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Bachelor Thesis

Evaluating the Impact of Bicycle Bridges on the X-Minute City Concept in Copenhagen, Denmark

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Table of Contents

List of Abbreviations

API	Application Programming Interface
CBS	Centraal Bureau voor de Statistiek
CO_2	Carbon Dioxide
CSR	Community Street Review
ECF	European Cycling Federation
GIS	Geographic Information System
HeiGIT	Heidelberg Institute for Geoinformation Technology
HOT	Humanitarian OpenStreetMap Team
NEWS	Neighborhood Environment Walkability Scale
NGO	Non-Governmental Organisation
ORS	Openrouteservice
OSGeo	Open-Source Geospatial Foundation
OSM	OpenStreetMap
PEQI	Pedestrian Environmental Quality Index
PERS	Pedestrian Environment Review System
POI	Points of Interest
QGIS	Quantum GIS
QNEAT3	QGIS Network Analysis Toolbox 3
RQ	Research Question
SDG	Sustainable Development Goal
VGI	Volunteered Geographic Information
XMC	X-Minute City

Table of Figures

Index of Tables

Abstract

Urban spaces face a multitude of challenges such as climate change, lack of physical activity, the growing world population, simultaneously ongoing urbanization movements, as well as an increase in number of cars within cities. This results in issues like overcrowded streets, increased travel times for citizens to meet basic needs and a decrease of urban quality. One concept that seeks to tackle those challenges is the x-minute city (XMC) concept, which focuses on providing essential services within a 15-minute reach. Since its introduction in 2015, the concept has continually gained global interest, even more so after the Covid-19 pandemic. The desire to become an XMC is ever-growing. However, the measurement of compliance with the concept lacks clear definition and rules, as methodologies and criteria employed across literature vary significantly. Furthermore, while walking as a transportational mean has been addressed by multiple studies, only few studies have focused on cycling as part of the concept. In many cities, cycling functions as a key method of movement. Addressing this research gap, this paper explores the application of the XMC concept in Copenhagen, whose cycling model share[1] makes up for 49%. A special focus is set on 20 bicycle bridges and their possible impact on accessibility across thresholds of 3-, 5-, 10-, and 15-minute traveling times. Using a grid-based methodology and open-source data, the study assesses the relation between amenities and categories as well as spatial distribution of both access and impact. Key findings reveal that the employment of substitution between amenities can significantly affect results on a categorical level. Furthermore, initial accessibility rates as well as the chosen locations of bridges and the considered time threshold affect the resulting impact rates. Generally, improvements were found to be relatively low and spatially restricted. In smaller travel time thresholds, impacted areas were found to be in the vicinity of the bridges. In the largest threshold, recorded impact was found to be low, as initial accessibility was already relatively high. Overall, this study contributes to the discourse on urban planning and provides a framework for evaluating accessibility in urban environments as well as assessing the impact that single structures have on measured compliance.

[1] Cycling model share: The number of citizens that use cycling as their primary mode of transportation

1 Introduction

Over the last few decades, urban spaces have been affected by a multitude of new developments. Climate change, the growth of the global population, immigrational movements and related cultural and societal changes, mixing and dispersion of social groups, as well as the emergence of issues in both physical health, like obesity, and mental health, such as a “pandemic of loneliness” (Lonergan-Cullum et al., 2022), are only some challenges that have arisen in urban spaces (Madanipour, 2006).

Due to continuing urbanization, more than half of the world’s current population lives in urban areas. This, as well as economic and technological growth, has led to a significant increase in the number of cars (Fenger, 1999; Madanipour, 2006). The growing number of cars entails that road space needs to be shared by more and more people. Consequently, urban spaces face issues of overcrowded streets, higher traffic demand, and additional obstructions like traffic jams and car crashes, all of which result in increased travel times to fulfill daily needs. As a result, many cities resorted to an expansion of road networks, and streets were constructed or widened. However, this led to a further increase in traffic, or, as Colville-Andersan (2018, p. 10) states: “If you make more space for cars, more cars come.” Consequently, air quality worsened (Knap et al., 2023) and noise levels increased (Bulucea et al., 2009), resulting in a diminished environment in cities and a decrease of urban quality (Knap et al., 2023). These developments display a need for rethinking urban spaces and emphasize the necessity for new urban planning concepts that present innovative solutions to tackle some of the challenges.

One new concept, which provides a potential solution to the previously mentioned challenges, is the 15-minute city concept. Introduced by Carlos Moreno in 2015, the concept gained further recognition during the Covid-19 pandemic and has since become increasingly popular on a global scale (Moreno et al., 2021). Lockdowns highlighted additional weaknesses in urban spaces and their underlying planning concepts (Knap et al., 2023). Particularly, the accessibility of daily necessities within close proximity to citizens' homes was found to be insufficient. They further revealed that certain locations may be difficult to access without a car, resulting in significant disadvantages and increased risks of infection for individuals dependent on public transportation (Knap et al., 2023). Simultaneously, the decrease of car trips during Covid-19 lockdowns resulted in measurable improvements of air quality, indicating that a decrease of motorised vehicles can help improve overall urban quality (Knap et al., 2023).

The 15-minute city concept was first introduced with the aim of reducing carbon emissions and in doing so, present a way of more environmentally friendly city planning. However, the advantages of the 15-minute city concept are versatile and include environmental, economic, and social benefits, making it a sustainable city planning concept. A more detailed overview of positive implications related to the concept can be found in figure 1.

Moreno’s 15-minute city is part of the later introduced umbrella concept “x-minute city” (XMC) that follows the same ideas and conceptualization, with the only difference being that it includes a variety of different travel time thresholds such as 5-,10-, 20- or 30- minutes. The need for an expansion of the concept derives from the varying travel speeds of different modes of transportation, as well as local characteristics.

Moreno introduces his concept as fully reliant on active means of transport like walking and cycling (Moreno et al., 2021). Concerning bicycle usage, the Charter of Brussels states that “cycling usage contributes to liveable cities, efficient urban transport, less congestion, less traffic noise, healthy physical activity, road safety, clean air, fighting climate change, saving fossil fuels and sustainable tourism” (ECF, 2009).

This thesis will mainly consider trips made by bicycle. To take the faster speed and wider travel range into consideration, the paper will look at a variety of thresholds. As this study incorporates different thresholds, the term “x-minute city” (XMC) will be used more frequently, whereas the term “15-minute city” will relate to only the threshold of 15 minutes.

2 State of the Art

2.1 Isochrones

Even though accessibility is crucial to any measurement concerning transportation, it is hard to define (Giuliano and Hanson, 2017). Referencing Dalvi (1979), Koenig (1980, p 146) states that accessibility "denotes the ease with which any land-use activity can be reached from a particular location, using a particular transport system." This clarifies that accessibility refers to a certain origin, transport system, and land-use activity (O'Sullivan, Morrison and Shearer, 2000).

Koenig then establishes a general formula for the accessibility A_i of a location *i* in the form:

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

(Koenig, 1980, p. 146)

In this context, *Oj* represents the set of facilities or opportunities available at location *j*, while *Cij* denotes the distance, time, or cost of the journey from *i* to *j*. The function *f(Cij)* captures the relationship between cost and accessibility, typically exhibiting a decrease in value as cost increases.

Consequently, more distant opportunities receive lower accessibility ratings. However, isochrone accessibility analysis presents a unique scenario where *f* takes the form of a step function. Here, *f* is '1' when the cost (here expressed in time units) is less than or equal to a specific limit, *t*, and is '0' when the cost exceeds *t*. To put it differently, only opportunities reachable from *i* within the time *t* are considered in the accessibility calculation (O'Sullivan, Morrison and Shearer, 2000).

Transferring the definition of accessibility by Koenig onto this work, the origin *i* is the residential spaces, the transport system is cycling, the land-use activities *Oj* are the different amenities and the time limit *t* denotes the thresholds of 3, 5, 10, and 15 minutes.

2.2 Literature Review

The XMC concept, as part of the 15-minute city concept, was first introduced in 2015 and gained global interest, especially in connection to the Covid-19 pandemic (Moreno et al., 2021). Since then, several researchers have conducted studies, both qualitative and quantitative on the topic. To acquire an overview of the given context and potential research gaps, the following sections will assess literature that has been published to date in relation to the XMC concept. First the chapter will provide an overview of the most relevant papers, which are closely linked to the choice of methods employed in this work. Both qualitative and quantitative approaches will be assessed. Then a variety of aspects, such as trip origins and destinations or input data, will be addressed and different approaches and resulting expertise across a variety of papers will be compared and discussed.

To review the current state of the art, the meta research analysis conducted by Papadopoulos, Sdoukopoulos and Politis in 2023 offers an especially thorough overview of 41 papers that were directly relevant to the XMC concept. In the preparational work, it became apparent that the majority of literature on the XMC concept had been published within the last four years (Papadopoulos, Sdoukopoulos and Politis, 2023). Out of the initial 41 papers, 15 were identified to use qualitative theoretical approaches, and 26 followed a quantitative approach. Further, Papadopoulos, Sdoukopoulos and Politis (2023) aimed to identify and discuss the major components of XMCs, as well as determine the predominant methodological practices for assessing compliance. Suggestions on how to achieve more holistic compliance assessments were presented and research gaps were detected (Papadopoulos, Sdoukopoulos and Politis, 2023).

2.2.1 Qualitative Research

Various papers conveyed a purely qualitative research evaluation of the XMC (Papadopoulos, Sdoukopoulos and Politis, 2023). Khavarian-Garmsir, Sharifi and Sadeghi (2023) explored underlying principles of the XMC concept, possible barriers, as well as its contribution to social, economic, and environmental sustainability. For instance, XMCs were found to increase mental health, promote social interactions, reduce costs of healthcare and housing, support the local economy, reduce car dependency and emissions, and increase the number of green spaces. A more thorough overview of the found benefits is presented in figure 1. To achieve those advantages, seven key principles were identified: “human-scale urban design, density, diversity, flexibility, proximity, digitalization, and connectivity” (Khavarian-Garmsir, Sharifi and Sadeghi, 2023, p. 3).

