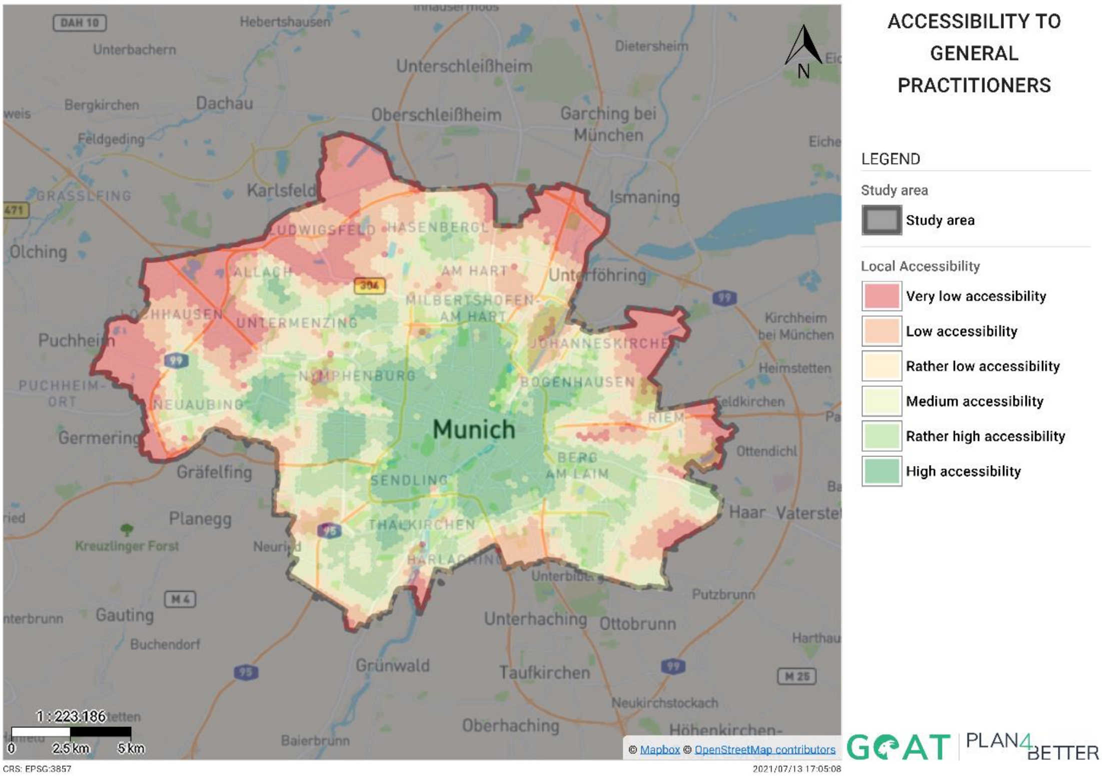


Figure 72 Heatmap for the accessibility to general practitioners

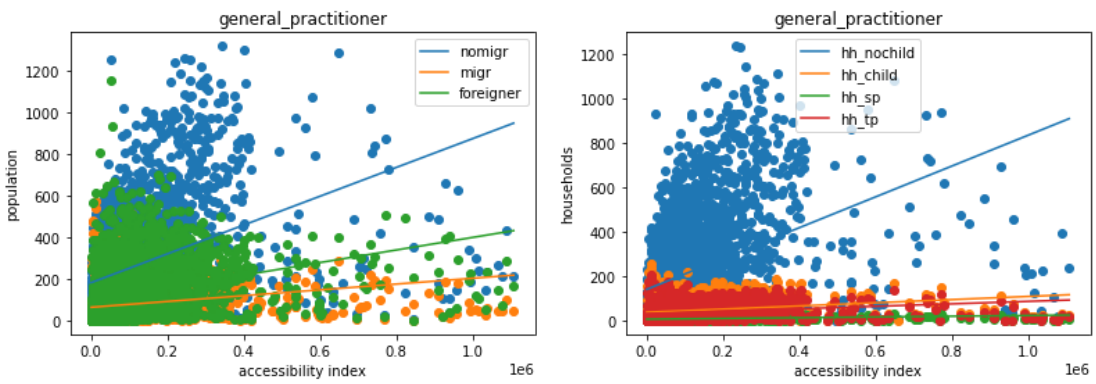


Figure 73 Scatter plots for general practitioners and socio-demographic groups

Paediatricians

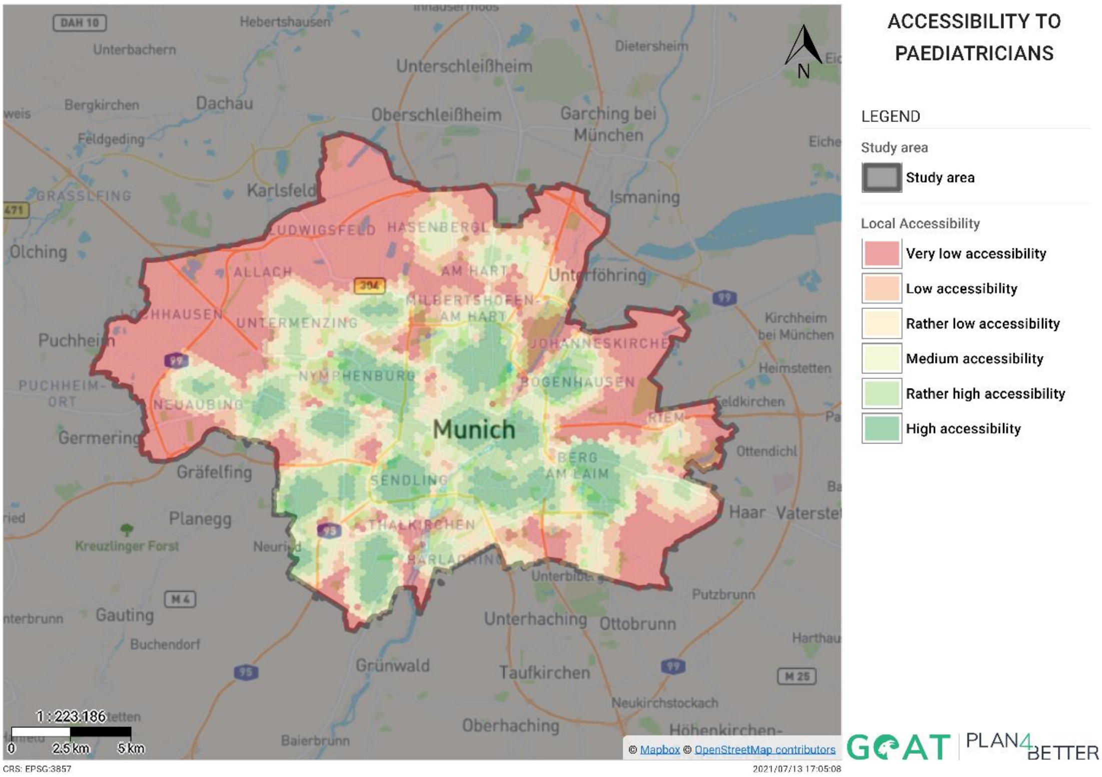


