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Towards the car-independent workplace:
A multimodal and intermodal accessibility tool for workplace locations

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Preface

There is a proverb in Uganda, that can be translated to *"A child does not grow up only in a single home"*[1]. I believe the same is true for writing a dissertation. While the act of writing the final thesis eventually lies in the hands of the author, the long process of getting to the point of being able to write such a work would never be possible alone. I am eternally grateful to have had a whole village around me, with of all kinds of different homes, that have helped me 'grow this child' and finally be able to submit my dissertation. With this little preface, I would like to express my sincere gratitude to everybody who supported me along the way.

My passion for research in the wide field of transportation, land-use, and everything in between, was sparked when in the first year of my Bachelor's in environmental engineering at TUM, I stumbled upon the display case on the hallway in front of the Chair of Urban Structure and Transport Planning: After desperately trying to motivate myself to be interested in all other aspects of my study program, I finally saw projects, topics, maps, and pictures that I immediately found myself enthusiastic about. Soon after, I applied for a student assistant position, Montserrat Miramontes accepted (thank you!), and *just a decade later*, I am submitting my own doctoral thesis. If the reader wonders why it took a decade, I must say that the colleagues quickly turned *frolleagues* and the unmatched atmosphere in this team never made me want to be somewhere else. I am very grateful for this amazing atmosphere across the years, with excellent, high-quality research and teaching, mixed with lots of fun, compassion, and endless (partly stupid) insider jokes to be told – a big thanks to all of you, my dear frolleagues (and that includes also our former colleagues). A special shoutout to David, who taught me so much as a co-author in my first paper.

Without the wonderful investment and the visionary thoughts that Julia Kinigadner, Benjamin Büttner, and Gebhard Wulfhorst put into their successful "*DFG-Projekt"* proposal, that I adopted and turned into "EMMA", I would never have had the chance to work for 2,5 years under perfect, focused conditions on this dissertation. Thank you for trusting in me! I am also thankful to our EMMA expert council members Daniel Krajzewicz, Alain L'Hostis, Rolf Moeckel, Klaus Nökel, Marcus Peter, Cecília Silva, and David Vale, who have enriched the project a lot through their constrictive feedback and guidance. A special thanks to Rolf Moeckel for accepting to become the third examiner of this dissertation.

After being busy with new projects and responsibilities after the EMMA project ended, the best decision I could make was asking Cecília Silva to become my second supervisor. Her clear guidance, wisdom, and a perfect balance of pushing me, while still being compassionate

[1] *„Omwana takulila nju emoi",* in case a reader from the Bunyoro region reads this

and understanding in times where financial audits and other fun-or-not-so-fun side gigs left barely any time and energy to make progress on the dissertation, was extremely important for me in this whole process. My three weeks in Porto this year were probably the most productive in the entire PhD and have re-ignited my enthusiasm about scientific work. Obrigado.

During the entire dissertation, Benjamim Büttner was not just formally the mentor of my thesis, but a continuous role model, source of inspiration, confirmation, guidance, and always good advice. He, his Accessibility Planning group, and his entire network have been an important pillar in my academic development, that is unmatched. I have learned professionally and personally from working with him, and I was never (openly…) judged for my poor choice of shoes. Thank you.

Last but not least on the professional level, I would like to thank my first supervisor Gebhard Wulfhorst, who encouraged, guided, inspired, and motivated me since we first talked on the Bachelor's excursion to Strasbourg many years ago (and where he was not embarrassed by my bad French). His broad experience and knowledge, and his critical, thought-provoking ideas and opinions about the state of workplace location development in the region have been continuous inspiration and I have always enjoyed our PhD meetings, where we discussed everything from the big picture to the nuts and bolts of the model. Thank you for your support and your long-term trust on all levels.

Coming back to the opening paragraph about the growing children, I would like to thank my family for providing all the support during all periods of my education and life in general, from pushing me to do my homework in primary school to supporting me in moving to Munich for my studies (even though they might regret the last part, because I stayed here).

I would like to thank my little daughters, Sophia and Elena, who were both born during my PhD time, for always cheering me up, distracting me in a positive way, and making sure my work-life-balance would not become unbalanced. I am so happy to have you in our life, and I apologize if you will ever feel intimidated by having two parents with a PhD. This brings me to the most important person in my life: my wife Anna. Even though she finished her own PhD in a record pace and made an impressive transformation from PhD candidate to full-time mother to super-hero project manager and clinical team leader, she never lost patience with me, who transformed from early-stage to late-stage PhD candidate in the same time. You are always my inspiration, my most important source of love, affection, advice, and confirmation, but also my partner for fun, adventures, and everlasting trust. Thank you for always believing in me and supporting me like no one ever could. I love you.

Maximilian Pfertner

Munich, June 26, 2024

Abstract

This doctoral thesis focuses on conceptualizing and operationalizing the vision of "car-independent workplace locations" through the development, application, and assessment of a multimodal and intermodal accessibility model for workplace locations, developed and tested in the Munich Metropolitan Region. It is motivated and driven by the crucial role of the workplace location for commuting decisions, which is associated with the mode choice for other trips, and daily routines in general, influencing entire mobility biographies and thereby being an important lever for sustainability in our cities and regions.

Apart from literature review, the research included a broad set of methods, from statistical analysis of survey data, to the development and application of the accessitility tool, and to the discussion of the tool’s usefulness in semi-structured expert interviews with practitioners from municipalities, developers, and consultants, among others.

The analyzed survey data includes workers who have changed their workplace location while maintaining the same residential location. By using "flow-diagrams" for a descriptive analysis of the data, a logistic regression on the increase in car availability as well as a Heckman Selection Model on the modal switch to driving, statistically significant associations of the workplace relocation and the associated change in accessibility with an increase in car availability and a change to driving were found. Thereby, it is argued that the workplace location and its accessibility can be a potential trigger for car commuting, which emphasizes the need to make these location choices in a well-informed and conscious way. At the same time, the literature and expert interviews show that in the current planning procedures, such considerations are usually not included.

A key component of the thesis is the development of the EMMA tool, which integrates OpenTripPlanner, PostGIS, and R into a model to analyze and visualize the accessibility of workplace locations by different transport modes, including intermodal options. The analysis of the Munich Metropolitan Region, conducted using this tool, provided both regional and local insights into how accessibility can be measured on both levels, and shows for example the discrepancies between urban areas with competitive public transport and cycling options to access the workplace, compared to other regions where the car accessibility is significantly higher than the alternatives. Using scenarios for individual locations, the tool is capable of showing the changes in accessibility when the transport system or land use is modified.

The expert interviews suggest the model’s usefulness for the early planning stages, where multiple locations can be compared, scenarios with variations of the transport supply can be modeled, and where there is still enough time to implement changes in the land use and transport system, along with the decision for a workplace location. Secondary levels of

usefulness were found for the use of the model for existing locations, to analyze weaknesses within the local/regional transport and land use system for commuting but also compare changes in transport infrastructure that could be introduced by new modes of transport, such as sharing options, company shuttles, or mobility stations.

The research implications of the thesis highlight the continuous relevance of the workplace location and its accessibility, despite major paradigm shifts in the society, triggered for example by the pandemic and the effects of the Russian war in Ukraine, with increases in fuel prices and inflation in general. It is advised to establish accessibility analysis as early as possible in the planning processes, in order to create the preconditions for sustainable commuting, but also for resilient, future-proof workplace locations.

In terms of future research on this path, a major next step is the transfer of the EMMA tool into a professionaly designed online tool. With this, planners and policy-makers could aim for an accessibility-based governance, that could enforce e.g. certain mobility management elements when workplaces are created in locations that do not fulfill the recommended accessibility standards. At the same time, locations with a good accessibility evaluation could benefit from supporting measures, such as tax reductions, faster project approvals, or other benefits.

Zusammenfassung

Diese Dissertation befasst sich mit der Konzeptualisierung und Operationalisierung der Vision von "autounabhängigen Arbeitsplatzstandorten" durch die Entwicklung, Anwendung und Bewertung eines multimodalen und intermodalen Erreichbarkeitsmodells für Arbeitsplatzstandorte, das in der Metropolregion München entwickelt und getestet wurde. Die Motivation für dieses Projekt liegt in der entscheidenden Rolle des Arbeitsstandorts für Pendelentscheidungen, die mit der Wahl des Verkehrsmittels auch für andere Wegezwecke und den täglichen Routinen im Allgemeinen verbunden ist. Dadurch kann ein Arbeitsstandort gesamte Mobilitätsbiografien beeinflussen und somit einen wichtigen Hebel für die Nachhaltigkeit in Städten und Regionen darstellen.

Neben der Literaturrecherche umfasst die Arbeit ein breites Spektrum an Methoden, von der statistischen Analyse von Umfragedaten über die Entwicklung und Anwendung des Erreichbarkeits-Tools bis hin zur Diskussion der Nützlichkeit des Tools in Experteninterviews mit Expertinnen und Experten aus u.A. Kommunen, Standortentwicklern und Beratungsunternehmen.

Die analysierten Umfragedaten umfassen Beschäftigte, die ihren Arbeitsort, aber nicht ihren Wohnort gewechselt haben. Durch die Verwendung von "Flow-Diagrammen" für eine deskriptive Analyse der Daten, einer logistischen Regression für die Zunahme der Pkw-Verfügbarkeit sowie eines Heckman-Selection Models (bezogen auf einen Wechsel des Verkehrsmittels hin zum Auto) wurden statistisch signifikante Assoziationen zwischen der Veränderung des Arbeitsortes und der damit verbundenen Veränderung der Erreichbarkeit mit einer Zunahme der Pkw-Verfügbarkeit und einem Modalshift zum Pkw identifiziert. Daraus lässt sich schließen, dass der Standort des Arbeitsplatzes und seine Erreichbarkeit ein potenzieller Auslöser für das Pendeln mit dem eigenen Pkw sein können, was die Notwendigkeit unterstreicht, diese Standortentscheidungen bewusst und basierend auf fundierten Daten zu treffen. Gleichzeitig zeigen die Literatur und die Interviews mit Expert:innen, dass solche Aspekte in den derzeitigen Planungsverfahren meist nicht berücksichtigt werden.

Ein zentraler Bestandteil der Arbeit ist die Entwicklung des quelloffenen EMMA-Tools, basierend auf OpenTripPlanner, PostGIS und R, um die Erreichbarkeit von Arbeitsplatzstandorten durch verschiedene Verkehrsmittel, einschließlich intermodaler Optionen, zu analysieren und zu visualisieren. Die Analyse in der Metropolregion München, die mit diesem Tool durchgeführt wurde, liefert sowohl Erkenntnisse auf regionaler, als auch lokaler Ebene darüber, wie Erreichbarkeit auf beiden Ebenen gemessen werden kann. Die Ergebnisse zeigen beispielsweise die Unterschiede zwischen städtischen Gebieten mit

wettbewerbsfähigem öffentlichem Verkehr und Radverkehr auf dem Arbeitsweg im Vergleich zu anderen Regionen, in denen die Erreichbarkeit mit dem Auto deutlich höher ist als die der Alternativen. Anhand von Szenarien für einzelne Standorte kann das Tool die Veränderungen der Erreichbarkeit aufzeigen, wenn Parameter am Verkehrssystem oder der Flächennutzung verändert werden.

Die Experteninterviews deuten auf die Nützlichkeit (‚usefulness') des Modells insbesondere für die frühen Planungsphasen hin, in denen mehrere Standorte verglichen werden können, Szenarien mit Variationen des Verkehrsangebots modelliert werden können und noch genügend Zeit zur Verfügung steht, um Änderungen der Flächennutzung und des Verkehrssystems zusammen mit der Entscheidung für einen Arbeitsplatzstandort umzusetzen. Weiterhin als nützlich gesehen wurde die Anwendung des Modells für bestehende Standorte, um Schwächen innerhalb des lokalen/regionalen Verkehrssystems und der Raumstruktur zu analysieren, aber auch um Veränderungen in der Verkehrsinfrastruktur zu vergleichen, die durch neue Angebote wie Sharing-Optionen, Firmenshuttles oder Mobilitätsstationen eingeführt werden könnten.

Die Forschungsimplikationen der Arbeit verdeutlichen die anhaltende Relevanz des Arbeitsplatzes und seiner Erreichbarkeit, trotz großer gesellschaftlicher Paradigmenwechsel, ausgelöst beispielsweise durch die Pandemie und die Auswirkungen des russischen Krieges in der Ukraine, mit steigenden Treibstoffpreisen und allgemeiner Inflation. Es wird empfohlen, Erreichbarkeitsanalysen so früh wie möglich in den Planungsprozessen für Arbeitsstandorte zu etablieren, um die Voraussetzungen für nachhaltiges Pendeln, aber auch für resiliente, zukunftssichere Arbeitsplatzstandorte zu schaffen.

Für die weitere Forschung hin zu „autounabhängigen Arbeitsstandorten" ist ein wichtiger nächster Schritt die Weiterentwicklung des EMMA-Tools in ein benutzerfreundliches Webtool. Damit könnten Planer:innen und politische Entscheidungsträger:innen eine auf Erreichbarkeit basierende Governance anstreben, die z.B. bestimmte Elemente des Mobilitätsmanagements einfordert, wenn Arbeitsplätze an Standorten entstehen, die nicht die erforderlichen Erreichbarkeitsansprüche erfüllen. Gleichzeitig könnten Standorte mit einer guten Bewertung der Erreichbarkeit von unterstützenden Maßnahmen wie Steuerermäßigungen, schnelleren Projektgenehmigungen oder anderen Vorteilen profitieren.

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I. Introduction, State of the Art, and Research Design

1. Introduction

1.1. Motivation

In Germany, 76,9% of the working-age population have a job. That means 45,7 million people are accessing some kind of workplace on at least one day of the week (Statistisches Bundesamt, 2024a). For some people, that means waking up and opening their laptop while lying comfortably in bed, while for others that means packing their suitcase, saying farewell to their family, and rushing to the airport. For the vast majority, however, getting to work means commuting to a workplace location that is more or less in the region. Across Germany, the average trip to work takes 16 kilometers (Nobis and Kuhnimhof, 2018), and around 70% of commuters need 30 minutes or less to reach their workplace (Statistisches Bundesamt, 2024b). Driving is thereby the most prevalent mode of transport to get to work, with 68% of commuters using the private car, followed by 14% of public transport users, 9% cycling, and 8% walking (Bauer-Hailer, 2019). Almost 50% of all car-kilometers travelled in Germany are related to commuting or work-related trips (Nobis and Kuhnimhof, 2018).

However, these nation-wide figures vary significantly depending on the actual spatial location within Germany: urban areas are associated with much higher mode shares for public transport and cycling, compared to rural areas where driving is more prevalent (Nobis and Kuhnimhof, 2018). On a more detailed level, it was shown in a vast body of research that the location of the workplace within a city or region, such as central vs. suburban locations, is associated with the share of driving to work. While centrally-located workplaces in urban areas are linked with public transport, walking, and cycling, the stereotypical suburban location close to the motorway and with very limited public transport options is associated with driving to work (Cervero, 1989; Engebretsen et al., 2018; Levinson, 1998; Naess and Sandberg, 1996; Schwanen et al., 2001; Simpson, 1987; Wali et al., 2024; Wolday et al., 2019; Yang et al., 2017, among others). In this context, the association between car commuting and the subsequent car use for other trip purposes (e.g. Wan et al., 2021) is an important factor that increases the importance of the commute mode choice for daily routines and mobility behavior even more. This can be seen as a ‘path dependency’ and is linked to activity-chains: when starting the day with a car trip, it is less likely that other modes will be used on the same day for other trip purposes, such as shopping, leisure, or other activities (cf. Kinigadner et al., 2016; Mao et al., 2018; Thierstein et al., 2016).

While driving to work might be for some the most comfortable commute and not problematic on the individual level, the necessity to drive in order to reach important destinations is a burden for others who don’t want to drive or do not have the option, due to financial reasons, their physical abilities, or other constraints. See, for example, the concept of 'forced car-ownership' (Mattioli, 2017) that describes the need to afford a car, even if car ownership leads to significant economic problems for a household. Also, on a societal level, it is nowadays commonly acknowledged that in order to be livable and sustainable, cities and regions must reduce the overuse of cars, since this is the mode of transportation with the highest external costs (including congestion, greenhouse gases, local air quality, consumption of space, health effects, accidents, etc.), as recently shown in the Munich Metropolitan Region, where 80% of all external costs from transportation are attributed to combustion-engine cars (Schröder et al., 2023). Ultimately, this quality of life for current, but also for future generations should be at the core of our decision-making today.

Our cities and regions strive for ambitious climate goals and significant modal shifts as a way to reach these goals. The City of Munich, for example, wants to achieve climate-neutral transportation until 2035, with 80% of all trips made by active modes, public transport, and emission-free cars by 2025 (LH München, 2021). Therefore, as outlined before, getting to work is a significant factor and it matters where the workplace is located. While technological progress, new transport modes such as on-demand services, autonomous driving, and other current trends might bring some relief to a certain extent, they cannot compensate for poor location choices and workplaces that are, for large shares of the population, only accessible within acceptable travel times by private cars. At the same time, we currently observe a lack of strategic planning and development of workplace locations in Germany in general. Due to the high importance of the municipal planning authority, there is no binding regional coordination of planning for workplace locations (Schmidt, 2009).

With this background, this research puts forth the vision of "car-independent workplace locations". It is inspired by the well-known and defined concept of car dependency, where car-dependent locations can be described as places where "the infrastructure maintains and reproduces the continued use of the car" (Stradling, 2007). The idea of car-independent workplace locations aims for the opposite and can be defined in the following way: "*A car-independent workplace location is a place that does not require a private car to be accessed within a reasonable commuting quality*". In contrast to car-dependence, which can be defined as an absolute definition ("This is a car-dependent location", e.g. for a place that does not provide any access than by driving), the notion of car-independent workplaces is thereby always a relative one: It describes a normative vision and multiple methodologies could be capable of capturing the level of car-independence, but absolute "car-independence" is a theoretical construct. It could be described as, for example, a location where the isochrones of access by car and public transport are identical. In light of climate change and the striving for sustainability, this vision becomes even more relevant, with car commuting and car-centric behavior in general as major barriers towards a more sustainable future. The prospect of contributing to the development of workplace locations that share this vision motivates this thesis and is the foundation for the following research.

Given this definition of car-independent workplace locations, it can be interpreted as a typical question in the field of land-use and transport interactions. The main elements relevant for the concept are visualized in Figure 1:

- the geographical location of the workplace,
- the multimodal transport system that allows accessing the workplace,
- the land-use of the region around the workplace, providing housing for potential workers that access the workplace.

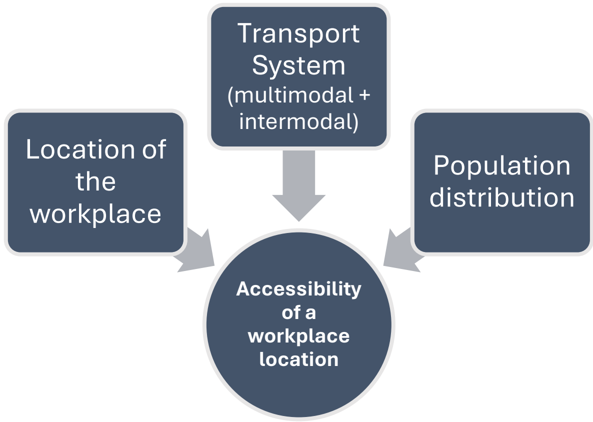


Figure 1: Elements of Workplace Accessibility

Thereby, multimodality (in the sense that mobility behavior becomes more flexible, relying on more than one mode) and intermodality (the combination of more than one mode within a trip) are two important aspects of today's mobility landscape and have been associated with sustainable mobility in general, even though the concepts are criticized for focusing entirely on the supply side of transport interventions, while neglecting the need for regulatory measures (Mattioli and Heinen, 2020).

The concept of *accessibility* for the integrated analysis of transport and land-use (Geurs and van Wee, 2004) seems therefore to be a suitable approach to analyze and interpret the idea of car-independent workplace locations. The details of the concept, its operationalization, and the existing body of literature about its application for workplace locations is discussed in Chapter 2.

1.2. Research Objective and System Boundaries

This dissertation aims at conceptualizing and operationalizing the concept of accessibility for the assessment of workplace locations, framing it within the idea of car-independency as a planning goal.

Thereby, the overall goal of the dissertation is the **„Development, application, and assessment of a multimodal and intermodal accessibility model for workplace locations".**

Three main research phases can be derived from this concept, as visualized in Figure 2.

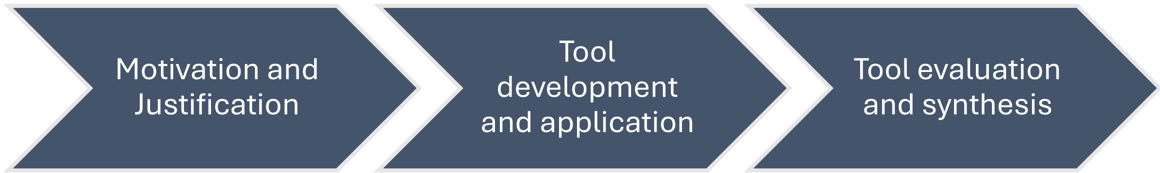


Figure 2: Research Phases of the Dissertation

The first phase, "Motivation and Justification" describes the research in literature and uses quantitative survey data to explain why the development of an accessibility model for workplace locations is important. The second phase, "Model development and application" explains how the accessibility model is designed, how it works, and subsequently presents and discusses its results. As the last step of the dissertation, the third phase "Tool evaluation and synthesis" is used to evaluate the model's usefulness and synthesize the overall results of the research.

Thereby, this dissertation is focusing on the particular topic of workplace accessibility, which is embedded in a broader context, as visualized in Figure 3.

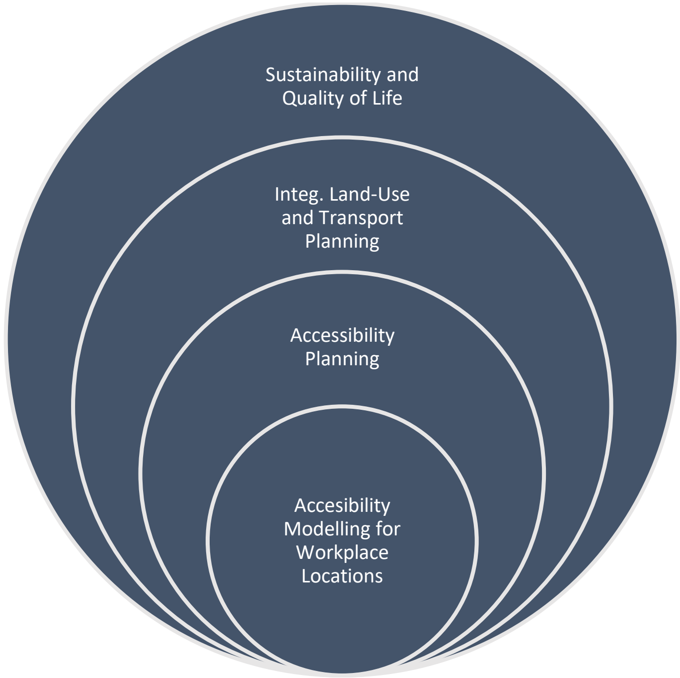


Figure 3: System Boundaries of the Dissertation

The overall motivation and reasoning for research like this is the need for sustainability in general and the striving for quality of life, which are both essential needs for societies to thrive. One particular aspect within this broad field is the integration of land-use and transport planning, which is also a previously recommended strategy for the Munich Metropolitan Region (Kinigadner et al., 2016). Therefore, accessibility planning is a promising tool to assess the spatial qualities within this context. And eventually, this dissertation narrows the field down to the very particular topic of using accessibility modelling for the assessment of workplace locations.

It is therefore important to exclude some research fields, which are important in the real-world context of workplace accessibility, but are out-of-scope in this dissertation:

- This dissertation will focus on the land-use perspective when discussing the development of workplace locations. It aims at answering the question how the general accessibility in terms of population that can reach the workplace can be modelled and assessed. It is thereby not focusing on the policy side of attracting individual companies, e.g. through targeted subsidies, tax cuts, proximity to related companies and industries, etc.
- It must be acknowledged that various types of workplaces have very particular needs. While a downtown location with very high accessibility might be perfect for an office building, the needs for a wastewater treatment plant might be completely different. This dissertation limits its scope to the location choices for

in the widest sense "normal" workplaces, in the sense of offices or other company buildings without special needs or hazardous activities.

- Due to limitations in data availability in the national context of Germany, it was decided during the process that some kind of jobs-accessibility balance is an interesting construct, but due to a lack of reliable spatial data about the exact distribution of the number of workplaces on a regional level, it is not feasible to produce results which are meaningful for practice.
- From the nationwide census, very fine-grained data is available about population in the region. This data offers the option to filter for persons within the usual working age (18-64 years), but not more details about individual attributes that are relevant for workplaces (e.g. education levels) and mobility (e.g. car ownership). Thus, more advanced personal attributes are out-of-scope in this dissertation. For a detailed classification of types of knowledge workers, see Zhao et al. (2017), for example.

1.3. Project context of the dissertation

This dissertation was enabled, inspired and guided by the DFG[2]-funded research project "Ein multimodales Erreichbarkeitsmodell für Arbeitsstandorte – Grundlage für die integrierte Siedlungs- und Verkehrsentwicklung"(„A Multimodal Accessibility Model for Workplace Locations – Foundation for Integrated Land-Use and Transport Development"), DFG Project Number 401093473. The proposal was written by Julia Kinigadner, Benjamin Büttner, and Gebhard Wulfhorst, based on the experiences and data collected within the project "WAM – Wohnen, Arbeiten, Mobilität" (Thierstein et al., 2016, see Chapter 4 for a detailed description of the data used). The central outcome of the DFG-project and also the basis of this dissertation, is the accessibility tool EMMA[3] – "Empowering multi- and intermodal accessibility analysis for workplace locations". Details about the tool are provided in the following chapters.

This project and the author's interest in accessibility modelling in general, and in particular the potential of intermodal combinations for commuting were the starting points of this research. Compared to the initial proposal of the DFG-project, the dissertation adapted and broadened the focus and work plan in some ways. The deviations are mainly:

- Inclusion of not just multimodal mobility options but focusing on intermodal mobility options as well. This is based on the advent of large-scale shared mobility options, such as bikesharing in the Munich Metropolitan Region during

[2] Deutsche Forschungsgemeinschaft / German Research Foundation
[3] www.emma-accessibility.org; github.com/maxpfertner/EMMA

the years prior to this thesis and the hypothesis that these intermodal combinations are relevant for trips to work

- The focus on open-source tool development instead of relying on commercial tools like ArcGIS and PTV VISUM. This is motivated by the increased availability of open-source alternatives and very powerful tools such as OpenTripPlanner and the hope, that this will enable future applications of the tool without high financial investments for licenses.
- Focus on the longitudinal data analysis (see Chapter 4) while omitting the company-based data analysis of associations between a concrete workplace and its workers. This is partly due to limitations in the data quantity and -quality, but also to the emphasis on the regional analysis.
- Inclusion of expert interviews to assess the tool's usefulness

In contrast to the linear approach described in the DFG-proposal, which was supposed to start with the data analysis, the actual research of the dissertation started with a proof of concept for the open-source accessibility model based on OpenTripPlanner. It was crucial to explore the feasibility of the chosen modelling approach and its competitiveness to other approaches. Once the initial concept was established, the focus was set on the data analysis section (presented in Chapter 4), establishing a solid motivation and foundation that explains the importance of workplace accessibility in the context of the Munich Metropolitan Region.

Once the tool development (see Chapter 5) and data analysis (Chapter 4) were both completed and published, the focus shifted on the third publication and last step of the dissertation: The exploration of the tool's usefulness (Chapter 6). Therefore, it was decided to use expert interviews to enable an in-depth analysis of the tool's usefulness from a practitioners' perspective. While this was not foreseen in the initial DFG-proposal, it was a critical step in order to start a dialogue with practitioners about the usefulness of the tool and the general approach, that contributes to the overall understanding of accessibility analysis for workplace locations.

Another critical element that was very valuable during the process was the feedback and discussion obtained through various formats:

- EMMA expert council: In three meetings (2019, 2020, 2021), the EMMA expert council[4], consisting of seven international experts, gave valuable feedback to the development of EMMA and the data analysis.
- Scientific conferences (2019, 2x in 2020, 2022)
- Scientific colloquiums at TUM (2019, 2021, 2x in 2022, 2024) and at the University of Porto (online: 2021, 2023)
- Multiple smaller exchanges with practitioners from the City of Munich, Munich Transport Association, Public Transport Provider, etc.
- Interaction about the EMMA tool as part of teaching activities (seminar, lectures, theses)

The received feedback contributed significantly to this thesis. Major aspects, that were frequently mentioned were, among other things:

- The need to keep the tool as simple as possible, both for future users (mainly planners, e.g. from municipalities) but also for decision-makers.
- The need to explain the purpose of the tool very well while making sure the focus of the tool is understood correctly. The idea of the tool and the research is understood well by both researchers and practitioners, but only if it is properly explained. The concept and results are not self-explanatory.

Apart from the conferences and other exchange meetings, the major milestones of the research process are the three publications that are embedded in this dissertation. They were written and submitted in the order as presented in the dissertation in Section II.

[4] EMMA expert council: Daniel Krajzewicz (DLR), Alain L'Hostis (Université Gustave Eiffel), Rolf Moeckel (TUM), Klaus Nökel (PTV AG), Marcus Peter (Hochbahn Hamburg), Cecília Silva (University of Porto),David Vale (University of Lisbon)

1.4. Structure of the dissertation

The dissertation follows a paper-based cumulative approach, where three scientific papers (Section II) are embedded in a framework (Section I and III). The detailed structure is presented in Figure 4:

Figure 4: Structure of the Dissertation

In Section I, the first chapter “Introduction” explains the motivation, research scope, and the structure of the dissertation. It is followed by a state of the art (Chapter 2) about “Accessibility Measurement for Workplace Locations”, which complements the literature research presented in the three included publications. Chapter 3 explains the overarching research design, including the three research questions and the methodology of the dissertation.

Section II presents integral reproductions of the three publications. The first paper (Chapter 4) uses a statistical analysis of survey data to emphasize the importance of the workplace location for mode choice and car availability in the Munich Metropolitan Region.

This is followed by the second paper (Chapter 5), that presents the EMMA accessibility model and its application in the region and the third paper (Chapter 6) that assesses and discusses the usefulness of the model for practice.

Section III, the last section of this dissertation, finally summarizes and synthesizes the results and conclusions of this dissertation. Specifically, Chapter 7 discusses and concludes on the research questions and Chapter 8 adds the research implications, by presenting an outlook, limitations, and future research.

2. Accessibility Measurement for Workplace Locations

2.1. The concept of accessibility in the context of transport and land use

The need to be mobile is rooted deeply in our DNA. Humans have always been mobile in some way, no matter if as hunters and gatherers or modern-day commuters (Barbosa et al., 2018). However, as the examples of hunting, gathering, or commuting to work show, humans usually do not travel for the sake of travelling. Bertolini et al. (2005) summarize three main assumptions about human behavior, based on previous studies (such as Hägerstrand, 1989; Schafer and Victor, 1997; Zahavi, 1974):

- Humans travel usually to reach some kind of (spatially separated) destination that is linked to an activity (such as living, shopping, working, etc.)
- Having one activity as an option is not enough – humans are striving for a large and diverse set of opportunities for activities
- These opportunities are not endless, since in general travel costs (typically travel time budgets) are limiting the accessible activities.

Accessibility combines these elements into a concept that has been researched, discussed, and applied for a long time and in various shapes, methods, and instruments. The first scientific description of the concept is usually attributed to Walter G. Hansen (1959), who defined accessibility as *“a measurement of the spatial distribution of activities about a point, adjusted for the ability and the desire of people or firms to overcome spatial separation”* and used it as a basis for a residential land use model (Hansen, 1959). In the “land use and transport feedback cycle” (Figure 5) by Wegener and Fürst (1999), accessibility is depicted as the link between the transport system and land use. According to the authors, accessibility has a wide range of theoretical impacts in that intersection between transport and land use: first, increased accessibility is associated with increases in the attractiveness of locations. For residential locations, that means, *“Locations with better accessibility to workplaces, shops, education and leisure facilities will be more attractive for residential development, have higher land prices and be developed faster.”* (Wegener and Fuerst, 1999, p. 9). On a second level, accessibility also influences the transport system. For example, the authors argue that accessibility influences mode choice: *“Locations with good accessibility by car will produce more car trips: locations with good accessibility by public transport will produce more public transport trips.”* (Wegener and Fuerst, 1999, p. 9).

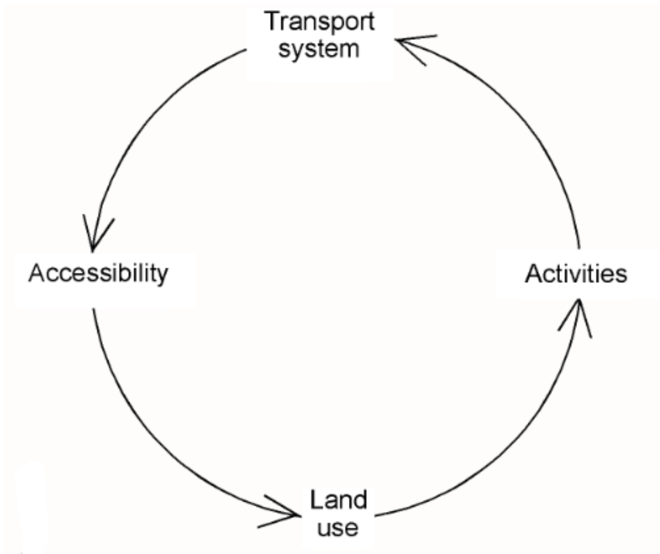


Figure 5: 'Land use and transport feedback cycle' (Wegener and Fuerst, 1999)

Thereby, some authors argue that the role and interpretation of accessibility has been constantly changing over time (Levine, 2020; Páez et al., 2012). Levine (2020) argues that, depending on the decade and wider cultural planning context, accessibility can either be a normative concept or a positive application. Normative, in this context, is explained as a way of using accessibility as a guideline how transport and land-use policy should be shaped, while the positive interpretation of accessibility refers to the concept of accessibility *"when it is applied to describing, analyzing, or predicting spatially dependent phenomena"* (Levine, 2020). Thereby, both interpretations are not exclusive, but can be overlapping each other.

Geurs and van Wee (2004) reviewed the state of accessibility for land-use and transport strategies, finding that it *"is often a misunderstood, poorly defined and poorly measured construct"*. They clustered the available applications of accessibility into the four main components *land-use*, *transport*, *temporal*, and *individual* (Figure 6) and describe a wide range of measures from simple location-based contour measures to highly complex utility-based Logsum benefit measures (Geurs and van Wee, 2004).

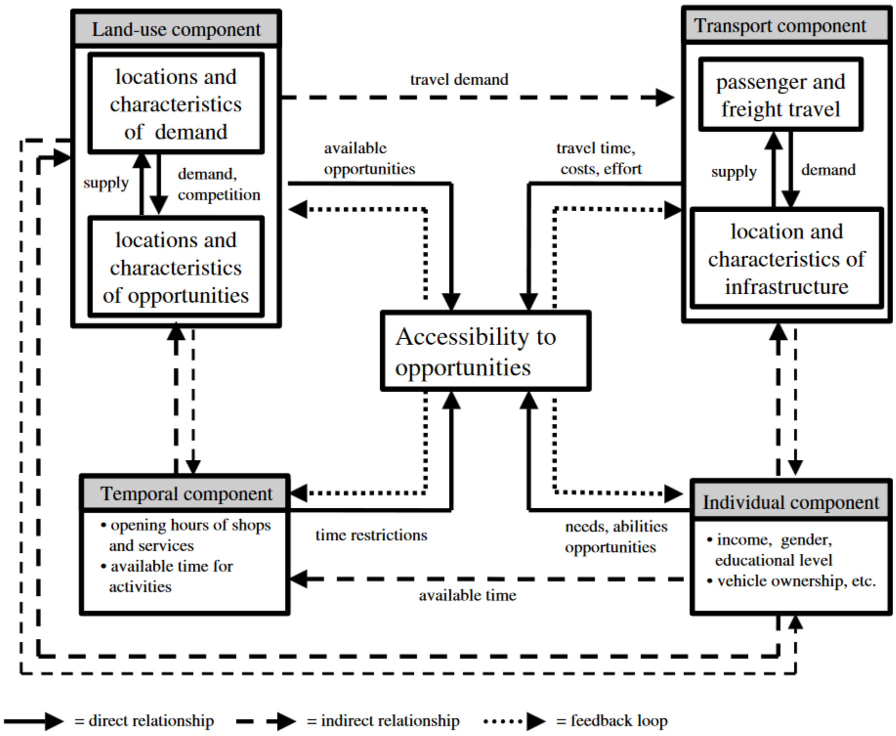


Figure 6: Relationships between components of accessibility (Geurs and van Wee, 2004)

However, all variations of measuring accessibility on a spatial level are *"unified by possessing the same intrinsic structure in measuring opportunities reachable, relative to the cost of travel"* (Wu and Levinson, 2020). This is the core of the accessibility concept: describing which opportunities are accessible within a given set of constraints, such as time, distance, actual cost, or a combination in the form of generalized cost.

2.2. Accessibility measurement and instruments (incl. multi- and intermodal)

Measurement

When it comes to operationalizing the concept of accessibility, the measures are usually classified into the dimensions that they are based on. Geurs and van Wee (2004) defined four "basic perspectives" how accessibility can be measured:

- **Infrastructure-based measures** evaluate only the quality of the transport network. Typical indicators include average speeds in the road network, congestion levels, or travel times between origins and destinations. In practice, these indicators are very common and used in classical transportation planning, for example within the German version of the Highway Capacity Manual (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2015). Also, in political debates, infrastructure-based indicators play an important role and applications such as travel time estimates from four-step transport models are frequently used in decision-making processes on multiple levels. However, these measures are limited to the transport-component and do not integrate the land-use component at all, ignoring thereby the fundamental core of the accessibility idea.

- **Person-based measures** are based on Hägerstrand's space-time geography (Hägerstrand, 1970), describing the potential action space of an individual, given other activities, time budgets, available transport options, etc. This is often explained with the Space-Time Path (Figure 7), that visualizes the two dimensions of time and space that a person is traversing in order to reach activities.

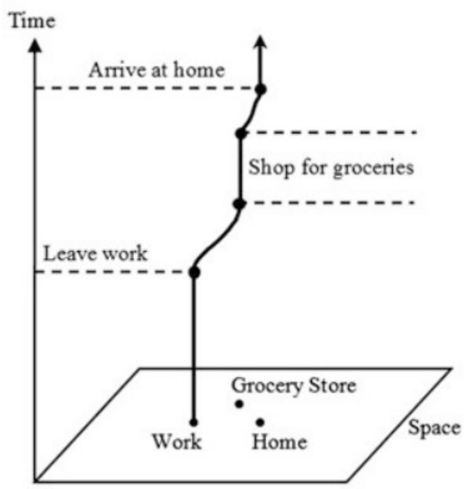


Figure 7: Space-Time Path based on Hägerstrand (Song and Miller, 2015, p. 191)

The perspective allows, for example, the accessibility-based assessment of multiple flextime or remote-working schemes (Wu and Miller, 2001).

- **Utility-based measures** combine multiple aspects of utility (such as travel time, travel costs, service quality/comfort, individual attributes) for each potential destination into an aggregated utility. A well-known example is the so-called logsum measure (de Jong et al., 2007), which is based on the denominator of a logit model for discrete choice modelling, assuming that the log of the denominator represents the option value for the decision maker (van Wee, 2016). For example, the logsum has been applied on a larger scale for a national model for the Netherlands (Zondag et al., 2015).
- **Location-based measures** evaluate accessibility from a location's point of view. A typical analysis of location-based accessibility is the indicator "accessible jobs within 30 minutes travel time by public transport" (e.g. El-

Geneidy and Levinson, 2006). Thereby, the measure is targeting one location for which the analysis is done, including the components land-use and transport. In general, this is a simple and easily understandable operationalization of accessibility, but complexity both in methods and data availability can vary.