Pozoukidou and Chatziyiannaki (2021) looked at the XMC concepts of Portland, Paris, and Melbourne, and measured how well those concepts performed when applied to a previously determined set of standards. To do so, they assessed how realistic and specific the planning ideas were and how well they performed in their criteria categories *inclusion, health,* and *safety*. The paper found that the XMC concept is neither a new or radical idea, nor can one model of it be applied to all cities. To comply with the criteria, neighbourhoods need to fulfill a mixture of physical and non-physical attributes, that vary depending on “the unique urban and social form, legislative provisions and governance structure of each city” (Pozoukidou and Chatziyiannaki, 2021, p. 22). Furthermore, neighbourhoods are considered “intimate places” instead of “unfamiliar spaces” (Pozoukidou and Chatziyiannaki, 2021 p. 22).

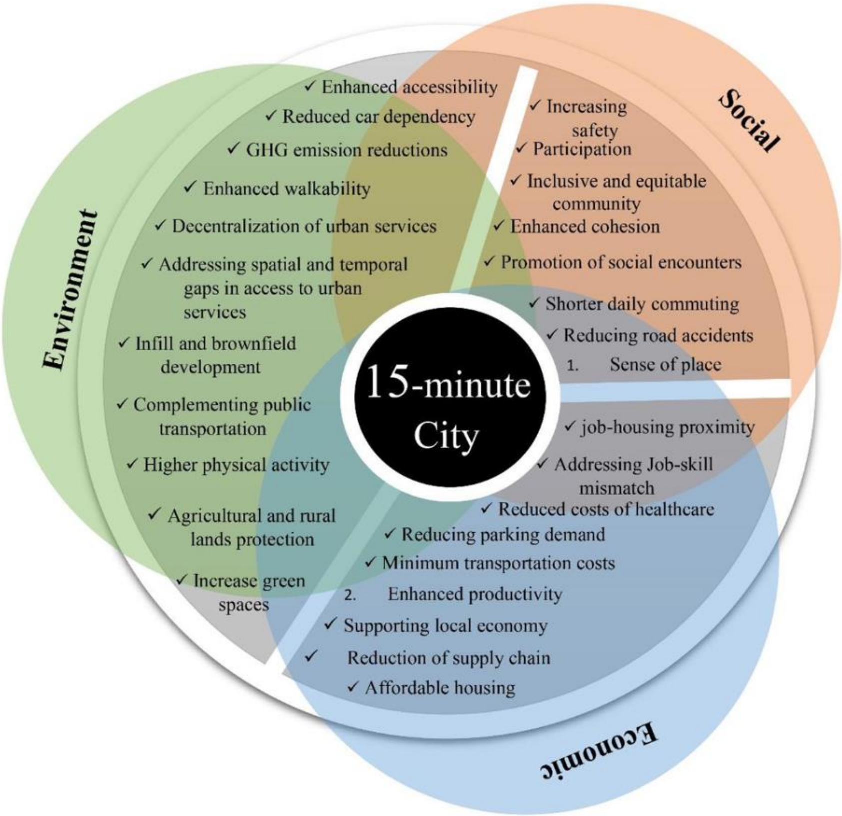

Figure 1: Sustainability Contributions of the 15-Minute City Concept
(Khavarian-Garmsir, Sharifi and Sadeghi, 2023, p. 4)

A major part of XMC planning is optimal resource allocation aiming to bring resources to neighbourhoods rather than people to resources (Pozoukidou and Chatziyiannaki, 2021).

While many papers focused on the Western world, Abdullah et al. (2022) tried to measure awareness levels of the XMC concept in third world countries. The work was based on a questionnaire conducted with planning and engineering students in Lahore, Pakistan, and found that awareness levels are on average lower than in westernized countries, even more so for engineering students (Abdullah et al., 2022).

2.2.2 GIS-Based Literature

Apart from qualitative research, several studies applied GIS-based methods to quantify compliance with the XMC concept.

Fazio et al. (2023) looked at train stations in Southern Italy and their role as access points to a bigger transportation system, as well as their function as an infrastructural element that enhances the areal value. In the study Fazio et al. (2023) assessed access to the station as well as the points of interest (POI) that can be reached from the train station. The GIS-based methodology analysed walkability as well as the stations' impact on their surrounding areas. While in the first perspective the stations were seen as goals, in the second perspective train stations were considered trip origins (Fazio et al., 2023). On the basis of an imported road network, 15-minute walking isochrones were created with QNEAT3 (QGIS Network Analysis Toolbox 3). The POIs were retrieved by using the QuickOSM plugin, which utilizes OSM Data. The walking speeds ranged from 2- 4 kilometres per hour (km/h) depending on the slope and sidewalk width. The study differentiated between three different POI categories: *recreational (tourist destinations, restaurants, etc.), commercial (general services) and educational (schools and university venues) amenities*. The aim of the study was not to assess the actual score of a XMC, but to indicate how many more POI could be accessed if sidewalks were improved. Its aim was to provide a starting point of a GIS-based methodology that could be expanded (Fazio et al., 2023).

Further studies also focused on walking. Web-based applications were the most prevalent tools for assessing walkability and helped to identify areas with low walkability as well as potential starting points for optimization. The most commonly used tools were "Walk Score", (Abdelfattah, Deponte and Fossa, 2022; Birkenfeld et al., 2023) which combines distance weighting with amenity accessibility, "Walk Shed", which creates a heat map of a neighbourhood's walkability and "Walkanomics", which evaluates street segments. Some developed countries have also proposed further programs such as the "Pedestrian Environment Review System (PERS)", "Neighborhood Environment Walkability Scale (NEWS)", "Pedestrian Environmental Quality Index (PEQI)", and "Community Street Review (CSR)" (Weng et al., 2019, p. 261).

Research by Weng et al. (2019) suggested modifications of the "Walk Score" metric calculation. The modifications took different pedestrian groups (children, adults, seniors and the entire population) into consideration and added weights to different amenity types. In the study, the compliance of neighbourhoods with the XMC concept in Shanghai, China was determined. The data was retrieved from official government sources such as the population census and locally provided data on POI. The six categories *education, medical care, municipal administration, finance and telecommunication, commercial services,* and *elderly care* were based on the "Shanghai Planning Guidance". Further subcategories were defined and amenities were chosen based on a questionnaire survey (Weng et al., 2019). The "Baidu Map" was used to acquire travel time information, and time thresholds of 5, 10 and 15 minutes were considered (Weng et al., 2019). Weng et al. (2019) found a dispersion between urbanized and rural areas, as well as a lower walkability score in areas with many children. Finally, four aspects for building walkable and healthy communities were suggested: "(1) providing full coverage service assurance, (2) building a continuous and pedestrian-friendly street network, (3) forming a compact and accessible layout, and (4) developing affordable housing" (Weng et al., 2019, p. 271).

In the paper “15-, 10- or 5-minute city? A focus on accessibility to services in Turin, Italy”, Staricco (2022) developed a method to operationalize the concept of the 15-minute city to show which parts of the city and what percentage of the population can access a location. Since in most European cities, services can already be reached within 15 minutes, Stariccio (2022) found the 15-minute city goal to be inappropriate. Therefore, time thresholds of 5, 10 and 15 minutes of walking were employed. The dataset used was the census track which took up the role of trip origins. Isochrones were created around the geometric barycentre of each census tract, and the number of services contained in each isochrone was counted. The final results indicated which census areas had access to at least one location of a service (Staricco, 2022).

Gaglione et al. (2021) sought to identify the urban characteristics that create a XMC by taking cities with that goal into consideration. A variety of qualities were defined (urban, geomorphological, physical, functional, socio-economic and settlement) and then assigned different weights. Furthermore, the “willingness to walk” was taken into account and different districts in Naples, Italy were analysed. The GIS-based methodology relied on a spatial matrix based on Euclidian distances from centroids of census sections to closely found services. To consider orographic characteristics and quality of pedestrian paths, 17 variables that determine walkability, such as slope, noise pollution and sidewalk width were defined and retrieved from various data sources like “Google Maps” or the “Geoportale Nationale” (Gaglione et al., 2022, p. 381).

Since the XMC concept incorporates not only walking as a method of movement within a space, but all active means of transportation (Moreno et al., 2021), some studies considered multiple methods of movement. Hosford, Beairsto, and Winters (2022) considered both walking and cycling. The study only considered a 15 minute threshold entailing that for cycling no cells without access could be identified (Hosford, Beairsto and Winters, 2022).

In the article “A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities” Knap et al. (2023) studied the impact of tunnels and bicycle bridges in Utrecht. The article of Knap et al. was the only reviewed article by Papadopoulos, Sdoukopoulos and Politis (2023) that investigated the XMC based on only bicycle usage.

Knap et al. considered two different scenarios. Firstly, planned bridges and tunnels were added to the existing road network. Secondly, the impact of an increasing number of e-bikes on traffic flow was assessed. The bicycle usage was applied based on a dataset of recorded bicycle usage so far. Furthermore, the ratio of need and supply numbers of different destination types were taken into consideration. To visualize the results, a grid of 500-meter cells was applied. The cell size was determined by the data source (CBD), which limited the choice to 100- or 500-meter grids. Each grid cell was considered a single neighbourhood, in which different services may be found. The grid cells were assigned different weights, stemming from various criteria such as immigration rates and age groups. As essential services, Knap et al. considered the categories *jobs, commercial, bars and restaurants, education, food, recreation, parks, entertainment, healthcare,* and *sports* that each incorporated a number of amenities. Taking supply and demand distribution into consideration, Knap et al. found that new connections only improve the XMC metric of the peripheries, whereas scores are decreased in the centre of Utrecht. The new structures increased accessibility to the centre grid cells, which led to higher demand in central cells with stagnating supply levels in Utrecht's centre (Knap et al., 2023).

Trip Origins

According to the XMC concept and the original definition by Moreno (2021), trips in a XMC start where people live (Ville de Paris, 2022) or, to be more specific, at residential buildings. Even though most studies employed trip origins based on residential living, the realization in their methodology differed significantly. While some considered individual home locations and addresses (Birkenfeld et al., 2023; Caselli et al., 2022; Zhang et al., 2023), or used manually defined grid cells (Gorrini et al., 2023), others used aggregated data, of which especially census data proved to be a popular choice. Trip origins then consisted of census sections (Abdelfattah, Deponte and Fossa, 2022; Gaglione et al., 2022; Rhoads, Solé-Ribalta and Borge-Holthoefer, 2023), census tracts (Burke et al., 2022; Graells-Garrido et al., 2021; Staricco, 2022) or census blocks (Logan et al., 2022). Further, some studies used grid cells that were determined by their input data (Abdelfattah, Deponte and Fossa, 2022; Knap et al., 2023; Willberg, Fink and Toivonen, 2023), or resorted to post code areas (Calafiore et al., 2022). However, there were also studies that used non-residential buildings. In some instances, train stations (Fazio et al., 2023), working spaces (Di Marino et al., 2023) and abandoned public buildings (Balletto et al., 2021) were considered. The trip origins were highly dependent on the data used for the study, as well as the studies' purpose and related research question.