Figure 74 Heatmap for the accessibility to paediatricians

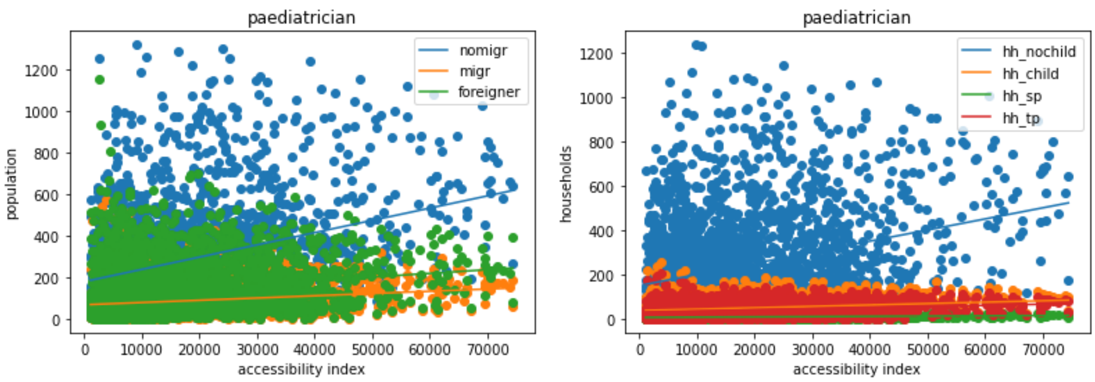


Figure 75 Scatter plots for paediatricians and socio-demographic groups

Gynaecologists

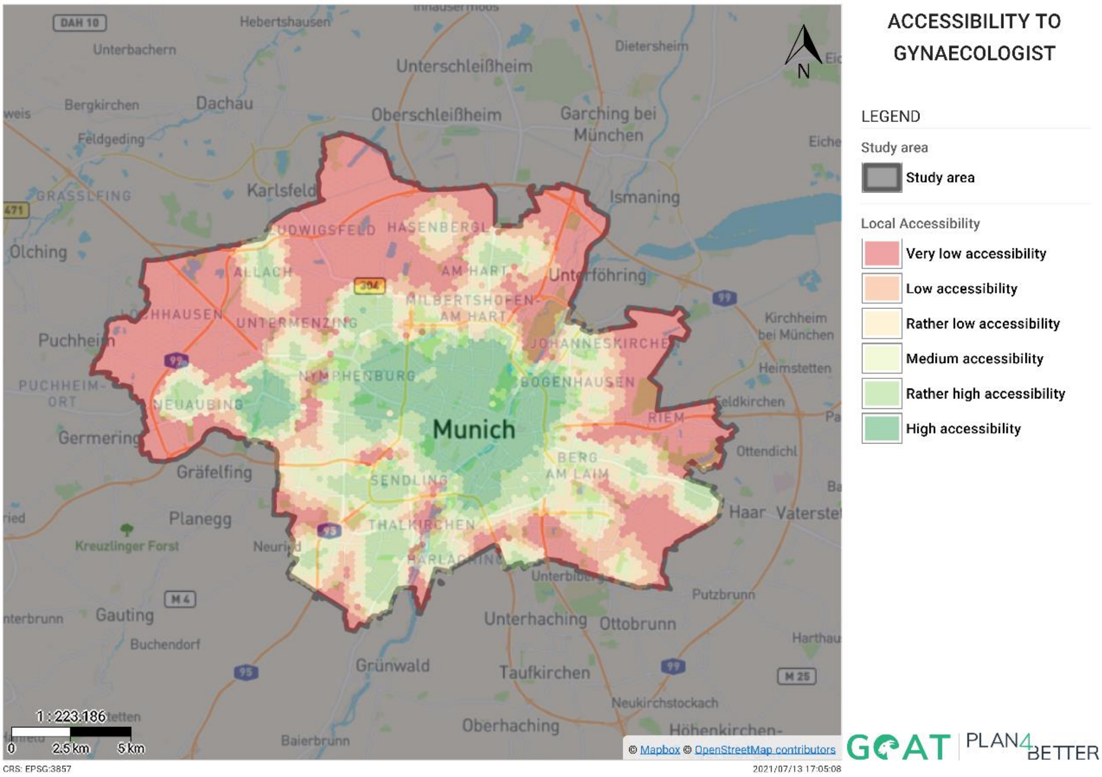


Figure 76 Heatmap for the accessibility to gynaecologists

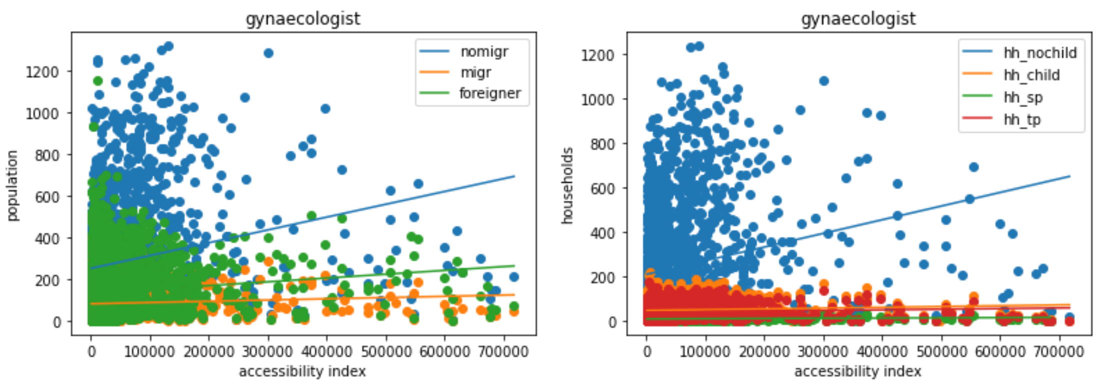