- The simplest form is a *distance measure*, that checks if two locations are connected or not, with limits of travel time or distance as potential extensions.
- If including more than two destinations, this is extended to an *isochrone-based measure* (also known as contour measure). Therefore, the accessible area within a given travel budget is calculated geographically ("isochrone") and then, the points of interests or destinations within that area are summarized. As a formula, this could be described (see for example El-Geneidy and Levinson, 2006) as

$$\boldsymbol{A_i = \sum_{j=1}^{n} B_j \, a_j}$$

where

A_i	Accessibility measured at point i to potential activity in zone j
a_j	Opportunities in zone j
B_j	A binary value equals to 1 if zone j is within the predetermined threshold and 0 otherwise

- In contrast to isochrone-based measures, *Gravity-based measures* (or potential accessibility measures) do not give each destination the same weight, but apply a distance-decay-function for each destination. Geurs and van Wee (2004) describe it with the following formula:

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

where

A_i	Accessibility measured at point i to to all opportunities D in zone j
c_{ij}	the (generalized) costs of travel between i and j
β	the cost sensitivity parameter.

Thereby, each destination is weighted by the travel cost to reach the destination, typically using a negative exponential function that reduces the weight of a destination with increasing costs, which is also used frequently in travel behavior models (Handy and Niemeier, 1997).

- Further complexity is added when competition effects are included, which respects the fact that not every opportunity (such as schools, jobs, etc.) has unlimited capacity (see Geurs and Ritsema van Eck, 2003, for a detailed discussion).

The location-based contour measure based on isochrones is criticized for ignoring these competition effects, as well as treating all opportunities equal, without attributing the actual travel cost to reach an opportunity (such as traveling 5 min or 29 min within a 30-min-isochrone) or the qualities of an opportunity (such as a discounter vs. luxury supermarket for groceries) (Geurs and van Wee, 2004). Furthermore, the high sensitivity to travel time changes was described as a disadvantage of the measure (Geurs and Ritsema van Eck, 2003).

On the other hand, the simplicity in operationalization and data requirements as well as the self-explanatory storyline for communicating the results are mentioned as benefits (Geurs and van Wee, 2004; Silva, 2013). Especially when the model results are targeted at decision-makers, there is a certain *"beauty in simplicity"* (Bertolini et al., 2005; Givoni et al., 2016), in a sense that models *"must take account of people needing to make decisions with their help, for example politicians, policymakers, and take account of the political nature of policymaking and thus the need for transparency and simplicity*" (Givoni et al., 2016, p. 15f). Also in other fields, such as forecasting in a business context, the value of simplicity is emphasized, criticizing at the same time a trend towards making models and decision-making tools overly complex for reasons that are sometimes undesired, such as reassuring decision-makers through incomprehensibility (Green and Armstrong, 2015). Therefore, in the context of the development of workplace locations, with municipal stakeholders as the critical players (Schmidt, 2009), the isochrone-based measures seem as suitable accessibility measures for practice-oriented contexts where simplicity is a key advantage in communicating the accessibility measurement and the results.

Instruments

In order to operationalize the general concept of accessibility and the various measures in particular, various tools or "instruments", as defined within the European COST Action TU1002 "Accessibility Instruments for Planning Practice" (Hull et al., 2012; Papa et al., 2016), have been developed. Typically, these instruments are based on some kind of Geographical Information System (GIS) that enables the preparation of the required data as well as the calculation, modelling, and visualization of the respective accessibility measures. Accessibility instruments can thereby built on existing GIS software, either commercial (such as ESRI

ArcGIS) or open source (such as QGIS), work as standalone software, either as a webtool (such as 'GOAT', the Geo Open Accessibility Tool by Pajares et al., 2022), or as software packages for existing programing languages (such as r5 by Pereira et al., 2021). Thereby, many accessibility instruments can be regarded as a subset of planning support systems (PSS). PSS serve a wide range of aspects in the planning process, such as *"problem diagnosis, data collection, mining and extraction, spatial and temporal analysis, data modelling, visualization and display, scenario-building and projection, plan formulation and evaluation, report preparation, enhanced participation and collaborative decision-making."* (Geertman and Stillwell, 2004, p. 292). Accessibility instruments can be classified in three main groups, according to the COST Action, based on previous research (Hull et al., 2012): Accessibility by public transport, Accessibility by private motorized vehicles, and other models that measure accessibility. This classification based on transport modes is a useful starting point but does not reflect the larger diversity of instruments in terms of other aspects that are currently available. The follow-up web database of the COST Action (TUM Chair of Urban Structure and Transport Planning, 2024), classifies the available instruments in the following categories, showcasing the wide range of options:

- Geographical area (supra-national to neighborhood)
- Spatial unit of analysis (municipal, district, traffic zone, grid, etc.)
- Type (web, desktop, software extension, guideline, other)
- Accessibility measures (distance, contour, potential/gravity-based, person-based, utility-based)
- Opportunities considered (work, leisure, healthcare, etc.)
- Transport Modes included (walking, cycling, private car, public transport, freight, intermodal, other)
- Level of expertise required (basic, advanced, expert)
- License (open access, closed source, open source, other)
- Developer (academia, NGO, private sector, public sector, transport authority, other)
- Target group (planners, academia, political decision makers, retail/real estate, citizens, other)

See Pajares et al. (2021) for a review of the current accessibility tool landscape with a focus on tools for active mobility. Siddiq and D. Taylor (2021) applied a slightly reduced, but generally similar scheme to 54 accessibility tools (meaning readily available tools to be used) and measures (meaning the components of tools or research methods that are not developed to be used by practitioners). Most of the included tools (36) were place-based. They complemented the review with expert interviews of planning practitioners who are using such tools and measures in practice. Their results emphasize that there is not the one accessibility instrument that is universally applicable but rather that targeted solutions are needed, which bring meaningful results, realistic data requirements, and can be understood by both practitioners and decision makers. The conclusion previously mentioned for accessibility measurement, that simplicity is important in order to deliver meaningful results for practitioners has been emphasized by the authors as well, backed by recent literature such as Levine (2019).

One factor that is highlighted by multiple authors is the need to go beyond individual modes of transport in accessibility analyses (Hull et al., 2012; van Wee, 2016). This includes multimodality, in the sense that analysis should not only rely on one transport mode in order to make informed decisions for land-use and transport applications. Also, with new mobility services such as bikesharing, electric scooters, etc. on the rise and integrations into public transport systems becoming more common (McCoy et al., 2019; Miramontes et al., 2017), intermodal travel options are becoming more relevant for accessibility analyses. As outlined by Pajares et al. (2021), nowadays, many accessibility instruments claim to be multimodal by offering the option to run e.g. isochrone calculations for driving and public transport. However, this multimodality is often just a side-by-side comparison, where no integrated perspective (such as relative comparisons of accessibility by modes) is applied by default.

Also, most tools capable of multimodal analysis are commercial software to date: Tools such as CUBE Access (formerly Sugar Access), an ArcGIS plugin developed by Bentley Systems, or TRACC Travel Time Analysis by Basemap are powerful analysis tools, but not openly available. The same is true for the multimodal analysis plugin “Urban.Access”, which relies also on ArcGIS (Benenson et al., 2011). However, with the advent of new open-source tools, such as OpenTripPlanner or r5r (Pereira et al., 2021), the opportunities for *accessible* accessibility models are increasing rapidly (Lovelace, 2021).

2.3. Workplace locations and sustainable mobility

Typically, the residential location and thereby its accessibility measurement has received much more attention as a major factor towards sustainable mobility practices than the workplace (Engebretsen et al., 2018; Næss et al., 2019). Thus, to date no specific tool exists that defines and measures the multimodal and intermodal accessibility of workplace locations. However, as outlined in Chapter 2.2, especially commercially available tools are capable of performing such tasks in general, even though it has not been documented and published extensively.

On the other hand, there is a substantial body of literature that values the role of the workplace location and its accessibility (measured/defined in different ways) as an important variable to explain commuting behavior: Simpson (1987) found that the inclusion of rudimentary accessibility parameters of the job location (such as distance to city center) improved the model's prediction of commuting distances. Cervero (1989) defined the Jobs-Housing Balance as a measure to explain increasing commuting distances in the US. He also found that un-balanced areas, namely workplaces in suburban areas with an imbalance between jobs and housing, are associated with low use of walking and cycling to work and high levels of congestions on the local roads. Naess and Sandberg (1996), identified the association between the peripheral, low-density workplace locations and increased driving to work and energy use for commuting to workplaces, compared to central, high-density locations. Levinson (1998) calculated, among other factors, the accessibility to housing from the workplaces' perspective and concluded that workplaces with better accessibility to housing (=to people) are associated with shorter commutes. The author also refers to the Jobs-Housing Balance (Cervero, 1989), arguing that the striving for a balance of jobs and housing should lead (in car-dominated contexts) to shorter commutes.

Similar results were identified by more studies from various global contexts, as collected by Engebretsen et al., (2018): North America (Cervero and Landis, 1992; Yang, 2005), Scandinavia (Hartoft-Nielsen, 2001; Naess and Sandberg, 1996; Strømmen, 2001), Netherlands (Schwanen et al., 2001), Portugal (Vale, 2013), and China (Yang et al., 2017).

Applying more sophisticated definitions and measurements of accessibility at the workplace, Wali et al. (2024) examined the regional accessibility and transit accessibility around the workplace in a sample of 648 participants, identifying significant associations between better accessibility of the workplace and more active mobility and less car use. In general, the study emphasized the location and the built environment around the workplace as an important factor in enhancing public health through active mobility.

In a mixed-methods study based on survey and in-depth interviews, Wolday et al. (2019) confirm the notion of increased car commuting to sub-urban workplace locations, but emphasize as well that even workplace locations at suburban transit centers do not perform significantly better, because of the high quality and comfort that these locations provide to car commuters. They argue that in order to make use of the potential that e.g. these workplaces attract workers living along the transit axis, *"deterrents such as reduced parking availability, parking fees, local road pricing, narrower streets and traffic signal priority for transit must be introduced to level out some of the car accessibility difference between the inner city and suburban centers."* (Wolday et al., 2019, p. 806).

Thus, there seems to be a mismatch between the importance of accessibility for workplaces and the availability of suitable tools that provide solutions for these kinds of analysis. It seems like the question of workplace accessibility is too simple and too complex at the same time: It is simple, because it is often regarded as the binary question which modes are available at the location or not; as a function of travel times, or just as being a central or suburban location. It is at the same time complex, because none of these indicators provide a reliable measure of a location's accessibility in the context of workplaces, even though state-of-the-art tools such as ArcGIS are technically capable of doing such analyses. This adds to the motivation of this thesis to develop a tool that is conceptualized from the start for workplaces, that is open-source in order to have no license- or cost-based barriers to its adoption by practitioners (in addition to the advantage of being open and transparent instead of a black box commercial software). The literature also shows a need for more than just monomodal analysis that is simply based on driving and rudimentary public transport modelling. Integrated networks, with multi- and intermodal transport options are necessary to deliver relevant information to real-world practitioners. The following Chapter 3 will build on this initial assessment from the state of the art and explain the research design to fill this gap.

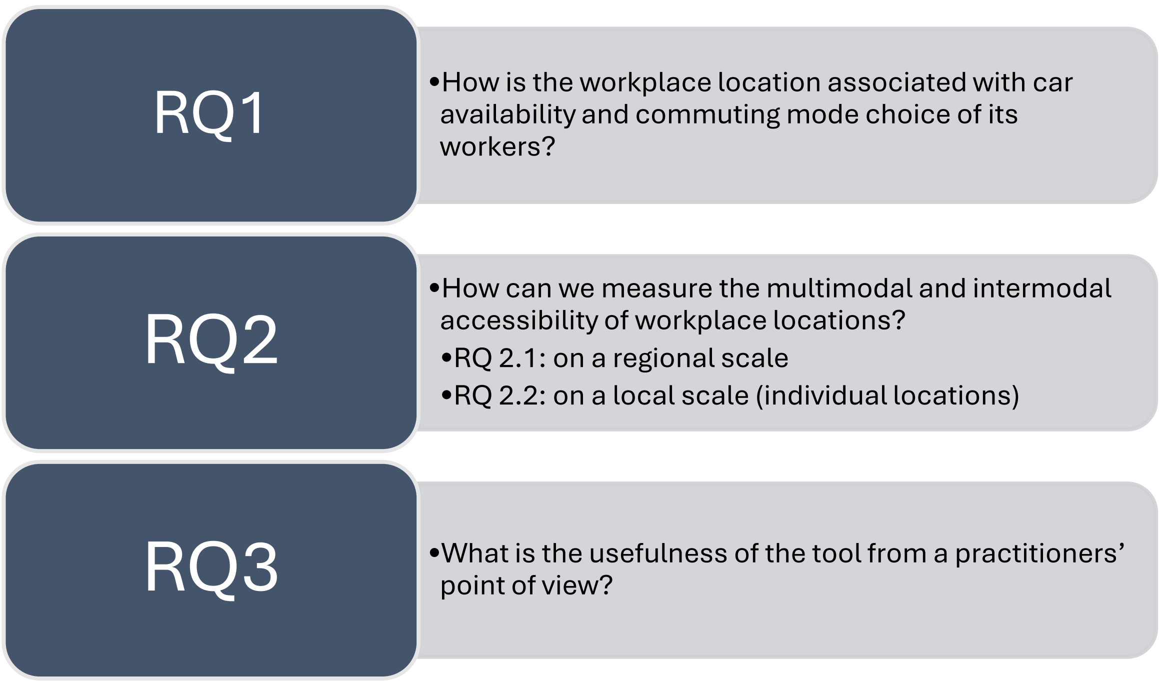
3. Research Design

3.1. Research Questions

As outlined in Chapter 2, there is a wide field of accessibility tools, but there is a lack of a tool that is focused and designated on accessibility analysis specifically for workplace locations. This dissertation aims at contributing to close this gap and formulates therefore the following overarching goal:

„Development, application, and assessment of a multimodal and intermodal accessibility model for workplace locations"

This goal has been translated into three main research questions to be answered within this thesis:



RQ1: How is the workplace location associated with car availability and commuting mode choice of its workers?

Based on the motivation and the literature review, the first research question (RQ1) deals with the importance of the workplace location as a determinant for mobility behavior in general, and mode choice to work as well as car ownership in particular. With this question, we want to find out how important the role of the workplace location is in order to justify and emphasize the need for all subsequent research toward the development, application, and assessment of an accessibility model.

RQ2: How can we measure the multimodal and intermodal accessibility of workplace locations?

If RQ1 confirms the importance of the workplace location, RQ2 is the logical next step: after reviewing the state of the art and available tools and methods for assessing the accessibility of workplace locations, the lack of adequate options motivates the development of the EMMA accessibility model, which is designed to measure the accessibility of workplace locations in a multimodal and intermodal way. Thus, the question refers to the development of the tool, its components, the technical background, the applied indicators, and the results the model produces. Thereby, two levels of measuring the accessibility of workplace locations have been applied:

RQ 2.1 asks about the measurement of accessibility on a regional level, using the Munich Metropolitan Region (MMR) as a reference. The starting hypothesis is that a grid-based calculation and visualization of accessibility can identify areas with good or bad accessibility from the workplace perspective. The answer to the question includes the operationalization of the model and its results on the regional level.

RQ 2.2 ‘zooms in’, since it is assumed that the regional perspective will not be detailed enough to assess the qualities of individual locations. Therefore, the same model will be applied not on a large-scale grid but rather on individual areas that are already used or in discussions for use as a workplace location. On this level, the importance of scenarios is assumed to be very high, so that, e.g., changes in the public transport supply should be integrated as scenarios in the model. The answer to this question includes the operationalization of the model (as explained in RQ 2.1) and the model results for exemplary locations, including the capability to model scenarios for these locations.

RQ3: What is the usefulness of the tool from a practitioners’ point of view?

After confirming the importance of the workplace location (RQ1) and the development and application of the accessibility model (RQ2), the final step is to assess the usefulness of the tool with the help of practitioners as potential future users of the tool. This is the final step, that closes the circle from motivation to tool development and application towards an understanding of the usefulness for practice – which is the foundation for any future uses of the tool. Only if the potential usefulness is confirmed by practitioners, there is a chance the tool actually contributes to better development of workplace locations in the future.

In this context, it is important to be aware that two perspectives to model scenarios are expected to be potential uses of the tool:

a) The location choice for new workplaces: Using accessibility measurement on both aforementioned scales can potentially be used to identify locations with good/bad accessibility, that are suitable or not for workplace development.
b) The improvement of the accessibility conditions for future or existing workplaces by changing the transport infrastructure

3.2. Methodology

The research questions were divided and answered within three scientific publications, applying together a mixed-methods approach that included the main elements of literature research, statistical analysis of survey data, tool development, and semi-structured expert interviews with practitioners. With this combination of methods, it is possible to document and explain the whole circle of tool development, from reasoning/motivation to tool development, application, and evaluation of usefulness.

Overview of Publications

The following Table 1 - Table 3 give a short overview of the three publications included in this dissertation.

Table 1: Overview of Paper 1

Paper 1	**Workplace relocation and its association with car availability and commuting mode choice**
Authors:	Maximilian Pfertner, Benjamin Büttner, David Duran-Rodas, Gebhard Wulfhorst
Accepted:	10 December 2021
Published in:	Journal of Transport Geography (98) 2022 103264
DOI:	https://doi.org/10.1016/j.jtrangeo.2021.103264

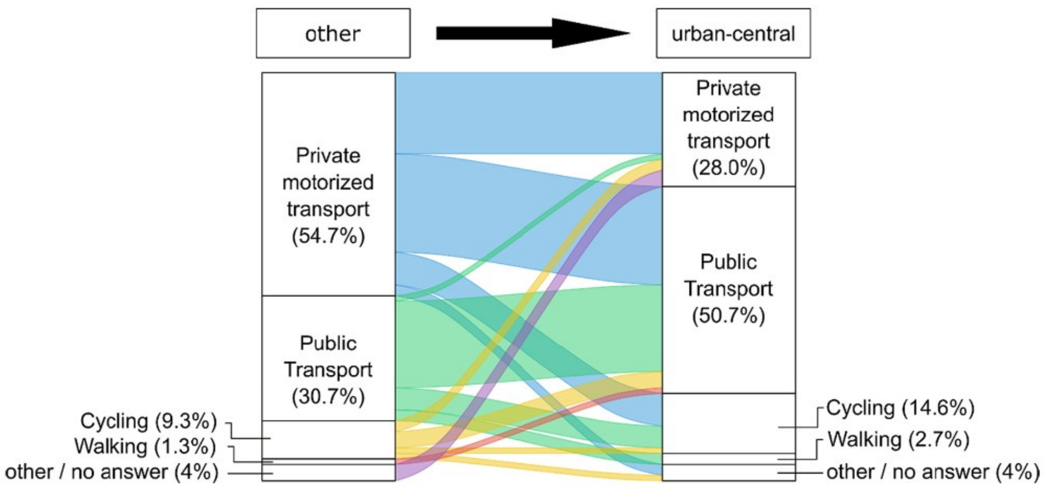


Figure 8: Mode Choice - flow from other to urban-central cluster (Pfertner et al., 2022)

The first paper uses the WAM survey data (Thierstein et al., 2016) and applies advanced statistics like the Heckman Selection Model in order to uncover statistically significant associations between workplace relocation and the increase in car availability and the change to driving. It confirms the importance of the workplace's location by showing that the relocation to a less central workplace is associated with a model shift to driving to work and an increase in car availability, while the relocation to a more centralized area is associated with a shift to alternative modes. Exemplarily, Figure 8 visualizes the change in the commuting mode of workers, whose new workplace location is more central than the previous one, showing a significant mode shift from driving to public transport. For details about the paper, see Chapter 4.

Table 2: Overview of Paper 2

Paper 2	**An Open-Source Modelling Methodology for Multimodal and Intermodal Accessibility Analysis of Workplace Locations**
Authors:	Maximilian Pfertner, Benjamin Büttner, Gebhard Wulfhorst
Accepted:	19 January 2023
Published in:	Sustainability 2023, 15(3), 1947
DOI:	https://doi.org/10.3390/su15031947

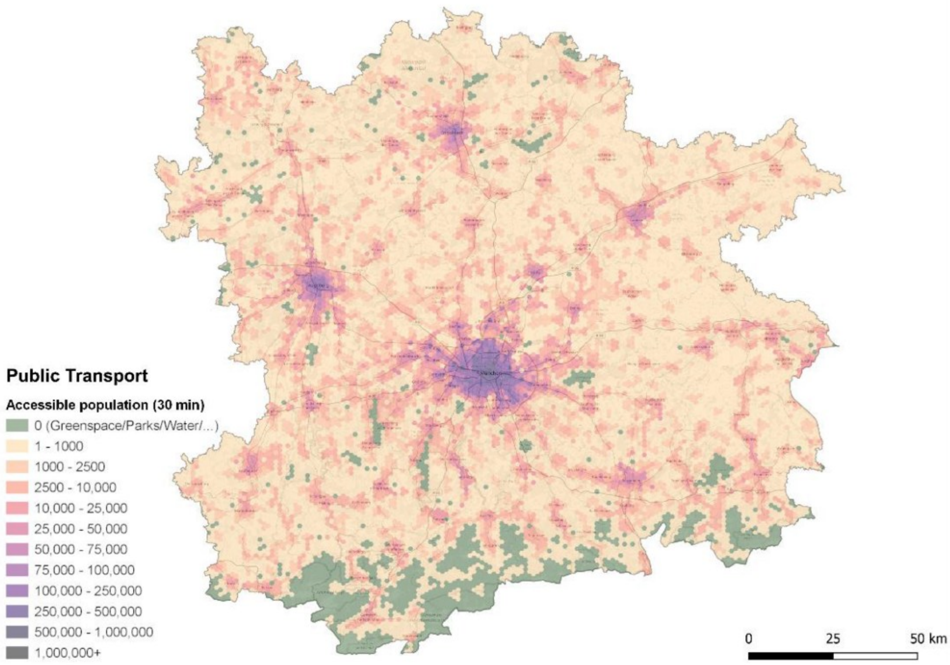


Figure 9: Thirty-minute accessibility by Public Transport for the entire MMR (Pfertner et al., 2023)

The second paper explains the technical details of the EMMA accessibility model and how it combines elements such as OpenTripPlanner, PostGIS, and R into the tool that allows a fast and efficient calculation of workplace accessibility for entire regions, such as the MMR, on regular consumer hardware. The methodology is based on an isochrone-based calculation of the population that can reach a potential workplace location within a given time budget (such as 30 minutes) during the workday peak hour. The results are presented in absolute numbers, but also relative (e.g. public transport vs. car) and in the form of a z-score based score from -100 to +100. Model outputs can be multimodal, for example in the sense of comparing car- and public transport accessibility, or intermodal by including e.g. bike and ride in the analysis. Figure 9 shows the resulting map for accessibility by public transport for the Munich Metropolitan Region.

Table 3: Overview of Paper 3

Paper 3	**The potential usefulness of accessibility modeling for workplace locations – the example of EMMA**
Authors:	Maximilian Pfertner, Cecília Silva, Benjamin Büttner, Gebhard Wulfhorst
Submitted:	26 June 2024 (currently under review)
Journal:	tbc

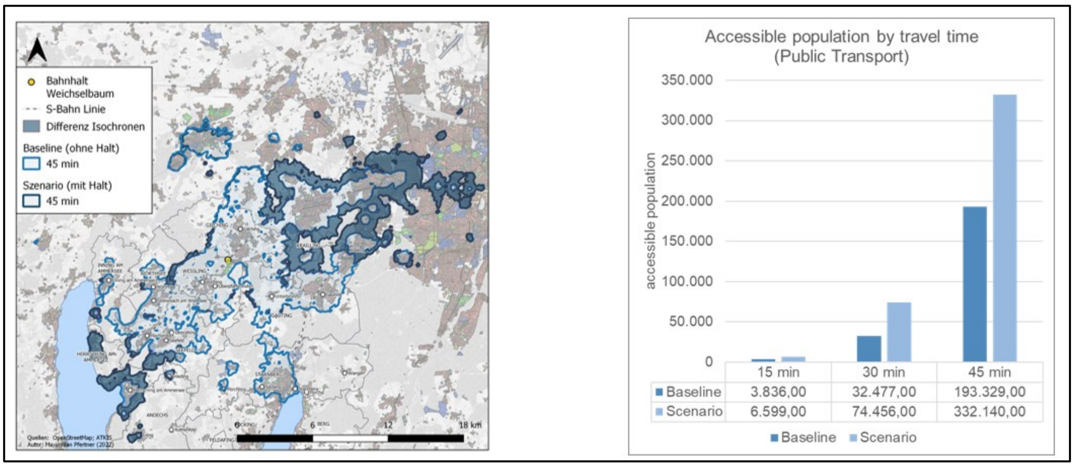


Figure 10: Local analysis and scenario in EMMA (Pfertner et al, forthcoming)

The third paper uses the regional and local results of the EMMA model to examine the usefulness for practice though semi-structured interviews with practitioners, breaking down the concept into utility and usability. The interviews included various perspectives (municipal planning, consulting, real estate, etc.) and the results confirm the model's usefulness to be used for the early planning stage, according to the interviewees. Further useful aspects were identified, such as using it for existing locations, to analyze weaknesses within a city's transport system for commuting, but also to compare changes in transport infrastructure that could be introduced by new modes of transport, such as sharing options or mobility stations.

Figure 10 illustrates such a scenario: The map shows two isochrones of a study area, comparing the with/without scenarios of a new train stop. The graph on the right visualizes the change in population that can access the workplace within 15/30/45 minutes.

Overview of Methods

Table 4 summarizes the applied methods, data sources, goals, and research questions by paper.

Table 4: Methods, data, and goals

Method	Data used	Goal	RQ	Paper
EMMA Expert Council	Three workshops with experts	To brainstorm, get feedback, and validate the project's development.	over-arching	over-arching
Literature research on workplace relocations	Scientific literature	Understanding the association between workplace relocations and car availability and mode choice	RQ1	1
Statistical Analysis (Flow-diagrams, logistic regressions, and Heckman selection model)	'WAM' survey from the MMR	Exploring the association between workplace relocation and changes in car availability + commuting, with a focus on the importance of the workplace location as an explanatory variable for these changes	RQ1	1
Literature research on accessibility tools	Scientific literature	Overview of existing tools for accessibility measurement (focus on workplaces)	RQ2	2
Model development	OpenStreetMap[5], Census data[6], GTFS feed[7]	Development the EMMA accessibility model	RQ2	2

[5] Data provided by OpenStreetMap. osm.pbf format provided by Geofabrik: https://download.geofabrik.de/
[6] German national census: Zensus 2011. Available online: www.zensus2011.de
[7] Nationwide GTFS data for Germany is provided by OpenData ÖPNV. Available online: https://www.opendata-oepnv.de

Regional model application	See model development	Application of the EMMA model on regional scale	RQ2.1	2, 3
Local model application and scenarios	See model development	Application of the EMMA model on local scale, applying scenarios	RQ2.2	(2), 3
Literature research on usefulness of PSS[8]	Scientific Literature	Understanding the literature about usefulness of PS	RQ3	3
Thematic analysis of semi-structured expert interviews	Ten interviews with practitioners	Understanding the usefulness of the EMMA model	RQ3	3

Thereby, the research questions are linked to the publications in the following way:

Table 5: Relation of Research Question and Publications

	Paper 1	Paper 2	Paper 3
RQ1			
RQ2.1			
RQ2.2			
RQ3			

RQ1 (“How is the workplace associated with ca availability and commuting mode choice of its workers”) is answered in the first paper, presented in Chapter 4 of this dissertation. RQ2 (“How can we measure the multimodal and intermodal accessibility of workplace locations?”) with both sub questions about the regional perspective (RQ2.1) and the individual location view (RQ2.2) is covered mainly in Paper 2 (Chapter 5), with more details on the use of the model in

[8] Planning Support Systems

Paper 3 (Chapter 6). RQ3 ("What is the usefulness of the model from a practitioners' point of view?") is covered in Paper 3 (Chapter 6) as well.

Main data sources

The statistical analysis of workplace relocations in the first paper is based on survey data from an online survey that was carried out from November 2014 to April 2015 within the project "Wohnen-Arbeiten-Mobilität" ("WAM", translates to "Residence–Work–Mobility") in the MMR. In sum, 7341 residents of the MMR who had changed their residential location or workplace location within three years prior to the survey were included. Relevant for RQ 1 was a subset of this sample, which consists of 787 respondents who matched our inclusion criteria, such as being employed, having changed their workplace location but not their residential location, sufficient data quality for locations of workplace (old and new), and residential address. This data is the only dataset used in this dissertation that is not openly available. See other papers from the project (Kinigadner et al., 2016; Thierstein et al., 2016; Zhao et al., 2017) for more details.

For the development of the accessibility model, only open data was used: In order to model multimodal and intermodal isochrones, the OpenStreetMap road network was used, and GTFS data was obtained for public transport timetables and routes. For the accessibility measurement, the German census data from 2011 provided population data in form of a 100x100m grid.

EMMA expert council

As part of the EMMA project, we set up an international council consisting of experts in the field of multimodal and intermodal accessibility modeling. The members of the council were Daniel Krajzewicz (DLR), Alain L'Hostis (Université Gustave Eiffel), Rolf Moeckel (TUM), Klaus Nökel (PTV AG), Marcus Peter (Hochbahn Hamburg), Cecília Silva (University of Porto), and David Vale (University of Lisbon). Within this group, three workshops took place:

- December 2019 (in person in Munich): The goal was to present the overall idea of the EMMA project and to get feedback for the development process of the tool. The debate was enriched by inputs from the experts, who presented their own research related to accessibility modelling, multimodality and intermodality, and workplaces.
- December 2020 (online, due to pandemic): In the second workshop, the concept and operationalization of the region-wide accessibility model was presented, and the experts were invited to give feedback in order to validate the

model. In the second part, the focus was set on an outlook and conceptualization of the local application of the tool for individual workplace locations.

- December 2021 (online, due to pandemic): In the final workshop, we presented the publication of the statistical analysis (see Chapter 4) and discussed the analysis for the Weichselbaum case study (see Chapter 5 and 6). We further brainstormed ideas, how to present the results (regarding absolute and relative indictors) and how to develop a score out of the results.

Across the workshops, the feedback from the experts was highly valuable and helped to steer the project into the right direction.

Statistical analysis

In order to successfully prove our initial motivation, that the workplace location is a critical factor for mode choice and car ownership of its workers, several statistical methods were applied (see Chapter 4 for details). The initial, exploratory data analysis was made with flow diagrams (also known as Sankey diagrams), which explored the mode shift (or changes in car availability) of workers along with the change of the workplace location. Figure 8 shows such a diagram. While these results were promising and indicated that our hypothesis holds true, more advanced statistical methods were needed to prove the hypothesis. Thus, first Chi-Squared-Tests and then logistic regression was used for the dependent variables *increase in car availability* and *change to driving*, with the change of the workplace location as one of the key independent variables. For the dependent variable *change to driving*, we faced the problem, that our model had a sample selection bias: *change to driving* is only observable in the data, when *car availability* is given, since without car availability, the option of a modal change to driving does not exist. A Heckman Selection Model (Heckman, 1976) was eventually found to eliminate this bias, by applying a 'selection model' first, before calculating the 'outcome model', that answers the research question.

Development and application of the EMMA accessibility model

For RQ2, both on the regional (RQ2.1) and local (RQ2.2), the development of a novel accessibility tool was needed. Therefore, the model "EMMA - Empowering multimodal and intermodal accessibility analysis for workplace locations" was developed within this dissertation. The model consists of three main components:

- OpenTripPlanner for calculating multimodal and intermodal isochrones
- A PostGIS database to process and store spatial data

- A custom R-Script to automate and control the model

Figure 11 visualizes the concept and includes the necessary data (gray boxes). The model produces, among other things, the following main results for the default modes driving, cycling, and public transport (multimodal perspective) and intermodal combinations, such as bike and ride:

- Grid-based regional accessibility in terms of population that can access the grid cell during the weekday peak hour in absolute numbers per mode and intermodal combinations (refers to RQ2.1)
- Grid-based regional accessibility in a relative comparison of two modes (and/or intermodal combinations), such as public transport compared to driving (RQ2.1)
- Grid-based regional accessibility as a relative comparison of two modes (and/or intermodal combinations), normalized using z-values into a score (e.g. -100 - +100) (RQ2.2)
- Accessibility for individual locations, presented as isochrones and resulting graphs of accessible population for status quo scenarios as well as for scenarios, where the underlying data of population and/or transport network can be changed

The model results are saved in a spatial database. An experimental web-based user interface was developed, but the main means of visualization is an integration of the database with QGIS.

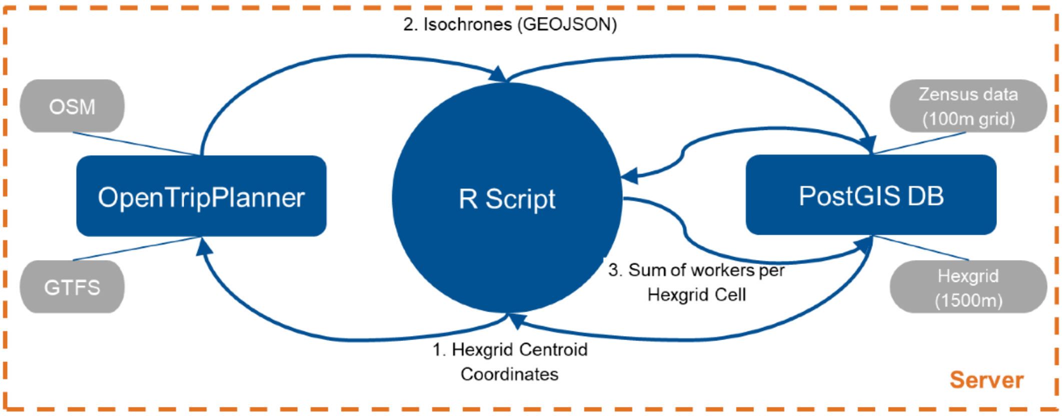


Figure 11: EMMA model concept (Pfertner et al., 2023)

All details about the methodology, its application and the outcomes are presented in Chapter 5.

Semi-structured expert interviews

The third main method is semi-structured expert interviews and a thematic analysis based on coding the interviews in MAXQDA (VERBI Software, 2024). Using the researcher's local network in the Munich Metropolitan Region and a subsequent snowball sampling approach, ten key stakeholders were interviewed about the usefulness of the EMMA accessibility model for planning practice. The interviewees represent the following sectors:

(1) Municipalities in various sizes (small, medium, large)
(2) Public Transport Association
(3) Real estate sector (developer/manager, consultants)
(4) Transport sector (consulting, software development)
(5) Private company looking for new locations (Co-Working)

After ten interviews, the interviewees did not suggest further perspectives that could be missing, and saturation towards the interview questions was reached, which is a suggested indication for a sufficient number of interviews (Glaser et al., 1968; Hennink et al., 2017). The interviews took place between July 2023 and January 2024 either in-person or online, mostly in German language. The duration ranged from 60 to 90 minutes. After recording the interviews, transcripts were created and coded for themes with the help of the MAXQDA software (VERBI Software, 2024). The analysis and synthesis of the coded interviews was then done manually with respect to the research questions (explanatory) and further suggestions and comments (exploratory). All details about the interviews are presented in Chapter 6.

II.Scientific Papers

4. Workplace Relocation and its Association with Car Availability and Commuting Mode Choice

This chapter presents an integral reproduction of: "Pfertner, M., Büttner, B., Duran-Rodas, D., Wulfhorst, G., 2022. Workplace relocation and its association with car availability and commuting mode choice. Journal of Transport Geography 98, 103264. https://doi.org/10.1016/j.jtrangeo.2021.103264"

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Abstract

The workplace location impacts both daily mobility behavior and long-term mobility decisions. Many case studies have observed significant effects of workplace relocation on car availability and mode choice to work, but there is a lack of studies that go beyond a single-company relocation to explore the association between workplace relocation and a subsequent change in car availability and car commuting, with a focus on the importance of the workplace location as an explanatory variable for these changes.

In this study, we examine the associations of workplace relocation with the increase in car availability and switch to car commuting in 6,404 surveyed workers in the Metropolitan Region of Munich. A subset of the data with workers who have changed their workplace location while maintaining the same residential location (n=787) is used to visualize the effect of the workplace relocation. By using "flow-diagrams" for a descriptive analysis of the data, a logistic regression on the increase in car availability as well as a Heckman Selection Model on the modal switch to driving, we find statistically significant associations of the workplace relocation with the increase in car availability and the change to driving.

Workplace relocations to less centralized areas are associated with an increase in car availability and a change to driving. Vice versa, a relocation to a more centralized areas is negatively associated.

Our results emphasize the importance of workplace locations and especially re-locations as triggers for changes in car availability and mode choice. We advocate for wisely designed planning processes and decision-making tools for analyzing and planning workplace locations, in order to make use of the window of opportunity for behavior change towards sustainable commuting and to foster well-working regional systems for living, working, and everything in between.

Key Words: workplace; commuting; car availability; relocation; Heckman model; accessibility

4.1. Introduction

The negative impacts of transport on the environment and the quality of life are ubiquitous in today's discussions about the future of metropolitan regions worldwide. Greenhouse gas emissions contribute to climate change, and the transport sector is the only sector that has experienced an increase in emissions since 1990 (European Commission, 2016) and nowadays represents around a quarter of all of Europe's CO_2 emissions (DESTATIS, 2021). With the *European Green Deal*, the European Union aims for a 90% reduction of transport emissions until 2050. Creating a transport system that is "smart, competitive, safe, accessible and affordable" (European Commission, 2020) is the strategy to reach this goal.

One of the main levers to achieve this goal is to reduce the need for individual car availability and reduce car use, since this land-based transport mode has shown the highest emissions per capita (Umweltbundesamt, 2019), the highest external costs (Van Essen et al., 2019), including effects on health, and the highest demand of space per passenger (Nello-Deakin, 2019). However, researchers have been arguing for a long time that approaches that affect singularly the transport system are not sufficient and that only a paradigm shift towards an accessibility-based, integrated perspective on land use and transportation planning can lead to a more sustainable future of metropolitan regions (Bertolini et al., 2005; Cervero, 2005). Thus, planners and policymakers need to be aware of the interdependencies between land use, car availability, and car use. In this context workplace locations are critical levers for the planning and fostering of sustainable mobility in a region since they are important determinants of regional development, both in terms of the structural properties of a region and the distribution of inhabitants (Hansen, 1959). Workplace locations are associated with car usage and car availability of their employees (Ding et al., 2017; Ding and Cao, 2019; Zarabi and Lord, 2019). Relocations of the workplace are thus of particular interest for fostering sustainable mobility, since they present a rare window of opportunity for behavioral change.

State of the Art

Workplace relocations and changes in car availability and car commuting

In contrast to planned interventions for sustainable mobility behavior, where the evidence for actual behavior change is often weak (Graham-Rowe et al., 2011; Ogilvie et al., 2007, 2004), the relocation has shown to be associated with actual behavior change in many previous studies (Bell, 1991; Hanssen, 1995; Rau et al., 2019; Sprumont et al., 2014; Walker et al., 2015; Zarabi and Lord, 2019). This is in line with expectations that arise from habit theory, which suggests a stabilizing effect of habits on travel choices (Gardner, 2009).

According to the habit discontinuity hypothesis (Verplanken et al., 2008), major contextual changes, such as relocations, open up a window for a reconsideration of these choices (Wood et al., 2005). This has been shown for habits related to sustainable mobility behavior, for example in an analysis of commuting mode changes as a result of a relocation in combination with environmental values of the employees (Verplanken et al., 2008).

Thus, it is a challenge for policy makers and planners to use this window of opportunity for making this behavior change a change towards more sustainable mobility. This approach has been successful for residential relocations before (Bamberg, 2006). For workplace relocations, literature shows that the relocation "can fundamentally disrupt employees' daily routines and reshape their own and other people's mobility practices" (Rau et al., 2019) – impacting trip chaining and general mobility behavior beyond the commute trip as well as the availability of mobility tools. On the individual level, workplace relocation affects daily mobility behavior (Silva et al., 2006) and long-term mobility decisions such as car ownership and annual public transport subscriptions (Beige and Axhausen, 2012).

How exactly the relocation is associated with changes in car availability and commuting mode choice has been analyzed in many previous studies: Bell (1991) studied an office relocation in the Melbourne area with ex-ante and ex-post employee surveys and found "substantial" impacts of workplace location on the employees' car ownership and commuting behavior. The share of one-car households decreased from 29% to 25%, and 8% of respondents have bought an additional car because of the new location. Car use rose from 34% at the old, central location to 76% in the new suburban office. Interestingly, it was observed that the change of this location also influenced the integration of other activities into the day and how trip chains are formed.