Trip Destinations

Many research papers grouped the considered essential amenities into broader categories (Burke et al., 2022; Calafiore et al., 2022; Fazio et al., 2023; Gaglione et al., 2022; Gorrini et al., 2023; Knap et al., 2023; Staricco, 2022; Zhang et al., 2023).Conversely, some studies did not look at single amenities but only overarching categories, and did not take substitution between amenities into account (Abdelfattah, Deponte and Fossa, 2022; Calafiore et al., 2022; Fazio et al., 2023; Zhang et al., 2023). Papadopoulos, Sdoukopoulos and Politis (2023) viewed this practice critically, as it may lead to incomplete or misleading results. For instance, the category *education* subsumes the amenity types *high schools* and *primary schools*. However, those school types serve different age groups and can therefore not be substituted for each other (Papadopoulos, Sdoukopoulos and Politis, 2023, p. 17).

Studies that did consider amenity relations and substitution differed significantly in their choice of amenities. While some only incorporated single amenities like *supermarkets* and *grocery stores* (Hosford, Beairsto and Winters, 2022; Willberg, Fink and Toivonen, 2023), *kindergartens* (Caselli et al., 2022), or *green spaces* (Ma, 2020), the majority defined different compositions of amenities belonging to varying categories. For instance in some studies, *elderly care* was not be taken into account at all (Vilhelmson and Elldér, 2021), was treated as part of *health care* or *civic services* (Papadopoulos, Sdoukopoulos and Politis, 2023), or was considered as an entire category itself (Weng et al., 2019). Due to the inconsistencies, Papadopoulos, Sdoukopoulos and Politis (2023) looked at 26 research papers and identified the most prevalent categories and, within them, the most frequently chosen amenity types.

The final assessment of accessibility differed widely as well. While some applied different weights to amenities (Weng et al., 2019) others counted all amenities or categories accessible (Abdelfattah, Deponte and Fossa, 2022; Guzman et al., 2021) and some applied the approach suggested by Moreno et al., which is the need for at least one amenity to satisfy each categorical need (Da Capasso Silva, King and Lemar, 2020; Graells-Garrido et al., 2021; Li, Zheng and Zhang, 2019; 2021).

Measuring of Distances and Tools

To assess proximity or accessibility, some studies resorted to Euclidean distance measures. In that, maximum walking distances of eight hundred metres (m) (Gaglione et al., 2022) or one kilometre (km) (Vilhelmson and Elldér, 2021) were applied. Since Euclidean distance does not contain realistic path characteristics, slopes and network conditions, there is a tendency to underestimate travel times (Shahid et al., 2009). Therefore, comparable, and realistic travel durations cannot be guaranteed. Hence many studies applied network analysis. Results were implemented by matrix creation, for instance using the “R5 routing engine” (Hosford, Beairsto and Winters, 2022), network distance travel sheds (Da Capasso Silva, King and Lemar, 2020) or isochrones (Balletto et al., 2021; Caselli et al., 2022; Fazio et al., 2023; Gorrini et al., 2023; Guzman et al., 2021).

Popular programs to perform the needed operations were QGIS (Fazio et al., 2023; Gorrini et al., 2023; Knap et al., 2023; Ma, 2020), or ArcGIS (Alawadi et al., 2022; Caselli et al., 2022; Guzman et al., 2021; Li, Zheng and Zhang, 2019; Zhang et al., 2023). Additionally, a variety of routing services as well as the previously mentioned “Walk Score” were used to perform network analysis (Papadopoulos, Sdoukopoulos and Politis, 2023).

Focus of research

As mentioned before, factors such as destination choice often resulted from the focus of research and chosen research question. Topics chosen included, but were not limited to, supermarket accessibility, (Hosford, Beairsto and Winters, 2022) assessing social equity (Guzman et al., 2021; Weng et al., 2019) and the possibility of transforming abandoned buildings to enhance compliance with the XMC concept (Balletto et al., 2021). In addition, some studies set out to explore the impact of structural changes and, based on that, compared the different states for compliance with the XMC concept. For instance, Vilhelmson and Elldér (2021) compared service proximity to citizens in 1994 and 2004 to evaluate the impact of geographical redistribution of the population and amenities, and Knap et al. (2023) assessed the future impact of planned bicycle bridges and tunnels in Utrecht.

Input Data

The input data consisted of mainly two data sets: trip destinations and trip origins. For trip destinations, some papers incorporated survey data provided for a specific area. For instance, Birkenfeld et al. (2023) employed the "Montréal Origin-Destination (O-D) survey 2018", which provided disaggregate mobility data, and was utilized to estimate trips as well as the built environment. Similarly, Zhang et al. (2023) included a questionnaire survey for older adults, as well as blood and saliva samples to asses differences in health.

Many researchers tried to incorporate open data sets. For the retrieval of street networks and amenity acquiring, OSM was frequently chosen to import road networks and measure distances, for instance by creating isochrones (Knap et al., 2023) or travel matrices (Hosford, Beairsto and Winters, 2022). OSM was also used to import buildings or amenity information (Burke et al., 2022; Rhoads, Solé-Ribalta and Borge-Holthoefer, 2023). Other papers also resorted to "Bing Maps" (Alawadi et al., 2022), "Baidu Maps" (Weng et al., 2019) and "Google Maps" (Gaglione et al., 2022).

For trip origins, many studies resorted to open but regional data sets. Hosford, Beairsto and Winters (2022) used geographical units provided by "Statistics Canada" as trip origin cells and "the City of Vancouver's and Burnaby's open data catalogue" for amenity information and trip destinations. Vilhelmson and Elldér (2021) retrieved data on workplaces from the Swedish statistical database "GILDA" to identify amenities.

2.2.3 Research Gaps

The awareness for, and research conducted on the XMC concept has increased exponentially in the scientific community since the Covid-19 pandemic. However, methodological processes vary greatly and there is a lack of cohesion in defining characteristics (Papadopoulos, Sdoukopoulos and Politis, 2023).

The reviewed literature indicates that while there has been plenty of research conducted on the basis of walking and walkable neighbourhoods, there is a lack of research focused on cycling as a method of transportation. This is supported by Papadopoulos, Sdoukopoulos and Politis (2023, p. 18), who expressed a need for “extension of methodologies to explore the X-min city based on cycling or public transit.” This gap in research is noteworthy, since bikeability in cities is one of the key instruments in today’s city planning. It allows for new and progressive planning goals like climate neutrality, while simultaneously responding to an increase in population in cities due to urbanization (Becker et al., 2018). For many people, especially in big cities and European countries, cycling is one of the major modes of transportation (Rahul Goel et al., 2022). Knap et al. (2023) state that whereas the majority of research has addressed the measurement of XMC based on walking, the role of cycling is yet to receive sufficient recognition.

Furthermore, many studies attempted the use of open data platforms and open-source tools like QGIS and OSM to achieve duplicability for their methodology (Fazio et al., 2023; Knap et al., 2023; Rhoads, Solé-Ribalta and Borge-Holthoefer, 2023; Willberg, Fink and Toivonen, 2023). However, the majority of them still incorporated locally specific surveys, records, or data sources. While local datasets might provide more detailed information on the area in question, it also complicates the replication of the methodology. For instance, many papers retrieved local census data for information on where and in what density people live and how social groups are distributed within the area. In contrast, research cases with limited data provision and access as well as scarce resources benefit from methodologies only relying on open data and openly accessible tools (Fazio et al., 2023, p. 538). Hence a more replicable methodology that relies on open data, is globally applicable, and incorporates the same data sources and steps for any region, is preferable. Similarly, Papadopoulos, Sdoukopoulos and Politis (2023, p. 19) suggest a “utilization of open-access sources with global data coverage.”

Moreover, reliance on census data, a common practice among researchers, provides only aggregated information, constraining the methodology and findings of studies. Trip origins consist of irregularly sized census sections or aggregated data tracks. In scenarios involving grid formation, cell sizes are confined to the input data cells, potentially leading to inaccuracies and less detailed results. Consequently, the utilization of disaggregated spatial units with consistent sizes as trip origins is preferable, as it yields more precise and comparable results.

Furthermore, not all researchers adhere to Moreno's (2021) suggestion regarding residential buildings and spaces as trip origins. While this approach may be appropriate in certain case studies, it is advisable to consider residential areas as trip origins in studies that aim at a more general assessment of XMC compliance. Unfortunately, there is no clear definition of what constitutes a trip origin. According to Papadopoulos, Sdoukopoulos and Politis

(2023), individual houses and addresses yield the most accurate results for measuring compliance with the XMC concept.

Grids were a frequent choice to visualize data. However, some studies additionally utilized grid cells as destinations that contain amenities, or employed cells as entire neighbourhoods. Overall, a more standardized approach would be preferable (Papadopoulos, Sdoukopoulos and Politis, 2023).

Studies varied strongly in their accounted service categories and amenities. While categories often overlapped, the amenities belonging to each category were diverse. Furthermore, the classification of categories and subcategories differed considerably. The need for a more uniform definition of amenities within each category becomes evident in the attempt of Papadopoulos, Sdoukopoulos and Politis (2023) to define the common ground between different papers. Furthermore, a review of the substitution between amenities within categories is highly recommended and should be clearly defined to avoid misleading results (Papadopoulos, Sdoukopoulos and Politis, 2023).

Finally, the objectives of studies exhibited significant variation. Many were centred on exploring potential strategies to achieve or enhance social equity, or to assess diverse needs and challenges across various age and social demographics (Gorrini et al., 2023; Knap et al., 2023; Zhang et al., 2023). Others concentrated on improving walkability (Gorrini et al., 2023) which in some cases incorporated structural changes like a widening and heightening of sidewalks (Fazio et al., 2023). However, research that emphasizes bikeability and bicycle structures was scarce. In the papers considered by Papadopoulos, Sdoukopoulos and Politis (2023), only Knap et al. (2023) evaluated the potential impact of structures, looking only at bicycle usage. Although closely linked, there remains a gap in the methodology to measure the effects of already constructed bicycle structures on the XMC concept by removing them from the road network. Further, Knap et al.'s study was based on the question of supply and demand, a topic which will not be explored as part of this work.