Figure 77 Scatter plots for gynaecologists and socio-demographic groups

Appendix D: Maps and scatter plots for amenities of the category grocery shops

Supermarkets

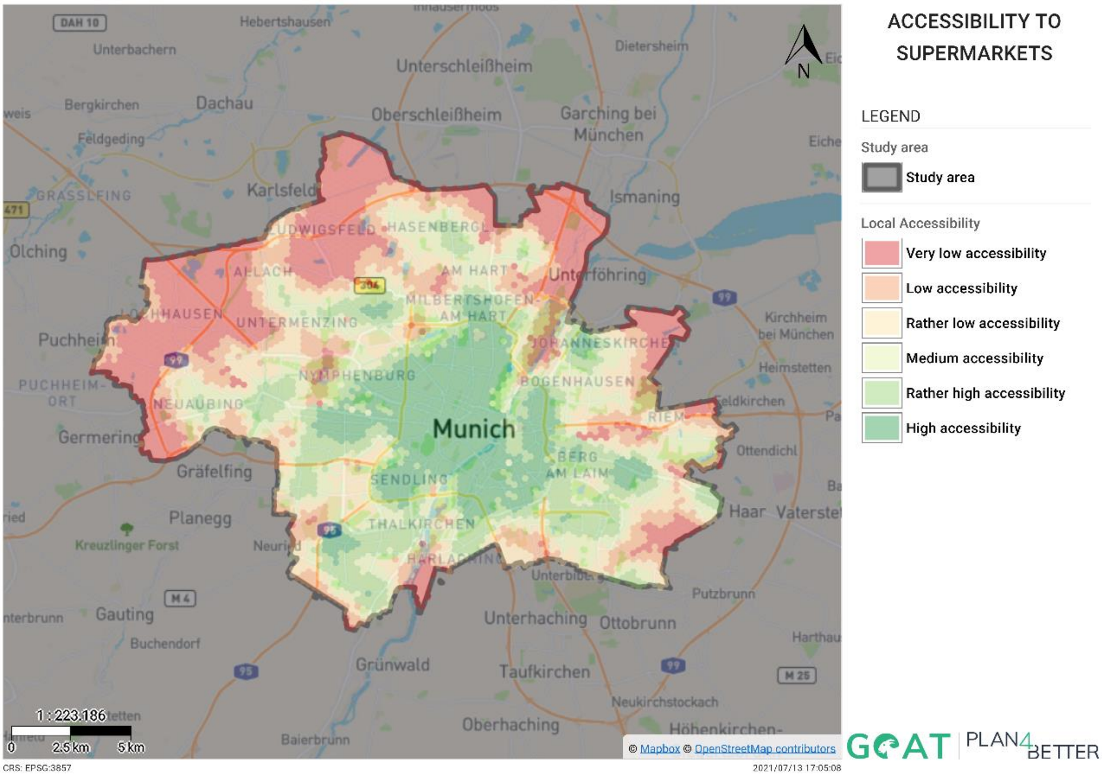


Figure 78 Heatmap for the accessibility to supermarkets

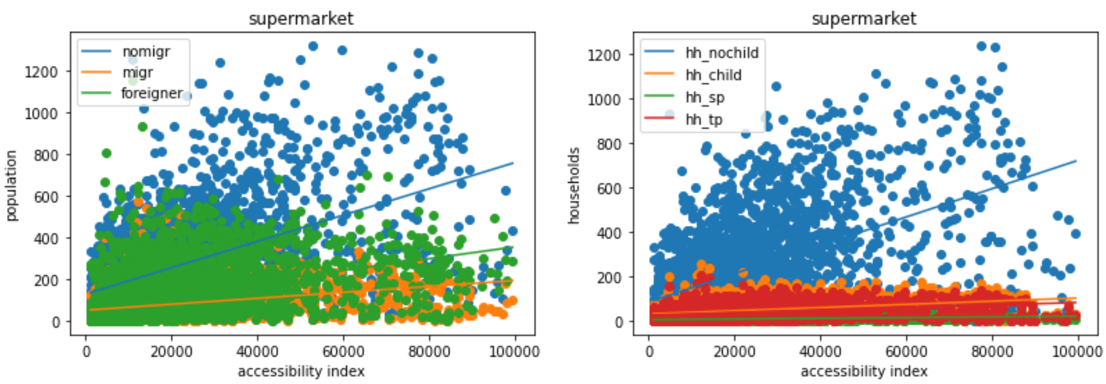