Hanssen (1995) used a similar study design that looked at a firm relocation from the central business district to the suburbs in Oslo. Apart from increases in car use and reduced public transport use – similar to the magnitude found by Bell (1991) – it was also observed that car ownership increased by 11% while the number of public transport season passes among employees decreased by 12%. Thus, even though the new suburban location provided access to public transport, for most centrally-dwelling employees an additional transfer was necessary to reach the new location, which is a possible explanation for the behavioral change towards more private car use – especially since the new location offered plenty of free parking.

One could speculate that these are only temporary effects because workers did not have enough time to re-evaluate and adapt their residential location to the new workplace location. However, Naess and Sandberg (1996) showed (also in an Oslo-based observation) that this increase in car use for the trip to work did not level out over time, which indicates that the new modal split is affected by the new location, instead of just being a limited adaption phase due to the relocation. Similar findings in Norway were shown by Aarhus (2000), who compared five company relocations. Although the new locations were selected based on national guidelines for integrated land-use and transportation planning, car commuting increased clearly in most observed companies. The author suggests that a lack of coordinated planning across municipalities is responsible at least in part for this observation, whereas planning on a regional level could have improved the outcomes.

More recent studies support the assumption that these findings from the 1990s are still valid. Vale (2013) assessed a workplace relocation from central Lisbon to a suburban mixed-use center, and even though this new location was relatively well-connected and has its own node-value (cf. Bertolini, 1999), the usage of private motor vehicles still increased, indicating the need for complementing additional travel demand management measures to avoid the modal shift towards driving. Sprumont et al. (2014) used a stated preference survey in Luxembourg to analyze the effects of the planned relocation of a university campus on its employees. They found the same trend of a modal shift towards driving, suggesting that only measures that increase the cost of driving or increase the car travel times might be suitable to reduce car commuting in this context.

In Munich, Germany, a recent analysis of a company relocation from a central location to a suburban location (Rau et al., 2019) found that car use increased from 46% to 71%, and especially workers who used to walk and bike to work did not continue to do so to the new location. One of the adaption strategies respondents reported was the increase of car availability – 19% of the surveyed workers bought a car after the relocation.

4.2. Research objectives

The main objective of this study is to explore the association between workplace relocation and a subsequent change in car availability and car commuting, with a focus on the importance of the workplace location as an explanatory variable for these changes.

While the existing literature shows evidence of changes in commuting behavior and car ownership as a reaction to workplace relocation, a frequent limitation of the case studies is that only one company is observed. Thus, only one type of relocation in terms of the centrality of the locations is observed: either the workplace is relocated to a more central location with better accessibility, or vice versa. Also, most case studies of a single company relocation have the limitation that there might be other, hidden factors included which are not generalizable to other companies. The interpretation of these results highly depends on the very particular attributes of the respective locations, companies, and their employee structure. However, the variation of characteristics of companies and the workplace locations could have a strong influence on the outcomes of the workplace relocation. For example, a company that is highly dependent on truck-based logistics will always relocate to a location where the road-based accessibility is high (such as described by (Rau et al., 2019), potentially limiting the non-motorized access options for workers; a company that offers company cars to many employees will have a different reaction to the relocation than a company that relies on staff with a high awareness of environmental issues (such as the company described by (Walker et al., 2015).

This study, in contrast, has recruited respondents independent of individual companies throughout the entire Munich Metropolitan Region, from various kinds of companies with no pre-selected relocation pattern. While this approach does not allow for an assessment of individual firm characteristics, the large and diverse sample reduces the bias that individual companies would introduce and averages out the particular characteristics of single companies.

The included respondents have experienced different changes of travel time, distance, or centrality of workplace with the new workplace location. Thereby, we can statistically assess the association between relocations from non-central to central areas (or vice versa) on changes in car commuting and car availability.

An extensive review of the literature about the association of workplace relocation and travel mode choice was done by Zarabi and Lord (2019). They conclude that in most relocations, a commuting mode shift from public transport and active modes to driving takes place. This trend is observed across various continents and independent of occupation categories. However, they argue that many studies ignore sociodemographic factors such as car ownership or family structure (including whether a household has dependent children or not). Our data, in contrast to that, allows to include some of those variables in the analysis, enabling to control for their association with changes of car commuting and car availability. For example, we can compare the association of the relocation with changes in car availability and car commuting with other potential predictors, both demographic (household income, age, family status) and relocation-related (changes in travel time, distance, centrality). Thus, the objective of the study is also to compare the effect of the workplace relocation with other potential predictors in the dataset.

Furthermore, our data allows to filter for respondents who did not change their residential location, focusing the analysis on the workplace relocation as a potential trigger for change in a descriptive way.

Method and expectations

We reach the objectives using a quasi-longitudinal survey including data on living, working, and mobility from the Munich Metropolitan Region in Germany. We consider this dataset quasi-longitudinal since we have information about behavior of the same worker at the old and the new workplace location, but this information has been gained with a single survey, asking questions about the current workplace, but also in retrospect about the old workplace. Variables are selected based on evidence in the literature for an association with commuting mode choice and car availability.

First, we group all locations (old and new workplaces, residential locations) into spatial clusters that summarize the accessibility and centrality of these locations. With descriptive analysis of flow diagrams, we explore the association between centrality of the workplace and changes in commuting behavior and car availability. Then, by using a logistic regression model, we explore the association between the change of workplace location, demographics, commuting characteristics with the increase in car availability statistically. Similarly, we explore the associations of change to car commuting with the same independent variables, and we fit a Heckman selection model, taking into account the sample selection bias by having a car available as a precondition for car commuting.

Based on the findings from the literature and the experiences from the reported workplace relocations in various contexts, we hypothesize that the workplace relocation will be associated with both an increase in car availability and a modal shift towards driving. We assume that a change from central locations to non-central locations will be positively associated with car availability increase and positively associated with the change to car commuting. Similarly, we expect changes with an increase of centrality of the workplace to be negatively associated with both dependent variables.

Paper structure

The rest of the paper is organized as follows: Chapter 4.3 describes the data and the applied methodology, chapter 4.4 presents the results of descriptive analysis and models. Finally, the results are discussed in chapter 4.5, and chapter 4.6 gives conclusions, recommendations for policy and practices, and an outlook for future research.

4.3. Methodology and Data

Region-wide survey

Overview

This study is based on an online survey that was carried out from November 2014 to April 2015 within the project "Wohnen-Arbeiten-Mobilität" ("WAM", translates to "Residence – Work – Mobility") in the Munich Metropolitan Region (MMR). In total, 7,341 individuals who had changed their residential location or workplace location within the observation period (three years prior to the survey) took part. Questions include a broad range of topics such as housing, workplace, and mobility choices. See Kinigadner et al. (2016) and Thierstein et al. (2016) for a full description of methods and results from this project.

Sampling

The survey invitation was spread through regional partners, including municipalities, transport authorities, private companies, a press conference, newspaper articles, and various websites and can thus be considered as non-probability sampling. As outlined in chapter 3.1, the non-random recruitment, and the focus on the WAM thematic area of relocations of both workplaces and residences attracted certain subset of the population more than others. Also, the marketing through the university and related institutions was attracting more respondents with an academic background, which is also reflected in the high share of respondents with university degrees and doctorates (see chapter 3.1 for details).

Data filtering and preparation

The complete dataset, filtered only for missing data with 6,404 responses remaining, was used to test associations with the dependent variables with a logistic regression and a Heckman model. A filtered subset of the data was used to visualize the effect of a change in the workplace location with the help of flow diagrams. Respondents had to fulfil the following conditions within the observation period in order to be included in these charts:

- Employed (at least partially)
- The workplace location has changed
- The residential location has <u>not</u> changed
- Both workplace (old and new) and residence coordinates are known at least on street-level.

This filtered dataset consists of 787 individuals. It is important to note that the survey was not conducted in an actual panel format. The time of the workplace relocation is different for each individual in the dataset and the variables can only distinguish before and after of this point in time. Participants were asked whether such a change (either workplace or residential relocation) has happened within 3 years prior to the survey.

Spatial Clustering of Workplace Locations

Thierstein et al. (2016) clustered the MMR into 5 spatial clusters: "urban-central", "urban-decentral", "urban catchment", "residential locations in tourist areas", and "peripheral areas". The clustering is based on the indicators settlement structure, services, accessibility to workplaces and population, residential costs, building types, and share of vacation apartments (Zhao, 2017). See

Figure 12 for an overview of the MMR and the classification in spatial clusters.

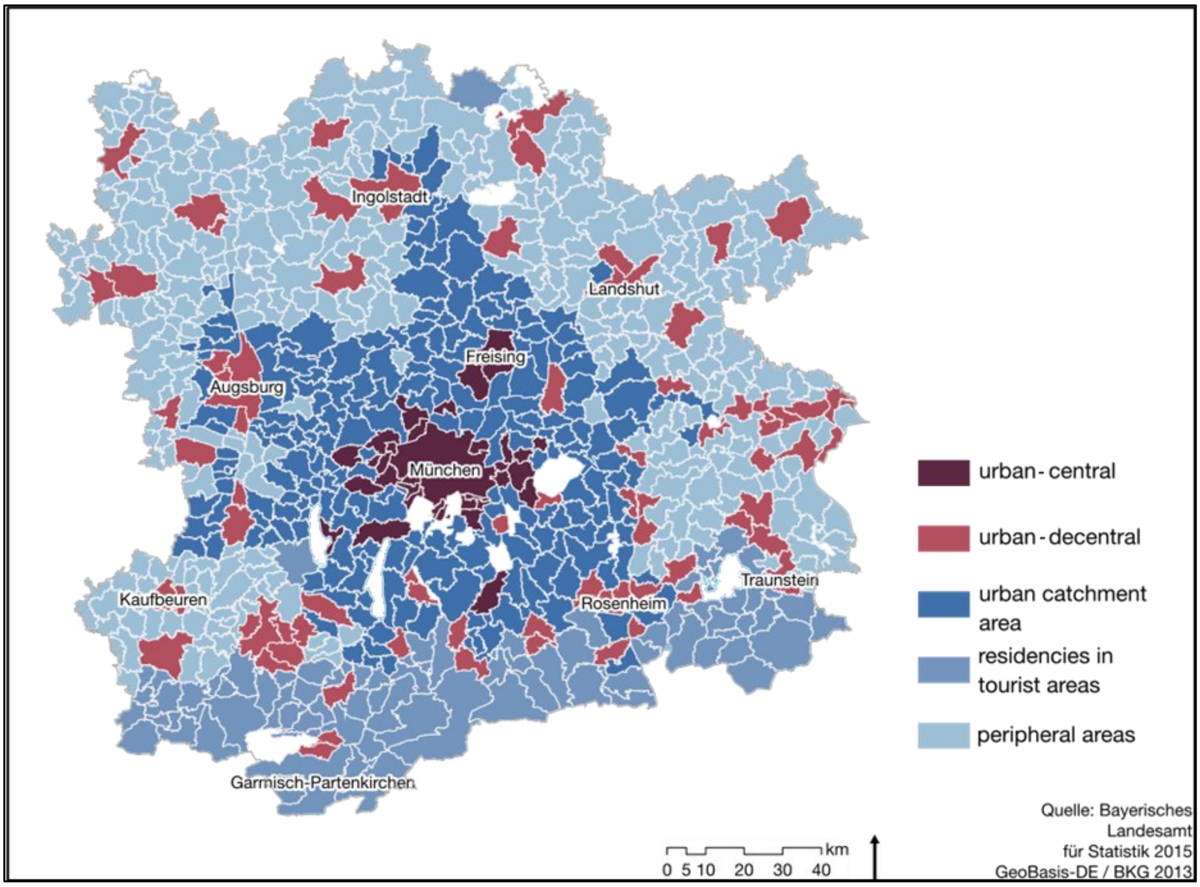

Figure 12: Spatial-functional structure of the MMR (Thierstein et al., 2016)

The clusters "residential locations in tourist areas" and "peripheral areas" have been combined into the latter for the purpose of this study due to the low number of respondents from these areas and many overlapping characteristics.

In this paper, we often refer to a change to urban-central locations from other locations – this means that the old workplace has been located in one of the other four clusters and is now in the urban-central cluster, indicating an increase in centrality. Similarly, when we refer to a change away from urban-central, this describes a change from urban-central to another cluster, indicating a lower centrality of the new workplace.

Travel times to work

Travel times between residence and workplace were collected with the Google Maps API, both for the old and the new workplace. The calculation included travel times for walking, cycling, public transport (travel time and number of transfers), and driving on a regular weekday in 2015. In combination with the survey data, this allows us to know the actual mode-choice and travel duration of the respondents, as well as the travel times for all alternatives.

Descriptive Data Analysis - Flow Diagrams

With the help of the *ggalluvial* package (Brunson, 2018) available in the programming language R, it is possible to generate "flow-diagrams" that help to illustrate and understand how individuals change between categorical variables. For example, this is commonly used in election analysis, where the flows illustrate how voters have changed parties between two elections. In our analysis, it describes the flow from the previous mode (used at the old workplace location) to the new mode used to get to the current location. Therefore, we can observe the group of drivers at the old location and analyze by which modes they commute to the new location. In order to illustrate the potential association between the workplace relocation, we are using a filtered dataset for the flow diagrams, where only respondents are included who have changed their workplace location, but not their residential locations. Later in the statistical analysis, we use the full dataset in order to be able to assess and compare the associations of both changes of the residential and the workplace location.

Statistical Analysis

Statistical analysis was done with the programming language R version 4.1.0 (R Core Team, 2021) and RStudio (version 1.4.1717).

Logistic regressions (on increase in car availability and change to driving)

In order to identify the effects of workplace relocation, we created two dummy variables:

- Car Availability Increase: If this is "Yes", the respondent has increased their individual car availability. After the workplace change, they have now always a private car available, whereas this was not the case before the relocation.
- Change to Driving: If this is "Yes", the respondent has not been driving to work at the old workplace location, but is now using the car for the commute to the new location.

These binary variables allow us to run logistic regressions with both dummy variables as dependent variables and the other included variables (see Table 1 and Table 2) as potential explanatory variables. As a preparation for the logistic regressions, Chi-Squared-Tests were used to test the association between the potential predictors and the dependent variables.

The Heckman selection model (on change to driving)

The Heckman selection model was developed to solve the problem of regression models with a sample selection bias. This problem arises when the dependent variable of a model can only be observed for a certain part of the data, and there is a reason for this selection bias. The classical example in Heckman's original paper (Heckman, 1976) uses women's wages as the dependent variable. In this case, an approach with a standard regression has the problem, that in the data collection, a woman's wage can only be observed if she decides to join the labor force and work. If a woman does not make this decision, the observer cannot determine what her wage would have been and thus the dependent variable is masked in a number of cases. Also, this masking does not appear randomly, but there are various variables that might affect the choice whether to work or not, such as the family status, number of children, household income, expected income, among others.

The Heckman model reduces this issue with a two-step approach: First, a selection equation determines whether an observation is included in the sample (in the example it determines whether a woman joins the labor force), using a probit model. Then, the outcome equation models the association between the explanatory variables and the dependent variable of interest (wage, in the example), using the Inverse Mills Ratio (IMR) as an additional predictor in the equation. By using the correlation coefficient between the residuals of both the selection equation and the outcome equation, the Heckman model provides a way to test whether the self-selection affects the outcome. Refer to Deka (2013) for a detailed overview of the Heckman model and some applications in transportation research and beyond and Greene (2020) for a general introduction.

In our analysis, we use the Heckman model to include the precondition of car availability for changing to commuting by car. If workers do not have a car available when changing the location of their job, we cannot observe whether they would have switched to driving. Thus, the model allows estimating the probability that a worker switches to driving, given that the worker has a car available. Thereby, it is assumed that the probability to switch to driving can be expressed with

$$y_j = x_j\beta + u_{1j}$$

where y_j is the probability of a worker j to switch to driving from another mode and x_j is a set of explanatory variables with the parameters β to be estimated. The error term u_{1j} is added, with mean zero and standard deviation σ to be estimated. Since the dependent variable is not always observed because workers can only switch to driving if they have access to a car, we can formulate that the dependent variable is observed if:

$$z_j\gamma + u_{2j} > 0$$

where z_j is a set of explanatory variables that are associated with car availability of worker j with the parameters γ to be estimated. The normally distributed error term u_{2j} is added, with mean zero and a standard deviation equal to 1. This formula defines the probability of having access to a car being greater than zero.

The error terms of both equations are distributed as follows:

$$u_1 \sim N(0,\sigma) \text{ and } u_2 \sim N(0, 1)$$

and the correlation is defined as $\rho = \mathrm{corr}(u_1, u_2)$.

If the error terms are correlated, meaning that ρ is not equal to zero, the model indicates that the sample selection would have introduced a bias if a standard regression model would have been used instead of the Heckman model.

Multicollinearity

In order to avoid multicollinearity, we use Generalized Variance Inflation Factors ("GVIF") to check the models since we are using only categorical variables. In R, GVIF can be calculated automatically for example with the car package (Fox and Weisberg, 2019). The established rules of thumb known from regular Variance Inflation Factors ("VIF") can be applied on the squared GVIF(1/(2×Df)). If this value is below 5, there is no evidence that multicollinearity is a problem in the model (Fox and Monette, 1992; Gareth et al., 2013).

4.4. Results

This chapter will present our findings in the following structure. We first present descriptive statistics of our dataset including the demographic overview of the sample, grouped by our two dependent variables: “Car Availability Increase” and “Change to Driving”. Then, we present our findings about the associations with the dependent variable Car Availability Increase. We start with an analysis of flows between old and new workplace locations and the associated changes in car availability, followed by a logistic regression to deepen the analysis on the effect of workplace location changes in conjunction with other factors.

Finally, a similar methodological approach is presented for Change to Driving as the dependent variable, where we explore the factors that make commuters start driving, when they experience a situation of change in their workplace location. In the second part of this analysis, we are using a Heckman model instead of a regular regression in order to address the sample bias introduced by the fact that only workers with a car available can change their mode to driving.

Demographics and Commuting

The demographic overview of the filtered sample is provided in Table 1, in which we crossed the demographic variables and information about the commute with an increase in car availability and the modal switch to driving. The variables have been selected from the survey dataset because the literature suggests a significant association with car commuting and car ownership:

Demographic variables (age group of workers, gender, household income, education, family status):

The review by (Zarabi and Lord, 2019) collected evidence from multiple studies that sociodemographic variables are influencing potential changes in car ownership and commuting mode choice. For example, respondents from single households were more likely to change commuting modes than households with kids. Also, age was found to be related to a mode change towards driving, as middle-aged workers were more likely to select this mode. Gender and income were not associated in the review. However, other studies suggest an association between income and commuting mode (Hu and Schneider, 2017; Schwanen and Mokhtarian, 2005) and car ownership (Clark, 2007; Dargay, 2001; Nolan, 2010). The same is true for gender (Scheiner and Holz-Rau, 2012; Wang et al., 2020), and education (Clark et al., 2016).

Commuting variables (always car available, distance home-work, mode to work, transfers home-work, travel time ratio):

Car availability is a precondition for driving to work and thus it is naturally selected for this study. The same is true for the current mode to work, which is needed for the analysis. The distance home-work has been identified as a significant predictor for both commuting mode choice and car ownership before (Dargay and Hanly, 2007), the same is true for the travel time ratio and the transfers on the commute (Ha et al., 2020).

As shown in previous research, we will include these variables in our analysis as potential predictors of changes in commuting mode choice and car ownership.

Table 6: Demographics and commuting

		Car Availability Increase			Change to Driving				
		Yes (n=549)	No (n=5855)	X^2-Test p-value	Yes (n=675)	No (n=5675)	X^2-Test p-value	Sample (n=6404)	Population[1]
Demographics	**Age group of workers**			**<0.001**			**<0.001**		
	18-24	73 (13.3%)	741 (12.7%)		49 (7.3%)	758 (13.4%)		814 (12.7%)	8.1%
	25-29	162 (29.5%)	1141 (19.5%)		139 (20.6%)	1154 (20.3%)		1303 (20.3%)	7.0%
	30-39	197 (35.9%)	2080 (35.5%)		282 (41.8%)	1980 (34.9%)		2277 (35.6%)	13.6%
	40-49	85 (15.5%)	1188 (20.3%)		140 (20.7%)	1124 (19.8%)		1273 (19.9%)	14.8%
	50-59	26 (4.7%)	625 (10.7%)		53 (7.9%)	586 (10.3%)		651 (10.2%)	14.9%
	60+	6 (1.1%)	80 (1.4%)		12 (1.8%)	73 (1.3%)		86 (1.3%)	24.8%
	Gender			**<0.001**			**0.584**		
	male	225 (41.0%)	2964 (50.6%)		329 (48.7%)	2834 (49.9%)		3189 (49.8%)	51.4%
	female	324 (59.0%)	2891 (49.4%)		346 (51.3%)	2841 (50.1%)		3215 (50.2%)	48.6%
	Household Income			**0.089**			**<0.005**		
	<= 1,500 €	22 (4.0%)	230 (3.9%)		20 (3.0%)	231 (4.1%)		252 (3.9%)	0,27
	1,501 € - 2,000 €	39 (7.1%)	514 (8.8%)		43 (6.4%)	507 (8.9%)		553 (8.6%)	0,14
	2,001 € - 2,500 €	59 (10.7%)	592 (10.1%)		63 (9.3%)	584 (10.3%)		651 (10.2%)	0,13
	2,501 € - 3,000 €	65 (11.8%)	561 (9.6%)		81 (12.0%)	538 (9.5%)		626 (9.8%)	0,13
	3,001 € - 4,000 €	107 (19.5%)	1062 (18.1%)		145 (21.5%)	1014 (17.9%)		1169 (18.3%)	0,1
	4,001 € - 5,000 €	101 (18.4%)	885 (15.1%)		111 (16.4%)	870 (15.3%)		986 (15.4%)	0,09
	5,001 € - 6,000 €	39 (7.1%)	485 (8.3%)		63 (9.3%)	457 (8.1%)		524 (8.2%)	0,05
	>= 6,000 €	35 (6.4%)	450 (7.7%)		57 (8.4%)	424 (7.5%)		485 (7.6%)	0,06
	no answer	82 (14.9%)	1076 (18.4%)		92 (13.6%)	1050 (18.5%)		1158 (18.1%)	0,03
	Education			**0.505**			**<0.05**		
	high school	145 (26.4%)	1653 (28.2%)		162 (24.0%)	1617 (28.5%)		1798 (28.1%)	34.1%
	apprenticeship	81 (14.8%)	952 (16.3%)		126 (18.7%)	891 (15.7%)		1033 (16.1%)	40.7%
	university degree	290 (52.8%)	2930 (50.0%)		347 (51.4%)	2855 (50.3%)		3220 (50.3%)	22.7%
	doctorate	33 (6.0%)	320 (5.5%)		40 (5.9%)	312 (5.5%)		353 (5.5%)	2.5%
	Family Status			**<0.001**			**<0.001**		
	single household	88 (16.0%)	1370 (23.4%)		120 (17.8%)	1331 (23.5%)		1458 (22.8%)	
	DINK[2]	195 (35.5%)	1723 (29.4%)		230 (34.1%)	1677 (29.6%)		1918 (30.0%)	
	family (1 working)	23 (4.2%)	352 (6.0%)		39 (5.8%)	334 (5.9%)		375 (5.9%)	
	family (both working)	121 (22.0%)	1151 (19.7%)		176 (26.1%)	1084 (19.1%)		1272 (19.9%)	
	shared flat	94 (17.1%)	970 (16.6%)		68 (10.1%)	981 (17.3%)		1064 (16.6%)	
	other	28 (5.1%)	289 (4.9%)		42 (6.2%)	268 (4.7%)		317 (5.0%)	
Commuting	**Always car available**			**<0.001**			**<0.001**		
	yes	549 (100%)	3689 (63.0%)		626 (92.7%)	3558 (62.7%)		4238 (66.2%)	68.9%
	no	0 (0%)	2166 (37.0%)		49 (7.3%)	2117 (37.3%)		2166 (33.8%)	
	Distance Home-Work			**0.224**			**<0.001**		
	0-5km	147 (26.8%)	1754 (30.0%)		117 (17.3%)	1775 (31.3%)		1901 (29.7%)	26.1%

5-10km	74 (13.5%)	920 (15.7%)		93 (13.8%)	892 (15.7%)		994 (15.5%)	20.8%
10-25km	173 (31.5%)	1593 (27.2%)		247 (36.6%)	1503 (26.5%)		1766 (27.6%)	30.4%
25-50km	97 (17.7%)	1005 (17.2%)		148 (21.9%)	942 (16.6%)		1102 (17.2%)	11.2%
50-75km	41 (7.5%)	411 (7.0%)		49 (7.3%)	397 (7.0%)		452 (7.1%)	3.2%
>75 km	17 (3.1%)	172 (2.9%)		21 (3.1%)	166 (2.9%)		189 (3.0%)	4.2%
Mode to Work			**<0.001**					
public transport	181 (33.0%)	2450 (41.8%)					2631 (41.1%)	13.5%
driving	104 (18.9%)	1251 (21.4%)					2418 (37.8%)	60.3%
other	264 (48.1%)	2154 (36.8%)					1355 (21.2%)	26,30%
Transfers Home-Work			**0.229**			**<0.001**		
no transfer	285 (51.9%)	3013 (51.5%)		293 (43.4%)	2978 (52.5%)		3298 (51.5%)	
1 transfer	165 (30.1%)	1942 (33.2%)		221 (32.7%)	1868 (32.9%)		2107 (32.9%)	
2 transfers	77 (14.0%)	726 (12.4%)		122 (18.1%)	673 (11.9%)		803 (12.5%)	
3 or more transfers	22 (4.0%)	174 (3.0%)		39 (5.8%)	156 (2.7%)		196 (3.1%)	
Travel Time Ratio (transit/car)			**<0.05**			**<0.001**		
<0.5	57 (10.4%)	486 (8.3%)		99 (14.7%)	435 (7.7%)		543 (8.5%)	
0.5-1	38 (6.9%)	561 (9.6%)		17 (2.5%)	581 (10.2%)		599 (9.4%)	
1-1.5	106 (19.3%)	1419 (24.2%)		88 (13.0%)	1428 (25.2%)		1525 (23.8%)	
1.5-2	124 (22.6%)	1168 (19.9%)		149 (22.1%)	1128 (19.9%)		1292 (20.2%)	
2-2.5	59 (10.7%)	637 (10.9%)		115 (17.0%)	578 (10.2%)		696 (10.9%)	
2.5-3	45 (8.2%)	325 (5.6%)		58 (8.6%)	306 (5.4%)		370 (5.8%)	
>3	43 (7.8%)	501 (8.6%)		80 (11.9%)	459 (8.1%)		544 (8.5%)	
Missing	77 (14.0%)	758 (12.9%)		69 (10.2%)	760 (13.4%)		835 (13.0%)	

[1] Sources: Income: Thierstein et al., 2016; Car Availability, Distance Home-Work, and Mode to Work: (Nobis and Kuhnimhof, 2018)); others: (Statistisches Bundesamt (Destatis), 2021)
[2] "double income, no kids"

The sample shows certain differences to the general population of the Munich Metropolitan Region (MMR) and the state of Bavaria. Our respondents are remarkably younger (sample: 68,6% between 18 and 40 years, MMR: 28.7%) and the population over 60 is heavily underrepresented (1.3% in the sample, 24.8% in the population). However, since the focus of our research is on employed persons, the lack of seniors is justifiable. Still, we must acknowledge that our sample is on average younger than the Bavarian working population.

The share of female and male is balanced, but low incomes are underrepresented while the groups between 3,001€ and 5,000€ are overrepresented. Another remarkable deviation between the general population of the MMR and the studied sample is the distribution of education levels. In our sample, the share of university degrees and doctoral degrees is higher (55.8%) than the average (25.2%). Thus, combining the deviations of age, income, and education, the sample is closer to the group of "knowledge workers" than to the general population, which is relevant for the policy implications of our results.

While no reference data exists for the family status, the share of respondents who always have access to a car (66.2%) is similar to the figure for employed residents of the MMR (68.9%). The distribution of distances from home to work is reasonably similar to the Bavarian distribution, but our sample has a much higher share of using public transport (41.1%) than the general population in Bavaria (13.5%). This can be attributed in part to the fact that the MMR has a better public transport supply than many other, more rural regions in Bavaria.

Across the dependent variables "Car Availability Increase" and "Change to Driving", we performed a Chi-Squared-test with all variables presented in Table 1.

For "Car Availability Increase", age, gender, family status, always car available, and mode to work were significantly associated with a confidence level of 95%. For "Change to Driving", age, family status, always car availability, distance home-work, transfers home-work, and travel time ratio yielded significant results. These relationships are studied to further explore the effects of a change of a workplace location.

In order to better understand how the change of workplace location affects the dependent variables, we are including another set of variables about the clusters of home and work location, as well as information about the changes associated with the change in workplace.

These variables have been selected because – similar to the sociodemographic and commuting-related variables in Table1 – the literature suggests an association between these variables and our dependent variables.

As described in the literature review, the location of both residence and workplace is important for car availability and commuting mode choice (Acker et al., 2014; Zarabi and Lord, 2019). Thus we also expect that changes of these clusters might be associated to our dependent variables. For the variables in the change section of Table 2, we follow the habit theory approach (Verplanken et al., 2008; Wood et al., 2005) that suggests that these major disruptions such as residence change and workplace change are associated to changes in car availability and driving. Change in trip characteristics (driving, travel time ratio, distance to work, number of transfers) are included because of the previously described significance of these factors in previous work (Dargay and Hanly, 2007; Ha et al., 2020). Lastly, we include a variable about the reason for the new workplace, since it can be assumed that some reasons for individual relocations might have other impacts than others (this is in part suggested as socio-professional factors by (Zarabi and Lord, 2019).

Table 7: Locations and changes

		Car Availability Increase			Change to Driving			
		Yes (n=549)	No (n=5855)	X²-Test p-value	Yes (n=675)	No (n=5675)	X²-Test p-value	Sample (n=6404)
Current Location	**Cluster Residence**			**0.474**			**<0.001**	
	urban-central	317 (57.7%)	3502 (59.8%)		292 (43.3%)	3510 (61.9%)		3819 (59.6%)
	urban-decentral	99 (18.0%)	907 (15.5%)		122 (18.1%)	872 (15.4%)		1006 (15.7%)
	peripheral-rural	38 (6.9%)	402 (6.9%)		84 (12.4%)	349 (6.1%)		440 (6.9%)
	urban-catchment	95 (17.3%)	1044 (17.8%)		177 (26.2%)	944 (16.6%)		1139 (17.8%)
	Cluster Workplace			**0.152**			**<0.001**	
	urban-central	374 (68.1%)	4170 (71.2%)		380 (56.3%)	4136 (72.9%)		4544 (71.0%)
	urban-decentral	98 (17.9%)	846 (14.4%)		149 (22.1%)	781 (13.8%)		944 (14.7%)
	peripheral-rural	17 (3.1%)	154 (2.6%)		39 (5.8%)	131 (2.3%)		171 (2.7%)
	urban-catchment	60 (10.9%)	685 (11.7%)		107 (15.9%)	627 (11.0%)		745 (11.6%)
Change	**Residence change**			**0.514**			**0.474**	
	yes	438 (79.8%)	4744 (81.0%)		554 (82.1%)	4588 (80.8%)		5182 (80.9%)
	no	111 (20.2%)	1111 (19.0%)		121 (17.9%)	1087 (19.2%)		1222 (19.1%)
	Workplace Change			**<0.001**			**<0.005**	
	yes	417 (76.0%)	3570 (61.0%)		455 (67.4%)	3491 (61.5%)		3987 (62.3%)
	no	132 (24.0%)	2285 (39.0%)		220 (32.6%)	2184 (38.5%)		2417 (37.7%)
	Change Residential Cluster			**<0.005**			**<0.001**	
	away from urban-central	81 (14.8%)	605 (10.3%)		150 (22.2%)	531 (9.4%)		686 (10.7%)
	to urban-central	24 (4.4%)	383 (6.5%)		15 (2.2%)	391 (6.9%)		407 (6.4%)
	other change / no change	444 (80.9%)	4867 (83.1%)		510 (75.6%)	4753 (83.8%)		5311 (82.9%)
	Change Workplace Cluster			**<0.001**			**<0.001**	
	away from urban-central	59 (10.7%)	323 (5.5%)		108 (16.0%)	268 (4.7%)		382 (6.0%)
	to urban-central	31 (5.6%)	358 (6.1%)		14 (2.1%)	369 (6.5%)		389 (6.1%)
	other change / no change	459 (83.6%)	5174 (88.4%)		553 (81.9%)	5038 (88.8%)		5633 (88.0%)
	Change in Driving			**<0.001**				
	no longer driving	16 (2.9%)	760 (13.0%)					776 (12.1%)
	new driving	225 (41.0%)	450 (7.7%)					675 (10.5%)
	other change / no change	308 (56.1%)	4645 (79.3%)					4953 (77.3%)
	Change in Travel Time Ratio			**0.082**			**<0.001**	
	public transport improved	194 (35.3%)	2215 (37.8%)		202 (29.9%)	2191 (38.6%)		2409 (37.6%)
	public transport worsened	217 (39.5%)	2209 (37.7%)		303 (44.9%)	2107 (37.1%)		2426 (37.9%)
	no change	17 (3.1%)	298 (5.1%)		22 (3.3%)	286 (5.0%)		315 (4.9%)
	missing	121 (22.0%)	1133 (19.4%)		148 (21.9%)	1091 (19.2%)		1254 (19.6%)
	Change in Distance to Work			**<0.01**			**<0.001**	
	reduction of 5 km or more	181 (33.0%)	1966 (33.6%)		209 (31.0%)	1919 (33.8%)		2147 (33.5%)
	reduction between 1 and 5 km	48 (8.7%)	630 (10.8%)		32 (4.7%)	641 (11.3%)		678 (10.6%)

relatively stable (+/- 1 km)	60 (10.9%)	732 (12.5%)		46 (6.8%)	738 (13.0%)		792 (12.4%)
increase between 1 and 5 km	46 (8.4%)	657 (11.2%)		61 (9.0%)	638 (11.2%)		703 (11.0%)
increase by 5 km or more	214 (39.0%)	1870 (31.9%)		327 (48.4%)	1739 (30.6%)		2084 (32.5%)
Change in Transfers to Work			**0.701**			**<0.001**	
less transfers	153 (27.9%)	1559 (26.6%)		149 (22.1%)	1551 (27.3%)		1712 (26.7%)
more transfers	141 (25.7%)	1469 (25.1%)		244 (36.1%)	1353 (23.8%)		1610 (25.1%)
no change	255 (46.4%)	2827 (48.3%)		282 (41.8%)	2771 (48.8%)		3082 (48.1%)
Reason for new Workplace[a]			**<0.005**			**0.060**	
private reasons	16 (2.9%)	102 (1.7%)		19 (2.8%)	96 (1.7%)		118 (1.8%)
shorter commute	45 (8.2%)	441 (7.5%)		65 (9.6%)	418 (7.4%)		486 (7.6%)
career starter	190 (34.6%)	1281 (21.9%)		160 (23.7%)	1290 (22.7%)		1471 (23.0%)
promotion	90 (16.4%)	976 (16.7%)		114 (16.9%)	945 (16.7%)		1066 (16.6%)
better offers around workplace	23 (4.2%)	189 (3.2%)		32 (4.7%)	179 (3.2%)		212 (3.3%)
relocation (job-related)	47 (8.6%)	512 (8.7%)		61 (9.0%)	493 (8.7%)		559 (8.7%)
more Public Transport-accessible location	9 (1.6%)	87 (1.5%)		5 (0.7%)	90 (1.6%)		96 (1.5%)
missing	129 (23.5%)	2267 (38.7%)		219 (32.4%)	2164 (38.1%)		2396 (37.4%)

[a] Explanation of categories:

- Private reasons: Respondents actively choose another workplace location for private reasons, such a living closer to a spouse, managing day-care routines of children, …
- Shorter commute: respondents actively choose another workplace location because they wanted to shorten their commute
- Career Starter: typically, students who are starting a new job outside the university
- Promotion: The new job location (or rather the new employer) offers a more attractive job
- Better offers around workplace: Respondents choose a new workplace because the old one was not attractive anymore in terms of services at the location such as shopping, lunch, day-care for kids, etc.
- Relocation (job-related): Respondents did not actively choose a new location, but corporate decisions affected the individuals
- More Public Transport-accessible location: Respondents were dissatisfied with the public transport accessibility of the old workplace and thus actively changed their workplace.

The clusters of residence and workplace are not associated with the increase in car availability, but significantly associated with the modal shift to driving. Across all clusters, 62.3% of respondents have changed their workplace within three years prior to the survey and 80.9% have changed their residential location in the same period. These relative high rates of workplace and residential mobility are caused by the recruitment strategy of the original survey, which set an emphasis on the situations of location changes and is in line with our focus on the change of workplace location.

Since we assume that not only the fact that a workplace has been relocated is important, but more importantly which kind of changes have which effect, we add information about the direction of change in the variables "Change Residence Cluster" and " Change Workplace Cluster". In order to maintain a sufficient number of observations per category, we have grouped these changes between cluster into "no longer urban-central" for those who left the urban-central cluster for another cluster, and "new urban-central" for those who moved in the urban-central cluster. Both workplace and residence changes are significantly associated with both dependent variables.

Changes in Driving (respondents who either start or stop using the car on the daily commute) are associated with the increase of car availability, as 41% of those who started driving did also increase their car availability. A set of variables covers the comparison between commuting options to the old and the new workplace: change in travel time ratio, change in distance to work, and change in transfers to work is significantly associated with the modal switch to driving, but not with the increase of car availability. Another variable "reason for new workplace" includes information about the reason why the workplace has moved. It is associated with the increase in car availability, but not with the uptake of driving to work. These relationships are also included to examine the effects of workplace location changes, among the other variables.

Association of workplace relocation with car availability

First, we examine whether the change of the workplace location may be a trigger to change the individual car availability, using descriptive methods. With a filtered version of the dataset, where only respondents are included who have changed their workplace location, but not their residential location, Table 3 summarizes the individual car availability at the old and the new workplace. Overall, 178 out of 787 filtered respondents (22.6%) reported a change in car availability after changing the workplace location.

Table 8: Car availability at old and new workplace by spatial cluster of workplace

	Cluster of Workplace				
	Urban-central	Urban-decentral	Peripheral-areas	Urban-catchment	**Sample**[1]
Car Availability (previous workplace)	n = 611	n = 84	n = 7	n = 71	n = 773
always (private car)	325 (52,0%)	59 (70,2%)	6 (85,7%)	41 (57,7%)	431 (54,8%)
always (company car)	28 (4,5%)	3 (3,6%)	0 (0,0%)	10 (14,1%)	41 (5,2%)
on request	74 (11,8%)	7 (8,3%)	0 (0,0%)	3 (4,2%)	84 (10,7%)
car sharing	13 (2,1%)	0 (0,0%)	0 (0,0%)	2 (2,8%)	15 (1,9%)
no car available	171 (27,4%)	15 (17,9%)	1 (14,3%)	15 (21,1%)	202 (25,7%)
Car Availability (current workplace)	n = 620	n = 58	n = 10	n = 70	n = 758
always (private car)	353 (56,6%)	43 (72,9%)	6 (60,0%)	43 (61,4%)	445 (58,3%)
always (company car)	36 (5,8%)	2 (3,4%)	0 (0,0%)	6 (8,6%)	44 (5,8%)
on request	86 (13,8%)	8 (13,6%)	1 (10,0%)	6 (8,6%)	101 (13,2%)
carsharing	31 (5,0%)	1 (1,7%)	0 (0,0%)	3 (4,3%)	35 (4,6%)
no car available	114 (18,3%)	4 (6,8%)	3 (30,0%)	12 (17,1%)	133 (17,4%)

[1] missing to 787: no answer

In general, we observe a trend towards more car availability across all clusters. The share of workers who always have access to a private car rises from 54.8% at the old locations to 58.3% for the point in time where a new workplace location was reported. At the same time, the share of workers who never have access to a car decreases from 25.7% to 17.4%, and this trend is present in all clusters. Between the clusters, however, there are significant differences between the groups urban-central and all other clusters combined (Chi-Squared-Test, $p<.01$ for old locations, $p<.001$ for current workplace). On average, workers employed in urban-central locations have a lower car availability compared to the other clusters.

Figure 2 visualizes the flow between car availability categories of those respondents whose workplace location changes from urban-central to another, non-central cluster.