2.3 Research Questions and Key Study Objectives

Based on the previously identified research gaps, this study will address the usage of bicycles, assessing the impact of bicycle bridges in Copenhagen. The methodology in this project will rely on open-source data and tools, namely QGIS, OSM and ORS, to avoid the drawback of costly commercial programs and make the methodology more accessible and repeatable for anyone. Furthermore, global data sources will be used to support duplicability as well as comparability. The following research questions (RQ) conclude the focus of this work, each addressing one study object.

- Research Question 1: Regarding individual amenities: Which have seen improvements, what factors determined that, and how does substitution of amenities affect accessibility on a categorical level?
- Research Question 2: Considering bicycle usage: To what extent has the city of Copenhagen implemented the XMC concept across 3-, 5-, 10-, and 15-minute thresholds and how is accessibility spatially distributed?
- Research Question 3: What impact did the newly constructed bicycle bridges have on the spatial distribution of accessibility for the XMC concept in Copenhagen overall and across different thresholds?

3 Case Study

The approach presented in this thesis was conducted for Copenhagen, Denmark. The following chapter will first look at Denmark as a country and then take a closer look at its capital Copenhagen, as well as the chosen area of interest.

Denmark, also known as metropolitan Denmark, is situated in the South-Central region of Northern Europe (figure 2) and is a constituent part of the Kingdom of Denmark. To the West, Denmark borders the North Sea, and to the Northeast, Denmark's islands divide the Baltic Sea from the sea area Kattegat. Its only land border is shared with Germany in the South (figure 2). The country is characterized by flat, arable land, sandy coasts, low elevations, and a temperate climate (Embassy of Denmark). Covering a total area of 42.943 km^2, metropolitan Denmark comprises the northern portion of the Jutland peninsula as well as an archipelago of 406 islands. The most populous island is Zealand, where the capital and largest city, Copenhagen, is located (Statistics Denmark, 2010). On the 1st of January 2024, Denmark had a population of 5.961.249 of whom 659.350 live in Copenhagen (Statistics Denmark, 2024).

3.1 Area of Interest

Copenhagen is the capital and most populous city in Denmark (Embassy of Denmark). Since the start of the 21st century, Copenhagen has experienced significant urban and cultural growth. The city anticipates a 20 percent population growth by 2025 (City of Copenhagen, 2024). Driven by investments in its institutions and infrastructure, it was rated "most liveable city in the world 2021" (City of Copenhagen, 2024).

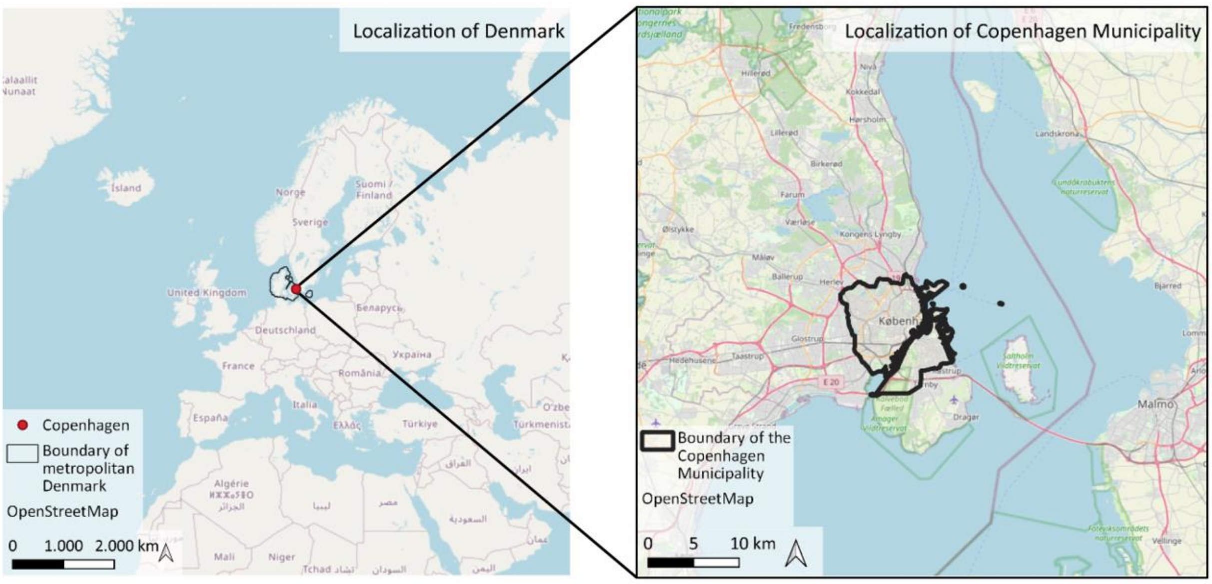

Figure 2: Localization of Denmark and the Copenhagen Municipality within their Context

Following the construction of the Øresund Bridge, that crosses the Øresund strait connecting Denmark and Sweden, Copenhagen has intensified its cooperation with the Swedish province of Scania and its main city, Malmö (City of Copenhagen). Because of the many water canals and river that cut through Copenhagen, its cityscape boasts parks, promenades, and waterfronts (City of Copenhagen, 2024). The city's economy has thrived, particularly in the service sector, with notable advancements in information technology, pharmaceuticals, and clean technology. Creative businesses in Copenhagen employ 70% more people than the European average.(City of Copenhagen, 2024).

The City of Copenhagen claims to be actively responding to the challenges of climate change by implementing measures to adapt accordingly. As both a city and capital, Copenhagen sates that it acknowledges its responsibility in addressing climate change. The city's goal is to integrate growth, development, and quality of life while reducing carbon dioxide (CO_2) emissions, aiming to achieve the distinction of becoming the world's first CO_2-neutral capital by 2025 (City of Copenhagen, 2012). Further, Copenhagen wants to contribute positively to global challenges as well as the realization of the United Nation's 17 Sustainable Development Goals (SDGs), especially regarding the reduction of greenhouse gas emissions (SDG 13). By 2050, Copenhagen seeks that 75% of all trips should be done by foot, bicycle, or public transport. Further, 50% of all commutes to work or educational facilities should be completed by bicycle (City of Copenhagen - Department of Finance, 2021).

Copenhagen was chosen as the study area because of its cycling popularity, as it is known as the "city of cyclists" (Colville-Anderson, 2018, p. 2). According to data from the European Cyclist Federation (ECF) in 2014, the country with the most people using cycling as their main mode of transport was the Netherlands with 35%, followed by Denmark with over 23% (ECF, 2016b). When examining the modal share of cycling in specific cities, Copenhagen has the highest urban cycling rate in Europe as of 2016. With 49% of residents naming cycling as their primary mean of transportation, it substantially surpasses Amsterdam (35%) and Berlin (13%) (ECF, 2016a).

This is especially remarkable when considering that in the 1950s and 1960s Copenhagen was still as car-congested as any other city (Colville-Anderson, 2018, p. 64). In the seventies, after the first oil crisis, tens of thousands of people demonstrated with bicycles, asking for safer conditions for cyclists. Over the last two decades the government had removed big parts of the cycling infrastructure and when people needed to use bicycles again, the number of fatalities peaked on an all-time high (Colville-Anderson, 2018). In the 1980s, the government had the will and the money to execute profound changes by rebuilding the former infrastructure, as well as constructing new bicycle structures (Becker et al., 2018).

Line Barfod, Copenhagen's Mayor of Technical and Environmental Affairs, states that one of the "top priorities in Copenhagen is to make cycling the obvious transportation choice" and that "97% of Copenhagen's population is satisfied with the cities cycling facilities" (City of Copenhagen, 2022). 85% of its population has access to a bicycle and 75% of Copenhageners feel that the cycling culture improves urban life. Further, the number of cargo bikes in Copenhagen has doubled since 2020 to 40.000, indicating that Copenhageners use their bicycles in various situations, as well as to fulfill daily needs (City of Copenhagen, 2022, p. 10). Therefore, the results found in this thesis can be considered relevant to the cities demographic and its population.

In addition to its high bicycle usage, Claus Billehøj, Chief of Section in the Municipality of Copenhagen, states that "the ambition is to make Copenhagen a role model for the sustainable development of cities all over the world" as the city aims to make all essential services accessible within a reach of 5 minutes (State of Green, 2016). In light of that, the city has constructed a variety of projects, constantly improving the bikeability of Copenhagen. A key feature of Copenhagen's improved bikeability are the newly constructed bicycle bridges. Of the 20 new bicycle bridges, 18 were built within the last 20 years. While some of them cross streets or train tracks, most bridges cross the many water canals that cut through the city.

Bicycle traffic is notably dense at the bridges over the lakes and the inner harbor. In fact, "there are as many cyclists here, as there are cars on major motorway bridges elsewhere in the country" (City of Copenhagen 2022, p. 11). For instance, 42.600 cyclists cross the Dronning Louises Bridge daily, which is more than three times the number of cars crossing the Øresund Bridge between Denmark and Sweden (City of Copenhagen, 2022, p. 11).

Despite the city's high cycling rates, and the completed changes in bicycle structure, no GIS-based study could be found that had assessed Copenhagen's compliance with the XMC concept. Lastly, given that nearly half the population relies on bicycles as their main mode of transportation, it is realistic to assume that impacts measured in this work will realistically display the impact on a significant portion of the population.

When choosing the study area, the aim was to identify an area that presented the city of Copenhagen, with a special focus on the locations of the bicycle bridges. The included bridges are listed in the description of figure 3. Copenhagen consists of four municipalities: Copenhagen, Tårnby, Dragør, and Frederiksberg (Statistics Denmark, 2007). Figure 3 shows the neighbouring cities and municipalities adjacent to the Copenhagen Municipality. As all 20 bicycle bridges are located within the Copenhagen Municipality (figure 3), the study focussed on this area as well as the enclave Frederiksberg, which is situated within the Copenhagen Municipality, west to the centre of Copenhagen (figure 3).