Figure 79 Scatter plots for supermarkets and socio-demographic groups

Discount supermarkets

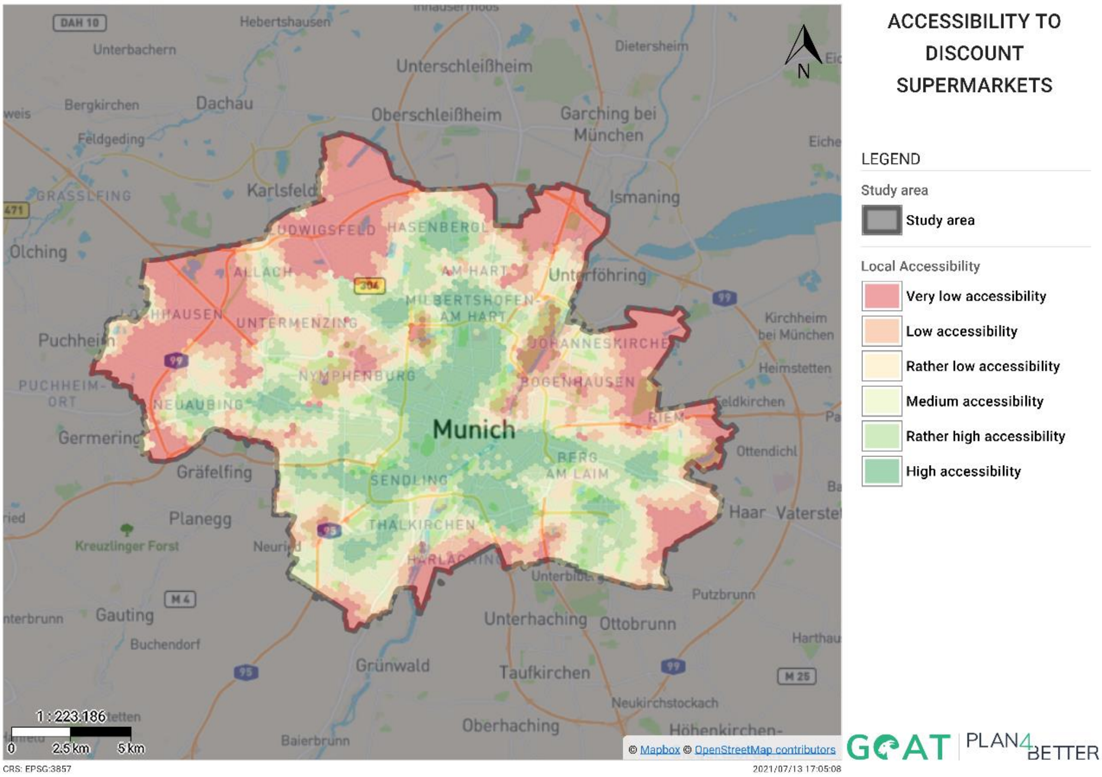


Figure 80 Heatmap for the accessibility to discount supermarkets

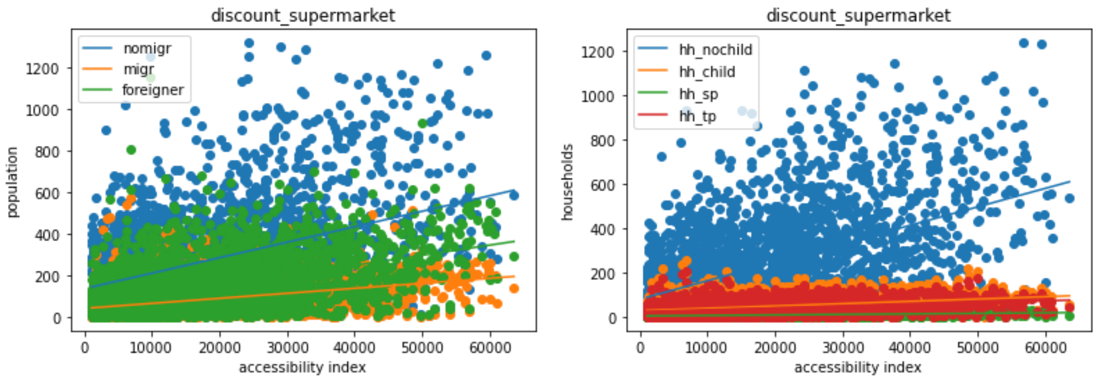


Figure 81 Scatter plots for discount supermarkets and socio-demographic groups

Organic supermarkets