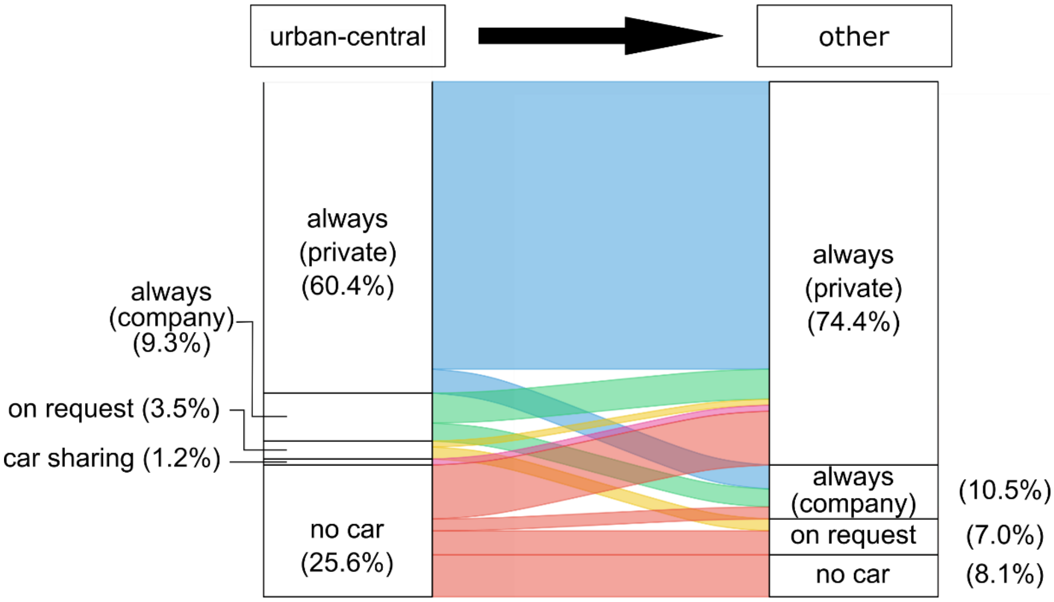

Figure 13: Car Availability - flow from urban-central to other cluster (n=86)

If the new workplace is located in a non-urban-central location, but was previously urban-central, we observe that the share of workers who always have access to a private car is increasing, while the share of those who do not have a car is diminishing. This is what one would expect – if the new workplace is located in a cluster that is more rural and less accessible by public transport than the old, urban-central workplace, workers buy a car to get to work.

However, we do not observe this elasticity when looking at changes in the opposite direction. If the old workplace was in another cluster and moved to urban-central, the share of workers who always have access to a car remains stable and does not decrease, while the share of workers without car decreases slightly. This is visualized in Figure 14.

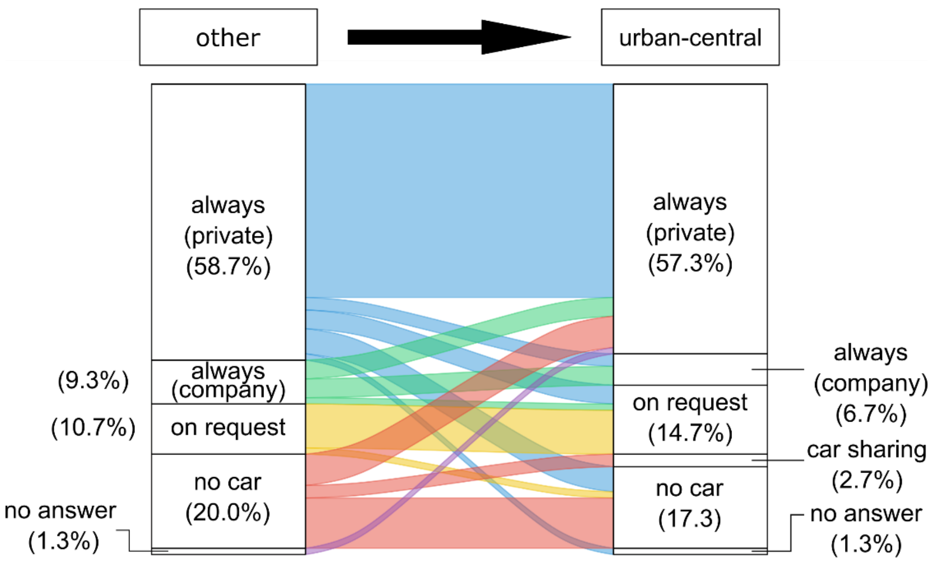

Figure 14: Car Availability - flow from other to urban-central cluster (n=75)

To analyze the explanatory variables of changing car availability along with the change in workplace location beyond the descriptive flow analysis, we use the variables presented in Table 1 and Table 7 to analyze their effect on the dependent binary dummy variable "Car Availability Increase" (Yes = before the change, a car was not "always" available, now the person has always access to a car).

In order to find potential predictors for the increase in car availability, we are using a logistic regression with the dependent variable "Car Availability Increase" and test an association with the significant variables presented in Table 1 and Table 2. Table 9 shows the resulting model, in which the predictors were selected through forward-selection and minimization of BIC.

Table 9: Logistic regression for increase in car availability

	Dependent variable			
	Car Availability Increase			
	Estimate	SE	T-statistic	P-value
(Intercept)	-3.834	0.33	-11.629	< 0.001
Age group of worker 18-24 (0,1)	**0.425**	**0.185**	**2.296**	**0.022**
Age group of worker 25-29 (0,1)	**0.56**	**0.138**	**4.05**	**< 0.001**
Age group of worker 30-39 (0,1)[a]				
Age group of worker 40-49 (0,1)	**-0.335**	**0.159**	**-2.116**	**0.034**
Age group of worker 50 and older (0,1)	**-0.686**	**0.231**	**-2.975**	**0.003**
Gender male[a] (1,0)				
Gender female (1,0)	**0.369**	**0.106**	**3.473**	**< 0.001**
Family status single household (0,1)[a]				
Family status DINK (0,1)	**0.585**	**0.159**	**3.675**	**< 0.001**
Family status family (1 working) (0,1)	0.269	0.291	0.925	0.35
Family status family (both working) (0,1)	**0.756**	**0.183**	**4.141**	**< 0.001**
Family status shared flat (0,1)	**0.525**	**0.183**	**2.867**	**0.004**
Family status other (0,1)	**0.838**	**0.272**	**3.079**	**0.002**
Travel time ratio better (1,0)	0.34	0.267	1.272	0.2
Travel time ratio equal (1,0)[a]				
Travel time ratio worse (1,0)	**0.482**	**0.266**	**1.813**	**0.07**
Change in Distance to Work (reduction of 5 km or more) (1,0)	0.186	0.196	0.945	0.34
Change in Distance to Work (reduction between 1 and 5 km) (1,0)	-0.076	0.245	-0.309	0.76
Change in Distance to Work (no sig. change) (1,0)[a]				
Change in Distance to Work (increase between 1 and 5 km) (1,0)	-0.065	0.238	-0.273	0.78
Change in Distance to Work (increase by 5 km or more) (1,0)	**0.405**	**0.193**	**2.1**	**0.036**
Change in Residential Cluster (away from urban-central) (1,0)	**0.27**	**0.152**	**1.771**	**0.077**
Change in Residential Cluster (no change) (1,0)[a]				
Change in Residential Cluster (to urban-central) (1,0)	-0.39	0.245	-1.591	0.11
Change in Workplace Cluster (away from urban-central) (1,0)	**0.683**	**0.175**	**3.9**	**< 0.001**
Change in Workplace Cluster (no change) (1,0)[a]				
Change in Workplace Cluster (to urban-central) (1,0)	0.133	0.212	0.63	0.53
Pseudo-R^2 (Nagelkerke)	0.058			

The model has a Pseudo-R^2 (Nagelkerke) of 0.058 and shows no signs of multicollinearity, according to Generalized Variance Inflation Factors (GVIF) well below 5 and $GVIF^{(1/(2 \times Df))}$ values below 2 (Fox and Monette, 1992; Gareth et al., 2013).

From the demographic variables, younger ages (18-29 years) are associated positively with an increase in car availability whereas the older ages (over 40) are associated negatively. This is expected, since car availability is already higher in older ages and the increase in car availability happens often during the phase of family growth or when starting a first job. Females are also positively associated. Comparing to the reference category single household, most other family statuses are associated positively, indicating that in situations with more household members than just a single household, an increase in car availability is more likely. From the variables about the location change, a worse travel time ratio between public transport and driving is associated positively with an increase in car availability and the same is true for an increase in commuting distance of 5 km or more. A change in the residential cluster from urban-central to another, less central cluster is associated positively on the $p<0.1$-level while a change in the workplace cluster in the same direction is associated positively on the $p<0.001$ level.

Association of Workplace Relocation and Commuting Mode Choice

In the next step, we analyze whether the change of workplace location is a trigger for modal change from driving to public transport and vice versa. We are again using the filtered dataset with only those respondents, who change their workplace with a stable residence for the flow analysis.

Figure 15 shows the modal split at the old (grey) and new (yellow) locations across all clusters.

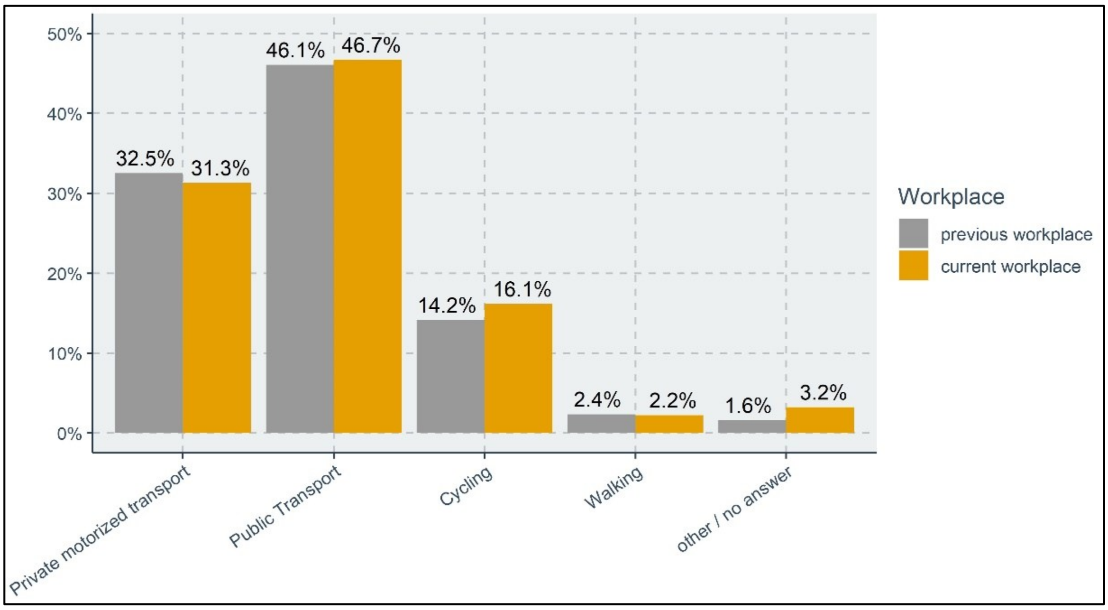

Figure 15: Main mode to work at old and new workplace location (n = 787)

This first attempt at understanding modal changes between the old and new workplace reveals no big trends within the max. 3-year-obervation period. A slight trend towards less car use (-1.2%) and more cycling (+1.9%) is observed, but these figures are marginal. In the filtered dataset, 32.4% of the respondents (n=255 participants) changed their usual mode to work.

Figure 16 visualizes the modal split of the "modal changers" at the old (left) and new (right) locations, for those workers whose workplace has moved from an urban-central location to a non-urban-central location.

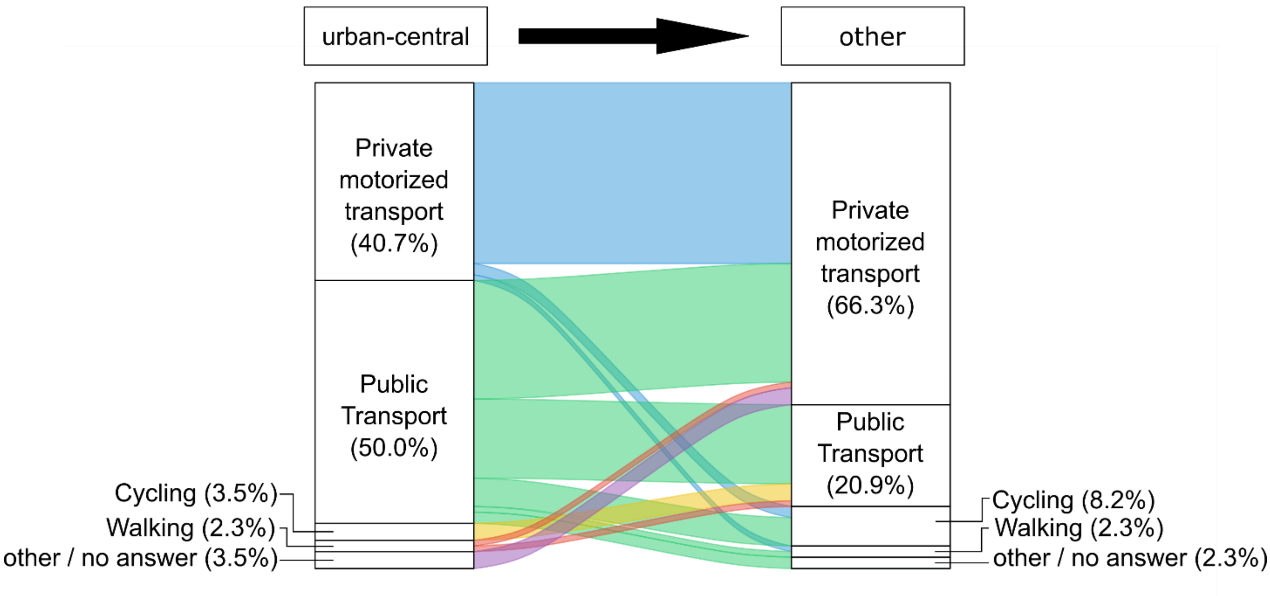

Figure 16: Mode Choice - flow from urban-central to other cluster (n=86)

We observe that along with the change of the workplace location to a non-urban-central cluster, the share of commuters using private motorized transport increases while the share of public transport shrinks. More workers drive to work and fewer use public transport for their commute after the workplace location changes from an urban-central area to another area.

This effect is present in both directions. If the new workplace – that was previously in another spatial cluster – is now in an urban-central area, we identify the opposite effect, as shown in Figure 17.

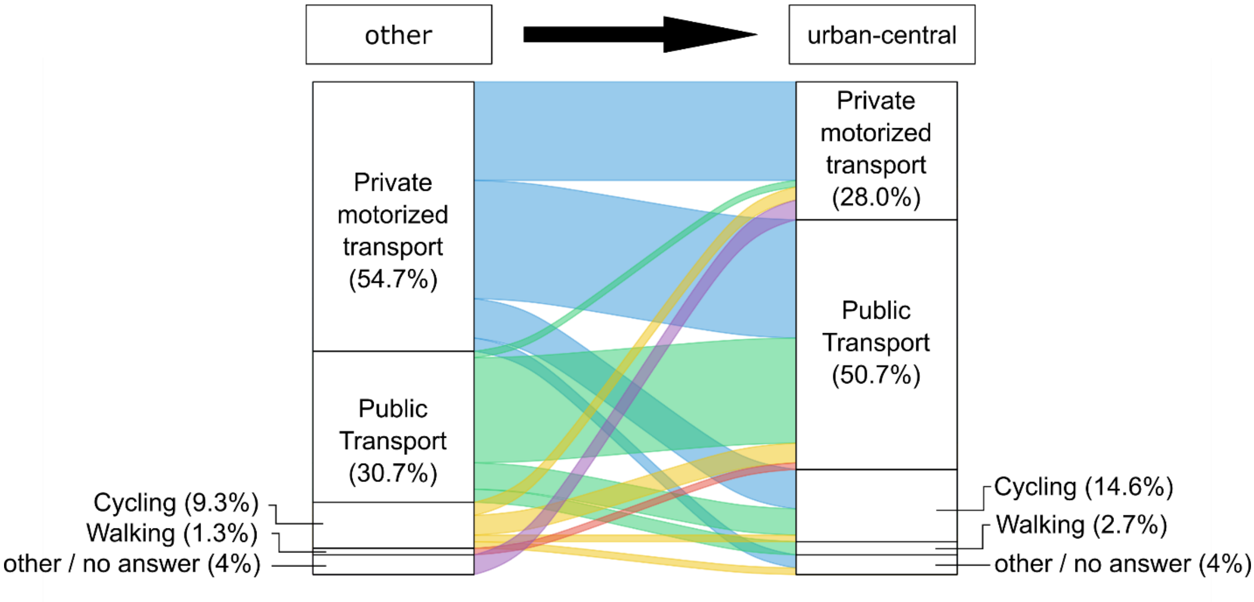

Figure 17: Mode Choice - flow from other to urban-central cluster (n=75)

When workplaces change to an urban-central location, driving is reduced while the share of public transport use increases. For modes other than driving and public transport, we can observe some trends, but due to the low number of cases this should be considered anecdotal. In these cases, we see a slight trend towards more cycling, which is independent of the change in spatial clusters of workplace locations (Figure 15).

Heckman model on change to driving

As described earlier, we are now using a Heckman selection model to understand the associations between the explanatory variables and the change to driving as dependent variable. As car availability is a precondition for the change to driving, since without access to a car, driving is not possible, we first fit a probit model with car availability at the current point in time (Always car available = 1) as the binary dependent variable in our Heckman selection equation (see Table 5). The variables were selected based stepwise regression considering the BIC as a comparative value. The Generalized Variance Inflation Factor (GVIF) showed values well below 5 and GVIF(1/(2×Df)) values below 2, showing no evidence of multicollinearity.

In the following step, we model the association with the change to driving in the outcome equation.

Table 5: Probit model (selection model) on workers having always access to a car

	Dependent variable (selection model)			
	Always Car Available (1,0)			
	Estimate	SE	T-statistic	P-value
(Intercept)	**0.734**	**0.112**	**6.559**	**< 0.001**
Age group of worker 18-24 (0,1)	**-0.242**	**0.074**	**-3.254**	**0.001**
Age group of worker 25-29 (0,1)	-0.052	0.055	-0.95	0.34
Age group of worker 30-39 (0,1)[a]				
Age group of worker 40-49 (0,1)	**0.203**	**0.054**	**3.749**	**< 0.001**
Age group of worker 50 and older (0,1)	**0.226**	**0.067**	**3.393**	**< 0.001**
Household income <= 1,500 € (1,0)	**-0.465**	**0.112**	**-4.143**	**< 0.001**
Household income 1,501 € - 2,000 € (1,0)	**-0.255**	**0.088**	**-2.898**	**0.004**
Household income 2,001 € - 2,500 € (1,0)	**-0.171**	**0.083**	**-2.062**	**0.039**
Household income 2,501 € - 3,000 € (1,0)[a]				
Household income 3,001 € - 4,000 € (1,0)	0.006	0.074	0.083	0.93
Household income 4,001 € - 5,000 € (1,0)	0.109	0.078	1.399	0.16
Household income 5,001 € - 6,000 € (1,0)	0.107	0.091	1.186	0.24
Household income >= 6,000 € (1,0)	**0.51**	**0.099**	**5.131**	**< 0.001**
Household income no answer (1,0)	-0.043	0.079	-0.543	0.59
Family status single household (0,1)[a]				
Family status DINK (0,1)	-0.037	0.065	-0.568	0.57
Family status family (1 working) (0,1)	-0.093	0.093	-0.999	0.32
Family status family (both working) (0,1)	0.086	0.073	1.18	0.24
Family status shared flat (0,1)	**-0.298**	**0.07**	**-4.28**	**< 0.001**
Family status other (0,1)	0.046	0.098	0.467	0.64
Travel time ratio (transit/car) <0.5 (0,1)	**0.274**	**0.095**	**2.871**	**0.004**
Travel time ratio (transit/car) 0.5-1 (0,1)	**-0.245**	**0.068**	**-3.612**	**< 0.001**
Travel time ratio (transit/car) 1-1.5 (0,1)	**-0.136**	**0.052**	**-2.608**	**0.009**
Travel time ratio (transit/car) 1.5-2 (0,1)[a]				
Travel time ratio (transit/car) 2-2.5 (0,1)	0.109	0.066	1.637	0.1
Travel time ratio (transit/car) 2.5-3 (0,1)	**0.18**	**0.087**	**2.082**	**0.037**
Travel time ratio (transit/car) >=3 (0,1)	**0.222**	**0.081**	**2.723**	**0.006**
Residence Urban-Decentral (1,0)[a]				
Residence Urban-Central (1,0)	**-0.266**	**0.069**	**-3.846**	**< 0.001**
Residence Peripheral-Rural (1,0)	**0.349**	**0.112**	**3.124**	**0.002**
Residence Urban-Catchment (1,0)	**0.32**	**0.08**	**4.019**	**< 0.001**
Workplace Urban-Decentral (1,0)[a]				
Workplace Urban-Central (1,0)	**-0.248**	**0.082**	**-3.03**	**0.002**
Workplace Peripheral-Rural (1,0)	0.311	0.2	1.552	0.12
Workplace Urban-Catchment (1,0)	-0.082	0.095	-0.857	0.39
N	5079			
Log-likelihood	-2916			
BIC	6088			
Model χ^2	691			
Prob > χ^2	0.000			

[a] Reference category

In accordance with the expectations, the model shows a negative association between the youngest age group (18-24) and car availability whereas the older groups (over 40) are positively associated. The middle age groups (including the reference group 30-39) did not show significant associations. Similarly, the lowest household income groups are negatively associated while the highest group is associated positively. The travel time ratio between transit and car shows expected results as relatively low rations between 0.5 and 1.5 are negatively associated whereas ratios of 2.5 or higher are positively associated. However, workers whose travel time ratio is below 0.5 show a positive association as well. Lastly, the associations of residence and workplace are included in the model. As expected, urban-central residences are negatively associated with having always access to a car, while the other, less central locations are positively associated. For workplace locations, only the urban-central cluster has a significant association, being a negative predictor if the workplace is located centrally.

The second step of the Heckman model is the outcome model, presented in Table 6. Predictors were selected based on a BIC minimization. Again, there is no multicollinearity as the Generalized Variance Inflation Factors are below 5 and GVIF(1/(2×Df)) values below 2.

Table 6: Heckman probit model (outcome equation) on change to driving

	Dependent variable (outcome model)			
	Change to driving (1,0)			
	Estimate	SE	T-statistic	P-value
(Intercept)	0.035	0.027	1.296	0.2
Gender male[a] (1,0)				
Gender female (1,0)	**0.026**	**0.012**	**2.222**	**0.026**
Travel time ratio better (1,0)	0.047	0.025	1.831	0.067
Travel time ratio equal (1,0)[a]				
Travel time ratio worse (1,0)	**0.091**	**0.025**	**3622**	**< 0.001**
Change in Distance to Work (reduction of 5 km or more) (1,0)	**0.065**	**0.022**	**3.012**	**0.003**
Change in Distance to Work (reduction between 1 and 5 km) (1,0)	-0.011	0.025	-0.428	0.67
Change in Distance to Work (no sig. change) (1,0)[a]				
Change in Distance to Work (increase between 1 and 5 km) (1,0)	0.044	0.025	1.778	0.076
Change in Distance to Work (increase by 5 km or more) (1,0)	**0.086**	**0.021**	**4.05**	**< 0.001**
Change in Transfers to Work (less transfers) (1,0)	-0.019	0.016	-1.238	0.22
Change in Transfers to Work (no change) (1,0)				
Change in Transfers to Work (more transfers) (1,0)	**0.059**	**0.015**	**3795**	**< 0.001**
Change in Residential Cluster (away from urban-central) (1,0)	**0.061**	**0.019**	**3.253**	**0.001**
Change in Residential Cluster (no change) (1,0)[a]				
Change in Residential Cluster (to urban-central) (1,0)	-0.046	0.027	-1717	0.086
Change in Workplace Cluster (away from urban-central) (1,0)	**0.195**	**0.024**	**8.047**	**< 0.001**
Change in Workplace Cluster (no change) (1,0)[a]				
Change in Workplace Cluster (to urban-central) (1,0)	**-0.08**	**0.026**	**-3058**	**0.002**
N	5079			
ρ	-0.271			

Inverse Mills Ratio (car availability)	-0.093 (SE 0.027, p<0.001)

[a] Reference category

In general, we found that gender is the only variable from the categories demographics (see Table 1: age, gender, household income, education, family status) and current location (see Table 2: cluster residence, cluster workplace) that is a significant predictor in the outcome equation. Females show a positive association with the change to driving, compared to the male reference category. The other explanatory variables describe changes between old and new location: A worsening of the travel time ration between public transport and driving is positively associated with a change to driving on the commute, which is expected. If the distance to work is reduced by 5 km or more, the odds of starting to drive is increasing as well. At the other end of the scale, if the distance increased by 5 km or more, we see the same association. Thus, we interpret that major changes in the distance to work, independent whether the trip is shorter or longer, are associated with a change to driving. With smaller changes, the old mode of transport might still work, and no change is triggered. Also positively associated is a change in transfers to work, in the sense that more transfers are needed. This is expected as well, since more transfers make the public transport commute less attractive. The remaining two variables deal with the spatial clusters of residential location and workplace location. As we have expected, a change away from urban-central of the residential location is positively associated with the change to driving. In line with our expectations, the change of the workplace location away from urban-central shows the strongest effect (it has also the biggest impact on the Pseudo-R^2) and has a highly significantly positive association with a change to driving. At the same time, the workplace relocation towards a location in the urban-central cluster is negatively associated.

The Inverse Mills Ratio is a highly significant predictor in the outcome model, which is an indication that the unobserved factors that cause someone to have changed to driving are also the ones causing car availability.

4.5. Discussion

Association between workplace relocation and car availability

In the flow diagrams, the workplace relocation is associated with a modal shift towards more car availability in those workers, whose workplace moved from an urban-central cluster to another cluster. Interestingly, the elastic was only unidirectional: a move to the urban-central cluster (from another cluster) does not make commuters reduce their car availability, even though many workers switch to public transport for their daily trips to work.

In the logistic regression for increase in car availability, we found a highly significant ($p<.001$) positive association with a change in the workplace cluster from urban-central to another cluster. This is confirming our expectation that the workplace relocation is strongly associated with an increase in car availability if the workplace is relocated to a less central location. It is a strength of our study that the results of descriptive analysis using flow diagrams and statistical analysis are coming to the same conclusion and that these results are also in line with the literature.

Association between workplace relocation and a change to driving to work

The flow diagrams showed important differences in the modal split at the old and new workplace, suggesting an association between relocation to a more central workplace location and a model shift away from car and to public transport. A relocation to a less central workplace location seems associated with more driving and less public transport.

In the Heckman model, the selection model with always a car available as the dependent variable found basically expected predictors. One aspect to be discussed is the positive association between a very good travel time ratio between public transport and driving of <0.5 and car ownership. Potentially, this could be explained by rural residential locations that provide a direct and very fast rail connection to the workplace (typical commuter rail) but require a car for other trip purposes. Regarding the family structure, we would expect, based on national mobility surveys (Nobis and Kuhnimhof, 2018), a positive association between living in a household with kids, which was not found. In our data, the only significant family status is living in a shared flat, presumably since shared flat dwellers are typically associated with lower incomes and urban areas.

The outcome model was then used to examine the associations with a change to driving to work. As we have hypothesized, the workplace relocation to a less central cluster is highly positively associated to a modal switch to driving. Also, the opposite direction (relocation from non-central location to urban-central) is negatively associated with a switch to driving, which is in line with our expectations. The other significant associations were as expected, showing that a decrease in public transport commuting quality (expressed by the travel time ration compared to cars and the number of transfers) is positively associated with a change to driving and that also a relocation of the residence to a less-central cluster is associated with a change to driving. Again it is a strength of our study that the results from descriptive and statistical analysis are in line and the findings match our expectations based on the literature.

Limitations

The approach of this study allows us to better understand the association between the workplace relocation, changes in car availability and mode choice to work with a focus on well-educated commuters with relatively high incomes in the Munich Metropolitan region. The relatively short period between the points in time of old and new locations help to minimize other influencing factors that are not part of our variables, such as non-surveyed changes in family situation, income, or major changes in the regional transport supply. However, there is still some extent of uncertainty in these assumptions. While we can control for some demographic variables and for variables about the location change, we miss some potentially important information such as changes in the family structure or in the household income, which were not part of the original survey (only static information is available). Still, the relatively short observation period helps to minimize these impacts. Also, information about attitudes and values of the workers could have been beneficial in understanding their behavior in terms of increasing their car availability.

Several factors impact the representativeness of the surveyed sample. In addition to the figures presented in section 5.1, we must acknowledge a self-selection bias in the sample. Seeing that participation in the survey was voluntary and the information about it was spread through partner organizations and the media, it is expected that the invitation attracted a population that is generally more interested in mobility and probably also more likely to re-consider their daily mobility choices and move towards sustainable alternatives. This is in line with the previously described skewness of the sample towards highly educated workers. This is important when concluding on policy implications, as the results do not speak for a representative average of the MMR's population, but rather for so-called knowledge workers, who are likely to have office jobs, a relatively high income, and no fixed shift times at work. Additionally, the observed willingness to switch to sustainable transport modes is probably overestimated as a result of the self-selection bias in the survey.

At the same time, self-selection of residence and workplace is a factor that we can only partially control for. Our variable about the reason for the workplace change gives us some information, such as "shorter commute" as the reason for a voluntary workplace relocation.

However, these factors were not significant in the model and did not contribute to better model metrics. Thus, the variable was removed in the stepwise model selection. Further studies could improve the categories of this variable and especially qualitative research could improve the understanding of the association of why a workplace relocation happens and the resulting changes in commuting behavior and car ownership.

The classification of the MMR into spatial clusters has been proven to be helpful for statistical analysis and already includes some aspects of the 5 D's mentioned in the literature: Density (number of opportunities per spatial unit), Diversity (mixed land use), Design (buildings, streetscape, …) and Distance to (rail-based) public transport (Cervero and Kockelman, 1997; van Wee, 2002), but further research on this subject could instead use more gradual categories, e.g. accessibility indicators (including destination accessibility), public transport quality indicators, and more detailed clusters, in order to uncover more details of what exactly is the key for influencing mode choice on the trip to work from a location perspective. Also, individual attitudes, values, and preferences have not been part of this study and future research should take these important attributes into account. The same is true for the micro-level of the built environment around the workplace locations, as well as availability and pricing of parking at the workplace. These are attributes which are not covered by the spatial clusters but were important explanatory variables for car commuting in the literature.

Discussion of our results considering the current COVID-19 pandemic

The COVID-19 pandemic has fundamentally disrupted the everyday life of people all over the world and has potentially huge implications for the role of workplace locations after the pandemic. During the pandemic, lockdowns and travel restrictions moved a significant part of the workforce into the home office, establishing new structures both technically but also structurally that enable working from home especially in many knowledge-intense firms (Kolarova et al., 2021).

One important question that goes beyond the short-term impacts is if and how these changes will persist for a post-pandemic world and what that means for the role of workplace locations, in our context. According to recent media articles, large companies such as Google or Microsoft are already implementing policies that allow a certain number of days working from home for all employees for the future. At the same time, these companies are reducing their offices spaces to save costs. If working from home is a permanent option, further research can explore the importance of workplace locations as an influence on car availability and mobility behavior is going to be reduced and that also the selection of the residential location is impacted, if a trip to the office is only needed for few days per week.

A recent paper by van Wee and Witlox (2021) is using a multiperspective view to give a first assessment of potential long-term effects on the pandemic on activity participation and travel behavior. They conclude that permanent effects on travel behavior are possible, but also that some fundamental characteristics of travel behavior such as constant travel time budgets are likely to be less affected. Thus, it is likely that also the role of workplace locations will be affected, but further observation and research after the pandemic is needed to concretize the potential shift in the role of workplace locations.

4.6. Conclusions and Outlook

Our results about the association of workplace relocation on increases in car availability and modal change to driving to work emphasize the importance of workplace locations for planning practice and mobility management concepts in metropolitan regions. While the trend has been previously confirmed in many case studies, this work adds the quasi-longitudinal observation which allows for the comparison of the effect of workplace location from other socio-economic, commuting characteristics and demographic factors. It was shown in the flow diagrams that in the affluent, booming Munich Metropolitan Region, commuters increase their car availability if they feel they need it for their daily commute but will not decrease it immediately if there is no longer a need to drive to work.

It was also shown with the flow diagrams that commuting behavior is more flexible than car ownership, which is a more long-term development. With the regression models, we could show that the relocation of the workplace towards a less centralized area is associated positively with an increase in car availability and with a modal shift to driving to work. At the same time, our models show that a relocation towards a more centralized area is negatively associated with increasing car availability and the model shift to car commuting.

Our findings emphasize the importance of the accessibility of workplace locations and have several implications for policy and practice. In terms of mobility management strategies, targeted programs should be aimed at new workers of a workplace location, informing them on an individual level about the mobility options to get to the location. This could reduce the perceived need to buy a car by reducing and avoiding misinformation. This strategy could focus on preventing (future) car ownership rather than trying to reduce existing cars and is using the window of opportunity for behavior change that is well-researched in the literature.

For regional and municipal planning, we have shown that workplace locations are associated with their workers' commutes and should thus be planned wisely to avoid car-dependent workplaces and eventually car-dependent workers and families, especially when considering the linked negative environmental, social, and economic effects. Regarding the paradigm of polycentricity in the MMR, our results that the changes occur only between the categories urban-central and not-urban central suggest that workplace locations in subcenters of the region (such as Augsburg, Ingolstadt, Landshut – all in the *urban-decentral* cluster) exhibit high levels of car ownership and driving to work, similar to less central locations. Therefore, these locations fail to contribute to the planning goal of sustainable commuting through polycentricity in our analysis. We speculate that low quality public transport services between the *urban-decentral* cities and their surroundings inhibits the potential benefits of a polycentric region. Further research could deepen this hypothesis and investigate whether intermodal combinations (Bike+Ride, Park+Ride, new mobility services) can improve the connectivity between urban areas and workplaces with the surroundings in order to help reduce car dependency.

Currently, most researchers and practitioners focus on the mobility component of workplace accessibility. Our results, however, advocate for a land-use-centric approach for assessing workplace locations, taking into account the accessibility and centrality of the locations. While planning for accessible, sustainable workplace locations, planners typically face the problem that they can only define workplace locations and residential locations, but not the residential locations for employees of a specific firm. The fact that the workplace location is associated with the mobility behavior of its workers emphasizes the importance and the power of these locations. The positive message for planners is that workplace locations are factor that can be influenced directly by land-use policies, but also corporate decisions. Wisely designed planning processes and decision-making tools for analyzing these workplace locations can contribute to creating well-working regional systems for living, working, and everything in between. The MMR is an ideal testbed for the implementation and testing of these kinds of models, and our findings advocate more research on the accessibility of workplace locations in the MMR, extending the existing work on accessibility analyses in this region (cf. Büttner et al., 2018; Wulfhorst et al., 2017).

5. An open-source modeling tool for multimodal and intermodal workplace accessibility analysis

This chapter presents an integral reproduction of: "Pfertner, M., Büttner, B., Wulfhorst, G., 2023. An Open-Source Modelling Methodology for Multimodal and Intermodal Accessibility Analysis of Workplace Locations. Sustainability 15, 1947."

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Abstract: Workplace location has a significant impact on daily mobility behavior, such as mode of transportation choice, as well as long-term decisions such as car ownership and residential location choice. Therefore, understanding accessibility to workplaces is crucial for promoting sustainable mobility. However, there is currently a lack of comprehensive, open-source methodologies for multimodal and intermodal accessibility modeling for workplace locations. In this study, we present a modeling concept based on open-source tools such as OpenTripPlanner, PostGIS, and R, which allows for efficient and fast accessibility analysis of workplace locations at a regional level. Using the Munich Metropolitan Region as a case study, we demonstrate the feasibility of our model in conducting large-scale, multimodal, and intermodal accessibility analysis on consumer hardware. The maps produced by our model provide both absolute and relative indicators of accessibility, such as public transportation versus car accessibility, as well as a score. The results show that Munich and other centers have high competitiveness for non-car modes and intermodal combinations, but smaller cities also have potential for workplace locations that are not reliant on car access, with a large number of potential workers able to reach these locations within 30 min without driving.

Keywords: accessibility analysis; workplace development; commuting; multimodal; intermodal; open source; OpenTripPlanner; Munich Metropolitan Region

5.1. Introduction

The location of our workplace, where we spend a significant portion of our lives, has a significant impact on the daily routines of the global working population. The commute to work is a constant feature of our daily schedules and can either be a burden or an opportunity to relax or focus. Research indicates that for many individuals, the location of their workplace and the mode of transportation they use to get there are significant factors that shape their daily lives (Brown, 1975; Naess and Sandberg, 1996; Simpson, 1987; Zhao, 2017). The location of the workplace is associated with the daily mobility behavior (e.g., mode choice), long-term mobility decisions (e.g., car ownership, annual transit passes), and also residential location choice (Thierstein et al., 2016). Many case studies and reviews in the literature (Ding et al., 2017; Ding and Cao, 2019; Pfertner et al., 2022; Zarabi and Lord, 2019) have observed these significant effects of the workplace location on its workers, and this effect can even be more formative than the effect of the residential locations (Pfertner et al., 2022; Vale et al., 2018). In the Munich Metropolitan Region, it was shown recently (Pfertner et al., 2022) that the relocation of workers to workplaces with a lower accessibility is associated with the uptake of car commuting and increases in car ownership. Vice versa, it was observed that a workplace relocation to a location with higher centrality is associated with a modal shift towards public transport, whereas car ownership is not decreasing (Pfertner et al., 2022). This emphasizes the workplaces' role as a potential trigger for increasing car availability and the subsequent uptake of driving for many trip purposes. Thus, there is both a potential and a risk for planners when we aim for planning workplaces that foster sustainable mobility and avoid car dependence, as outlined by regions and cities. Thereby, it is neither sufficient to look at these locations only from a land-use perspective nor from a mobility perspective. Both the structural properties of the surrounding region, e.g., in terms of settlement structures for housing, but also the mobility networks that connect the workplace to the potential workers are of high importance for the assessment of a location.

For this integrated analysis of land use and transport, the concept of spatial accessibility, as first introduced by Hansen (Hansen, 1959) and defined in different ways, e.g., [12–16], is a suitable approach. Accessibility analysis has been widely used for various types of analysis (Bertolini et al., 2005; Geurs and van Wee, 2004), and countless approaches to operationalize it have been developed (for an overview, see "META-Accessibility," 2022; Papa et al., 2015; Siddiq and D. Taylor, 2021; Silva et al., 2019, 2017a).

A recent review by Siddiq and Taylor (2021) looked at 54 accessibility metrics. Adding up to previous reviews (Bhat et al., 2000; Geurs and van Wee, 2004; Malekzadeh and Chung, 2020; Páez et al., 2012; Papa et al., 2016; Wu and Levinson, 2020), they classified them in terms of theoretical basis, data requirements, units of analysis, travel modes, and trip purposes. They acknowledge and categorize a wide range of tools and metrics, with the main categories being place-based and people-based tools. While the former look at the accessibility of places (such as workplaces, often aggregated in zones), the latter look at individual persons (or households) with their respective attributes. In line with other authors, they describe that while research advances theories and measures with a high pace, the application in practice still lags. Using interviews with practitioners, they explain that tools are either too complex or too in-transparent (“black box”) for practitioners to be used in their work. Results are often too difficult to understand and to explain, in their opinion. Moreover, practitioners state that there is a lack of expertise in their institution when it comes to applying existing tools and methods. Further, intense data collection and data processing efforts are a burden for the implementation of accessibility measures.

However, they argue that a new generation of tools makes it easier for practitioners to include accessibility analysis in their work—if these accessibility tools are meaningful, do not have overly complex data requirements, and are easy to be communicated and understood by practitioners.

Especially in the German context, few to no standardized, established accessibility measures that fulfill these criteria are used in planning practice (Papa et al., 2016; Peter, 2021; Silva et al., 2017a).

In general, however, the development and availability of geographic information systems (GIS) such as ArcGIS (commercial) and QGIS (open source) as well as other geospatial tools and packages has greatly improved the ability of researchers and planners to run various kinds of accessibility analyses (Reggiani and Martín, 2011). In combination with an increase in openly available data, such as OpenStreetMap, but also public transport networks in GTFS format (Malekzadeh and Chung, 2020; Pajares et al., 2021), the potential for accessibility analysis is now greater than ever.

Pajares et al. (2021), for example, focus on open-source accessibility modelling for active mobility. They also emphasize the still-existing implementation gap between science and practice while highlighting the emergence of successful open-source approaches such as QGIS and OpenTripPlanner (OTP), empowered by the increasing availability of open data sources.