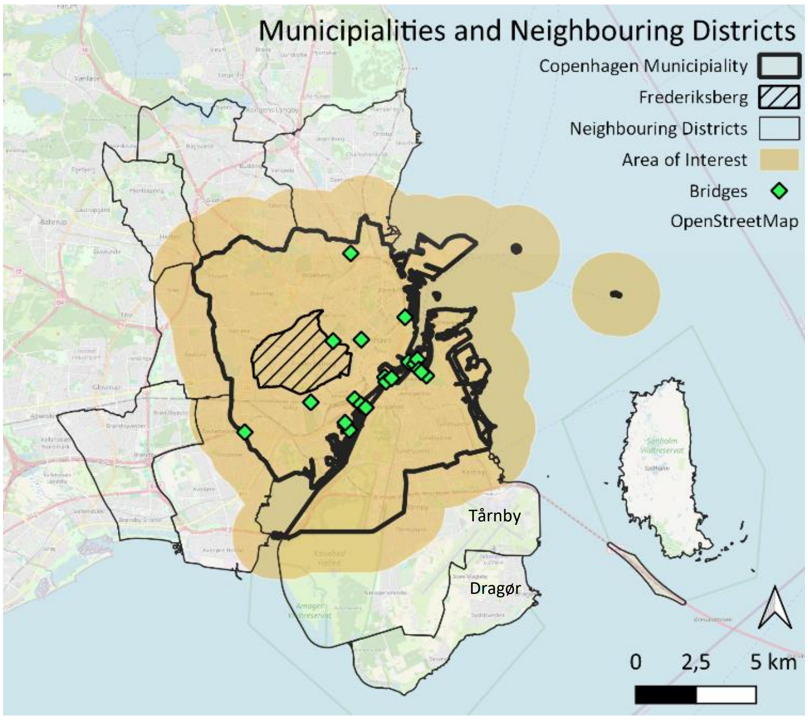

Figure 3: Municipalities and Neighbouring Districts

Bridges included in the study: Inner Harbour Bridge, Lille Langebro, Bicycle Snake, Circle Bridge, Bryggen Broen, Dronning Louises Bridge, Folehave Bridge, Alfred Nobels Bridge, Belvedere Bridge, Abuen, Langelinie Bridge, Lersoparken-Ryparken Bridge, Trangravs Broen, Proviant Broen, Dyssengraven Broen, Laboratiegraven Broen (two bridges), Bryghusgade- Frederiksholm, Carlsbergviadukten, Dybbolsbro Bridge

Projection: WGS 84/Pseudo Mercator, EPSG 3857

Due to the boundary effect described in chapter 4.1.1, the Copenhagen Municipality was buffered by 3 km to create the final area of interest. This led to the partial inclusion of the Tårnby Municipality to the South as well as some other adjacent districts to the West and North (figure 3).

3.2 Tools and Data

This chapter will offer a brief description of the tools used in this study to gain or analyse data. All tools employed are open-source and free of charge.

OpenStreetMap (OSM)

The OpenStreetMap (OSM) project was established in 2004 with the objective to gather spatial data on a global scale and make them available free of charge. The OSM community contributes to mapping activities primarily on a voluntary and unpaid basis. Mapping activities focus on spatial elements such as traffic infrastructure, points of interest, buildings, land use, and administrative boundaries (OpenStreetMap contributors). Real world features are mapped as 'nodes', 'ways' and 'relations' elements, which are linked with several tags that describe the respective attributes (OpenStreetMap contributors, 2020). Although OSM is known as “the world’s largest Volunteered Geographic Information (VGI) platform” (Anderson, Sarkar and Palen, 2019, p. 1), mappers might receive payments as part of a specific projects (Anderson, Sarkar and Palen, 2019). Further, levels of completeness and detail vary significantly between rural and urban regions (Haklay, 2010) which might correlate with personal interest of the mappers and their potential focus on areas of interest (Bégin, Devillers and Roche, 2013).

OSM is already employed in various applications which consider it a viable alternative to authoritative map services (Senaratne et al., 2017). One of the key advantages of OSM is its vast amount of data, along with the ease of access, download, and utilization for further research, all available at no cost. As part of this study, OSM functioned as a main data source, providing the input data of trip origins and destinations as well as the road network.

HOT Export Tool

The Humanitarian OpenStreetMap Team (HOT) (2018) is “an international team dedicated to humanitarian action and community development through open mapping.” The organization developed an export tool that “creates customized extracts of up-to-date OSM data in various file formats” (OpenStreetMap contributors). The tool can be accessed through https://export.hotosm.org. As part of this study, it was used to extract building data.

Quick OSM

Quick OSM is a QGIS Plugin that “executes custom Overpass queries in QGIS to get OSM data” (Etienne Trimaille, 2023), shows all OSM keys available and enables the down load of OSM data with the help of an Overpass IPA (Etienne Trimaille, 2023). As part of this work the tool, version 2.2.3, was utilized to extract OSM data of the required POIs.

OSM Place Search Plugin

The OSM Place Search Plugin for QGIS is a location search tool that allows to locate POI on the basis of OSM data in the OSM XYZ tiles in QGIS (Xavier Culos, 2023). For this work, OSM place search version 1.4.5 was used to identify the location of the 20 bicycle bridges in Copenhagen.

Openrouteservice (ORS)

“Openrouteservice is being developed and provided by Heidelberg Institute for Geoinformation Technology (HeiGIT) and offers routing services by using user-generated, collaboratively collected free geographic data from OpenStreetMap” (HeiGIT gGmbH, 2022). The registration to access the API is free of charge and allows for over 7.000 requests per day. The data is retrieved from OSM, which provides global coverage. Based on the user-generated tags and values from the OSM database on road infrastructure, ORS offers spatial services including routing, isochrone calculation, and distance-time matrices. For this study, isochrone calculation was the most frequently used tool. The generated isochrones incorporate different cycle speeds, depending on the track type and surface. Incorporation for slopes is available but was turned off, as it occasionally leads to undesirable routes. Used in this work was the “regular bike profile”, for which speeds vary for different surfaces and track types between 6 km/h on sand or wooden surfaces, to 18 km/h on asphalt and paved surfaces. Speeds further rely on whether a separate bicycle path is available (18km/h), or whether cyclists are forced to ride on the street (16 km/h) (HeiGIT gGmbH, 2024b). In this work the state of cycling structure developments were incorporated in the isochrone calculation.

In the case of *bicycle rental stations,* the profile walking was used, which is set to an average walking speed of 5 km/h and avoids the way types: highway= primary or primary _link, secondary, secondary_link, tertiary, and tertiary_link (HeiGIT gGmbH, 2024b).

ORS was implemented via the ORS QGIS plugin, version 1.7.1, which provides access to the majority of functionalities available on openrouteservice.org, based on data from OSM. Its toolkit encompasses routing, isochrone generation, and matrix calculations (HeiGIT gGmbH, 2024a). This study primarily utilized the isochrone function, especially making use of the “avoid polygons” feature.

Quantum GIS (QGIS)

Qantum GIS (QGIS) is a free and open-source geographic information system (GIS) founded by the Open-Source Geospatial Foundation (OSGeo). It supports several vector, raster, and database formats and functionalities and enables users to create, edit, analyse, visualize, and share geospatial information (QGIS Development Team, 2024). Within this study the QGIS version 3.34.2 was used to obtain, analyse and visualize data through map creation.

4 Methodology

The following chapter will present the methodology used for this work. To make the separate steps more comprehensible, an overview of the steps within each section will be presented in form of individual flow chart segments. For a full overview, the entire flow chart is displayed in appendix A. Each step presented in the flowchart will be closely described, including information on the correct execution of the steps, things to note and a brief overview of possible limitations connected to each step.

4.1 Data Preprocessing

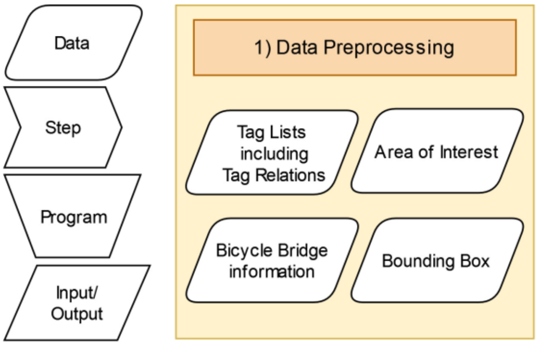

Figure 4: Flowchart Segment 1) Data Preprocessing

To enable the subsequent analysis, the data needed to be prepared and pre-processed. This consisted of three major steps: First the area of interest and bounding box were defined, secondly the bridges were sketched out as polygons, and thirdly amenities and categories were selected, and their treatment and relations were defined (figure 4). The following sections will provide information on the specific execution of each step.

4.1.1 Area of Interest

To extract the area of interest, the boundaries of the Copenhagen Municipality were dispatched with OSM Boundaries[2]. As displayed in figure 3, some bridges in Copenhagen are situated very close to the municipality's boundary. Particularly, Folehaven Bridge in the West, and Lersoparken Ryanparken Bridge towards the North, are near the border. Since Copenhagen's boundaries directly connect to neighbouring urban areas, the proximity of these bridges to the boundary may have significant effects on the surrounding areas.

To address this, the Municipality boundaries were buffered by 3 km, a methodology also applied by Knap et al.(2023). This allowed to further incorporate buildings that are located close to boundaries and may hence also be affected by the bridges- however, the focus

[2] OSM Boundaries: Online at https://osm-boundaries.com/Map

remains set on the Municipality of Copenhagen. The resulting area was implemented as the area of interest, shown in figure 5, which was to be assessed in the methodology and visualized in the final results.

Similar to this, buildings at the edge of the area of interest (in Copenhagen) might sometimes find their closest amenities located outside of that area. To mitigate potential inaccuracies, a much larger bounding box, shown in figure 5, was chosen to aggregate amenity point data. As explained in chapter 4.1.3, this was done to ensure that all amenities within reach of these edge buildings were included. These steps have commonly been implemented by a variety of research works, of which many used buffers or similar methods to address the boundary effect problem (Papadopoulos, Sdoukopoulos and Politis, 2023).