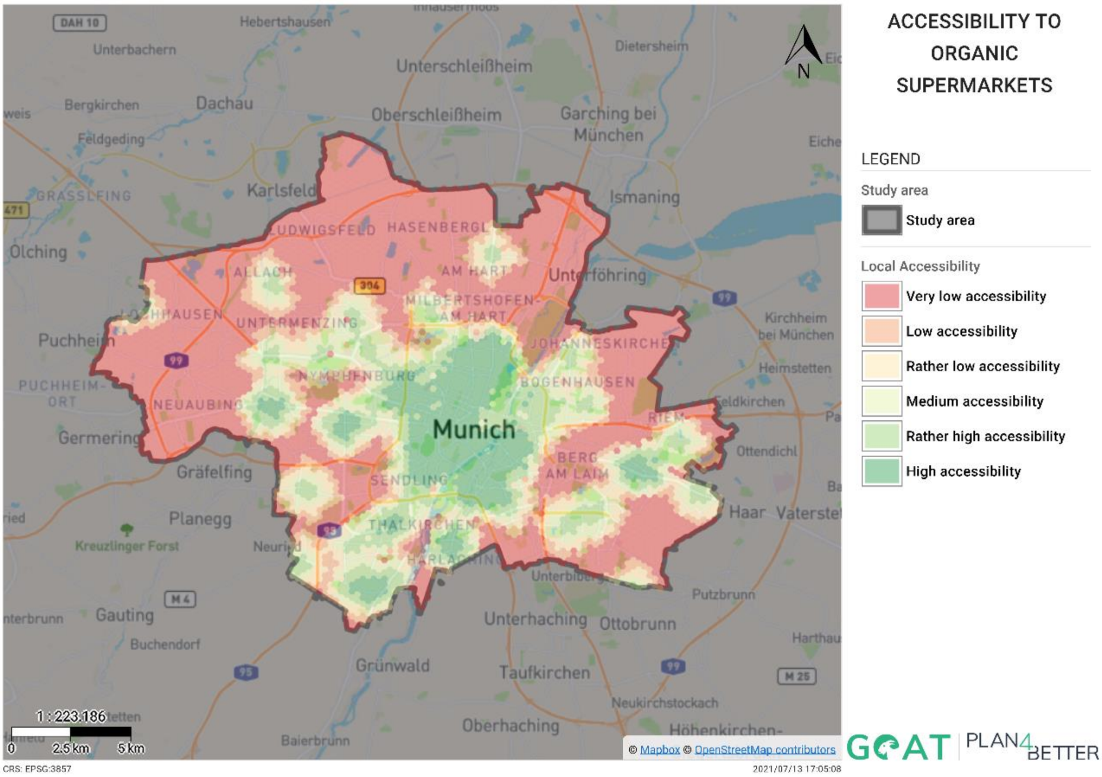


Figure 82 Heatmap for the accessibility to organic supermarkets

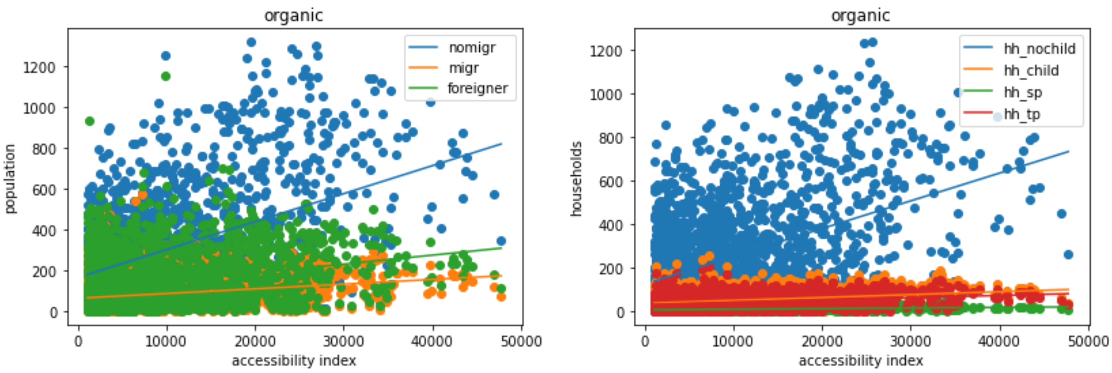


Figure 83 Scatter plots for organic supermarkets and socio-demographic groups

Appendix E: Maps and scatter plots for amenities of the category public transport