For accessibility models that are capable of modelling public transport, Malekzadeh and Chung (Malekzadeh and Chung, 2020) reviewed the state of the art. They distinguish three approaches for measuring public transport accessibility: The first approach deals with “physical access to the public transit network”, measuring the ability to reach public transport stops with different modes of transport. This dimension can usually be modelled with tools developed for active mobility, since access and egress modes are often non-motorized. The second dimension “system-facilitated accessibility” describes the “traveler’s ability to reach an opportunity by incorporating the travel time or cost spent in the transit network”, including first- and last-mile trip legs by walking. This already requires some sort of public transport routing algorithm. The third dimension “access to destinations” measures the ability of individuals to reach multiple opportunities within the network, using potentially many different routes in the public transport network. Therefore, a high-performance routing tool is necessary, and usually, simple travel time queries to interfaces of commercial services do not suffice. Similar to Pajares et al. (2021), they conclude that the availability of open data, especially public transport network information in GTFS format, is an important achievement in order to model public transport accessibility in a realistic way, taking into account the variations in the network.

There are many examples for operational accessibility models that are generally suitable for the accessibility analysis of workplace locations: Commercial software packages such as the geographic information system ArcGIS Pro (Higgins et al., 2022) or the transport modelling software PTV VISUM are capable of calculation fundamental accessibility analysis, e.g., [31], such as contour measures or gravity-based indicators. These tools are frequently used by researchers and practitioners to calculate accessibility (Stein, 2019). The major disadvantage, however, is the high cost of obtaining a license for these commercial products.

Recently, new tools have been emerging, with a trend to publish algorithms and tools as open-source code. Well-known examples for this are OpenTripPlanner (Young, 2019) and the r5 routing engine, developed by Conveyal (“Conveyal R5 Routing Engine,” 2022) and based on methods presented in (Conway et al., 2018, 2017; Conway and Stewart, 2019). The use of both tools has been facilitated by R packages that ‘wrap’ the functionalities of the routing engines into comfortable R packages, namely, opentripplanner (Morgan et al., 2019) and r5r (Pereira et al., 2021). Both sets of tools, commercial and open-source, were tested and compared in depth by Higgins et al. (Higgins et al., 2022). The authors found all tools suitable in general for place-based accessibility calculations based on OD matrices. ArcGIS’ network analyst was found to have an in-transparent ‘black-box’ algorithm for public transport travel time calculations. R5r was capable of the fastest OD matrix calculations while OpenTripPlanner was capable of using realistic travel behavior for its calculations, e.g., through including weights for transfers. In conclusion, the authors emphasize that each tool produced different travel time results for the study area. They also warn of a risk of algorithmic dependence for travel times, which can impact the accessibility results. Another problem, especially with open-source tools, is the dependence on data quality in OpenStreetMap.

On the basis of the literature, there is no conclusion on how to model accessibility in the context of workplace locations. Thus, it is our contribution to propose an open-source methodology to advance the capabilities of researchers, municipalities, and companies to better understand the accessibility of workplace locations in order to derive recommendations for policy and practice in a subsequent step.

For a holistic and useful accessibility assessment of workplaces, we define the following criteria for a suitable assessment method:

- All relevant modes of transport need to be included (multimodal perspective): In Germany, these are walking, public transport, cycling, and driving (Nobis and Kuhnimhof, 2018).
- For results that better reflect the real-world travel choices of commuters, combinations of these modes (intermodal perspective) should be included as well. Especially the bicycle, as an emission-free, space-efficient mode to access or egress rail-based public transport, is of particular interest for current policies in the region (Drees & Sommer, 2018) and beyond (Chan and Farber, 2020).
- All analysis should be conducted using real timetable-based travel times in public transport so that the particular conditions of commuting are reflected in the model (e.g., higher frequencies during the morning peak hour).
- The methodology should be fully adjustable so that both changes in the land-use component as well as in the mobility supply can be included, e.g., in the form of scenarios. This includes new housing, new public transport lines, changes in timetables, and new cycling infrastructure, among others.
- To create a universally applicable and transferable methodology, it should be based on open-source tools. This avoids black boxes in the methodology and maximizes the potential impact, since no license fees are necessary to apply the method. Moreover, an open-source methodology makes the modelling process transparent and replicable.
- In order to make the methodology useful for practical applications, the calculation time for a grid-based analysis of a functional urban area should be below 12 h in order to allow relatively fast scenario comparisons.
- In line with (Silva, 2013) and on the basis of the proclamations by (Bertolini et al., 2005), these requirements support that the assessment method will find a good balance between accuracy/detailedness on the one hand and transparency and simplicity on the other.

The first goal of this paper is thus the development of a methodology that allows for the measurement and evaluation of the accessibility of workplace locations throughout a region with the help of open-source tools, with the aim of making better informed decisions about workplace locations with good multimodal and intermodal accessibility. The second goal is then to test this this methodology by applying it to the region of Munich in order to better understand the implications of the modeling results, as well as strengths and weaknesses of the methodology. Thus, the research questions can be defined as follows:

1. How can multimodal and intermodal accessibility measures for workplace locations be operationalized on the basis of open-source tools and open data?
2. What do we learn from the application of a region-wide analysis of workplace accessibility?

On the basis of these questions, we formulated the research hypothesis: A multimodal and intermodal accessibility model for workplace locations will be a useful planning support instrument for assessing the capability of the integrated land-use and transport system to enable potential workers to access the workplace location within a given time budget with a selected set of travel modes.

5.2. Methodology

Modeling Concept

Our proposed accessibility model “EMMA—Empowering multimodal and intermodal accessibility analysis for workplace locations” consists of three main components:

- OpenTripPlanner is used to calculate isochrones (see (Young, 2019) for an introduction);
- A PostGIS database is used to store spatial data (permanently and temporarily) and perform spatial queries;
- A script (written in R) is used to steer and automate the process.

The working principle is visualized in Figure 18. In contrast to existing models, this approach does not calculate an OD matrix for all cells. Instead, this approach calculates one isochrone per grid cell, which is then used to calculate the number of people who can reach the hexagon grid cell (=the workplace location) directly.

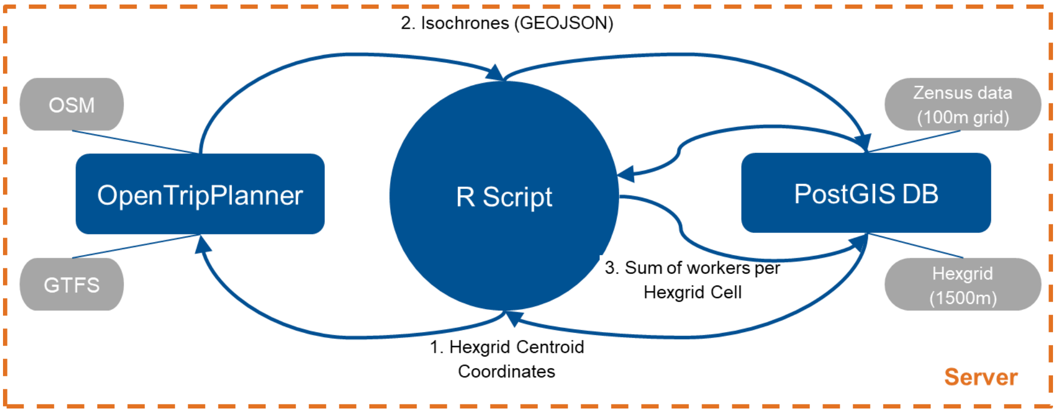

Figure 18: Concept of the EMMA Accessibility Model.

After setting up the necessary software and data sources, a hexagon grid of the study area (width: 1500 m) is created (see Section 5.4 for details about this choice). This determines the spatial resolution of the modelling results. The hexagon grid is saved in the database, together with the census points. Using an R script, each grid centroid coordinates are sent to the OTP instance via the API, where an isochrone is calculated and returned to the script. In OTP, we can model multimodal isochrones (walking, cycling, driving, transit + walk) as well as intermodal travel in the form of various combinations of cycling and transit (bike and ride, ride and bike, bike—transit—bike, bike sharing).

The isochrones are created with a cutoff value of 30 min (see discussion in Section 5.4) with a specified arrival time at 9 a.m. at the workplace location. Optionally, we repeat the calculations for public transport (and intermodal combinations) in certain intervals for various arrival times (e.g., every 6 min between 8 a.m. and 9 a.m.) and merge the isochrones to reduce the impact of the timetable and headways. Using SQL in the PostGIS database, the number of potential workers within the isochrone is calculated and saved in the hexagon table, on the basis of a census grid with a 100 m resolution ("ZENSUS 2011," 2011). If a centroid yields an error (no isochrone found), the script moves the centroid by a random value between +/− 750 m in both the x- and y-directions and tries again. That way, we minimize errors where the centroid is, e.g., located between two railway tracks and the routing algorithm is unable to produce an isochrone. This step is iterated three times in total to minimize this error while avoiding unnecessary calculations for hexagon cells that have a 'null-isochrone' because there is no street network leading to the cell.

The resulting hexagon grid with the accessible population is then visualized either as a web map (for example using the leaflet package in R) or exported and mapped via QGIS.

Data Sources

For the mobility-related components of the model, raw data from OpenStreetMap is downloaded in the compressed .osb.pbf format. The relevant data mainly include the street network for routing in OpenTripPlanner. Official and up-to-date information about public transport routes, stops, and schedules is obtained from the national open data portal DELFI in GTFS format ("Datensätze - OpenData ÖPNV," 2022).

Population data in the form of a 100 m grid are provided by the national census ("ZENSUS 2011," 2011). This fine level of detail fits well to our isochrone-based approach, where we can see in relative detail which of the 100 m cells provides access to our destination within 30 min. However, to speed up calculations, we reduced the square grid cells to the centroids, resulting in a 100 × 100 m point grid with population data. For further details on data preparation, see Annex A.

Software and Technical Setup

All necessary software tools (OpenTripPlanner 1.4, PostGIS 12.4, R 4.03, RStudio Server 1.3) were installed on a VPS server running Ubuntu 18.04. OTP's graph building function is used to combine the filtered GTFS data and the OSM network into a routable graph that is stored on the server as well (see Young, 2019). All scripting and controlling of the model's calculations are performed within the browser interface of RStudio Server.

Assumptions and Parameters

Several assumptions and parameters have an influence on the modelling results. The following paragraphs describe the reasoning behind our decisions.

Isochrone Generation

Isochrones are calculated for a 30 min trip duration for all modes. This is backed by actual travel behavior, since depending on the source, 50–70% of all trips to work in Germany (independent of modes) are shorter than 30 min (ADAC, 2019; Statista, 2022; Statistisches Bundesamt, 2020). Moreover, the goal of the accessibility analysis is not forecasting travel behavior but rather the assessment of the locations' quality. Thus, the planning goal with this approach is to maximize the number of accessible workers within this threshold, given an optimization of both the transport system and land use.

The actual generation of the isochrones is performed by OpenTripPlanner. Using the API and the "isochrone" function, we send the centroid coordinates and the relevant parameters (such as 30 min cutoff and mode of transport) to OTP on the server. OTP is then, using its graph, based on the previously provided GTFS file and OSM street data in order to calculate the area from which it is possible to reach the grid centroid within the given travel time limit. The information is provided as a GeoJSON file by OTP, which is stored and further processed in the PostGIS database.

Temporal Parameters

Since the focus of the model is workplaces, a regular weekday (Wednesday) is selected for the calculations. Isochrones are calculated for a given arrival time at the workplace. For all timetable-based modes or intermodal combinations, we sample in 6 min intervals for an arrival between 08:00 and 09:00 a.m. Thereby, we minimize the error induced by unfavorable headways in relation to the arrival times. By using 6 min intervals instead of 5 or 10 min, we reduce the impact of randomly matching actual departure times. (e.g., if a bus departs at 07:02/12/22/…, our intervals at 07:06/12/18 deliver better results than 07:00/10/20/…). We also assume a certain flexibility in the desired arrival time within the given interval: If the fastest route from one home location to a workplace would result in an arrival at 08:15, for example, and another residential area would have the shortest travel time with an arrival at 08:45, we accept both trips as valid options. Thus, we calculate all isochrones according to this sampling and merge them to get the final isochrone for the hexagon centroid.

In the case of fixed-shift workplaces, however, this approach would not be fitting. On the other hand, most large workplaces with these work schedules have typically coordinated public transport services for these hours in Germany so that the proposed approach seems to be the most suitable.

Resulting Hexagon Grid

We suggest using a hexagon grid for the model results. This choice is based on two assumptions: (1) With hexagons, we can provide a comparable level of sampling detail with 30% less grid cells, compared to a usual squared grid (Burdziej, 2019). Since the computing time of our model is proportional to the number of grid cells, this is a crucial factor. (2) Hexagon grids have the advantage that the distance from the center to the edges is more evenly distributed compared to squares. This is beneficial for the clarity of visualizations (Shoman and Demirel, 2017). The grid width of 1500 m is a tradeoff between a high level of detail on the one hand, and acceptable computing times on the other hand. This grid results in 17,208 cells for the entire Munich Metropolitan Region. It is based on the idea that it provides roughly a 750 m average radius from the centroid, which is in public transport an acceptable walking distance from a station. Of course, this grid is only suitable for interpretation on a regional level. For detailed analysis of individual locations, a smaller level of detail is recommended in subsequent steps.

Comparison to Existing Approaches

Our proposed methodology has four main differences from existing approaches:

- Perspective: Most accessibility models in the realm of job and workplace accessibility apply the place-based perspective for residential locations, calculating access to jobs for workers (Grisé et al., 2019; Hu and Downs, 2019; Pritchard et al., 2019; Siddiq and D. Taylor, 2021). Our approach, however, focuses on access to workers from the perspective of (potential) workplace locations. To date, only few operational models have applied this approach—mostly, within the context of 'jobs–housing–balance' approaches (Deboosere et al., 2018; Levinson et al., 2017).
- Calculation method: Usually, spatial accessibility is calculated using origin destination matrices that contain travel times (or generalized costs) between all zones in the study area (Burdziej, 2019; Higgins et al., 2022). One disadvantage of this approach is that the computational effort required is exponential with respect to the number of zones. While it offers many opportunities for more complex analyses and is a prerequisite for gravity-based measures, the high computational burden may be a limitation in practice. Thus, focusing on simplicity, we apply a calculation based on isochrones around the zone centroids (see Section 0) that only requires one operation per cell. Moreover, this approach allows us to use the resulting isochrones both for quality checks and for communication of the results, which is especially useful when comparing scenarios.
- Multimodality and intermodality: In contrast to approaches that allow only the analysis of one mode of transport (often either automobile or public transport) (Siddiq and D. Taylor, 2021), our model is capable of calculating accessibility in a multimodal and even intermodal way, on the basis of the features of OpenTripPlanner ("OpenTripPlanner," n.d.; Young, 2019).
- Open Source and Open Data: As outlined in Sections 5.1 and 5.2, all software, tools, and data sources used in this proposed approach are openly available. This makes our approach, depending on data availability, replicable anywhere and without any license costs. This is a major difference to approaches relying on commercial tools like ArcGIS Pro (Higgins et al., 2022; Siddiq and D. Taylor, 2021).

5.3. Results

In this section, we focus first on the result of our proposed modelling concept: Section 5.3 presents the resulting main maps and some findings about the computation performance. Later, in Section 5.4, we interpret the results and discuss their implications for the region.

The model was calculated for the entire study area and the following modes:

- Cycling;
- Public transport;
- Bike and ride;
- Driving.

Walking is technically possible but was excluded for the analysis on the regional scale.

Processing time for all modes, including OTP calculations and PostGIS operations, was around 12 h for the entire study area, consisting of 17,208 grid cells on a VPS Server with 8 GB RAM and an 8-core CPU.

Across all modes, the larger cities in the region Munich, Augsburg, Landshut, and Rosenheim are clearly identifiable by their higher accessibility compared to the less urban areas in between. Depending on the mode, this discrepancy between urban and rural is expressed in a different form.

Driving has the lowest differences between regions, with relatively high accessibility even in remote areas. The map (Figure 19) also shows quite a high number of cells with zero accessible population by car—this is explained by natural areas (lakes, forests, environmental protection areas), where driving is prohibited. In Munich, this is true in areas with large parks that are larger than the snapping distance to the closest network element. Driving reaches the highest number of accessible populations in the center of Munich, from which a large portion of the city is accessible within 30 min of driving. Along the region’s major highways, a higher accessibility was observed compared to adjacent areas.

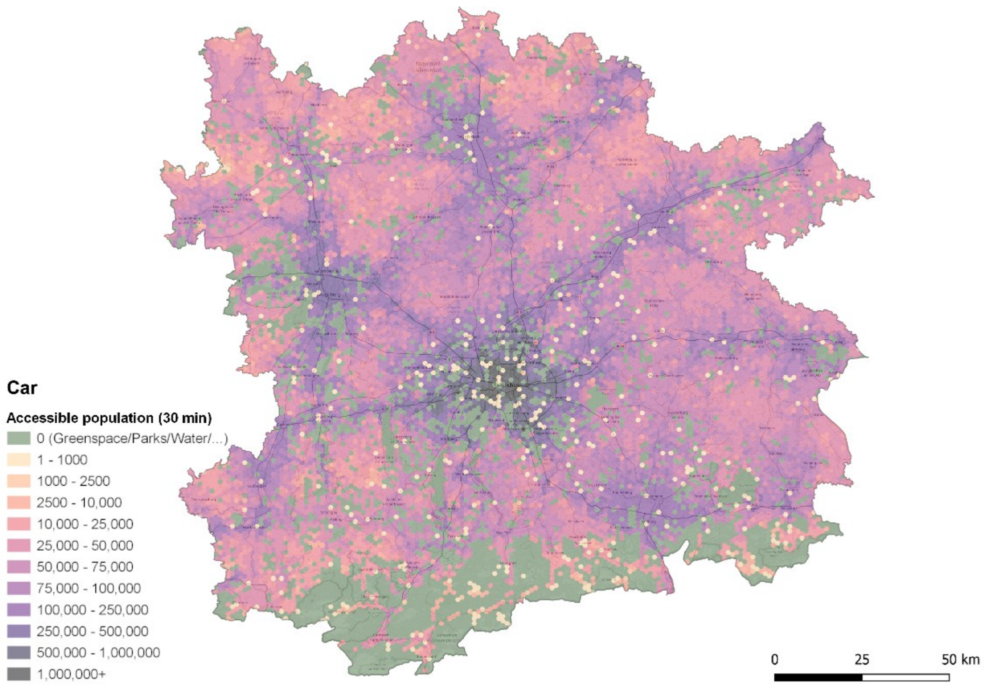

Figure 19: Thirty-minute accessibility by car.

The **public transport** map (Figure 20) reveals huge differences between urban and non-urban areas. In the centers of Munich and Augsburg, a relatively large area shows values comparable to driving, but with increasing distance to the centers, the accessibility decreases. Due to the organizational structure of public transport, we can see sharp drops in accessibility at the tariff systems' boundaries. Also remarkable are the "island effects" around regional public transport lines such as the "S-Bahn" (commuter rail). However, these areas with relatively high accessibility are focused narrowly on areas around the stops, becoming smaller with longer travel times to the center. If we use the more detailed approach with arrival time intervals of 6 min between 8 and 9 a.m. as described earlier (Figure 21), we see higher values in general, but especially the areas around the urban areas profit.

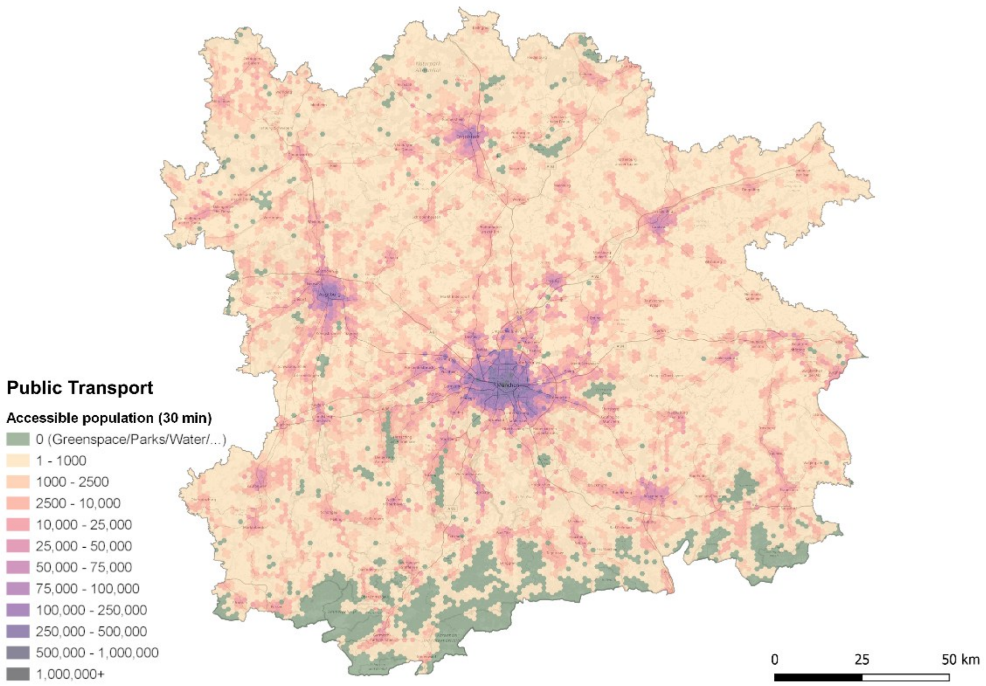

Figure 20: Thirty-minute accessibility by public transport (arrival 09:00 a.m.).

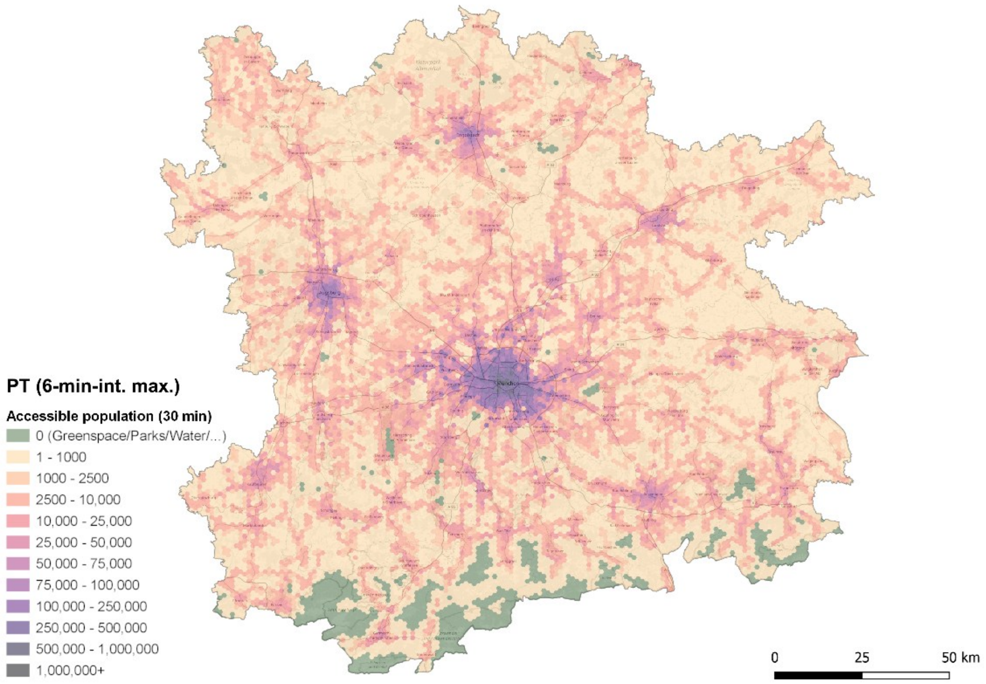

Figure 21: Thirty-minute accessibility by public transport (max. between 8 and 9 a.m. in 6 min intervals).

In those areas, public transport connections to dense areas exist, but headways are low compared to the centers, and therefore sampling over multiple arrival times makes a large difference there. This effect is visualized in Figure 22, where we can see the ring around the City of Munich, where the impact is very high.

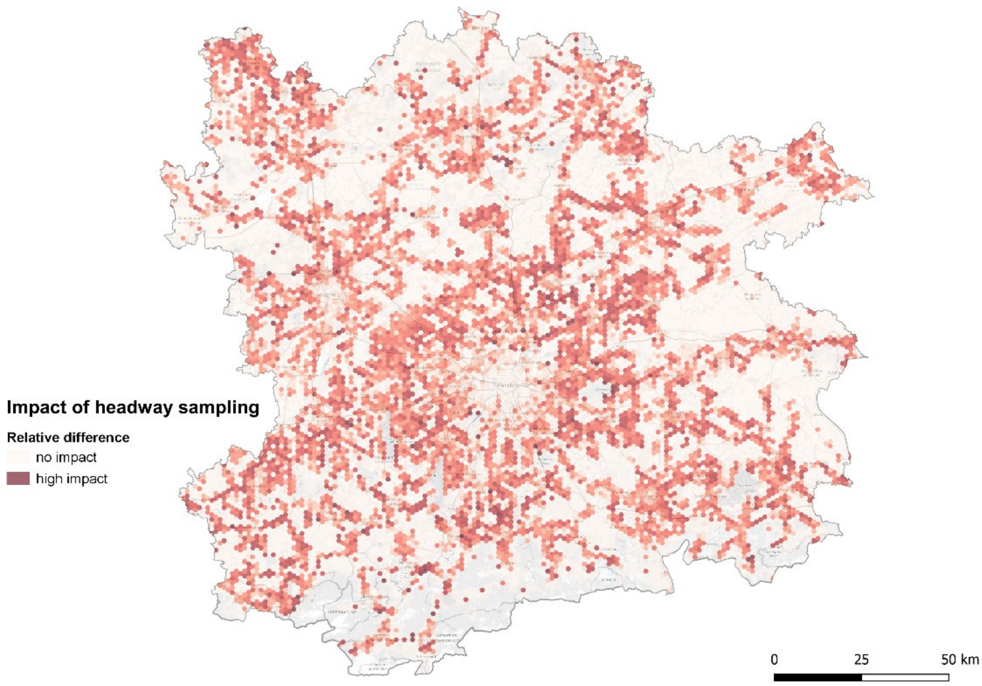

Figure 22: Impact of arrival time interval sampling.

Accessibility by **bicycle** (Figure 23) provides the most evenly distributed results. The map shows that the values are again the highest in the centers of the urban areas and reduce with increasing distance to the centers, forming rings around the cities. In all urban areas, the values are in similar magnitudes as the private car, whereas in rural areas, due to lower densities, cycling yields relatively low accessibility in absolute numbers, compared to the other modes.

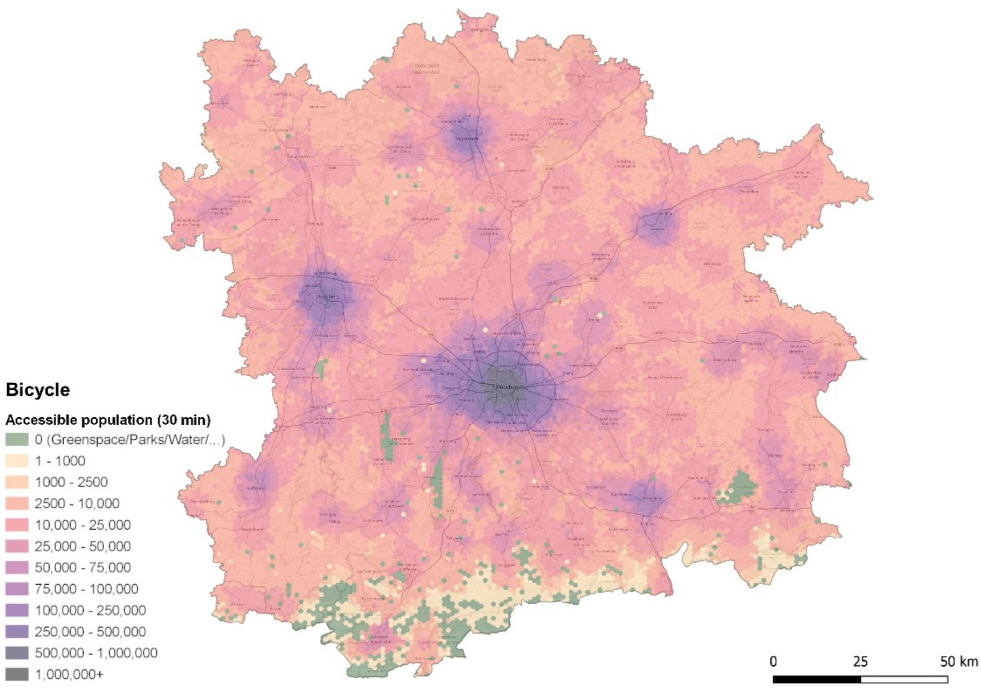

Figure 23: Thirty-minute accessibility by bicycle.

Intermodal **bike and ride** accessibility shows very high accessibility in the centers and increases the size of the highly accessible central areas in the cities, but reveals lower accessibility than cycling alone in many rural areas. At the same time, the 'islands' around rail-based public transport stops are now larger than previously in the public transport analysis and have higher accessibility—something that is expected when cycling is essentially replacing the walking trip leg.

The resulting map (Figure 24) assumes that a bike must be used for the first trip leg. In some cases, e.g., in one-way streets, however, walking to the stop would be faster, since pedestrians can walk directly against the one-way direction to the stations whereas bicycles have to use the street in its designated direction and make a detour. Other examples such as pedestrian-only paths/zones, stairs, etc., produce the same effect. Moreover, in rural areas with long headways of one hour or more in bus networks, cycling could be an option to cycle to the next train station, but often this bike trip comes close to the 30 min cutoff value, whereas the bus (despite its low frequency) provides a much faster trip to the train, with huge accessibility gains compared to the forced first-leg bicycle trip. Thus, we argue for an indicator that selects the larger value from either bike and ride or walk and ride in order to assess an intermodal system of public transport and walking or cycling. This indicator is mapped in the following Figure 25 and presents higher values in rural areas with cycling times close to 30 min (or more) to the next rail-based public transport service.

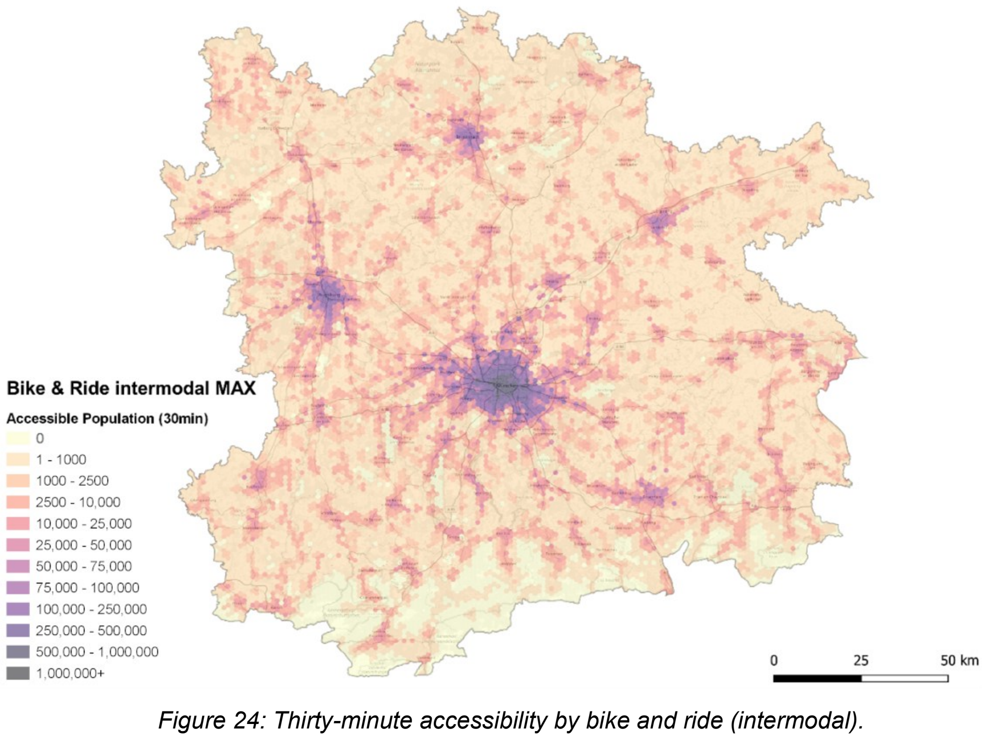

Figure 24: Thirty-minute accessibility by bike and ride (intermodal).

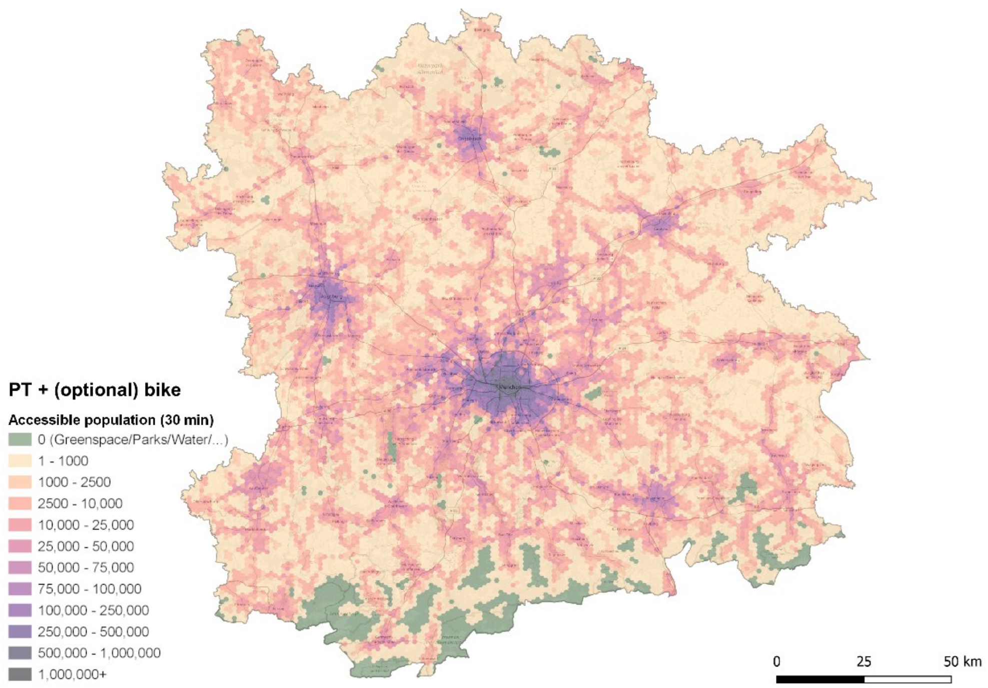

Figure 25: Accessibility for maximum value of bike and ride or public transport.

5.4. Model Interpretation and Discussion of Results

After the technical analysis in Section 3, we now shift the focus to the implications we can derive from the modeling results and take also relative comparisons across the modes into account, which are better suited for interpretation. To obtain these, the values from the previously presented calculations were simply divided to create a percentage score.

Relative Accessibility—How Well do Public Transport and Cycling Compare to the Private Car?

All assumptions on workplace accessibility are hypothetical per definition, since one job position does actually need one suitable person to be filled. It is important to note that the aim of this analysis was not to match actual workers with open positions, but to assess the quality of workplace locations in terms of their potential to be reached by workers. This takes into account both the mobility supply and the land use. With the aim of workplace locations that are car independent, it is a planning goal to minimize the need for a private car to get to work. Thus, a ‘good’ workplace location is accessible by multiple modes in a good way, and these alternatives to the private car provide comparable accessibility. Thus, an important indicator is the relative accessibility compared to driving. The first analysis shows cycling accessibility compared to driving (Figure 26):

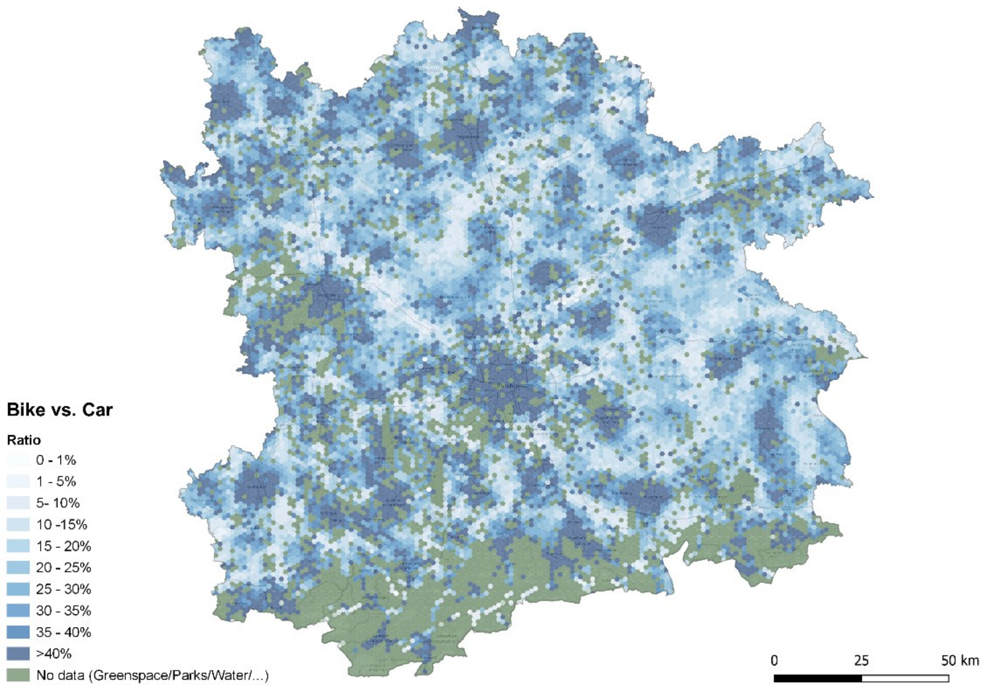

Figure 26: Relative accessibility: bicycle vs. car.

In many cities, independent of the size, cycling reaches the highest category of >40% of the population accessible by driving. We see clear edges between these urban areas with a higher density and the rural areas in between. Important for the interpretation is that no quality of bicycle infrastructure plays a role in this analysis—the routing is based only on streets/paths where cycling is legal, independent of the type of bicycle infrastructure. The perception that cycling is a mode that has benefits in urban areas is confirmed, but it is important to understand that these urban areas do include also small cities in the region, not only Munich, Augsburg, and Ingolstadt. To make use of this accessibility potential, administrations need to provide safe and comfortable bike infrastructure. Employers can play a role in lobbying for this infrastructure and provide facilities for cyclists such as safe parking, lockers/showers, bad-weather backup services (such as taxi vouchers), or financial incentives for the purchase or leasing of bicycles or e-bikes.

Figure 27 shows a similar analysis for public transport in comparison to driving.

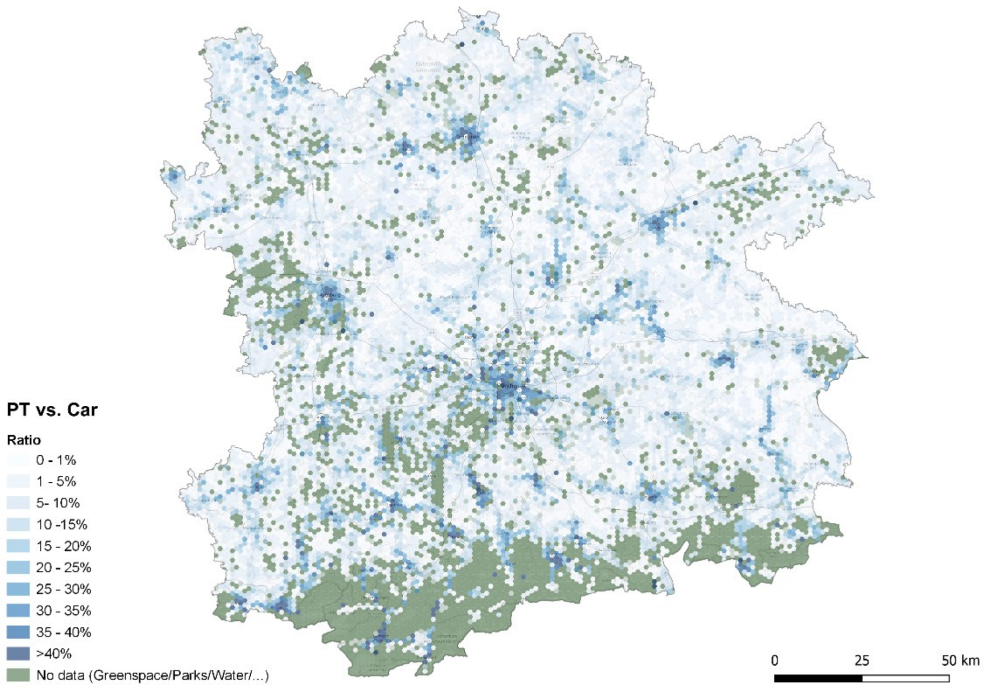

Figure 27: Relative accessibility: public transport vs. car.