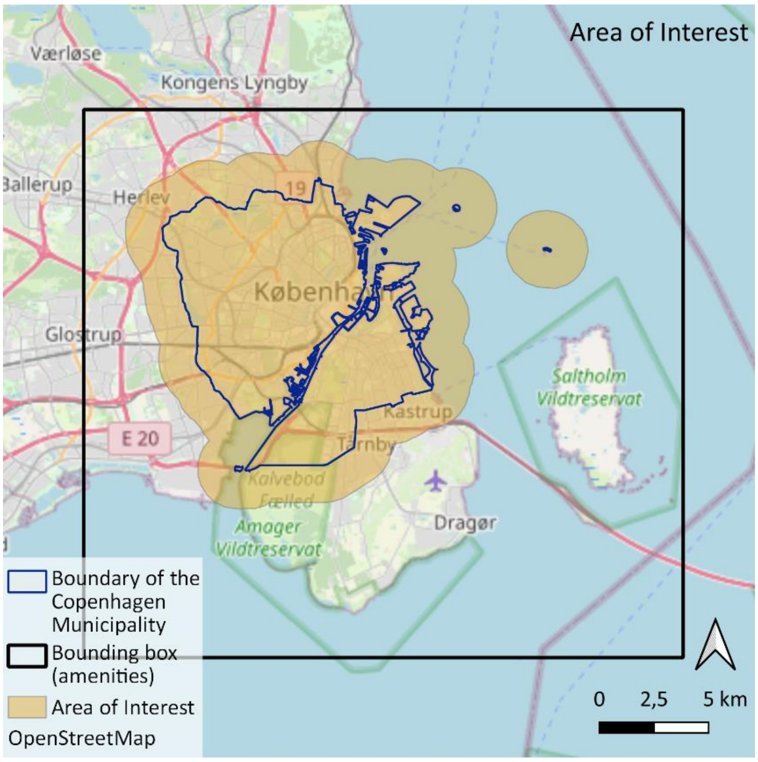

Figure 5: Area of Interest

Displayed is the study area that resulted from buffering the boundary of the Copenhagen Municipality by 3 km, as well as the bounding box used to extract amenities.
Projection: WGS 84/Pseudo Mercator, EPSG 385

4.1.2 Bridge Polygons

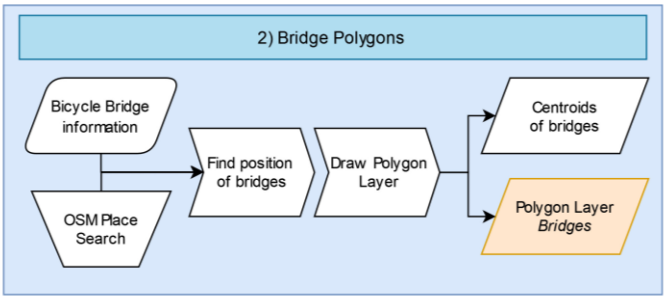

Figure 6: Flowchart Segment 2) Creation of Bridge Polygons

After having gathered the relevant information on the 20 bridges (description of figure 3), their locations were identified in QGIS with the OSM place search tool.

Each bridge was then polygonised (figure 6). This was necessary as, explained in chapter 4.2.1, the bridge passageways will be excluded from the routing process with the function "avoid polygons". The polygons were manually drawn to cover the bridge passageways. Here it was crucial that the polygons only covered the bridges and not any passageways that might run underneath.

As shown in figure 7, in the case of a bridge crossing a road, the polygon had to be drawn in a manner that only covered the entrances and exits of the bridge (right). As shown on the left, if pathways that run underneath were blocked as well, the routing mechanism did not consider that path and computed a way around it. This would lead to longer pathways and consequently false results in isochrone calculations. As visible on the right, covering all entrances and exits of bridges solved the issue, as only the bridge was avoided but the highway running underneath stayed accessible.

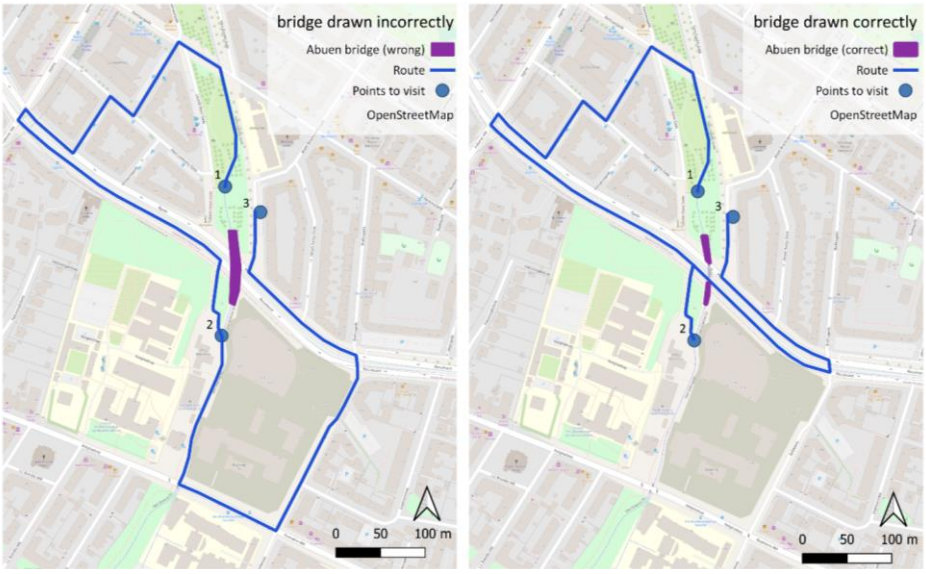

Figure 7: Falsely (left) and Correctly Sketched Polygons (right)

Left: The routing system avoids the bridge but also the path underneath.
Right: The routing system avoids the bridge, but the path underneath is implemented
Projection: WGS 84/Pseudo Mercator, EPSG 3857

4.1.3 Category and Amenity Selection

As discussed in chapter 2.2.3, the definition of categories and amenities varied significantly across the related literature. To find common ground, Papadopoulos, Sdoukopoulos and Politis developed an overview, shown in figure 8, which depicts frequently used categories, subcategories and belonging amenity types. To define categories, subcategories, amenities and their substitutional relations, a qualitative approach was chosen.

The categories in this study were chosen based on the six categories suggested by Moreno et al. (2021) as well as the suggestions made by Graells- Garrido et al. (2021) and Knap et al. (2023). In the next step the suggested amenity types and their overarching subcategories of Papadopolous, Sdoukopoulos and Politis (2023) were considered. After defining the categories, subcategories and belonging amenities, OSM tags that matched the individual amenities were obtained. Lastly, as suggested by Papadopoulos, Sdoukopoulos and Politis (2023), substitutions of amenities were defined, and amenities which belong to the same category were assessed and their relations were clarified. The results can be found in table 1.

Selection of Categories

Moreno (2021, p. 100), who first introduced the XMC concept, defined six key functions that need to be fulfilled: *(1) living, (2) working, (3) commerce, (4) healthcare, (5) education* and *(6) entertainment (including recreation)*. Graells- Garrido et al. (2021) then added two further categories that were *(7) (healthy) food* and *(8) government facilities*. Lastly, Knap et al. (2023), added *(9) green spaces*. The importance of green spaces derived from their capability to reduce heat islands in urban spaces (Knap et al., 2023). Additionally, Papadopoulos, Sdoukopoulos and Politis (2023) found that various papers, as well as the 15-minute city concept implemented in Paris (Ville de Paris, 2022), also included *public transportation* as a category, to enable citizens to leave the XMC space and access the entire city without relying on car usage. Therefore, the category *(10) transportation* was included.

In the next step, the category *workspaces* was again excluded, because of its difficult assessment and unclear definition. Even though the availability of job opportunities may be measurable, it is challenging to determine if people living in an area will find their field and choice of deployment, fitting job offers and availability of work in their neighbourhood. To measure *workspaces*, some studies focused only on newly available working spaces or based their methodology on surveys conducted on that topic. Furthermore, most of the categories considered in this study also fulfill the provision of *workspaces*. For instance, in *education*, teachers are employed, and in *healthcare,* pharmacists, doctors and nurses will find work. For this reason, most studies excluded the category *work / job opportunities* from their assessment (Papadopoulos, Sdoukopoulos and Politis, 2023). Finally, the suggested categorizations by

Papadopoulos, Sdoukopoulos and Politis were considered (figure 8), and eight categories and subcategories or broad amenities were determined, as shown in table 1.

Table 1: Categories and Corresponding Subcategories

Categories	Subcategories and Specifications
(1) Living	residential buildings
(2) Education	kindergartens and schools
(3) Commerce	food supply, retail, economical services
(4) Healthcare	healthcare services and supply
(5) Entertainment and Socialising	entertainment and socialising opportunities for various age and social groups
(6) Green and Recreational Spaces	greenspaces and sports facilities
(7) Government Facilities and Civic Services	police stations, nursing homes, postal services
(8) Transportation	public transportation, bicycle rental stations

Amenities, Substitution, Point Layer Creation

The next step was to analyse the considered amenities in each of the categories. Papadopoulos, Sdoukopoulos and Politis (2023) found that the most frequently used amenities were *grocery stores, primary schools, high schools, parks / squares, pharmacies, and supermarkets.* Here, the majority of literature agreed on the aforementioned amenities to be essential. On the other hand, fewer papers considered amenities like *counselling centres, festival venues, barber shops, museums* and *public administration* as essential, which signifies the assumed lower importance of those amenities in local citizen's everyday life (Papadopoulos, Sdoukopoulos and Politis, 2023, p. 8).

To gain a better overview of the assumed importance of individual amenities, Papadopoulos, Sdoukopoulos and Politis gathered the treatment and chosen amenities and categories of the various papers and illustrated them in a radial plot tree, as shown in figure 8. Here the individual amenities chosen were connected to the categories considered in the papers which were then connected to larger umbrella categories, following the suggestions made by Papadopoulos, Sdoukopoulos and Politis (figure 8). These umbrella categories were used in this work for category construction in chapter 4.1.3, section "Selection of Categories". In addition to the umbrella categories, figure 8 depicts the repetition or scarcity of amenities in each umbrella category. For instance, within the category *food / groceries,* the amenities *catering,* and *farm shops* were considered as relevant by only one study each. *Supermarkets*, however, were a common choice. Hence, this work considered the most prevalent and reoccurring amenities, as they were assumed to be of higher importance.