Bus stops

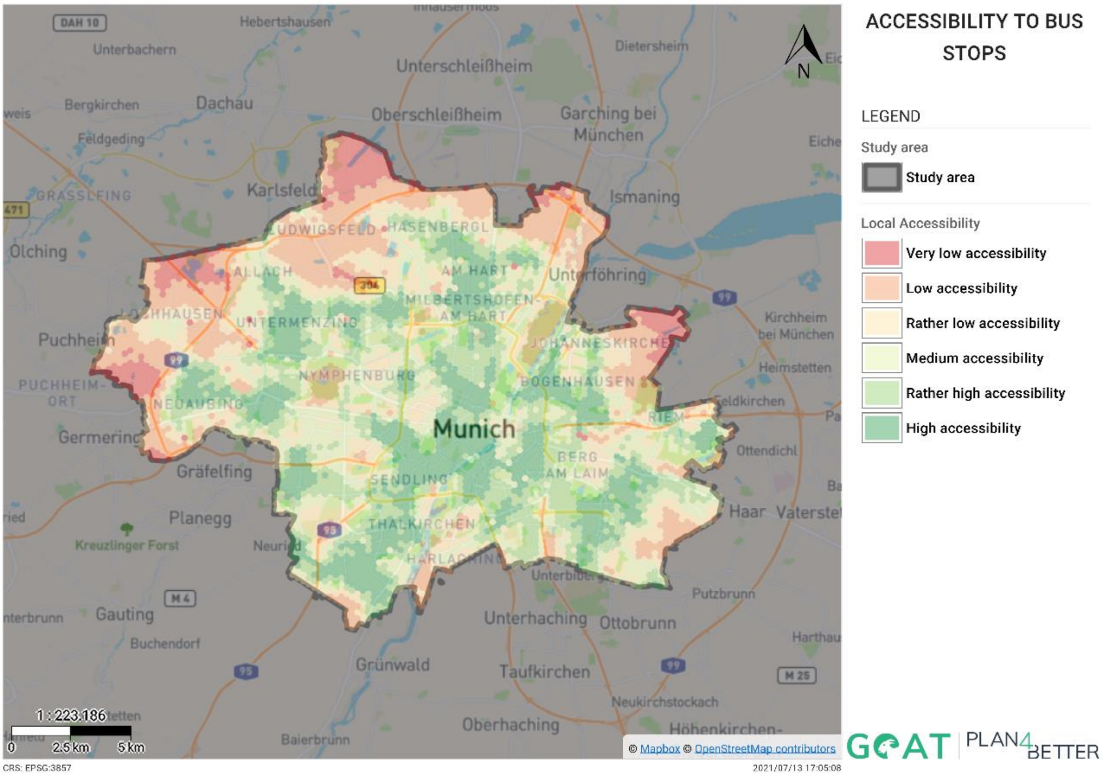


Figure 84 Heatmap for the accessibility to bus stops

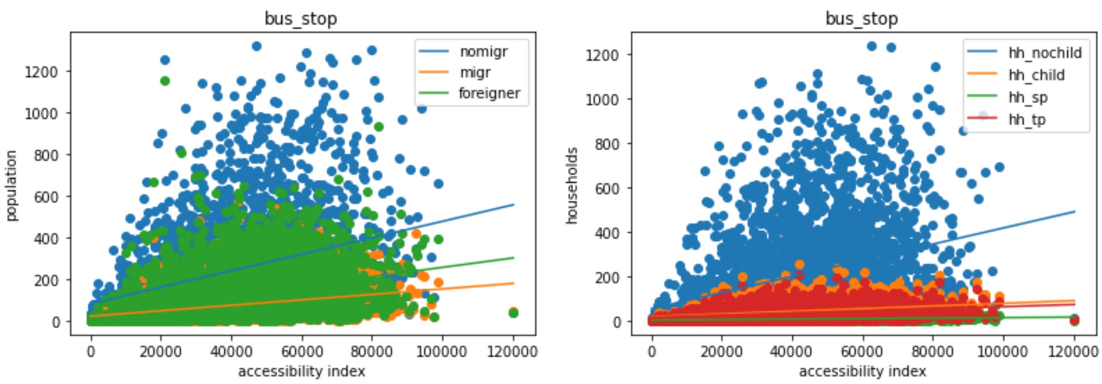


Figure 85 Scatter plots for bus stops and socio-demographic groups

Tram stops

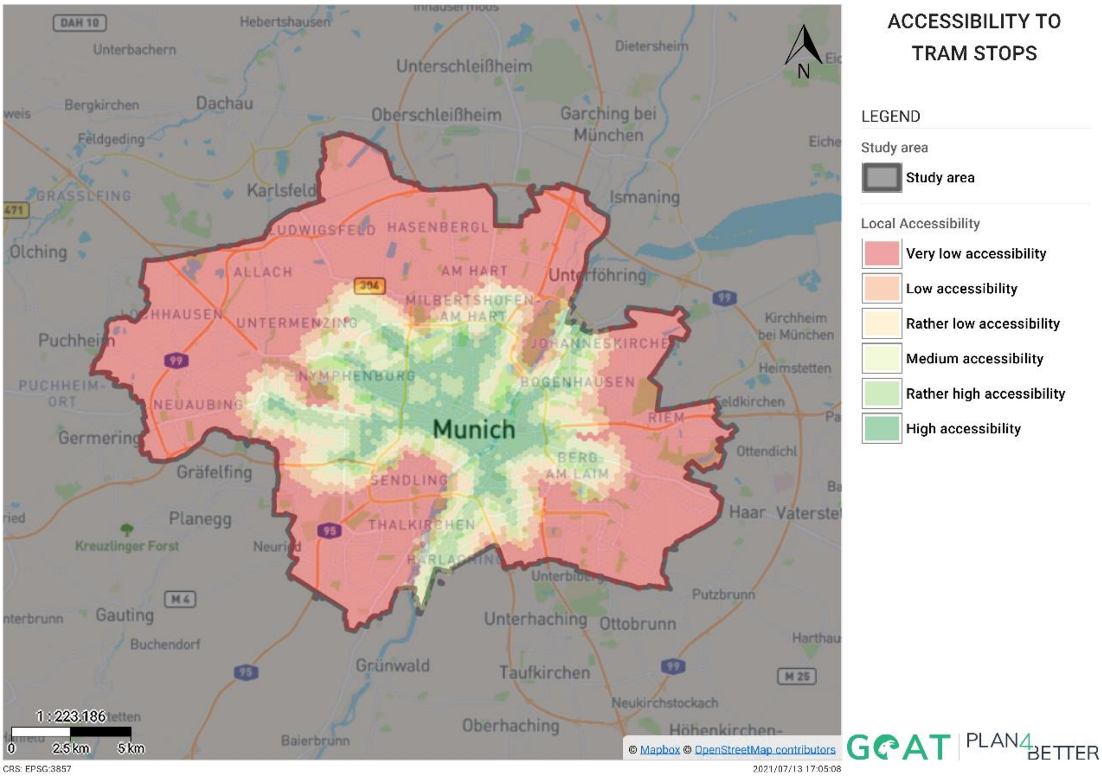


Figure 86 Heatmap for the accessibility to tram stops

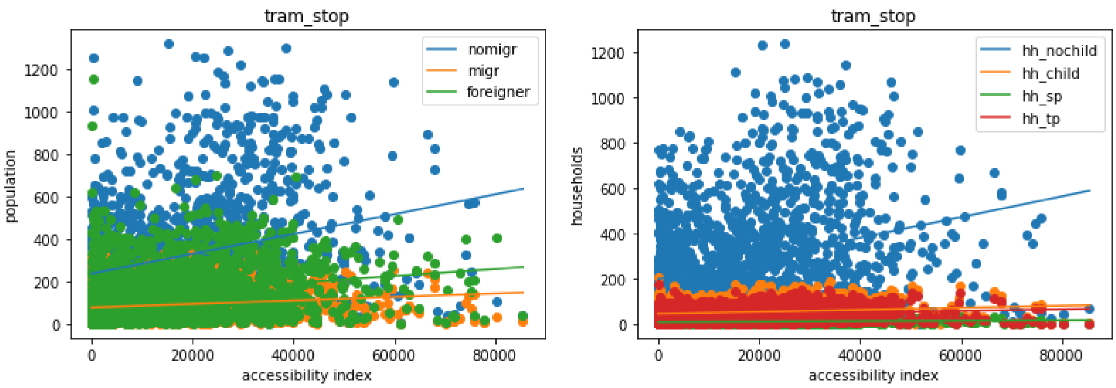