We found good PT accessibility again in the centers of the big four cities in the region. In the case of Munich, we see spikes especially for locations located at the central part of the commuter rail's trunk line ('Stammstrecke'). Moreover, many stops of rail-based public transport lines (local and regional) are visible, for example, the train from Munich to Rosenheim. Similar to the results for cycling vs. car, many small towns exhibit a strong accessibility by public transport as well, while we also know from mobility surveys that public transport plays a smaller role in the daily mobility of these residents compared to urban dwellers. While smaller towns in the regions do typically have a public transport network that covers the town and surrounding region quite well, they often lack high frequencies, direct routes, fast travel times, and alternative options in case of delays. These are factors that are not identifiable in the logic of the model but might well play a large role in the promotion of public transport on trips to work in these locations.

Another observation is the high relative accessibility in mountain areas in the south of the region. Whenever a town (such as Garmisch-Partenkirchen) is located in a valley, surrounded by mountains and connected by just one main access road, public transport can provide a viable alternative to private cars in terms of accessibility within 30 min. Even if most public transport stops are located on the main road, distances to potential destinations along the road are short. This effect is also visible in Lenggries, Tegernsee, Schliersee, and Mittenwald. Factors that are hindering this potential are congestion on the roads, which also affects buses; steep slopes for walking and cycling as access and egress mode to the stops;

and harsh weather conditions in winter. Moreover, a lack of suitable options for trip chaining is an issue, along with reliability and punctuality problems.

Intermodality—Where Do Workplaces Benefit from Combining Public Transport and Cycling?

Intermodality, defined in our case as public transport combined with another mode such as cycling, has two main effects that can improve the accessibility of workplace locations:

- Increase in the accessible area (and thereby population) within a certain time threshold by faster first mile and/or last mile trip legs. This is the expected effect when walking is replaced by cycling, for example.
- Increase in the accessible area (and thereby population) within a certain time threshold by enabling new public transport routes that were not possible without the intermodal combination. For example, when stops can be reached by bike easily where the first public transport trip leg would be very slow.

The combination of both effects is visible in Figure 24, but also in the relative comparison when comparing bike and ride with driving (Figure 27).

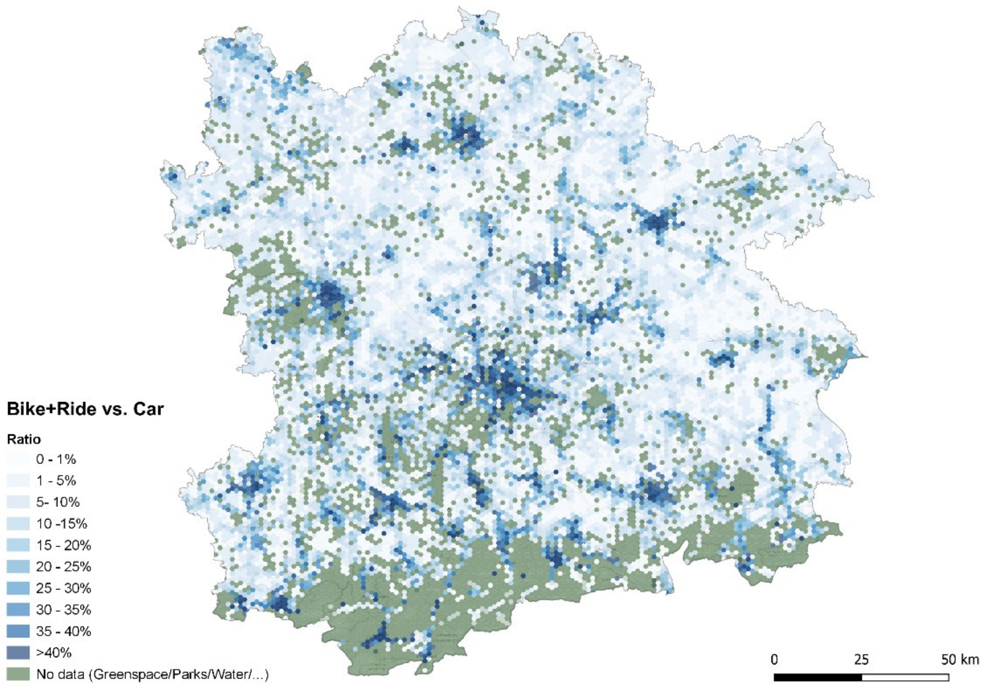

Figure 28: Relative accessibility: bike and ride vs. car.

Overall, the mean of accessible workers for all grid cells across the region increased by 17.2% when using bike and ride instead of public transport only (Figure 29).

Figure 29: Mean of accessible workers, PT vs. bike and ride (log scale).

Spatially, this increase was mainly found in the urban centers, but also along the rail axis in the region. The map in Figure 30 visualizes the areas with improvements in the accessibility by bike and ride in green.

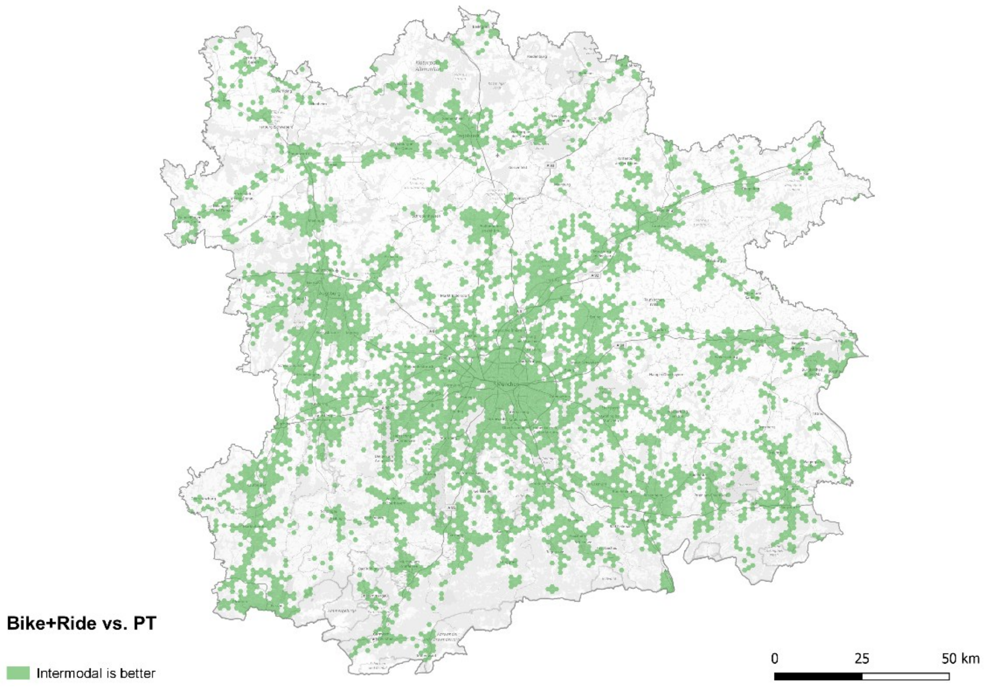

Figure 30: In which cells does intermodality improve accessibility?

Score Transformation

In order to increase the interpretability of the model results, we propose a score transformation that scales the model result on a range from −100 to +100. Therefore, we used one of the fundamental indicators, the ratio of accessible workers by PT vs. car as a baseline, and transformed it into z-scores. In order to smooth out extreme values, the z-scores were capped at +/− 3 standard deviations. The result was then transformed into a range of −100 (lowest possible ratio PT vs. car in the observation area) to +100 (highest possible ratio). While this approach is very simple in its method, it helps to communicate and interpret the model results. Figure 31 shows the resulting map.

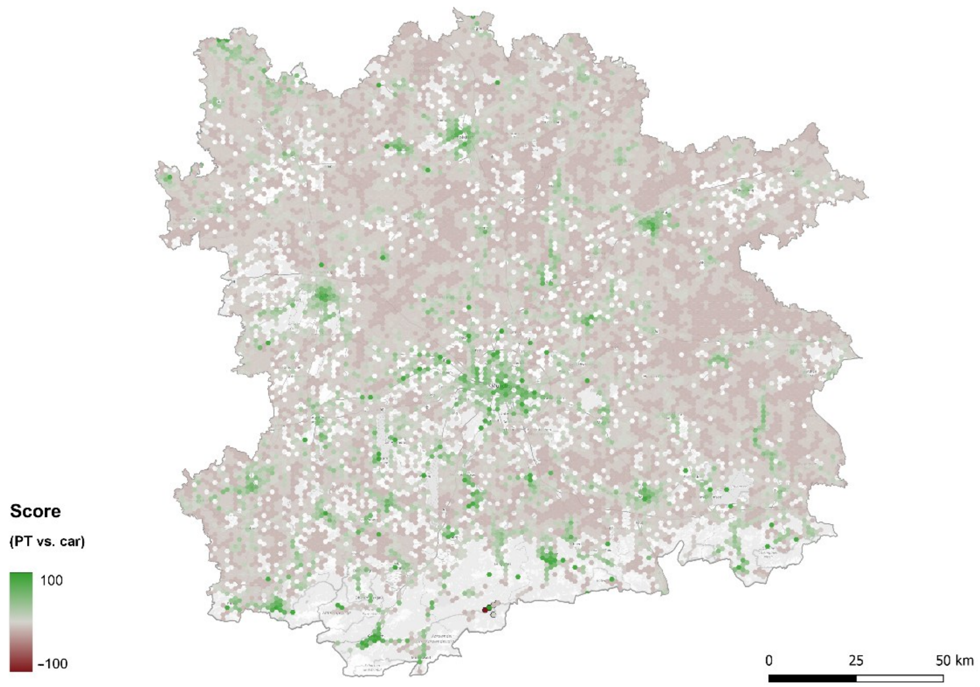

Figure 31: Score of relative accessibility (PT vs. car).

In contrast to the relative visualization, where we present directly, e.g., the share of accessible population by public transport compared to private car, the score transformation allows for an interpretation that is independent of the actual values. A score of 0 represents a cell where the ratio is equal to the mean in the distribution of shares. Thus, the map shows in dark green the areas in the region that are among the best PT vs. car ratio, whereas the red areas are below the mean.

In this context, it is important to note that a score of −100 is never reached in this application. Instead, wide areas of the region are classified below median, which is in line with the observation that the public transport accessibility in the region spikes at certain centers, but is very low in wide areas of the region.

Role of Munich as the Most Accessible Area for Workplaces in the Region

Across all modes, Munich stands out as the area that can provide workplace locations with the highest accessibility. With a private car, the entire area within the outer motorway ring road provides a huge number of accessible residents within 30 min of driving. By public transport, we still see very high results for the entire functional urban region, and the same is true for cycling. At the same time, Munich is also the area in the region that already has the highest density and the lowest number of available areas for new workplace development. We can thus confirm the outstanding role within the region. Smaller-scale investigations will help identify optimization potentials on a smaller scale and be able to provide a more differentiated picture for areas of interest.

Polycentricity in the Region? The Role of the Other Centers

Especially in the cycling analysis, we do not only see the large cities in the region, but also small towns such as Freising, Weilheim, and Dachau show up with relatively good accessibility by bike (cf. Figure 23), whereas these cities report high driving rates to work in mobility surveys (Nobis and Kuhnimhof, 2018). The explanation for this is based on the fact that these towns are typically compact (the entire area is accessible within 30 min of cycling from most starting points in the city) and have clear boundaries. They are surrounded by sparsely populated areas and, thus, the larger area that is reached by car does not result in huge accessibility gains due to a lack of population living there. Workplaces in these locations should provide a mixed use (shopping, childcare, post services, doctors, etc.) and proximity to the local centers to maximize this potential of short, non-motorized trips. If single-use workplace locations are developed in fringe areas of these towns with longer distances to the center, the probability that a car is needed for effective trip chaining is high. Bicycle infrastructure should be a priority in these compact sub-centers, and mobility management should emphasize the benefits of utilitarian cycling in these areas, where cycling is often seen as a mode of recreation and leisure activities.

5.5. Discussion

This work builds on the importance of workplace locations and their effects on daily mobility behavior such as mode choice, but also on long-term decisions such as car ownership or residential location choice. Accessibility analysis and accessibility modeling have previously shown a large amount of potential to improve the understanding of the qualities of locations of any kind, contributing to better decision making for municipalities, other regulatory bodies, or even companies. However, to date, there is no comprehensive methodology focused on multimodal and intermodal accessibility modeling for workplace locations that fulfills our defined criteria such as being open-source, transparent, flexible, and based on real-world data.

Therefore, we present a modeling concept based entirely on open-source components such as OpenTripPlanner, PostGIS, and R, allowing for efficient and fast accessibility analysis with a focus on workplace locations for entire regions on a grid-level and based on actual travel time isochrones for various modes (instead of the usually used OD matrices) and combinations of modes, with real-word public transport schedules.

Running the model for the entire Munich Metropolitan Region, we found the concept is capable of running large-scale accessibility analysis on moderate, consumer-grade hardware in an acceptable amount of time. The results show a coherent picture of the region, in line with expectations. With our maps, we argue for the use of relative indicators, such as public transport vs. car accessibility, in order to derive conclusions from the model. Moreover, a score transformation is advised in order to make results better understandable. In our analysis, Munich, but also other centers in the region such as Augsburg, stand out for their high competitiveness of non-car modes and intermodal combinations. However, also smaller cities, if they are relatively dense and compact, were shown to have a high potential to provide workplace locations that are not car dependent in the sense that a large number of potential workers can get there within 30 min without driving.

These results should be taken into account when considering various methods to apply accessibility modelling for workplace locations. Following the classification of Siddiq and D. Taylor (2021), the EMMA model has the goal to evaluate the accessibility of (potential) workplace locations on a regional scale. It is thus a place-based model that includes various travel modes (multimodal and intermodal). The inherent function is a contour measure, operationalized through isochrones that count the number of people who can access the workplace in a given time threshold. Therefore, the data requirements are limited to OSM (street network), public transport schedules and stops (GTFS format), and population data. The model is thus one that focuses on simplicity both in operationalization and presentation of its results, in line with suggestions in the literature (Silva et al., 2019). Its main distinction to usually applied methodologies is the focus on open-source software, which makes it transferable and replicable anywhere in the world, where the aforementioned data requirements are fulfilled. It builds on the existing frameworks and open source tools such as OpenTripPlanner (Young, 2019), which was reviewed and compared by Higgins et al. (2022), who determined it as a suitable tool for place-based analysis. Our approach that uses directly the isochrone output of OTP addresses a common limitation of OTP, which is the computation speed (and is greatly improved in newer tools like r5r (Pereira et al., 2021)). The proposed EMMA model fulfills all criteria for a suitable accessibility model we derived in the introduction, which is a major contribution compared to the state of the art: it includes all relevant modes, including intermodal combinations, it is based on actual GTFS public transport schedules, it is open and transparent enough to allow adjustments in both land use and transport for the analysis of scenarios, it builds only on open-source tools, and our regional analysis runs within the required 12 h of computing time.

This helps us to validate our research hypothesis at least in part: The model shows potential to be used as a planning support instrument for regional planning of workplace locations. However, in order to determine whether it is actually ‘useful’ in comparison to existing tools, future research should include the feedback of practitioners in order to deliver a final conclusion on this hypothesis.

Of course, this analysis gives only a high-level overview of the region, and some limitations apply: A common problem of many accessibility models for workplace is the discrepancy between potential workers and actual workers. However, even though we do not have information about where the actual workers of a workplace reside, we can still assess the level of accessibility that is provided at the location and identify locations where the accessibility is high or low. Thus, we start from the land-use and transport system as a basis for future decision making of workers and firms, without trying to project their individual behavior.

Another limitation is the uniform cutoff value of 30 min travel time. It could be one option to increase the travel time for public transport compared to cars. This is commonly done in German regulations (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2009) and is based on observed mobility behavior. However, we assume that different time thresholds among the modes might be hard to understand in practice and thus we argue for the simpler approach with 30 min cutoff for all modes. This also applies for the use of more complex gravity-based measures instead of our isochrone-based approach.

For more detailed insights and especially for concrete recommendations for actual locations (or planned locations), a perspective beyond the grid level is necessary. However, our model sets the foundation for this since the isochrone-based approach can be applied to individual locations rather than grid cells as well. With the open and modifiable network data, this will allow us to analyze and compare scenarios in both land-use and mobility supply with this framework in the future.

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Data Availability Statement: Publicly available datasets were analyzed in this study. These data can be found here: Census 2011 Population data: https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html;jsessionid=916003915C754E15594AD09E469F7130.live342?nn=559100 (accessed on 12 November 2022); Nationwide GTFS data: https://www.opendata-oepnv.de/ht/de/organisation/delfi/startseite?tx_vrrkit_view%5Bdataset_name%5D=deutschlandweite-sollfahrplandaten-gtfs&tx_vrrkit_view%5Baction%5D=details&tx_vrrkit_view%5Bcontroller%5D=View (accessed on 12 November 2022); Public OSM downloads: https://download.geofabrik.de/ (accessed on 12 November 2022).

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6. The potential usefulness of accessibility modeling for workplace locations – the example of EMMA

This chapter presents an integral reproduction of: "Pfertner, M., Silva, C., Büttner, B., Wulfhorst, G., 2024. The potential usefulness of accessibility modeling for workplace locations – the example of EMMA. Currently under review at Transportation Research Part A: Policy and Practice"

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Abstract

The EMMA accessibility model is designed for calculating accessibility of workplace locations based on the population that can reach a (potential) workplace location within 30 minutes on a typical workday during the peak-hour. This is new and additional information to be used in planning procedures, which is currently not available. The aim of this paper is to assess the usefulness of this model for the assessment of existing and potential workplace locations regarding the dimensions utility and usability. Therefore, semi-structured interviews with practitioners from various perspectives (municipal planning, consulting, real estate, etc.) in the Munich Metropolitan Region (MMR) were conducted. The results suggest the model's usefulness for the early planning stages, where multiple locations can be compared, scenarios with variations of the transport supply can be modeled, and where there is still enough time to implement changes in the land use and transport system. Secondary levels of usefulness were found for the use of the model for existing locations, to analyze weaknesses within the local/regional transport system for commuting, but also compare changes in transport infrastructure that could be introduced by new modes of transport, such as sharing options, company shuttles, or mobility stations.

Key Words: planning support system; accessibility; workplace; commuting; model; usefulness

6.1. Introduction

Workplace locations and the idea of car-independent workplaces

A vast body of research has shown the association between land use and transport, making the way our cities and regions are designed from a transport and land-use perspective a major factor in how we get around in our daily lives (Naess and Sandberg, 1996; Silva et al., 2006; van Wee, 2002; Wegener, 2021; Zhai and Zhang, 2023). In this context, the location of the workplace and, thereby, the commute to work plays a critical role for large parts of the population since it often determines mode choice not only for the trip to work but is associated with mode choice in general (Vale and Pereira, 2016). A typical observation is the association between driving to work and car-centered mobility behavior for other trips. When starting the day with a car trip to work, it is less likely that a person will use other modes such as walking, cycling, or public transport during the rest of the day for other trips (Chatman, 2003). Thus, we argue that the certain workplace locations in a city and/or region influence the driving decision of its workers, due to their location. For the Munich Metropolitan Region (MMR) example, it was previously shown that a relocation to a new workplace with lower accessibility is associated with increases in car availability and driving to work, independent of the residential location (Pfertner et al., 2022).

On a societal level, this is problematic for all the various reasons which cities and regions are trying to reduce the number of kilometers driven by car, such as high emissions (Umweltbundesamt, 2019), demand for space per passenger (Nello-Deakin, 2019) and, in general, the highest external costs of all transport modes (Van Essen et al., 2019). The latter was recently shown in an analysis which showed that in Munich, almost 80% of all external costs from transportation are caused by private (diesel and gasoline) cars, taking into account a wide range of categories such as congestion, climate, air pollution, land use, and accidents, among others (Schröder et al., 2023). Also, the typical commuting hours are usually the times of day when the transport system is used to its capacity, resulting in congestion on the roads and crowding in public transport (Loder et al., 2019; Rempe et al., 2016; TomTom, 2024). While the COVID-19 pandemic temporarily changed this logic fundamentally, congestion in Munich has almost reached the pre-pandemic levels again (BR, 2024; TomTom, 2024).

On an individual level, having workplaces with low accessibility becomes problematic when the choice of using a car is not voluntary, and people are forced into car ownership and driving because of the need to reach their workplace. The term “forced car ownership” is usually attributed to households who have a car despite economic struggles to afford it (Mattioli, 2017), for example because there is no acceptable public transport connection to their workplace. The same study elaborates that based on an analysis commissioned by the government, between 0.9% of the German population in urban areas and 5.7% in rural areas fall under this category (Scheiner et al., 2012). More prevalent in the Munich region, however, is what could be called “forced car commuting”, where not the economic situation is in focus, but the higher attractiveness of driving to work compared to alternatives such as public transport and cycling is making commuters use their cars. This is, among other factors, caused by workplace locations that can be considered car dependent.

Car dependent places (not to be confused with car-dependent trips and persons) can be explained as places where “the infrastructure maintains and reproduces the continued use of the car” (Stradling, 2007). The opposite notion of “car independency” or “car-independent places” has not been used frequently in the last years, but seems to becoming more popular with recent papers such as a works on “car-independent neighborhoods” (Aumann et al., 2023), “car-independent lifestyle” (Soza-Parra and Cats, 2023) and “car-independent mobility practices” (Selzer and Lanzendorf, 2022). Similar to these authors, the majority of research on sustainable planning focuses on the residential areas or on the level of urban neighborhoods; only few papers focus on the properties of the workplace as a destination (Cervero and Kockelman, 1997; Vale and Pereira, 2016). Therefore, we look at the idea of car-independent workplace locations as a vision of workplace development that offers various options of access for workers at the location. According to this idea, a car-independent workplace is defined as a workplace location with multimodal access and competitive alternatives to the private car for many of its workers.

Current planning instruments in the context of Germany, and Bavaria in particular, where this case study is based, do not include the idea of car-independent workplaces. The existing standards of choosing locations for new workplace developments on a land-use planning level do not require extensive accessibility analysis (Schmidt, 2009; Zaspel, 2012) and are limited to “Anbindegebot” (can be translated as “connection requirement”) from the state’s development program (“Landesentwicklungsprogramm”), which defines that, apart from exceptions for example for logistic hubs, new developments must be linked to existing settlements rather than pursuing new greenfield developments (STMWI, 2023). Compared to the previous edition of these guidelines (STMWI, 2013), the goal has even been weakened. While this is an important element that goes beyond requirements of other countries, it is still not sufficient for ensuring good multimodal accessibility of all new workplace developments. Municipal standards can go beyond this, however they are usually limited to the mere existence of a bus stop near the area, independent of its quality, for example in terms of frequency, capacity, or provided accessibility.

Accessibility Modeling and the usefulness for workplace locations

Accessibility modeling, in the sense of spatial accessibility according to the definition by Geurs and van Wee (2004) has been discussed for integrating land use and transport planning questions like better workplace accessibility for a long time (Bertolini et al., 2005; Bruinsma and Rietveld, 1998; Geurs et al., 2015; Morris et al., 1979; Reggiani, 1998). On the tool-level, a large number[9] of indexes, tools, and methods exists (see, for example, Bhat et al., 2000; Malekzadeh and Chung, 2020; Siddiq and D. Taylor, 2021; Wu and Levinson, 2020) for recent reviews and summaries.

However, as argued by te Brömmelstroet et al. (2016) and Silva et al (2017b), accessibility tools should be targeted at specific planning questions and scenarios, rather than being universally usable. Thus, for the context of workplace accessibility and the idea of car-independent workplaces, specific tools and methodologies are needed. Therefore, this study uses the 'EMMA' accessibility model (www.emma-accessibility.org, see Chapter 2.2 for an introduction) to model workplace accessibility. The model is designed for calculating accessibility of workplace locations based on population that can reach a (potential) workplace location within 30 minutes on a typical workday during the peak-hour. The model is multimodal and uses cycling, driving, and public transport as main modes, with optional intermodal combinations of these modes (such as bike and ride, for example). To assess the value of integrating this approach into the planning process for workplace locations, this paper aims at assessing the usefulness of this tool for planning practice.

The concept of usefulness and research questions

In general, a tool such as the EMMA accessibility model does only create added value and benefits towards the goal of the tool, if it is accepted and used in practice. Therefore, the term 'system acceptability' of a tool describes "whether the system is good enough to satisfy all the needs and requirements of the users and other potential stakeholders (…). [It is] a combination of its social acceptability and its practical acceptability" (Nielsen, 1994, p. 24). While this concept is very important, it is also hard to assess the system acceptability as a whole. Therefore, multiple authors break it down into more precise aspects, such as 'usefulness'. This is a concept of assessing planning support systems (PSS) such as the EMMA model, that aims at describing the "added value of use of a PSS in planning practice" (Silva et al., 2017b), always focusing on the goals of the PSS and the context where it is supposed to be used. The overarching research question of this study is therefore:

[9] See also https://www.accessibilityplanning.eu/ for a continuously updated database of accessibility tools, based on the COST Action TU1002

What is the usefulness of the EMMA accessibility model for the assessment of existing and potential workplace locations?

To answer this question, we applied the EMMA accessibility model in the Munich Metropolitan Region and break the research question down by following the conceptual framework by Pelzer (2017), who describes usefulness as the outcome of the two main dimension utility (=a fit of the PSS capabilities and the planning tasks) and usability (=how well the PSS can be used by the planner). Within these dimensions, further categories (novelty, clarity, communication, credibility, and completeness) are derived from te Brömmelstroet (2013), as visualized in Figure 32:

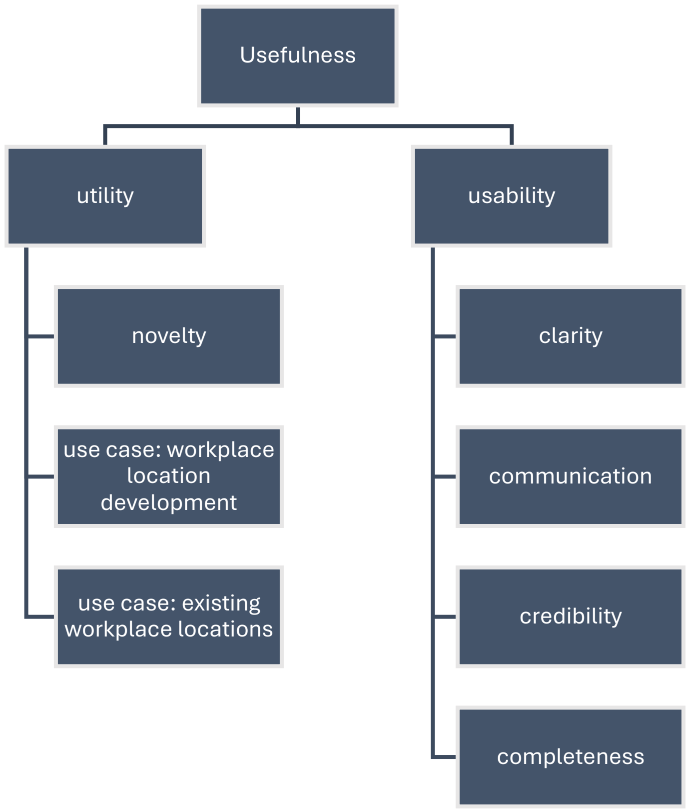

Figure 32: Dimensions of usefulness in the context of the EMMA accessibility model

In detail, the dimensions and categories are answering the following questions:

- Utility:
    - **Novelty**: Which standards, methods, and tools are already used by stakeholders for assessing the accessibility of a workplace? How does the EMMA tool compare to the existing methods? What is new?

- **Use cases:**
  - **Workplace location development**: Where in the planning process can the model improve decision-making for new workplace locations?
  - **Existing workplace locations**: How can the model results contribute to improving the situation at existing locations?
- Usability
  - **Clarity:** Do practitioners understand the EMMA model? Does the model provide the right balance between simplicity and sophisticated methods? Are certain aspects of the tool unclear?
  - **Communication**: Will the target audience be able to understand the results, according to the experience of the experts? What is the added valued of communicating the model results to decision-makers?
  - **Credibility:** Will decision-makers trust the model results? Are there aspects of the tool that raise credibility concerns?
  - **Completeness:** Which features are missing from a practitioner's point of view? Does the tool provide all the necessary information in the context of workplace accessibility?

Chapter 6.2 presents the EMMA tool and the testbed. Chapter 6.3 presents the research methodology used to assess the usefulness. Chapter 6.4 will summarize and discuss the findings of our study, based on the aforementioned dimensions of utility and usability, while Chapter 6.5 will present our conclusions.

6.2. The EMMA tool and testbed

The Munich Metropolitan Region (MMR, as visualized in Figure 33) was selected as a reference area for this study, since the city and the region are experiencing a significant growth in residents and jobs, along with subsequent challenges for housing and commuting.

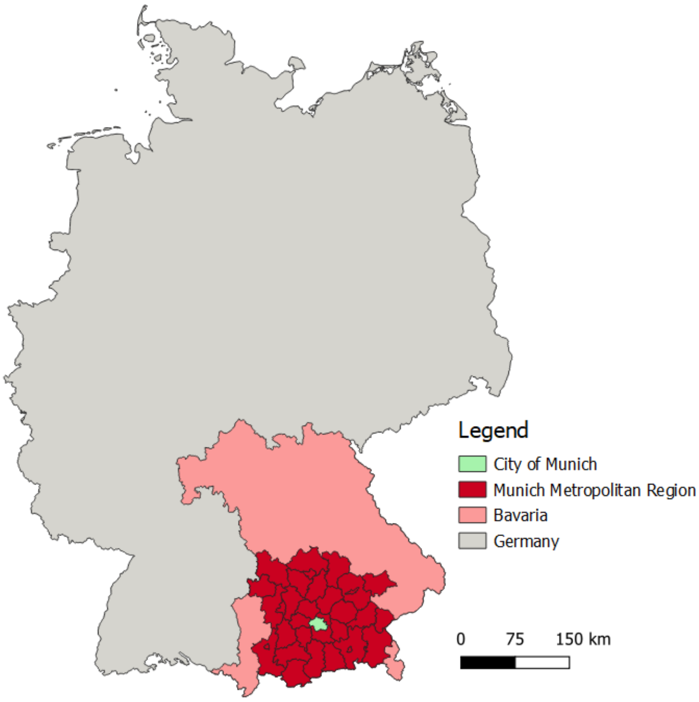

Figure 33: The Munich Metropolitan Region in the Context of Germany (own map)

The region is located in the south-east of Germany and consists of roughly a third of the surface of Bavaria, being home to around 6 million inhabitants (47% of Bavaria). The region is named after Munich, located in the center of the region.

One of the strategies the region is striving for, in order to combat increasing congestion and overcrowded public transport lines, is the development towards polycentricity (Bentlage et al., 2021; Kinigadner et al., 2015). In recent years, the region has faced both large re-locations of companies (such as Microsoft) towards the central parts of the city (Kinigadner et al., 2019), along with large new developments e.g. along the regional train lines' trunk line in the center of the city. On the other hand, not all workplace developments are automatically placed near high-quality public transport, and the stereotypical business park next to the motorway junction, connected at best with a bus line, is still a reality in wide areas of the MMR, especially in more rural areas with lower density in general.

EMMA ("Empowering multi- and intermodal accessibility analysis") is an open-source tool, developed and applied in the Munich Metropolitan Region. It is based on

OpenTripPlanner (Young, 2019), a PostGIS database, and the programming language R. It is built on openly accessible data:

- The German GTFS dataset for public transport (stops, timetables, etc.) ("Datensätze - OpenData ÖPNV," 2022)
- Road network from OpenStreetMap (OpenStreetMap contributors, 2024), accessed as an .osm.pbf file via Geofabrik (Geofabrik, 2022)
- Population data in a 100x100m grid, provided by the national census ("ZENSUS 2011," 2011)

With the same kind of data available, the approach is replicable anywhere in the world, but the first full-scale implementation on a regional level was done for the MMR. See Pfertner et al.(2023) for an in-depth technical explanation of the method and its results on a regional level.

Figure 34 shows the entire MMR (as 17,208 grid cells), visualizing the amount of population that can reach each grid cell within 30 minutes by a combination of public transport and bicycle. This serves as an exemplary result for region-wide analyses with the EMMA accessibility model, with the results as absolute numbers of population. Notable observations are the strength of the big cities. Not only Munich, but also Augsburg (west), and Ingolstadt (north) show very high values of population that can access the grid cells within 30 minutes. Towards the south, where the region is very rural and mountainous, we observe relatively high accessibility along the valleys, compared to the other rural areas.

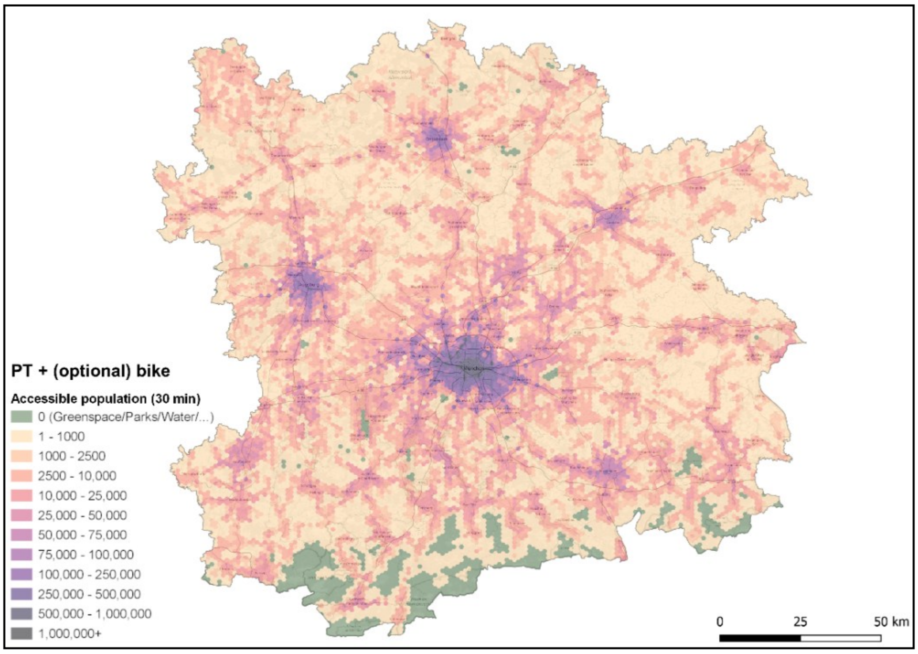

Figure 34: Region-wide accessibility by public transport and bicycle, absolute numbers

Figure 35 shows the same study area, but with a relative indicator, compared to the absolute numbers used in Figure 34. Thus, the displayed ratio is the amount of accessible population by public transport, compared to the accessibility by private car. This is used to demonstrate the use of relative indicators with the EMMA tool. The observations include again the expected peaks in the urban centers of the region, but also relatively high values in small, compact cities like Rosenheim, for example. In areas where the next big city is far away, however, the relative accessibility by public transport compared to driving is very low.

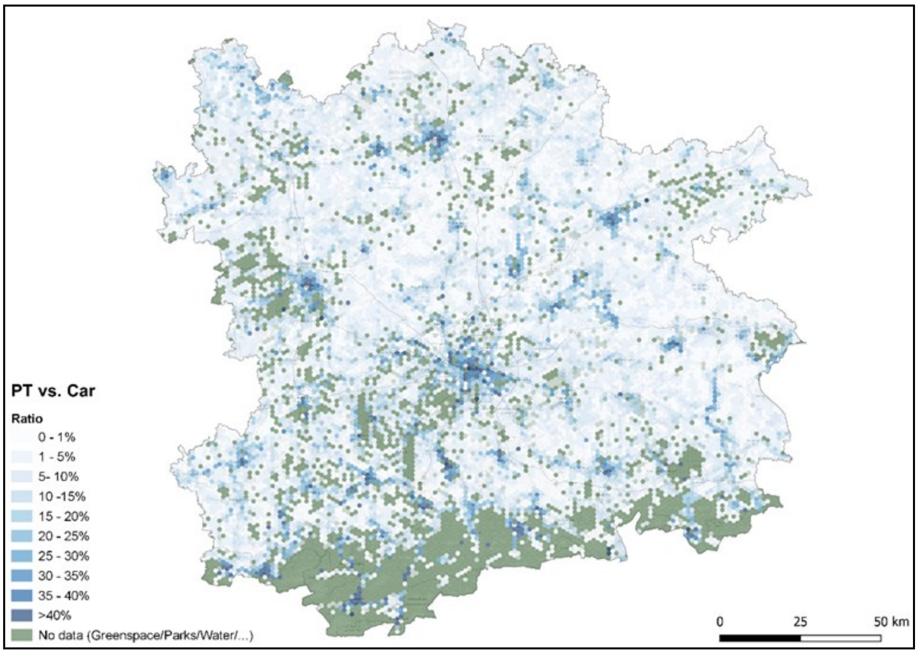

Figure 35: Region-wide accessibility in relative numbers: public transport vs. car

Figure 36 shows the relative indicator from Figure 35, but transformed into a z-score based score, ranging from -100 to +100. This is used as a simplified visualization of the model results, avoiding absolute or relative population figures and relying on the score-logic instead. The interpretation is similar to the results seen before, but the relative score makes the interpretation between grid cells easier.

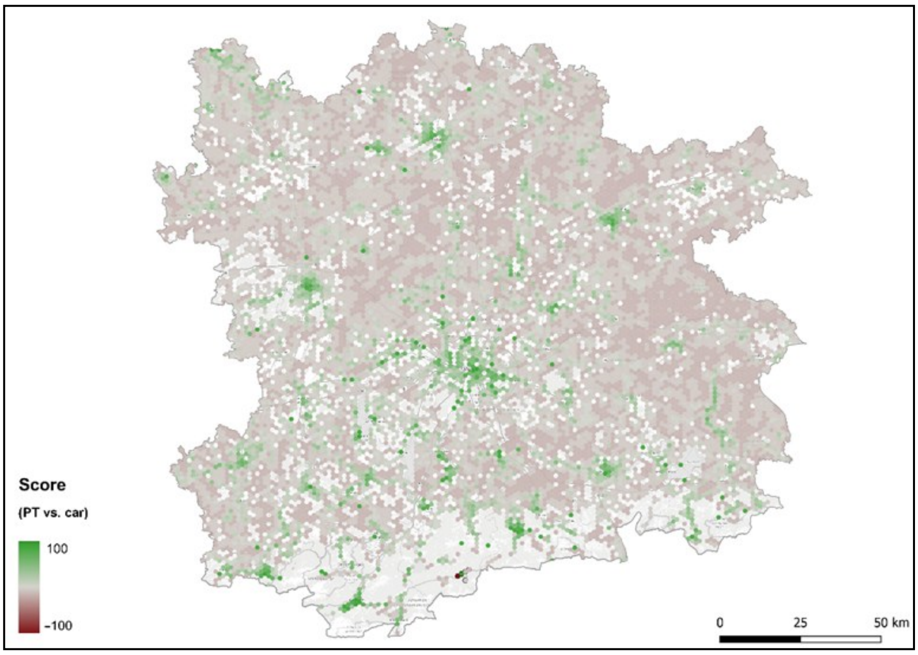

Figure 36: Region-wide accessibility visualized as score

A local case study (Figure 37) explores the application of the tool on concrete workplace locations in the form of scenarios with changes in the mobility system.