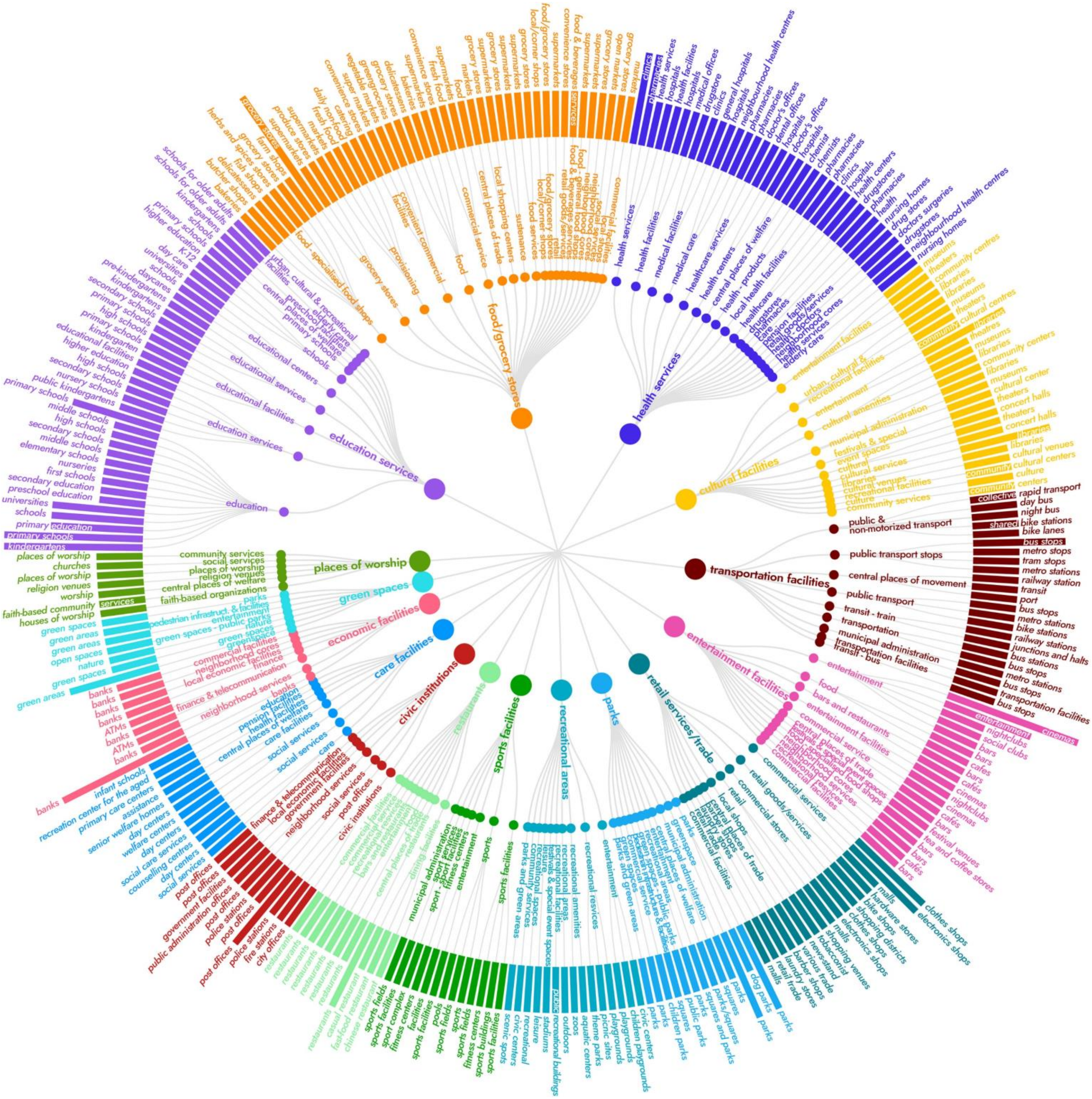

Figure 8: Radial Tree Plot Illustrating Amenities, Categories and Suggested Umbrella Categories (Papadopoulos, Sdoukopoulos and Politis, 2023, p.10)

The illustrated amenities and categories were chosen within the literature that Papadopoulos, Sdoukopoulos and Politis looked at. Based on this the umbrella categories were suggested (Papadopoulos, Sdoukopoulos and Politis, 2023, p.10).

4.1.4 Retrieval of Data

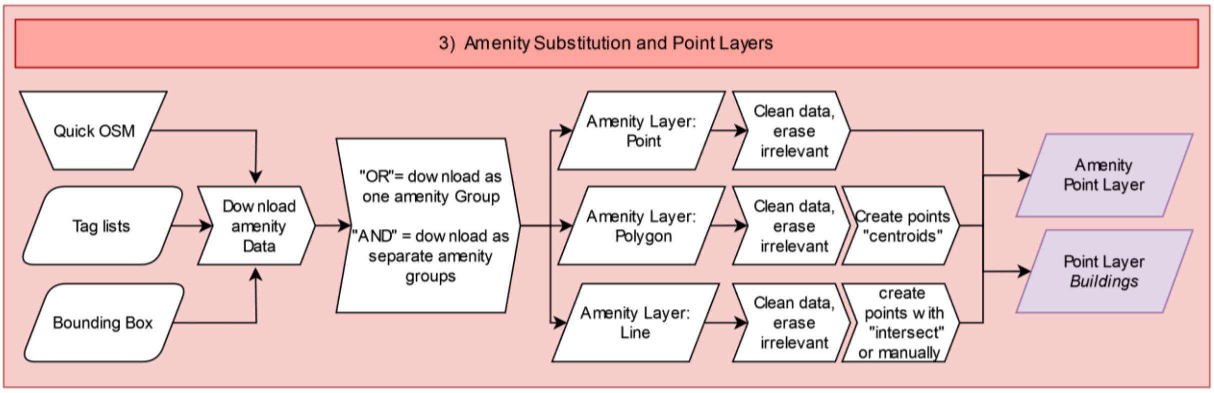

Figure 9: Flowchart Segment 3) Amenity Substitution and Point Layer Creation

Workflow step 3 correlates with the description in chapter 4.1.4

After defining the theoretical amenities, matching tags were identified with the help of the OSM Tag Finder[3] and the "map features" section in the OSM Wiki[4]. Next, the locations of all considered amenities were obtained from OSM data with the tool Quick OSM. For large data sets, such as the residential buildings in the category *living*, the export tool HOT was used. This led to an output of point, polygon and line layers.

The resulting layers were handled as followed: In a first step attribute tables were checked and items that were identifiably false or irrelevant were deleted. Next, where appropriate, polygons were converted into a point layer by using the centroid function and lines were completely deleted, since they only depicted outlines, barriers, entrance ways, etc. and not the amenity itself. Lastly, point layers and centroid layers were merged to create one final amenity point layer. This step was repeated for all amenities needed. Finally, the relations and ability for substitution between individual amenities was defined. The individual steps are presented in figure 9.

An overview of all the theoretical amenities, the connected practical level of OSM tags and substitutional relations between them can be found in table 2. The column on the right clarifies substitutional relations of amenities. Here the term "OR" indicates that items are interchangeable and the presence of either one is satisfactory. Hence amenities grouped with "OR" were extracted as one amenity group. In contrast, "AND" indicates that items cannot be substituted, and both need to be available to achieve satisfaction of the related need. Here, amenities were extracted as an individual amenity type.

[3] OSM Tag Finder: online at https://tagfinder.osm.ch/
[4] OSM Wiki: online at https://wiki.openstreetmap.org/wiki/Map_features

Table 2: Categories and Amenities with Corresponding OSM Tags and Substitutional Relations

Category and Subcategory	Subcategories and Amenities	OSM tags [key=value] and their substitutional relations [“AND” ; “OR]
(1) Living	residential buildings	building= hotel OR building = appartement OR building= yes
(2) Education	kindergartens, schools	amenity =school AND amenity = kindergarten
(3) Commerce • Food	supermarkets, restaurants, bakeries	shop = grocery OR shop =supermarket OR shop = convenience AND (shop = grocery OR shop =supermarket OR shop = convenience) OR shop= bakery AND amenity = restaurant OR amenity= foodcourt AND
• Retail	electronic shops, chemists, shopping malls, hardware stores, bicycle shops,	**(**(shop= clothes OR shop= fashion) AND (shop= electronics OR shop= electrical) AND shop = chemist**)** **OR** **(**shop=mall OR shop = department store OR shop =general**)** AND (shop= hardware OR shop = doityourself) AND shop= bicycle AND
• Economics	banks, ATMs	amenity = atm OR amenity = bank
(4) Healthcare Services	services (hospital, clinics, doctors), pharmacies	amenity= clinic OR amenity = hospital OR amenity = doctors AND amenity = pharmacy
(5) Entertainment and Socialising	diverse cultural facilities, libraries, nightlife, cafes, playgrounds	amenity = arts_centre OR tourism= gallery OR tourism = museum OR amenity= theatre OR amenity= events_venue OR amenity= community_centre OR amenity= social centre OR amenity= marketplace OR leisure= stadium AND amenity= public_bookcase OR amenity=library OR shop=books AND amenity=music_venue OR amenity=bar OR amenity = nightclub AND amenity=café AND leisure= playground
(6) Leisure and Recreation • Green Spaces	all types of open public green or natural spaces free of charge	leisure= common OR leisure=garden OR leisure= nature_reserve OR leisure=park OR landuse= forest OR landuse= meadow OR landuse=recreation_ground OR natural= fell OR natural=grassland OR natural=heath OR natural=shrub OR natural=wood OR natural=bay OR natural=beach (OR landuse= grass) AND
• Sports	sports facilities	leisure= pitch OR leisure= sports_centre OR leisure=swimming_area OR leisure=swimming_pool OR leisure=track OR leisure= fitness_centre OR leisure= fitness_station
(7) Government Facilities and Civic Services	police stations, nursing homes, postal services	social_facility=nursing_home OR amenity = nursing_home AND amenity= post_office OR amenity= post_box AND amenity=police
(8) Transportation	public transportation, bicycle rental stations	amenity=bus_station OR highway=bus_stop OR highway=platform OR public_transport=platform OR public_transport=station OR public_transport=stop_area OR public_transport=stop_position OR railway=halt OR railway=platform OR railway=station OR railway=tram_stop AND amenity- bycicly_rental

To understand the construction of the final amenity selection, the following paragraphs will give a brief overview of the most important things to note as part of the amenity selection and treatment shown in table 2. It will especially address singularities for amenities, for instance in the data collection process. A more detailed overview of each category, including the importance and need for each category as well as brief discussions on which amenities were excluded and the related reasons can be found in appendix B.

The category of *living* is a distinct category, as the related layer *buildings* does not function as trip origin but as destination. Due to the high feature count, the data for *buildings* was retrieved with HOT. *Buildings* further provided the basis for the grid cells used for the visualization of results.