Figure 87 Scatter plots for tram stops and socio-demographic groups

Subway stations

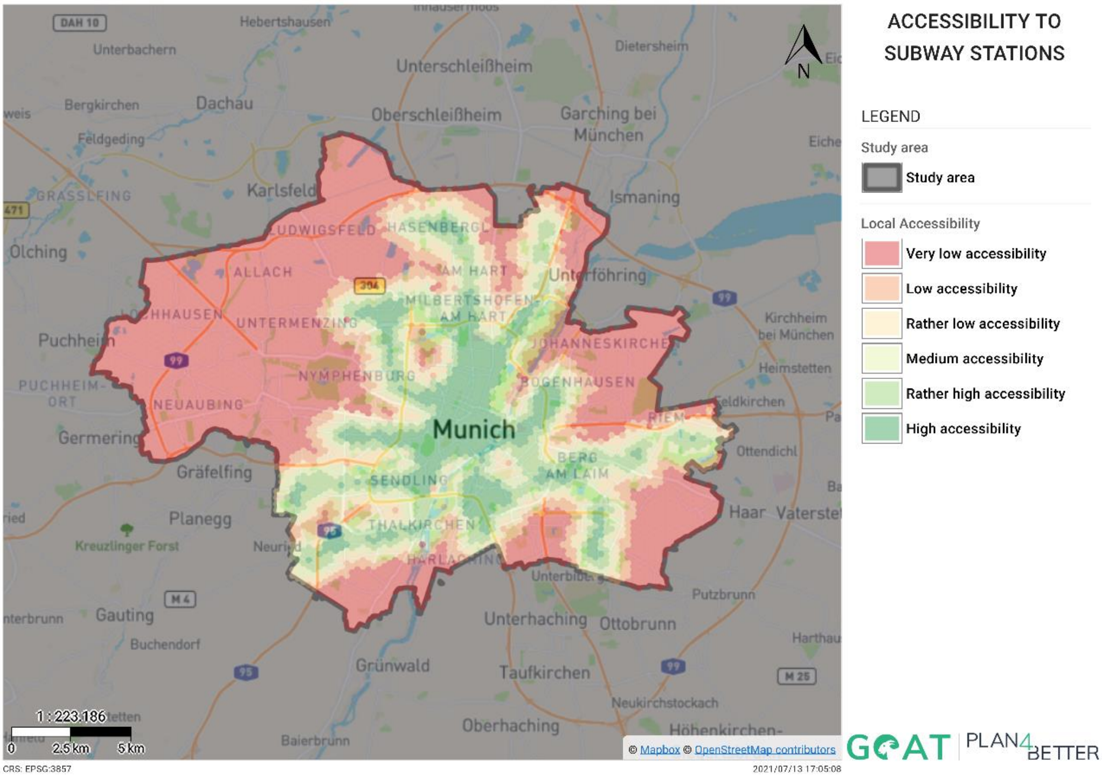


Figure 88 Heatmap for the accessibility to subway stations

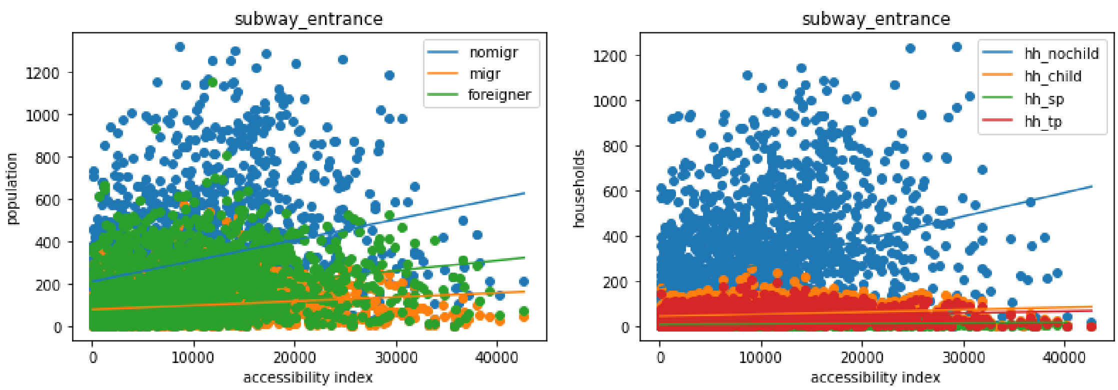


Figure 89 Scatter plots for subway stations and socio-demographic groups

Rail stations

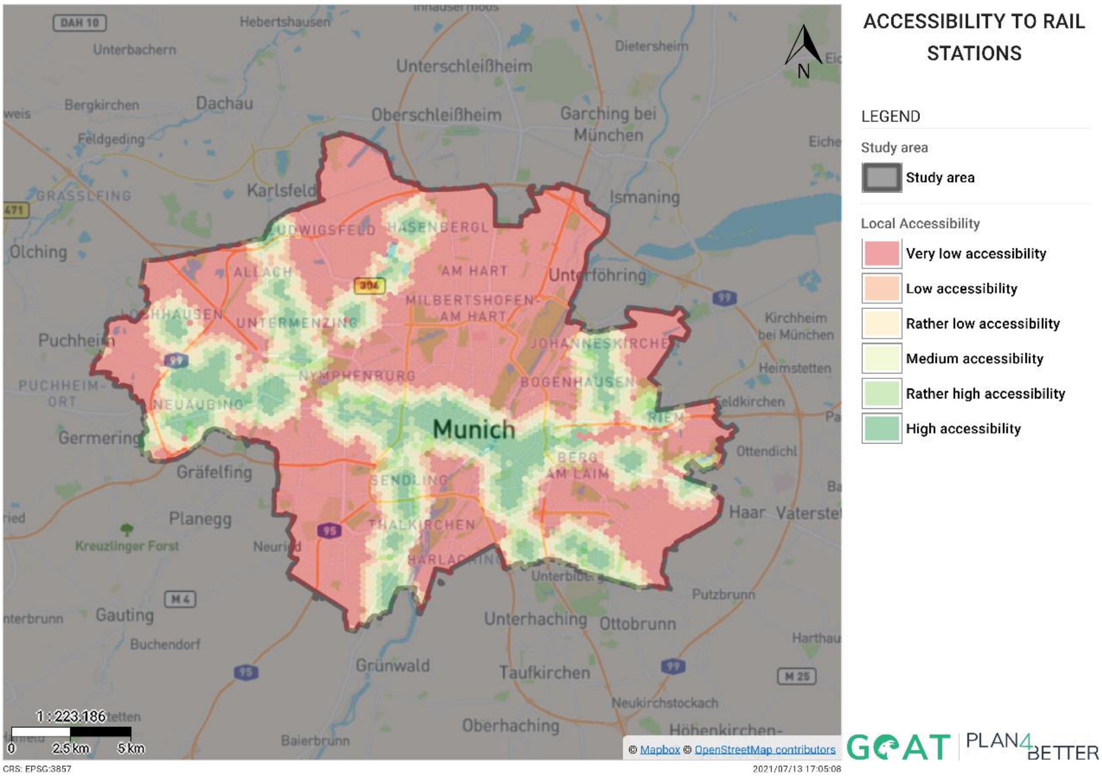