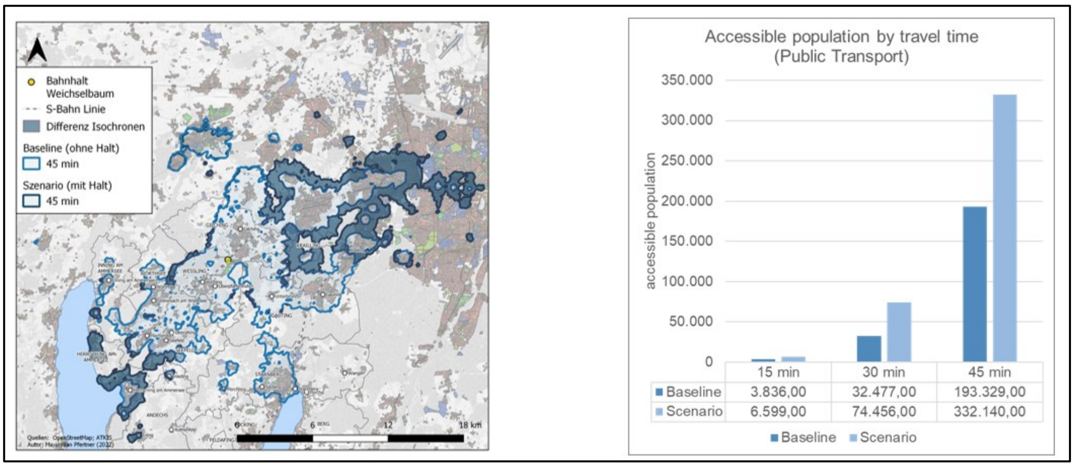

Figure 37: Case study and scenarios in EMMA

The scenario used is the hypothetical re-opening of a regional commuter-rail station south-west of Munich next to a large workplace location, that is currently expanding significantly. With the help of the tool, we compared public transport isochrones of 45 minutes towards the location for the status quo and for a scenario with the re-opened stop (left image), in order to show the effect towards the City of Munich and the surrounding area. The right graph shows the result of the isochrone-based analysis by summarizing the population who can reach the location within 15/30/45min in both scenarios.

In addition to these main model results, Figure 38 shows a location-based analysis for one particular workplace location in the center of Landshut, a medium-sized city in the MMR.

The color-coded grid cells represent the travel time ratio (public transport compared to car) towards the workplace, which all areas in orange/yellow showcasing a travel time ratio of 1.5 or lower.

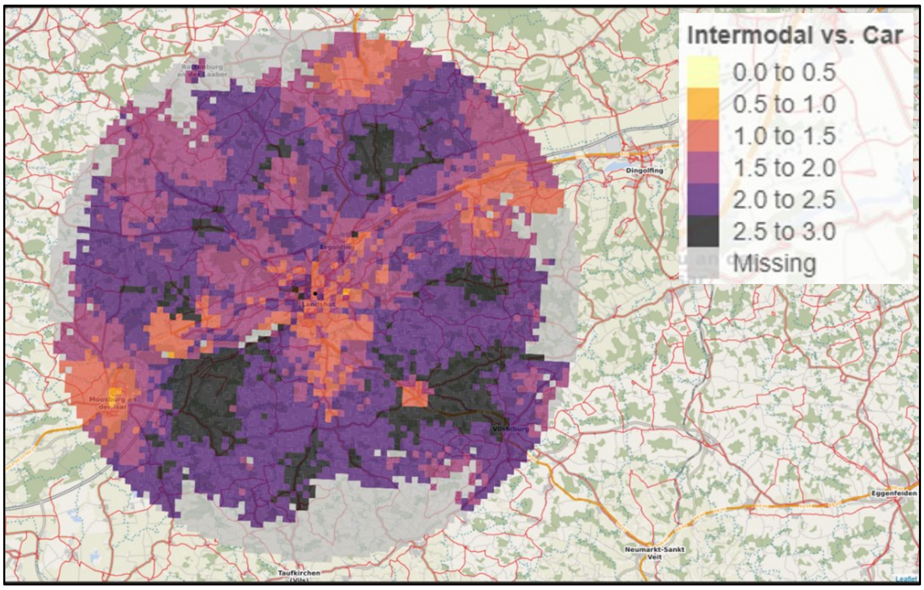

Figure 38: Alternative way to use the model

Additional options to visualize the tool's results (not depicted) are actual, intermodal routes calculated with the model, with the purpose of explaining that the model allows to explore individual routing results in order to check and validate the model.

6.3. Assessing usefulness

To answer the research questions, the aforementioned maps of the EMMA model were used as a foundation for semi-structured interviews with practitioners from the MMR and beyond.

The decision for semi-structured interviews (Misoch, 2019) rather than workshops (as used e.g. by Kinigadner and Büttner, 2021; Silva et al., 2022, 2017b) or other exchange formats with practitioners such as additional surveys (Bicalho et al., 2019), that are frequently used in the literature, was made based on the following arguments:

First, in order to get a multidisciplinary view on the methodology, the interview partners selected (see Table 10) were very heterogeneous in terms of previous experience with spatial accessibility in general, and with modeling accessibility in particular. Due to the various institutional backgrounds and roles of the interviewees, the knowledge of such models ranged from novice to expert. Therefore, interviews allowed to spend more time on the fundamental ideas of accessibility modeling where necessary, while giving the chance to go into deeper technical details when there was interest.

Second, interviews provide the chance to provide more in-depth information from all selected practitioners (Creswell, 2021), while in workshops there is a risk of overlooking individual aspects that are not part of the group's consensus. While this is an advantage in homogenous groups of practitioners, this does not apply to practitioners with different roles and backgrounds.

Table 10 lists the interviewees recruited for this study. The interview partners were initially recruited based on our local network of partners, followed by a snowball sampling approach, where interviewees were asked for recommendations for future interview partners. The recruiting goal was to have the following key stakeholders and potential users of accessibility modeling for workplace locations in the sample. The number in parentheses refers to the ID in Table 10:

- Municipalities in various sizes (small: #1; medium: #5, large: #8 + #9)
- Public Transport Association (#7)
- Real estate sector (developer/manager: #2, consultants #4)
- Transport sector (consulting #3, software development #10)

In the process, a co-working company currently expanding their locations in the region of Munich was found (#6), bringing in a mixed perspective of real estate and entrepreneurship. The second recruiting goal was to stop data collection once theoretical saturation was reached (Glaser et al., 1968; Hennink et al., 2017), defined as "point in data collection when no additional issues or insights emerge from data and all relevant conceptual categories have been identified, explored, and exhausted" (Hennink et al., 2017). After ten interviews, the questions were answered from various perspectives and no additional insights were generated, thus saturation was assumed.

Table 10: List of interview partners

ID	Institution	Role
#1	Small municipality close to Munich	Transport Planner
#2	Business campus developer & management	Manager of a Business Campus close to Munich
#3	Transport consulting firm	Consultant
#4	Real estate consulting firm	Head of Analytics
#5	Medium-sized Municipality in the MMR	Head of Urban Planning
#6	Co-working company	Head of Location Development Munich
#7	Munich Public Transport Association	Transport Planner
#8	City of Munich, Mobility Department	Head of Data and Models

#9	City of Munich, Municipal Department	Geodata / digital twin
#10	Mobility Consulting and Software firm	Founder and product owner

In order to prepare for the interviews, an interview guideline was developed and tested with one pre-test interview. Personalized invitations were used to increase the response rate, which ended up high with 77% of requested interviews taking place within the scope of this work.

The interviews took place between July 2023 and January 2024, partly in-person and partly online. Except for interview #10, all interviews were conducted in German language. The duration ranged from 60 to 90 minutes and the interviews were recorded.

The interviews were split into two blocks with one section of input about the accessibility model, followed by a set of questions per block developed. The first block explained background about the project, definition of accessibility, explanation of our perspective of accessibility for workplace locations, a brief technical explanation about the EMMA model (how it works and what it produces), followed by the EMMA model results on regional scale with explanation (see Figure 1 - Figure 3). The questions focused on the interviewees understanding of the model and existing standards or methods. The second block shifted from regional perspective to actual workplace locations and scenario modeling. Questions ranged around the potential use of the model in the planning process and the added value.

After the interviews, the recordings were transcribed. Using MAXQDA (VERBI Software, 2024), the transcripts were coded by themes and questions and manually summarized and analyzed by each dimension and category of usefulness, as outlined previously. Thereby, the analysis focused on an explanatory perspective with a clear focus on the research questions and its dimensions and categories, while adding additional observations and notions with an exploratory mindset (as suggested by Næss, 2020).

6.4. Findings and discussion

Based on the coded interviews, the following findings were obtained from the practitioners. The section "Utility of the Method" will summarize and discuss the utility while "Usability of the Method" will explain and discuss findings that describe the usability, in the sense of how well the actual model results can be used and understood in practice.

Utility of the method

Novelty

To be useful, the EMMA model needs to be a novel approach and significantly different from existing standards, methods, and tools that are already in use by practitioners in the field of workplace development. In general, none of the interviewees reported existing established accessibility standards for workplace development in the sense of our model, so that the novelty can be assumed. This is in line with the literature research, where no comparable model with the same focus (cf. te Brömmelstroet et al., 2016) was identified. In previous work about the model, the novelty compared to the state of the art was summarized in the following four aspects (for details, see Pfertner et al., 2023):

- Perspective: To date, no accessibility model specifically designed for the multimodal and intermodal accessibility analysis of workplace locations exists. While the assessment of accessible jobs per residential location is widely used, our approach focusing on how many potential workers can access a workplace in given time limits is rarely used.
- Calculation method: Most accessibility measurements in this context are working with origin-destination matrices, our simplistic and transparent approach based on isochrones around the workplace locations is new.
- Multimodality and intermodality: compared to traditional analyses that usually focus on driving and/or public transport only, the EMMA tool is multimodal and intermodal.
- Open Source and open data: The whole set of software packages and data used in the tool is open source, so that the tool can be replicated by anyone, free of charge and without the need for specific software licenses.

In addition to the technical perspective, and no standard exist that would make use of accessibility analysis in established planning procedures in the context of workplace locations (Schmidt, 2009; Zaspel, 2012).

The interviewees confirmed this general notion of novelty. On the municipal level (interviews #1, #5, #8, #9), the complexity of decisions increases with the size of the municipality. The small municipality (#1) is limiting their accessibility analyses of new workplace developments to the existence of a bus stop nearby, but with a low priority in the process. The options to change the mobility supply, however, are limited, since the bus network is organized on the county-level. The medium-sized municipality (#5) as well as Munich (#8, #9) also do not have established criteria, but use more advanced methods, such as buffers around public transport stops to better assess the coverage of an area with public transport (#5). The same method is applied by the Public Transport Association (#7). An example for advanced standards in a similar field is planning of social infrastructure (such as daycares), where methods exist to compare population density and the accessibility to e.g. daycares or municipal service centers. Standards for workplaces exist rather in the domains of mobility management, bicycle-friendliness, etc., but not on the spatial/location level that accessibility modelling aims at (#5, #8).

In the real-estate sector (#2, #4, #6), the standards are rather hands-on than systematic: the business campus management requires acceptable car accessibility (ideally in areas not too dense, where congestion levels are low) but also rail-based public transport as a prerequisite for an attractive location. All three interviewees emphasized the hierarchy of public transport modes, with subway being the preferred option, followed by other rail-based options (S-Bahn and Tram), with walking distances lower than 10 minutes and headways <= 10min for 'good' accessibility (based on estimates, not models). Buses were seen as an unattractive option that are usually not considered. The co-working developer (#6), for example, classifies their locations into 'car-locations', without attractive public transport, but more parking supply instead, compared to other locations with rail-based public transport options available.

From the transport consultant perspective (#3, #10), both consultants regularly use isochrone-based analyses, but typically not for the assessment of workplace locations in general, but rather for re-locations of companies, where data about the residential addresses is provided by the companies and outcomes such as new travel times for the workers are relevant factors. Asking the interviewees individually, good accessibility for them is, similar to the other perspectives, always multimodal and with access to high-quality public transport (#3, #6). The Public Transport Association referred to travel time ratios, such as public transport taking 50% longer than driving as a threshold between good and bad accessibility and as an additional factor to consider.

On a technical level, the only interviewees who have the capabilities to run analyses similar to the EMMA model were the transport consultants (#3, #10). They used in-house developments and standard GIS tools such as QGIS or ESRI ArcGIS for these kinds of analyses. However, none of the methods were open-source and the population-based accessibility calculation was not part of their analyses. On an experimental level, also the

Public Transport Association (#7) and the bigger municipalities (for walking and cycling, #5, #8, #9) ran some analyses, for example with the help of their existing PTV VISUM Transport Model (#7).

First use case: Workplace location development

The EMMA accessibility model is tailored to being used for the assessment of new workplace developments. This is one of the major novel aspects and potential added value of the tool. In the interviews, all interviewees confirmed that the biggest potential of the tool is the early planning stage, when, in the best-case, multiple location options can be compared and there is an option to add changes in the mobility supply to the discussion, with enough time to implement both the workplace location and, for example, a new public transport line in parallel. For example, the public transport association explained *“if I see an area, were let’s say 5,000 new workplaces are being developed, but a large number of the population can only get there with multiple transfers, then we need to find better solutions and consider a new express bus line, for example”* (#7). According to the interviewees, this is a common case in the region and no planning procedure exists to change this. Thus, the EMMA tool provides a method to calculate such population-based figure and inform the debate about the suitability of locations for workplace development. Thus, this use case seems to be a useful application of the model.

However, especially the municipal interviewees (#1, #5. #8. #9) and the transport consultants (#3, #10) explained that the early involvement of accessibility planning expertise is rarely the case: *“The tragedy is that we are usually only involved, when the location is already determined. The option of explaining that another location would be better does usually not exist.”* (#3). This showcases the need for more coordination, for example in the form of an integration of accessibility considerations in official planning processes that take place at the start of the project. In line with this, most interviewees referred to a lack of regional governance in Germany in general and in Bavaria in particular, which makes it harder to use the full potential of such analyses and is again in line with the literature (Zaspel, 2012). One aspect of added value, however, was emphasized by those who work with municipal decision makers (#3, #4, #5, #7, #8#, #10): the tool explains the accessibility of locations in a fact-based and visual way, which makes it much harder for decision-makers to ignore the results and move on with the planning of locations with low accessibility:

> *“I believe it has lots of added value because if you leave it [location decisions] to the market, they always say this is a really good accessible work site because it's really near to the highway and there's a bus stop at 500 meters, so this is the best accessibility you can get, bringing you from nowhere to nowhere really fast. So, you really need to get objective*

measures and that's what your model does, so I think that it's extremely valuable for decision making on a regional level and on a company-level as well." (#10)

Thus, the tool has the potential to influence the planning process, even if no formal regulations and procedures are in place that make accessibility analysis mandatory. However, planners need to take the initiative and use such tools in the respective processes as an element of additional information. On the long run, a change in governance is necessary to implement such analyses on a broader scale, because it could be hypothesized that only developers/municipalities that work with locations with a relatively good accessibility might be open to using the tool. The locations with poor access conditions, that would need it the most, might stick to the existing minimal requirements of access without driving a private car, and make a decision on the location development before rigorous and well-informed integrated planning of transport and land-use even starts.

Several additional strategies were recommended, in order to use the potential of the tool efficiently and find an entry point in established structures:

- Starting with analyzing small, municipal projects (e.g. a new bus line) before analyzing larger investments: thereby the decision-makers learn to use the method's results with easier case studies before looking at very complex and large-scale decisions (#1)
- Focusing on shared mobility, mobility options, ODM services, intermodal combinations (bike and ride, park and ride) and other innovative aspects, because in these areas the uncertainty is the biggest and the existing tools are not sufficient to showcase the potential of these services to improve workplace accessibility (#1, #5, #7, #10)
- Current municipal projects such as the 'digital twin' will soon provide much more detailed structural data and details about the mobility system. With that, synergies could be used to model e.g. cycling accessibility based on actual (protected) cycling infrastructure rather than the OpenStreetMap network. (#9)

Second use case: existing workplace locations

In general, the interviewees referred to the development of new locations more often than to usefulness of the model for existing locations. The usefulness was found for certain aspects (see below), but it was agreed that the most important aspect of workplace development in the sense of our model is the first use case.

The municipal practitioners (#1, #5. #8. #9) and the public transport association (#7) mentioned two main use cases for the model:

- Transport Development Plans: Municipalities could model scenarios of future transport infrastructure in order to compare the accessibility changes for workplace locations. Thereby, decision-making could be improved by adding a very concrete and understandable accessibility indicator to the set of analyses (#5).
- Municipal analysis of existing commercial areas: A repetition of the regional analysis, not on a grid-cell level for the whole MMR but rather for all existing commercial areas according to the land use plan would be very interesting for the City's business development team (#8). Deficits in the existing structure would be highlighted and together with the stakeholders (/municipality, companies, business park management, mobility providers), solutions could be developed to improve the accessibility (#1, #5, #8).

From the perspectives of consulting (#3, #10), real estate (#2, #4) and co-working business (6), it was added that all company-organized solutions such as shuttle buses are an interesting use case for the model, but the responsibility for the provision of good multimodal accessibility is with the public authorities (#2). It was further emphasized, that the analysis of weaknesses in the land-use and transport system is possible with the accessibility analysis and that, similar to the municipal perspective, it should be applied and used to identify and improve deficits in workplace accessibility (#4). Individual employers or users of workplace locations, such as the co-working company, already act depending on their perceived accessibility of locations, for example by cooperating with shared-mobility providers or by using adaptive parking standards depending on the location (#6).

Usability of the method

Clarity

The clarity of the model process and results is evaluated through first-hand statements from the interviewed practitioners, as potential future users of the model, who need to fully understand and be able to follow the logic of the model and its results. In general, the interviewees had only minor questions of understanding after having seen the model and its results presented by the researchers. The simple but clear methodological approach based on isochrones was highlighted and is in line with certain voices from the literature that argue for simple and clear tools (Bertolini et al., 2005; Givoni et al., 2016; Silva, 2013) .

However, the model results need a verbal (or written) explanation and are not self-explanatory to someone who has not used accessibility modelling before (#2, #5, #7, #9): *"I would always expect you [the researcher] to explain the maps to me orally, so that I can ask you 30 follow-up questions and make an informed decision afterwards"* (#2). From the presented regional maps, the relative accessibility was highlighted as the most clear and interesting, since the interpretation is easy and with implications towards ‘car-independent’ workplace locations. According to the interviewees, the level of complexity of the model was suitable for the planning questions.

Communication

In order to be useful, it is not enough if experts, such as the interviewees understand the model and its results. It is of critical importance that decision-makers, such as mayors, city councils, CEOs of companies, and others are able to understand and interpret the results when communicated by an expert who used the model, as explained for example by Pan and Deal: *“Engaging planning practice requires a PSS that can effectively communicate results in simple and understandable terms to a nontechnical audience.”* (Pan and Deal, 2020, p. 138). In all interviews, the communication potential of the model results for the practitioners and their typical target audience (for example, the City Council for the municipal planners) was confirmed, highlighting a good balance of easy indicators while still bringing added value to the discussions.

Especially the practitioners from the municipal sector (#1, #5. #8. #9) and the consultants (#3, #4, #10) highlighted the importance of clear visual representations and maps and the notion to keep the results short and simple:

“The most important thing for us in consulting is to be able to explain the important findings fast and easy – that is everything, that counts. Therefore, we usually need a map that visualizes, ideally in green, yellow, red – where is good, medium, and bad” (#4).

Another highlighted aspect of the accessibility model was the isochrone-based analysis because of its simplicity that can also be understood by novices in the field (#5). The absolute indicator allows for effective storytelling with the clear statement of how many people can reach a location with which mode in a given time (#3, #6, #9) and according to a consultant, the explanation would be even stronger when combined with personas:

“I think it is really useful to try explaining isochrones with personas: ‘this is Heinrich and he lives here, from which his commute is 40 minutes by car and 55 minutes by public transport’. (…) People start recognizing themselves and will start to adopt the model behind it” (#10).

Some potential pitfalls in the interpretation were mentioned, such as the question whether a location in the middle between two centers in the region (such as between Augsburg and Munich) might lead to the conclusion that this is a ‘good’ location, because residents from both cities can get there, which induces relatively long car commutes. This emphasizes the need to put the tool and its result into a context of planning questions, explained and moderated by a knowledgeable user of the tool. The results are never stand-alone and need interpretation by persons with explicit knowledge about how to use and interpret such models.

Credibility

Due to the simple storyline and relatable assumptions such as travel times on a weekday based on actual timetables, 30 minutes travel time budget, and official, reliable data sources, the interviewees did not have doubts about the credibility of the model results. Also, the open-source character of the model and the use of publicly available data was seen as positive for the model's credibility (#7). From the interviewees' experience, decision-makers will follow along the argumentation and do not question the credibility of the approach:

"I believe that this is well understood. Since you are not highly theoretical, but based on very clear conditions, such as I want to reach this place between 8 and 9 and then you compare the modes to see how many can do that, visualized on a map, stakeholder will trust you and do not question each individual modelling step" (#9).

However, practitioners reported that some decision-makers might try to attack the model if the results do not fit into their political agenda (#8, #9). Therefore, it is crucial to be open about the method and limitations, because potential mistakes in the model open the doors for these kinds of attacks, diminishing the value of the whole analysis in decision-making settings (#9). When it comes to multimodal and intermodal analyses, some interviews remarked that – while multimodal comparison are very clear and understandable – the intermodal aspects might be more controversial. The combination of modes, especially with cycling or shared modes has too many alternative routes and options, and thereby a high number of assumptions about user behavior, that decision-makers might have problems following the argumentation (#5, #8).

Completeness

First, most interviews noted that the role of accessibility is only one of many factors that influences the development of workplace locations: *"choosing a workplace location is a strange process with all different unexpected arguments"* (#10). These factors include, but are not limited to, political agendas, costs, land availability (incl. zoning, environmental protection, etc), economic reasons, agglomeration effects, type of suitable businesses, decisions on a company-level, logistics, and *"sometimes even the potential commute of the CEO"* (#10). For the goals of the model to enable accessibility analysis of workplace locations, the provided model data, indicators, and results were mostly seen as fitting and suitable and relevant, with no major items missing. The general notion, that decision-making for workplace locations is highly complex and goes beyond discussions of accessibility was expected and acknowledged in the design of the tool, and also explained in the literature (Zaspel, 2012)

The following aspects were mentioned with regards to completeness or potentially missing elements or features: On the mobility level, the punctuality, frequency, and reliability of the included modes were mentioned multiple times (#2, #3, #4, #5, #8, #9, #10). This includes also car travel times, which can have a wide range of possible values, especially when focusing on the peak-hour of getting to work. Furthermore, the availability of backup options (#6), for example in case of bad weather when cycling, or delays on public transport lines, was mentioned as a factor that is not included in the model, along with information about headways and frequencies. On the user-level, it was commonly noted from all sectors that, in order to become useful for practitioners, the model should be turned from open-source code into an actual tool, ideally as a web-based tool where practitioners have easy access to without the burden of running code or installing complicated packages on (often heavily restricted) work computers (#1, #3, #5 - #10).

6.5. Conclusions

Our research question "What is the usefulness of the EMMA accessibility model for the assessment of existing and potential workplace locations?" was answered using expert interviews with practitioners mainly from the MMR. Overall, the usefulness of the model was highlighted for the early planning stage, where multiple locations can be compared, scenarios with variations of the transport supply can be modeled and where there is still enough time to actually implement changes in the land use and transport system in time. Thereby, a very clear and understandable use case for the tool has been identified. The results suggest that the tool has the potential to bring added value to the current planning practice by providing a simple, replicable, and open-source approach to assess the accessibility of potential workplace locations. Across the interviews it was notable that the eventual decision-makers are very receptive to the way the model results are presented and explained, especially when using maps and explanations of the isochrone-based calculation, highlighting a positive evaluation on the model's usability. Among the presented indicators, the relative comparison was emphasized as the one with the clearest story line. Within the interviews, multiple secondary levels of usefulness were uncovered. This includes the use of the model result for existing locations, to analyzed weaknesses within a city's transport system for commuting, but also compare changes in the transport infrastructure that could be introduced by new modes of transport, such as sharing options, company shuttles, or mobility stations – an area, where conventional assessment tools struggle to deliver meaningful insights. Another concrete scenario, where the model could bring added value was the case of company-relocations, and the search for new company locations from a company- or real estate perspective.

Some limitations arise from the chosen methodology: Expert interviews, as a qualitative research method do always leave room for some interpretation, especially when only transcribed and coded by one researcher, as in this case study. Also, the number of interviewees is not very high (n=10). On the other hand, research question could be answered and saturation from the interview questions was reached, which indicates a fitting number of interviewees. Also, all relevant perspectives were included in the sample, as confirmed by the interviewees. The main limitation of this work is the fact that usefulness could be induced from the expert interviews, but the interviewed practitioners were not able to use the model on their own, they based their opinions and expectations on the presentation of the model and its results by the researchers. This limitation is necessary by design, since the tool is currently not available as a refined application to be used by practitioners without coding experience. However, as suggested by many experts, such as Russo et al. (2018) and Pelzer (2017), to develop the model further into a webtool, after getting positive feedback from practitioners in this initial evaluation, isa potentially useful next step.

The main challenge for further research about the EMMA model in particular is the implementation of the tool into a webtool to be used and tested by practitioners themselves. Some other minor research aspects were suggested by the practitioners, such as focusing the model on all business- and industrial zones of a city for an evaluation, focusing on on-demand mobility services for new and existing locations, or limit the public transport modes to rail-based services in order to comply with the standards of real estate practitioners.

As the next big methodological achievement, as suggested by Pelzer (2017) and te Brömmelstroet (2013), the ultimate goal should be to establish a method to measure the usefulness of accessibility instruments in general in situ, measuring the added value by using and evaluating the tool for real decision-making processes. Because eventually, the positive findings about the usefulness of this tool provided by the practitioners are still contrasted by a lack of usage of such tools in established planning procedures around workplace locations. While our findings provide some ideas, how to change that, (such as starting with small projects and research questions, and then grow the influence of the method), it remains a challenge to implement accessibility into decision-making processes.

III.Discussion and Conclusions

7. Discussion and Conclusions on the Research Questions

So far, the three overarching research questions have been answered separately and partially within the publications (see Chapters 4-6). Now, the questions will be answered through an overarching discussion and conclusions in Chapters 7 and 8.

In general, the goal of this dissertation **„Development, application, and assessment of a multimodal and intermodal accessibility model for workplace locations"** was reached. First, the importance of workplace accessibility for commuting mode choice and car availability was proven for the Munich Metropolitan Region. Then, the EMMA accessibility tool, as presented in the previous chapters, has been developed, applied, and assessed for usefulness. The EMMA model can measure the accessibility of workplace locations through the isochrone-based calculation of population (=potential workers) who can access the location within pre-defined travel times (with 30 minutes as the default value). Thereby, it was shown that the model is capable of calculating the accessibility in a truly multimodal perspective: not only separate values for each mode are computed, but both the relative indicators and the z-value based score provide insights about the competitiveness of accessibility by various modes (public transport, cycling, and driving), aiming at an assessment of workplace accessibility 'towards the car-independent workplace'. In addition, using the example of bike and ride, it was shown that intermodal accessibility calculations are feasible with the EMMA model. The assessment of the model was done with the help of expert interviews with practitioners who were asked about the utility and usability of the EMMA tool.

The following sections present integrated conclusions and discussions for each research question.

7.1. How is the workplace location associated with car availability and commuting mode choice of its workers? (RQ1)

This section focuses on the findings both from the literature and the own statistical analysis presented in Chapter 4.

General findings

According to the literature, the idea that the workplace location is an important factor for the mobility behavior of the people working at the location is not new. Hansen (1959) already identified workplaces as critical elements in regional development that are impacting, for example, where inhabitants locate. Both older and recent papers in the field conclude that the workplace location is significantly associated with modal split (Hu and Schneider, 2017; Næss et al., 2019; Naess and Sandberg, 1996; Peña et al., 2022; Vale et al., 2018; Wali et al., 2024; Wolday et al., 2019), energy use (Naess and Sandberg, 1996), commuting distances (Cervero, 1989; Levinson, 1998; Simpson, 1987), and car ownership (Ding and Cao, 2019).

However, compared to the literature on the effects of residential location on the aforementioned dependent variables, the body of research about the workplace location specifically is still smaller and the workplace location is less in focus. One potential reason could be the difficulty to collect high-quality data about the commuting behavior of workers from many different workplace locations with varying characteristics, that would enable a statistically sound analysis. One common solution for this problem is the analysis of workplace relocations of individual companies or, more rarely, the quasi-longitudinal analysis of workers who changed their workplace location, independent of the company (ideally while keeping their residential location). This allows, to some extent, insights about the importance of the workplace location and the effects on commuting behavior. For the first option, two relevant literature reviews have been concluded in the last years: Zarabi and Lord (2019) focus on the effects of involuntary workplace relocations on mode choice. They analyzed 22 studies and concluded that the following four main factors are associated with car use at the new workplace location: (1) access to high-quality public transit, (2) access to (free) parking, (3) access to roads system, and (4) home–work distance (Zarabi and Lord, 2019, p. 53). Similar to the literature about the workplace characteristics alone, they find that there is a strong link between workplaces to suburban, less accessible areas, and driving to work.

A second review was done by Maheshwari et al. (2023), broadening the focus of workplace relocations effects on commuting behavior, but also on commuting satisfaction and well-being. Thirty-five papers were included in their systematic review and in line with previous research, they found mode shifts towards active mobility and public transport use are associated with relocations to more centralized areas. In case of relocations to less centralized areas (center to suburb), they found the expected effect of a modal shift towards driving in all relevant studies.

Specific contributions from the statistical analysis

Given these findings from the existing literature, our findings presented in Chapter 4 are not unexpected and in line with the recent literature. In contrast to previous work, our statistical analysis stands out for the fact that the dataset is unique and offers novel kinds of analysis: The survey from the WAM study (Thierstein et al., 2016) included a wide range of respondents who had changed their workplace location (for various reasons) within the Munich Metropolitan Region and was not limited to a small number of municipalities or companies. The dataset included not only the coordinates of both old and new workplace, but also the usual commuting modes as well as the individual availability of a private car at both points in time, allowing a quasi-longitudinal analysis. With the help of advanced statistics, such as the Heckman Selection Model, we found an association between the change in centrality of the workplace and changes in car availability and driving to work. The fact that these tendencies were also visible with the qualitative flow diagrams underlines the significance of these trends. While a relocation to a more centralized workplace location with higher accessibility is associated with a mode shift towards public transport and cycling, the opposite mode shift towards driving is associated to a less-centralized new workplace. This dynamic was described in the literature before, but is now reinforced in the Munich Metropolitan Region in particular, with robust statistical significance.

In the existing literature, there is fewer evidence of associations between workplace location and individual car ownership (Ding and Cao, 2019). Therefore, our findings presented in Chapter 4 are important in suggesting that the elasticity of car ownership in relation to the workplace location is asymmetric: In case of relocations towards workplaces with less centrality and lower accessibility, the expected effect is observed: Workers increase their individual car availability, e.g. by buying a car. It is important to consider, however, that the sample of the WAM survey was skewed towards ‘knowledge workers’ (Zhao et al., 2017) with relatively high incomes, so that the increase in car ownership is likely to be feasible for a large part of the sample - in contrast to the theme of forced car ownership as discussed by Mattioli (2017), that might occur in cases of workplace relocations. In the other case, when workplaces are relocated to locations with higher centrality, we did not find significant changes in car availability. That means than even if we found evidence of a modal shift in this scenario, the workers do not sell their car, but rather keep it (and use it less, presumably). This is highly relevant in the context of using the reduction of car ownership as an evaluation indicator for all kinds of policies and measures, in the sense that a project is expected to reduce car ownership by a certain percentage. Planners and decision-makers should not expect reduced car ownership as an immediate outcome if even the quite substantial mode shifts observed along with the workplace relocation did not trigger this effect.

Conclusions and questions that are still open

To conclude on RQ1, the location of the workplace, categorized by various definitions ranging from “suburban” to ”urban” (as frequently used in the literature) to spatial cluster as used in Chapter 4, is significantly associated with car availability and commuting mode choice. It was shown that locations with a lower centrality are associated with more driving to work and less use of public transport, whereas locations with higher centrality are associated with less driving and more public transport and active modes. The literature provided sufficient evidence from case studies and reviews, and our own contribution (mainly presented in Chapter 4) could deepen these findings with novel data, advanced statistics and specifically for the Munich Metropolitan Region. The evidence for car availability is weaker from the literature perspective, since only few studies have focused on the association between workplace location and car availability (or ownership), but Chapter 4 was able to show the association between an increase in car availability and workplace locations with low centrality – whereas a decrease in car availability was not found in any scenario.

Thus, the evidence for our answer to RQ1 is robust. Some limitations can be mentioned in terms of representativeness of the survey data used in the WAM study, which is dominated by knowledge workers and not very representative for other sectors, such as low-income jobs. Due to the snowballing-approach of data collection, the results are also not spatially representative for the whole region, because some municipalities recruited much more participants than others.

Also, in the literature and our own research, various definitions have been applied for the categorization of the workplace location. Further research should aim at collecting a large sample of information about commuting mode choice from a regional context and try to correlate it with workplace accessibility measured in a consistent way. The EMMA model developed within this dissertation could be a promising tool for this task.

For policy and practice, these results emphasize the crucial role of the workplace location as a driver for mobility decisions of its workers. In order to reach their ambitious climate goals and plan for a high quality of life, the planning processes for the development of workplace location should be improved by giving more weight to the question of workplace accessibility from the start of planning such projects. As outlined for example by Zaspel (2012) current practices in regional planning are often lacking the power and legal consequences to enforce an analysis of locations in terms of their accessibility, even when limiting it to rudimentary questions of availability of public transport at the location. This could be discussed as a wasted potential to use integrated transport and land-use planning as a means to reach sustainability goals in the region. With more and more policy measures to combat climate change and to-be-expected increases in prices for (fossil) fuels and other drivers of global warming, the role of 'good' locations that are at the same time more resilient towards these increasing costs, is expected to become more relevant. There is a chance that the importance of accessibility considerations will also be picked up by market-oriented stakeholders, such as developers and companies. Until then, it is recommended to strengthen the role of a rigorous assessment of geographical locations and their accessibility in the planning procedures for workplace locations.

7.2. How can we measure the multimodal and intermodal accessibility of workplace locations? (RQ2)

The second research question is split into the two sub-questions **RQ 2.1,** that asks about the measurement of accessibility on a regional level, using the Munich Metropolitan Region (MMR) as a reference while **RQ 2.2** 'zooms in' to assess the qualities of individual locations. Thereby, the general answer to the overarching question is the EMMA model presented in Chapter 5: By combining open-source components such as OpenTripPlanner, PostGIS databases and R as a scripting language, we can provide a tool that enables planners to calculate workplace accessibility in an easy, fast, and replicable way. Based entirely on open-source tools and open data, the tool offers an easy and comprehensive way for this modelling task. It is also advantageous to planners using the tool that it runs efficiently on regular consumer laptops, where the calculation for more than 17,000 grid cells in the entire Munich Metropolitan Region works within a few hours (e.g. overnight).

On the regional level (**RQ2.1**), the indicators chosen for the measurement of multimodal and intermodal accessibility of workplace locations, as presented in Chapter 5 are:

(1) Absolute number of population (in the working age 18-64) that can access the locations within 30 minutes on a typical weekday during the morning peak hour. Calculated individually for cycling, driving, and public transport (multimodal) and intermodal combinations (such as bike and ride)

(2) Relative multimodal comparison of accessible population (18-64), based on (1) and calculated as the ratio between modes (incl. intermodal combinations), for example public transport vs. driving.

(3) Accessibility score from -100 to +100, based on (2) and presenting the relative accessibility compared to all other grid cells on a regional level (based on z-values/standard deviations).

The technical details about the calculation are presented in-depth in Chapter 5. According to the expert interviews with practitioners (see Chapter 6 for details), the relative indicator (2) is seen as the most promising, due to its balance between simplicity and added value. According to the practitioners, the ratio is well-understood by most of the decision-makers and planners and can inform the discussion about workplace accessibility. Especially when talking about the theme of car-independent workplaces, the comparison of car accessibility compared to the alternative modes is a very intuitive way to operationalize the concept. Thereby it is important to note that the accessibility indicator is one out of many potential factors that can contribute to the assessment of car-independency. For a detailed analysis of the usefulness of the tool, measured in the dimensions of utility and usability, please refer to Chapter 6 and the conclusions and discussions in Chapter 7.3.

For the analysis of individual locations (**RQ2.2**), the EMMA tool with the same technical framework as used in **RQ2.1** can be applied. However, instead of using grid centroids as target coordinates for the isochrone generation, we can apply directly significant coordinates of the to-be-examined workplace location, such as representative points like future campus entrances. The model can generate the multimodal isochrones for the particular location. A simple application is the comparison of multiple locations that are available for a decision. As outlined by the interviewed practitioners, however, this is rarely the case in projects, since municipalities, as the key decision-makers for new workplace locations on the land-use level, often only have a very limited number of available locations due to other constraints, such as land ownership, conservation areas, etc. This emphasizes the need to discuss accessibility questions as early as possible in the process, when there is still the maximum potential number of options available.

A main application that is also presented and discussed in Chapter 6 is the use for modelling scenarios. Due to the openness of the tool and its data, planners can change and modify both the land-use and the transport component of the accessibility model. This was demonstrated and discussed for the Weichselbaum area, where the EMMA tool was used to compare scenarios that include the opening of a new regional commuter rail stop next to the proposed extension of a large business park.

To conclude, this dissertation successfully describes how multimodal and intermodal accessibility for workplace locations can be defined and measured (**RQ2**) using the EMMA accessibility tool developed within this dissertation as a showcase for both the regional level (**RQ2.1**) and the location-specific approach (**RQ2.2**). Compared to the range of existing tools for a similar purpose (see Chapter 5.1), it stands out for the fact that it is entirely open-source, using open data, and providing a clear set of indicators that are specific to the use case of workplace locations. The range of potential scenarios to compare include thereby in essence:

- Different locations that are potential workplace locations
- Transport supply towards the (potential) workplace location
- Land-use patterns in the region, influencing the distribution of housing, and thereby potential workforce that can access a location.

7.3. What is the usefulness of the tool from a practitioners' point of view? (RQ3)

The third research question asks about the usefulness of the EMMA accessibility model for workplace locations from a practitioner's point of view. Thereby, we define 'usefulness' according to the recent literature on Planning Support Systems (PSS), in the sense of *"added value of use of a PSS in planning practice"* (Silva et al., 2017a). In order to make this concept measurable, we split *usefulness* into the two main dimensions *utility* and *usability,* as suggested by Pelzer (2017). Both dimensions were identified in the analysis of the expert interviews (see Chapter 6).

Utility of the tool

Utility describes the fit between the tool's capabilities and the needs of practitioners for the designated planning tasks (Pelzer, 2017). According to te Brömmelstroet (2013) this was detailed further:

- *Novelty*: describes the tool's relation to existing standards, methods, and tools that are currently in use by practitioners for similar purposes
- *Use cases:* the initial hypothesis of the EMMA tool approach includes two use cases:
    - Use Case 1: Using EMMA to support planning for new workplace locations (location scenarios, where a development site needs to be chosen)
    - Use Case 2: Using EMMA to assess (and potentially improve) existing workplace locations (transport scenarios, where access conditions are improved by improving the mobility supply)

The *novelty* of the tool was confirmed both by the reviewed literature on existing tools, and on existing standards for workplace accessibility (Chapter 2). In the expert interviews (Chapter 6), all interviewees confirmed in general the novel character of the tool for the accessibility assessment of workplace locations. While the general model approach is replicable with other existing commercial tools such as ArcGIS Pro, the openness of the EMMA model and its easy replicability were highlighted by the interviewees.

For *Use Case 1*, the utility was highlighted with a focus on the early planning stage, where EMMA can be used to compare multiple options for workplace location development. Especially at this stage, the current level of available information about accessibility or mobility-related questions in general is very low and often depends on gut-feelings, or knowledge about availability of public transport options (but only in a binary way, like "there is a subway stop nearby"). It was further found, that on a decision-maker level, the tool's results can be useful for visualizing and factualizing the topic of multimodal accessibility to potential locations. This is a useful option, when entering discussions towards the question of how car-dependent or, in the best case, car-independent the future workplaces can be. The simple approach and clear results, especially from the relative indicators are hard to ignore, according to the expectations of the practitioners, and have thereby the potential to influence decision-makers when they are confronted with it – independent of the fact that the use of accessibility is not mandatory in the process.

For existing workplace locations (*Use Case 2*), the utility is less obvious to practitioners, but was seen for municipal applications, such as modelling and comparing scenarios in future transport development plans, or the planning for improvement of existing workplace locations, such as business parks. Future potential useful applications of the tool could be discussions about company-initiated measures, such as shuttle buses to train stations, shared mobility options at the workplace, or improvements to the bike infrastructure.

Usability of the tool

Usability describes how well the tool can be used by its users in order to fulfill its goal. Inspired by te Brömmelstroet (2013), for RQ3 this is detailed into:

- *Clarity:* Do practitioners understand the EMMA model?
- *Communication*: Will the target audience be able to understand the results?
- *Credibility:* Will decision-makers trust the model results?
- *Completeness:* Which features are missing from a practitioner's point of view?

Due to the simplicity of the EMMA tool and its results, *clarity* was attributed by all interviewees. This is in line with expectations from the literature, where exactly this is described as the advantage of using simple elements, like isochrone-based accessibility indicators. However, it was also mentioned that a good and easy-to-follow storyline is always important to have an impact on decision-makers. This is closely related to the aspect of *communication*, which was also assessed as positive. With the clear, relative comparison on a regional level and the easy-to-follow scenario assessment for individual locations, the model results can be communicated to and understood by decision-makers. Among the suggestions collected through the interviews, the introduction of personas and their individual perspectives, within the isochrone-based analysis was highlighted to improve the communication value of the model results even more.

The category *credibility* was not a big topic during the interviews in contrast to the researcher's expectations. Again, this is partly explained due to the simplicity of the indicators, but also to the openness of both the tool and its underlying data. Thereby, no issues of credibility or trust in the result were stated. However, interviewees mentioned the problem, that results might be criticized and attacked by political actors, who see the model results as not in line with their political agenda. Again, the clarity, simplicity and openness of the EMMA tool were mentioned positively to counteract this and in contributing to credible and trustworthy results.

Completeness is a very complex undertaking and always depends on the actual planning questions. Within the context of this dissertation, with its overarching goal and research questions, the EMMA approach can be considered as a complete approach. However, as the theme "*towards the car-independent workplace"* suggests, this conceptualization and operationalization of workplace accessibility is only a part of the puzzle towards an overarching definition and declaration of car-independent workplaces. The same logic applies for planning questions to be worked on with the model. Accessibility considerations from the EMMA model have been already used in small consulting projects (cf. the Weichselbaum project), but the accessibility was just one factor of many included in decision making. If we refer to the primary use case identified in this thesis, namely the use of accessibility to make better informed decisions about the development of future workplace locations, we can similarly conclude that the tool is complete enough to assess the accessibility, but that accessibility alone is obviously not enough to base the decision for a new workplace location on. Therefore, many more factors need to be considered. As one interview phrased it: "*choosing a workplace location is a strange process with all different unexpected arguments*" (Interview #10, see Chapter 6).

To summarize RQ2 and the questions of usefulness of the model, it can be concluded that the reception of the EMMA tool by practitioners was very positive, and the general usefulness is given. The prime application scenario was described as the early planning stage, where there is currently a shortcoming of accessibility considerations by all involved stakeholders. With the advent of tools like EMMA, decision-making on that level could be improved in the future, and with the high importance of the workplace location for sustainable mobility in general (see RQ1), cities and regions, but also the business sector with real estate developers and consultants should make use of this potential.

7.4. Summary of Research Questions

The association between the workplace location and both driving to work and individual car availability was shown (RQ1) and discussed. In line with the literature, a strong link between these variables with data from the Munich Metropolitan Region could be established, setting the foundation for the subsequent development of the EMMA tool. The question about how workplace accessibility can be measured and operationalized for multimodal and intermodal commuting options led to the development of the EMMA tool (RQ2). It was shown successfully that the proposed EMMA accessibility model is capable of modelling workplace accessibility both on the regional (RQ2.1) and local (RQ2.2) scale, including reasonable calculation times, using open-source methods, and offering the possibility to model scenarios in both the transport perspective as well as on the land use and location choice. The aspect of usefulness for practice was until this point based on literature research and hypotheses only. With RQ3, the potential usefulness from the users' point of view was researched, with positive results from the expert interviews.

8. Research Implications

8.1. Outlook

With the vision of car-independent workplace locations as a perspective towards the ultimate goal of quality of life for current and future generations in Metropolitan Regions and beyond, this dissertation aims at a very big picture that needs to be broken down into several aspects to be able to conclude:

Role of workplace accessibility in a changing environment due to external factors

First, during the years of this dissertation, major external disruptions influenced the role of workplaces and commuting in the society tremendously, as outlined in Figure 39.

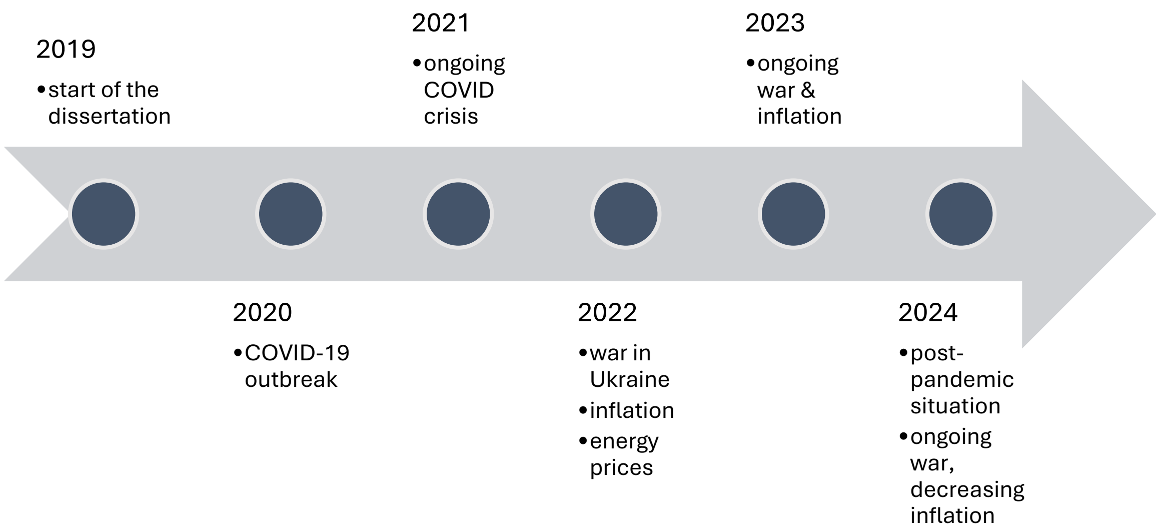

Figure 39: External disruptions relevant for the role of workplace accessibility during the dissertation

The outbreak of the COVID-19 pandemic in 2020 and the following measures to fight the virus had extreme short-term consequences on workplaces and commuters: lockdowns and travel restrictions made millions of workers in Germany stay at home, often with rudimentary options to work from home (Kolarova et al., 2021). While in some sectors, working from home is just not possible (e.g. construction work, craftsmanship, gastronomy, etc.), the lack of the adequate infrastructure, services, and tools made it also for office workers often not easy to be in the home office over a longer period. However, this shock triggered an unprecedented shift towards teleworking, online collaboration, hybrid work, new communication formats, and technologies in Germany that persists until now in 2024, having potentially a long-term impact on the work culture related to workplace locations (cf. van Wee and Witlox, 2021). Online meetings, digital collaboration tools, cloud infrastructure, and many other aspects of the post-pandemic work life are here to stay.

Apart from technical innovations, the work culture has changed as well. In many companies, working from home was an exception before 2020, but is now still frequently used after the pandemic. Rules have changed, along with the expectations of workers. Especially in sectors like knowledge work, where there is a shortage of qualified personnel, a certain number of home office days every week is nowadays an argument in job postings and an important factor for potential employees. Along with this change, companies are facing an oversupply of office space and the need to make the office an attractive place to be, so that the undoubted synergies and advantages of working at least a few days per week in the company's office are used by employees. In this context, the question of attractive locations needs to be seen differently than in pre-COVID times: On the one hand, one could argue that with less days of commuting to the office per week, the importance of the location is diminishing, e.g. measured in kilometers driven to work and the related emissions, or on a general level in terms of external costs of commuting (cf. the statistics in Chapter 1.1) and in personal importance for the employees, such as the implications on trip chains and daily activity spaces and routines. On the other hand, however, attractive locations are linked to the hope that employees 'voluntarily' return to the offices, creating vibrant places of co-creation rather than empty office buildings and isolated home-workers. Thus, attractiveness also in terms of accessibility is very likely to remain a strong factor for workplace locations. Anecdotical examples in the Munich Metropolitan Region show that it is usually the well-located, central offices with good public transport accessibility that are the ones that are retained or expanded (e.g. the new Apple offices close to the central station) – rather than shifting office space to decentral locations (such as business parks far away from good public transport options). This is also in line with the observed increase in cycling to work since the pandemic, which is usually most frequently used to reach central locations with short trips below 10km. Thus, the importance of accessibility models like the EMMA tool is now more relevant than ever in light of the post-pandemic changes in the work culture.

Second, Russia's war against Ukraine that started in 2022 led to a significant increase in fuel prices in Germany. Saving oil and gas became a national priority, and at the same time, households were suffering from both the increase in fuel prices and the subsequent inflation, that lead to strong price increases for energy, but also other expenses. As a result, households with a higher car-dependency were more exposed to these price increases than those that can handle most of their daily errands without a private car. This vulnerability to fuel price (cf.

Büttner, 2017) increases, if a car is needed to get to work. Similarly, the attractiveness of a workplace is decreasing under these conditions, if workers rely on a private car to get to the workplace. In times of a shortage of skilled workers, car-dependent workplace locations can thereby turn into a risk for companies. This effect might be even stronger when looking at low-wage jobs, for example in logistics or fabrication, where the fuel price increase is having a bigger effect on household income, compared to high-salary jobs and workers (see also the concept of ‘forced car ownership’ by Mattioli, 2017, as introduced in Chapter 1.1). In this context, it is also to note that especially for executive staff and well-paid positions, it is common in Germany to provide company cars that come with free fuel and tax subsidies. This makes this target group even more receptive towards car commuting and might be used as a justification for company locations that cannot be considered car-independent.

Third, the change in workplace culture had started already before the global shock events. Key words like “new work” came up a long time before the pandemic, along with a striving for more flexibility, a better compatibility of family and career, and new work formats such as flexible offices, remote work, part-time models, etc. Of course, this is also linked to accessibility questions, as outlined for example by the expert interview with the manager of a co-working company (see Chapter 6) who classified their locations into car-based and non-car-based locations, with implications for mobility concepts, parking availability, and other adaptions at their co-working locations. In the Munich Metropolitan Region, these ‘third places’, in the sense of important regular locations beyond home and work gain more attention recently: cafés are offering designated work areas with good Wi-Fi and quiet spaces, and the public rail operator Deutsche Bahn is experimenting with co-working hubs at train stations outside of the big cities in the region, offering an alternative to the commute to the city center on some days while avoiding working from home. For these ‘third places’, accessibility has a huge impact on the suitability of the location, similar to ‘normal’ workplaces, as outlined by the interviewed co-working manager. However, they might require a specific analysis, especially if they are designated as alternative to the regular office. Therefore, a general accessibility analysis as presented in this dissertation is not sufficient, because it lacks the interaction between the three elements home, workplace, and 'third place’. However, the tool provides the necessary elements to deepen such an analysis, maybe in cooperation with practice partners in the future, in order to develop a suitable framework.

Overall, it is to conclude that despite big changes in the culture of workplace locations and the societal aspects of working in general, the accessibility of workplaces remains a very important factor that is still at the center of determining the qualities of a workplace location and could even become more important than before.

Development of workplace locations in the Munich Metropolitan Region and beyond

Given this ongoing importance of the location and the nature of real estate investments that are in the most direct sense ‘immobile’ and have very long development cycles, developing workplace locations that do not follow the proposed car-independent accessibility criteria now could turn out to be a risk. Due to the aforementioned external factors like pandemics and global energy crises, but also for the fact that due to the climate crisis, it is likely that further restrictions and cost increases for private car use might be introduced in the future, putting locations that have insufficient non-car-based accessibility at risk of becoming less desirable both for companies and workers.

This is contrasted by the way workplace locations are planned in the Munich Metropolitan Region at the moment and, potentially to an even higher degree, in the past decades. One interviewee from the expert interviews phrased it like that: “choosing a workplace location is a strange process with all different unexpected arguments” (#10, see Chapter 6 for details) while another expert referred to the well-known running gag in the field, that in the end, the quality of the commute of the CEO is the most important factor for a company relocation decision. On a more serious note, the process of workplace location development in Germany and in the Munich Metropolitan Region in particular needs to be dissected into multiple levels, as illustrated in Figure 40.

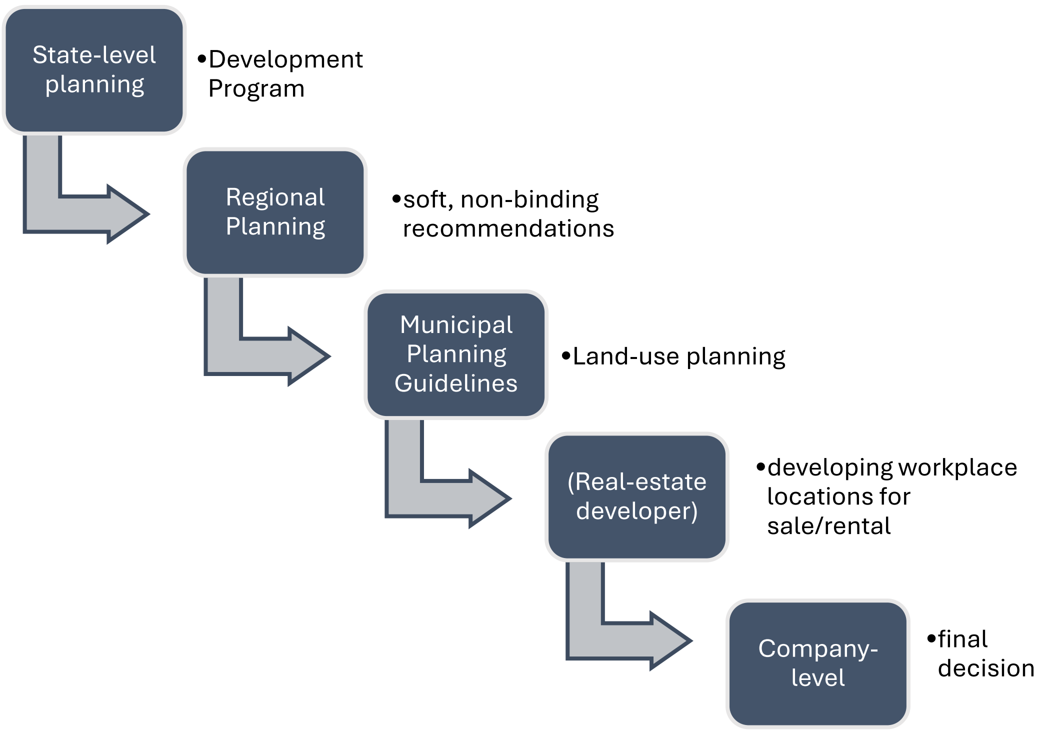

Figure 40: Planning hierarchies for workplace locations

Regional planning is not very powerful in the context of Bavaria in general, and the Munich Metropolitan Region in particular. While the old version of the Bavarian State Development Program (“Landesentwicklungsprogramm Bayern (LEP)”) included the goal to allow the development of new settlements (including workplaces) in general only within certain public transport catchment areas (STMWI, 2013), this goal has been softened in the latest edition of the LEP. In this 2023 version of the LEP (STMWI, 2023), the idea is only represented in a paragraph that describes that the definition of new settlements ‘should’ reflect existing or potential public transport supply (with this wording being a downgrade from the previous ‘goal’).

After this state-leve and non-binding recommendations on the regional level, the first concrete level is the land-use planning dimension: Before a company can build anything, the municipal planning authority ensures that the municipality has the right to shape its settlement structure through land-use planning, such as the zoning plan (‘Flächennutzungsplan’) and the binding building plan (‘Bebauungsplan’). The critical disadvantage of the strong role of the municipality is the lack of a regional planning approach that goes beyond the individual municipal perspective. In the competition for workplaces, taxes, and prestige, municipalities are likely to prioritize their own advantage over regional effects, such as mobility considerations or even accessibility (cf. Schmidt, 2009; Zaspel, 2012).

The second level, after the land-use planning, is the actual decision of a company to invest in a location and build (or remodel) a company building at a specific location. Here we can differentiate between ‘company’ in the sense of a) a real-estate developer who builds a workplace location in order to sell or rent it to other companies, and b) companies that plan their own facilities, such as office buildings or production sites. Again, this complex is ‘strange’ and messy, and a multitude of arguments and factors plays into the decision, such as: suitability for the kind of business, space, purchase costs, taxes and other recurring costs, regional knowledge and cooperation clusters, proximity to customers and partners, logistics, just to name a few. However, the availability of workers and thereby the accessibility as measured with the EMMA tool is certainly one of the factors. So far, the vision of car-independent workplace locations has not been directly part of the process, even though it was well understood in the interviews with practitioners from the field.

Implications for practice

With the development of new tools and models, such as EMMA, the question arises how the tool can contribute to the improvement of the status quo. There are a few potential perspectives how EMMA can contribute to bringing the vision of car-independent workplaces into the planning process.

Given the two dimensions previously mentioned (land-use planning and company decisions), the two natural clients of the EMMA results are decision-makers on the municipal level and companies on the second level. This turns planners in the administration as well as in consulting firms into the potential users of the tool (apart from researchers, who can act as consultants as well). Thus, if this target group understands the idea of car-independent workplaces and the EMMA tool as a way to measure workplace accessibility, the following implications could be achieved:

On a short-term basis and given the current laws and regulations, companies and municipalities could use the vision of car-independent workplaces as a label for sustainable, human-scaled workplace locations that are easy to access by the workers and provide a long-term benefit to the company. Being car-independent makes the location less vulnerable to changes e.g. in fuel prices or other restrictions to car use. Providing a car-independent workplace could be an aspect of inclusion and social justice, because the labor opportunities at the location are not limited to those who can drive there. Thus, car-independent workplaces could be seen as sustainable, resilient, and future-proof, bringing a market advantage to the location when compared to other locations. As outlined in the introduction, modelling the multimodal and intermodal accessibility of these locations is thereby an important factor to check whether the strategy towards car-independence is on the right path, but this analysis alone is not enough to label a location as “100% car-independent”.

On an analytical level on the land-use side, the analysis done with the EMMA tool can be used already now to compare different locations to make better informed decisions when it comes to selecting one of multiple candidate locations (both in the land-use and in the corporate domain). Having an easy-to-use and understandable metric is beneficial and, according to Chapter 6, brings added value to planners and decision-makers. For the mobility perspective, the tool can facilitate designing and assessing changes to the transport system around a given location. Multiple transport options could be included, and according to the interviewees in Chapter 6, the inclusion of the intermodal perspective is helpful for current discussions around shared mobility and its combination with public transport.

On the strategic level, the capability to run the multimodal and intermodal accessibility analyses for workplace locations on a grid for the entire metropolitan region enables new perspectives for regional planning. However, for this to become useful beyond the stage of informing the debate, the laws and regulations need to be adapted towards a stronger regional governance that has the power to influence and steer the development of workplace locations on a scale beyond the municipality. The results of the EMMA model could be used to advocate and explain the need for better regional cooperation and planning within the context of car-independent workplaces. Until that is the case, maybe the municipal planning authority could be used to establishing the core of car-independence and accessibility modelling for workplaces on a smaller scale. As suggested by some of the interviewed experts, thanks to the power of individual municipalities, it would be worthwhile to start applying the concept to smaller developments, together with motivated and open-minded local planners and practitioners. Starting this process bottom-up could be a successful way to plant the seed of car-independence and the EMMA tool in local municipalities, while giving the idea the space and time needed to grow. The high interest expressed by the interviewed experts as well as the positive feedback from the scientific community is a good starting point for such endeavors.

Overall, given the trends in the political landscape and the still-increasing importance of reducing CO_2-emisions for the future, it seems likely that ideas such as the inclusion of accessibility into planning for workplace locations and the idea of developing new workplaces in a sustainable and future-proof way will find their way into planning practice. With the EMMA tool and the notion of car-independent workplaces, decision-makers now have a concept and a tool at hand, that fully relies on open data and open-source components. The requirements to get started with the implementation are minimal and political will is the crucial element that can make it happen.

If that is the case, of course the proposed idea and tool are not perfect and as mentioned multiple times, the accessibility model is an important step towards defining and measuring car-independence, but there is much more to this vision than accessibility. Some open questions around the tool development include other facets of “workplace accessibility”. Within the EMMA approach, certain indicators were chosen, but as the discussion of the existing accessibility tool landscape (see Chapter 2) shows, there could be other ways. On a hypothetical range from simple to complex indicators, EMMA is certainly at the simpler end of the spectrum. This is a conscious decision, approved through the expert interviews, and the author shares this notion.

It needs to be mentioned that other researchers might be in favor of much more complex definitions and measures to answer this research question. However, the expert interviews and the literature on usefulness of Planning Support System backs this approach for the given context. As stated by one interviewee in our expert interviews, the current lack of accessibility modelling and planning in our municipal and regional institutions can be addressed most efficiently when starting with both simple questions and simple measures. This is in line with the previously introduced concept that can be summarized as the “beauty in simplicity” (cf. Bertolini et al., 2005; Givoni et al., 2016, see Chapter 2.2). On the other hand, however, politicians might interpret tools that are very simple as not ‘complex enough’ and ‘too simple be to be meaningful’, which might cause complications in some cases.

8.2. Limitations

A detailed set of individual methodological limitations is included in each publication (see Chapters 4-6). On a summarized level, however, there are some general limitations to be mentioned after concluding on the research.

Going back to the fundamentals of accessibility, as described by Geurs & van Wee (2004), it is clear that not each accessibility instrument can fulfill all theoretical criteria outlined in the literature. According to the authors, that would be impossible in terms of complexity and level of detail needed. However, they demand a critical reflection and explanation for violations of the following theoretical criteria:

(1) *"If the service level (travel time, costs, effort) of any transport mode in an area increases (decreases), accessibility should increase (decrease) to any activity in that area, or from any point within that area.*
(2) *If the number of opportunities for an activity increases (decreases) anywhere, accessibility to that activity should increase (decrease) from any place.*
(3) *If the demand for opportunities for an activity with certain capacity restrictions increases (decreases), accessibility to that activity should decrease (increase).*
(4) *An increase of the number of opportunities for an activity at any location should not alter the accessibility to that activity for an individual (or groups of individuals) not able to participate in that activity given the time budget.*
(5) *Improvements in one transport mode or an increase of the number of opportunities for an activity should not alter the accessibility to any individual (or groups of individuals) with insufficient abilities or capacities (e.g. driver's license, education level) to use that mode or participate in that activity."*

(Geurs and van Wee, 2004, p. 130)

The EMMA approach presented in this dissertation is able to fulfill the criteria (1) and (2), at least given the limitations of the isochrone-based approach with a time-cutoff e.g. at 30 minutes. Criterion (3) is not fulfilled, since it was decided not to include complex indicators that can account for competition effects, since there is no information available about the exact roles and competencies needed to work at a particular workplace location – neither on the side of workplaces, nor on the side of population. The same is true for criteria (4) and (5), because the individual perspective is on-purpose not reflected in the EMMA approach.

Reflecting on the used data and tools, it is notable that in general, the tool would allow for much more detailed analysis if more detailed data was available. One fundamental aspect is, for example, the quality of jobs and potential workers: Given the limitations of the German census data, accessibility is calculated for persons in the general working age (18-64) only. If we had more information about qualifications, education, job status, etc., workplace accessibility could be targeted at certain professions, educations levels, etc., which would increase the benefit for the corporate / labor market perspective significantly. With this kind of data, there could even be sector-specific recommendations based on education levels and skills, to cope with the shortage of skilled labor that is prevalent in many German businesses. Also, the use of population as a measure to assess the quality of workplace locations is a limitation by itself, because the meaning of a certain number of people who can access a location is very abstract per se, and always needs context for interpretation (e.g. by using relative indicators that compare modes of transport).

Regarding the calculations, public transport travel times were modelled relatively accurately, but car travel times were estimated based on some approximate parameters of potential congestion. The inclusion of real-world travel times, such as provided by commercial suppliers, would make the car travel times in the analysis more accurate. For the intermodal aspects of the model, travel times and isochrones could be calculated relatively accurately, but the calculations are missing capacity constraints: Especially when dealing with larger workplace locations, that offer for example bikesharing as a first-/last mile to a train station, the problem arises that the number of workers exiting the train is potentially much higher than the number of available bicycles to rent during the peak hour, turning the accessibility analysis into an incomplete picture. To a less critical extent, this also applies to capacities of public transport services and roads for cycling and driving. Other elements that are relevant, but not covered in the tool, are parking, costs, detailed access/egress conditions, safety/security, attractiveness of space, etc.

Another methodological limitation of this dissertation is the fact that while the EMMA model was presented and explained to practitioners, the research does not include active workshops or other formats, where practitioners can use the tool hands-on, on their own computers, for a given planning exercise. Due to the nature of the EMMA tool as an open-source development, it was not planned to reach a level that provides a polished user interface and advanced capabilities, e.g. as a webtool. However, this is a potential next step for the tool that can come after this dissertation. Also, the EMMA expert workshops, and the expert interviews provided intense exchange with experts and practitioners, that contributed significantly to the development of the tool.

8.3. Future Research

As described within the limitations, the proposed accessibility model for workplace locations, EMMA, was developed within this dissertation and a first evaluation of its usefulness was positive. For future research and to give the concept the chance to actively improve decision-making for workplace locations in the future, it is advised to continue the development process and turn the EMMA tool into a user-friendly, easily applicable webtool that can bring its ideas and results to practitioners in the Munich Metropolitan Region and beyond. A follow-up project with a very applied, hands-on focus in cooperation with practice partners should be considered for this. Within the expert interviews, the potential for this step was included in the closing questions and it was received with a lot of support and interest, especially when it comes to implementing the analysis done with the EMMA tool into a web-based application that offers simple and fast analysis without knowledge of programming or other complex tools.

In terms of the research landscape in the intersection of accessibility instruments and workplace locations, there is still a lot of room for future research that links the current decision-making processes with potential changes induced by accessibility tools. Further integration of accessibility tools like EMMA into real-world planning questions is advisable, with close scientific monitoring and evaluation of its effects and potential benefits. As advised in the expert interviews, it is recommended to start with small, and/or innovative ideas, where traditional assessment tools fail to support planners and decision-makers in their decisions. The long-term vision could be accessibility-based governance, that could enforce e.g. certain mobility management elements when workplaces are created in locations that do not fulfill the accessibility standards required. At the same time, locations with a good accessibility evaluation could benefit from supporting measures, such as tax reductions, faster project approvals, or other benefits.

To conclude, the idea of the car-independent workplace location was born within this thesis, but it has only been a start. It is now an interesting task, maybe even a responsibility, to further advance and concretize the idea, with the vision that one day, the idea of car-independent workplaces could become a certification, or even a requirement for future-proof, sustainable, and equitable workplace locations, that contribute not only to sustainable mobility, but to a better quality of life in our regions, for current and future generations.

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Annex

Annex A – Data Preparation

Preparing GTFS Data

Since the public transport data are provided as a single GTFS dataset for all of Germany, a script to reduce the size of the data was developed. In R, the package ‘gtfsr’ (McVey and Noriega-Goodwin, 2021) is used to import the entire dataset. Then, a bounding box is defined that will define the GTFS elements that will be retained in the filtering process. To avoid issues with broken line segments, this bounding box was defined with a buffer > 50 km to the boundaries of the study area, and the following steps were executed to filter the dataset:

- stops.txt: filter only those stops that are located within the bounding box (by latitude /longitude).
- stop_times.txt: filter only those features whose stop_id is also found in the filtered stops.txt dataset.
- trips.txt: filter only those features whose trip_id is also found in the filtered stop_times.txt dataset.
- routes.txt: filter only those features whose route_id is also found in the filtered trips.txt dataset.

Optionally and depending on the existence of these files in the raw data, the same process can be repeated with calendar_dates.txt, calendar.txt, and shapes.txt to decrease the file size even more. The result of the process is a filtered GTFS dataset (in .zip format) that includes only information on public transport stops, lines, and schedules that are relevant in the study area.

Preparing OSM Data

The OSM raw data in a compressed format can be downloaded, e.g., from Geofabrik (Geofabrik, 2022). After downloading the data for Bavaria, the file was cut to the identical bounding box used for the GTFS data with the help of osmconvert.exe (Weber, 2020).

To improve intermodal routing, the tag ‘amenity=bicycle_parking’ was added automatically to all rail-based public transport stops. OTP only allows bike parking at these designated locations, whereas in reality, it is usually possible to lock a bike near every rail-based public transport stop in Germany, independent of the infrastructure. This makes routes that include public transport and cycling more realistic but does not include capacity for bike parking.

This level of detail is sufficient for the regional analysis. For detailed analysis of locations, the actual bike parking facilities at public transport stops should play a role, however.

Preparing Census Data

Census data from 2011 is available for the whole of Germany in a 100 m grid ("ZENSUS 2011," 2011). The separate files with spatial information of the grid and population counts for each cell were imported into the spatial database. After cutting the grid to the previously mentioned bounding box to reduce the file size, a join operation was used to combine the remaining grid with population counts for each grid cell. Since we used a relatively high resolution, we reduced the grid cells to the centroids in PostGIS, and therefore the result of the preparation process is a point grid for the study area where each point indicates the population for the 100 × 100 m grid around the point. To speed up the calculation later, all points with no population were deleted.

Annex B – Interview Guideline

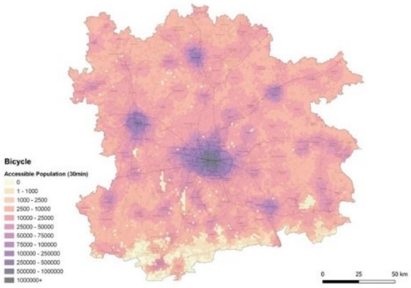
Gefördert durch DFG Deutsche Forschungsgemeinschaft

TUM

Towards the car-independent workplace: A framework for multimodal and intermodal accessibility analysis of workplace locations

Interview guide

EMMA
WORKPLACE ACCESSIBILITY



Maximilian Pfertner
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TUM School of Engineering and Design
Technical University of Munich

Winter 2023/24

TUM

Project context

"Development, application and evaluation of a model for the evaluation of the accessibility of work locations in the sense of multimodal and intermodal mobility"

1. Identification and quantification of relevant factors influencing the mobility behaviour of employees
2. Development of an accessibility model that enables multimodal and intermodal accessibility analysis of workplaces
3. Application of the model in the metropolitan area (regional scale) as well as on a smaller scale to selected case studies in order to develop and evaluate scenarios for future development
4. Contribute to a better understanding of multimodal and intermodal accessibility analysis for location development in the workplace

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Accessibility?

"Accessibility is the extent to which the system of land use and transport enables people to achieve activities or objectives"

Karst Geurs & Bert van Wee (2004)

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Erreichbarkeit?

„Erreichbarkeit ist das Ausmaß, in dem das System aus Flächennutzung und Verkehr es dem Einzelnen (oder Gruppen) ermöglicht, Aktivitäten oder Ziele (mit verschiedenen [Kombinationen von] Verkehrsmitteln) zu erreichen (im Tagesverlauf)"

vgl. Karst Geurs & Bert van Wee (2004)

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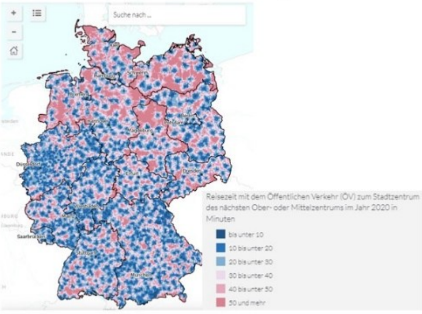
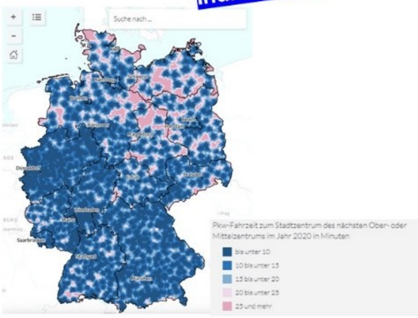
Erreichbarkeit? Beispiel: Deutschlandatlas

Indikator: Reisezeit





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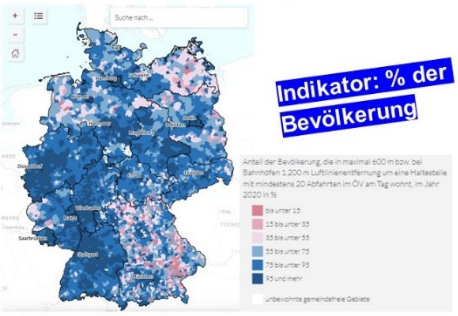
Erreichbarkeit? Beispiel: Deutschlandatlas



In order to determine the locational advantage of regions and the supply of infrastructure facilities, travel times to spatially significant facilities and places (...) are calculated on the basis of the accessibility model. The analyses cover different modes of transport and range from the regional to the European level. They are therefore a building block for reporting on spatial development in Germany and Europe.

Accessibility model of the BBSR (2023)

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Accessibility of work locations

Common Calculation:

How many jobs can I reach by A/B/C from a residential location?

→ enables information about residential locations, job potential in the area, transport network

However, we are interested in the work locations (= industrial parks / business park / campus / location) with the guiding question:

What is the (multi- and intermodal) accessibility of the site?
Is the location a good (or bad) location in terms of the goal of "car-independent" work locations?

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Das Erreichbarkeitsmodell

- Accessibility indicator: **Sum of the population** (18-64 years) who can reach the site within 30 minutes on a weekday during the morning peak hour.
- multimodal = car / bicycle / public transport separately, in comparison
- intermodal = combinations of means of transport, e.g. Bike & Ride
- Data basis: Census, OpenStreetMap, DELFI e.V. (Germany-wide public transport data)
- Calculation methodology: Open source model, based on Opentripplanner, PostGIS, R
- Resolution: Regional grid cells (hexagon, ~750m radius)
- Calculation time: approx. 17,000 grid cells for the Munich metropolitan region approximately overnight

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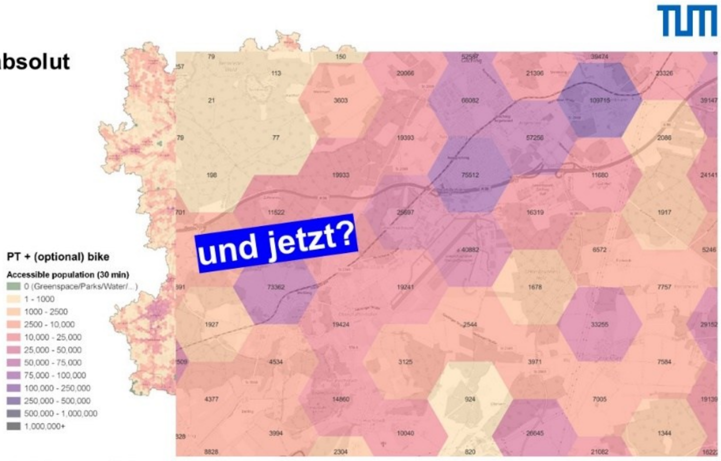
Regional - absolut



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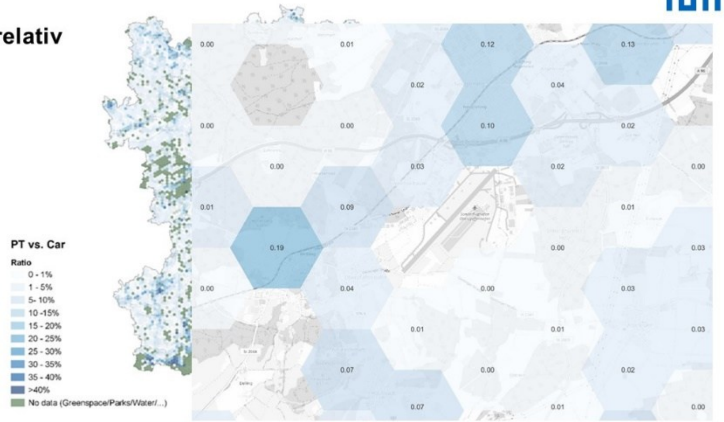
Regional - relativ



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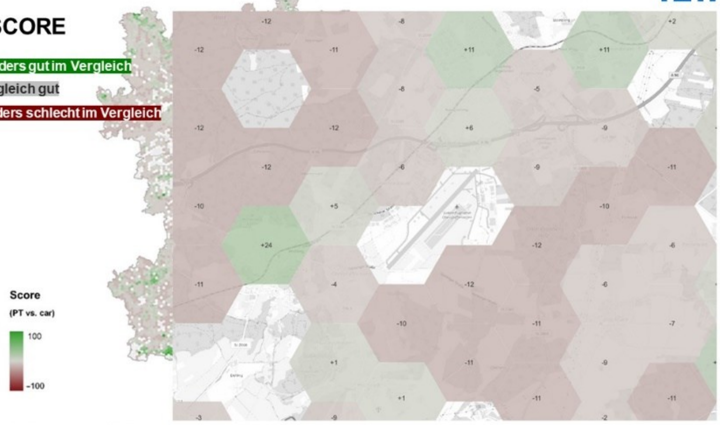
Regional - SCORE

+100 = ÖPNV besonders gut im Vergleich
0 = ÖPNV und Auto gleich gut
-100 = ÖPNV besonders schlecht im Vergleich



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QUESTIONS I

(1) Do you understand our concept of accessibility to work locations? Are there any comprehension questions?

(2) Do you already have criteria or standards for the accessibility of work locations in your company/institution?

(3) Do you already use some kind of tool/software/method for such calculations?

(4) With this in mind, how would you rate good or poor accessibility of work locations?

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Regional view vs. local conditions

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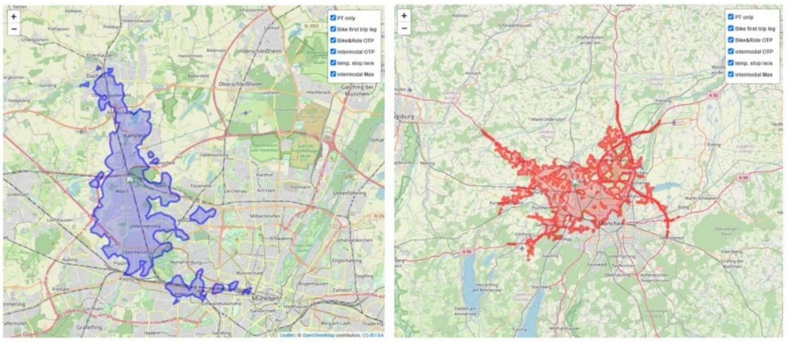
Local Consideration of a Location: The Malt, Allach

exemplarisch!



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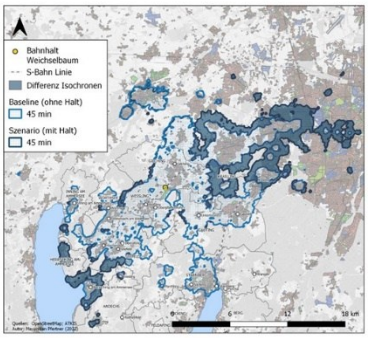
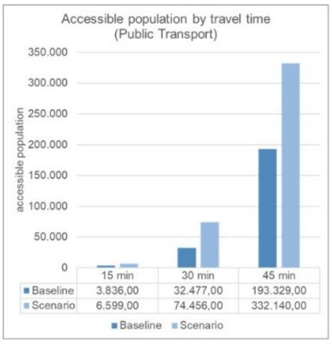
Local consideration of a location (incl. scenario)





	15 min	30 min	45 min
Baseline	3.836,00	32.477,00	193.329,00
Scenario	6.599,00	74.456,00	332.140,00

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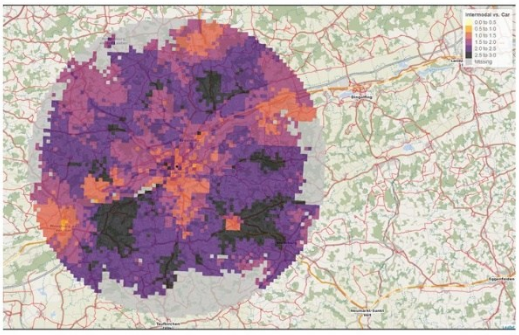
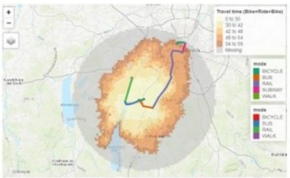
Local Scale: Alternative Considerations





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(5) How and when in the planning process can the model results influence the planning of work sites?

(6) How could the use of the model:

- (a) influence the planning and decision-making process for work sites?
- (b) in the case of existing areas: bring about consequences/changes?

(7) What added value and limitations do you see in using the model?

(8) What kind of validation do you need to be able to "trust" the results?

(9) Can the results be understood by your target audience?

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Abschluss

– Do you have any other questions or suggestions?
– Do you know of any current possible use cases for the tool?
– Can you recommend other interviewees?
– How do you see the potential further development of the methods into an interactive online tool that makes the analyses easily accessible to specialists?
– Would you be interested in accompanying such a development?

Thank you very much for your support!

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