Figure 90 Heatmap for the accessibility to rail stations

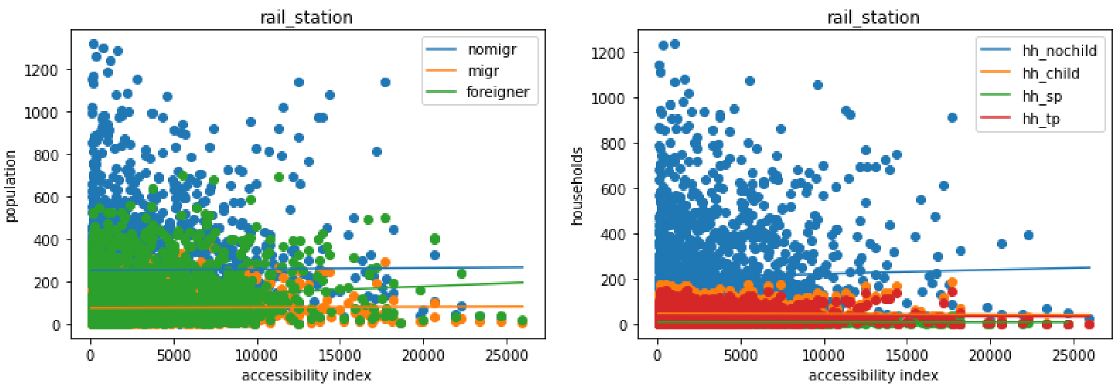


Figure 91 Scatter plots for rail stations and socio-demographic groups

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Declaration of Academic Honesty

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

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