As part of *education*, the data obtainment was limited, since OSM Tags do not differentiate between school types. Therefore, only *schools* and *kindergartens* were included. Due to the difference in age groups, the two were treated as not substitutional. The umbrella category *commerce* consists of three subcategories: *food, retail* and *economics.* For *food,* it is important to note that *supermarkets / grocery stores* were treated as a substitute for *bakeries,* but not the other way around. Further explanations can be found in appendix B. Within *retail,* the amenities *shopping centres or malls* were treated as substitute for the amenities c*lothing, electronic stores*, or *chemists*. Further, *hardware stores* and *bicycle (repair) shops* were considered essential, to ensure cycling functionality and availability of bicycles.

Within *healthcare*, the amenities were divided into their provision of services (*doctors, clinics*, *hospitals*) or substances (*pharmacies*).

Entertainment and socialising within the XMC concept aims to fulfill the needs of diverse age and social groups. Therefore, a variety of facilities and amenities were chosen and treated as not interchangeable.

Leisure and recreation was divided into *natural spaces / parks* and *sports.* Due to the large areas covered by items of *natural areas / parks,* the centroid method, used for other polygons to create point layers, would not have offered realistic results. Instead points of entrance to big areas were selected. Furthermore, the size of items with the tag *landuse= grass* differed significantly and no justified limit of what is to be incorporated could be found. Therefore, two scenarios were assessed with *a) including no grass areas*, and *b) including all grass areas*. This was done to assess if there was a difference in accessibility. The results in table 3 show that no difference in accessibility could be detected. Therefore, in the case of Copenhagen this does not play a role, it might however need further investigation for other study cases. Similarly, the item *vineyard* was excluded from this study but might be relevant to others. As part of *sports,* only the most popular and general sport amenities were chosen.

Within *transportation,* the inclusion of *bicycle rental stations* ensures access to bicycles for all citizens of Copenhagen. As it is unrealistic for people to cycle to a *bicycle rental station*, for this amenity the isochrones were calculated based on walking. The rest of the public transportation amenities, such as *bus stops, train stations, etc.,* were treated as interchangeable as they are part of an entire network.

4.2 Quantification of Impact on Individual Amenities and Buildings

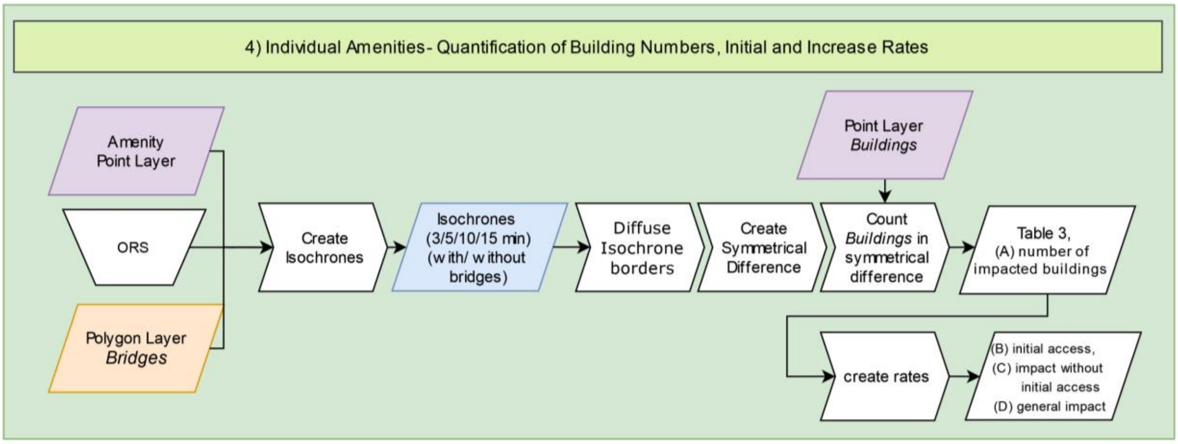

Figure 10: Flowchart Segment 4) Individual Amenities- Quantification of Building Numbers and Increase Rates

Workflow step 4 correlates with the description in chapter 4.2.The purple-coloured items were created in step 3, the yellow item resulted from step 2.

To answer RQ1, the study assessed the level of individual amenities and buildings with the goal of quantifying the impact that the bridges had on each amenity. To extract the areas and buildings whose accessibility was increased by the bridges, isochrones were created for both the initial situation, where bridges were not taken into consideration, and the topical situation, where bridges were incorporated in the routing calculations.

Then the buildings within the impacted areas were counted for each amenity type and threshold. The following sections will describe this process in more detail. An overview of the individual steps is presented in figure 10, and a graphical representation of the steps from the isochrone calculation to the counting of points can be found in figure 11.

4.2.1 Isochrone Creation

To analyse the impact of the bridges on accessibility of the individual amenities, a building count was conducted in which all the additionally reached residential buildings were counted for each amenity type and threshold. This was done on the basis of isochrone creation around the previously created amenity points with the tool Openrouteservice (ORS). The individual steps are displayed in figure 10.

In the first step, travel time thresholds were defined. Across the literature on XMC concerning walkability, travel time thresholds of 5, 10 and 15 minutes were commonly used (Papadopoulos, Sdoukopoulos and Politis, 2023). Research by Knap et al (2023), which focused on cycling as a mode of transport, also utilized those thresholds. However, since bicycle usage is faster than walking, the utilization of the same thresholds for the two different means of travel lead to significantly different results. For instance, on a paved surface, the average speed for walking is 5 km/h, and for cycling 18 km/h, therefore more than thrice the speed of walking (HeiGIT gGmbH, 2024b). As a result, the cyclist would cover the same distance on a paved surface that a person would walk in 10 minutes (833 m) within 2:46 minutes, and the distance that a person would walk in 15 minutes (1.250 m) within 4:10 minutes. Thus, a 3-minute threshold for cycling was employed and considered as a compromise between the walking thresholds of 10 and 15 minutes. Of course, the 3-minute cycling threshold lacks walkability specific criteria, however, it can provide a general idea of what pedestrian accessibility might look like. Therefore, the resulting thresholds included in the study were 3, 5, 10 and 15 minutes.

Having established the thresholds, isochrones were computed using ORS. This was done for every amenity point and each of the four thresholds. This step was repeated with the additional function “avoid polygons” using the bridge polygons created in chapter 4.1.2.

As a result, this process yielded two layers for each amenity: topical accessibility, which incorporated the passageways of the 20 bicycle bridges, and initial accessibility[5], for which the bridges were excluded. As shown in figure 11, the resulting layers consisted of multiple polygons which were then dissolved, so that no polygons would overlap with each other. Next the symmetrical difference was extracted from each of these layer pairs. Each dissolved layer presented the area that could additionally reach an amenity type because of the bicycle bridges. In the next step these areas were then used to count the number of residential buildings.

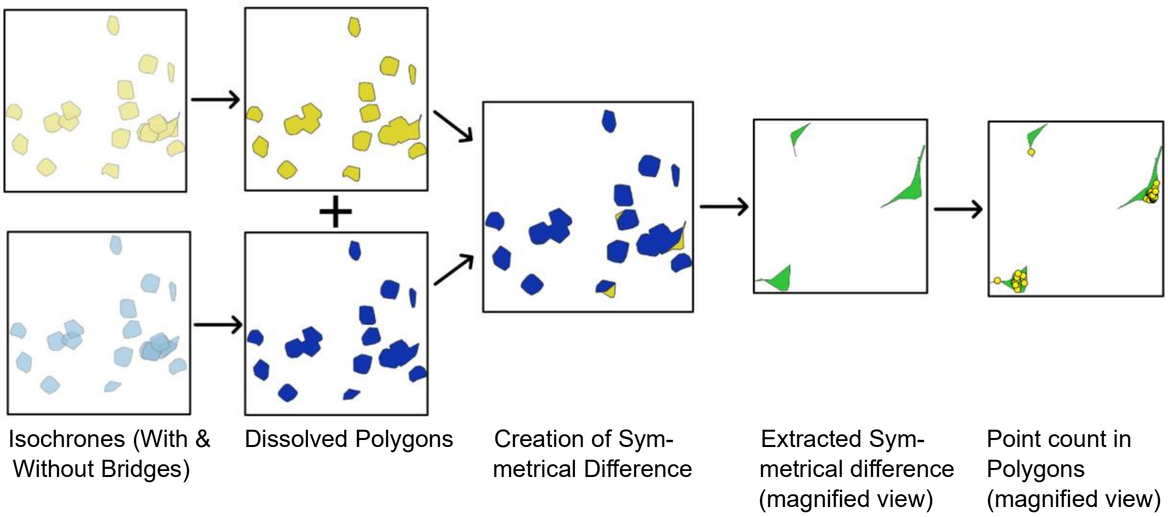

Figure 11: Overview of Steps from Isochrones Around Amenity Points to Count Affected Buildings for an Individual Amenity and Threshold

[5] Initial accessibility: When talking about “initial accessibility” it could yield the impression that the accessibility was measured before the construction of the bridges. As the first bridges were constructed in 2006, this would also incorporate a different road network that was applicable at the time. However, the application of two different road networks would yield misleading results that show impact of other structural changes, that have no correlation to the bridges. To avoid that, “initial accessibility” in this work was computed by avoiding the bridges while using the exact same road network for both cases. “Initial access” therefore does not refer to the state before the bridge construction but just the absence of the bridges in the current road network.

To simplify and accelerate the amenity layer creation process, a model was created that can be found in the GitHub repository “Copenhagen_Bachelor-Thesis_Friedrich”[6]. It incorporates all the steps described in this chapter and lets users receive the isochrone layers as well as the symmetrical difference layers with the counted buildings for each amenity type. The input data consists of the amenity point layers, the point layer of all the buildings as well as the polygon bridge layers.

4.2.2 Count of Buildings

Acquired from the previous steps were 112 layers of symmetrical difference, four for each amenity layer, belonging to the four travel time thresholds. Next, in each of these layers the building points were counted with the vector analysis tool “Count Points in Polygon”, which is implemented in QGIS. The counted points were then added with the field calculator and the “SUM” function. Here, the previous step of dissolving polygon boundaries is essential to ensure that no buildings were counted twice as part of overlapping polygons. The resulting sums present the number of buildings that can additionally reach an amenity within a certain threshold because of the bicycle bridges. The resulting numbers are displayed in table 3 in (A) “Number of buildings that can additionally access an amenity in 3, 5, 10, or 15 minutes.” In order to interpret the amount of newly accessible buildings, a comparable number is needed to show the state without the bridges. Therefore, the steps of dissolving isochrone borders and counting building points were repeated for the initial accessibility isochrones. The resulting data of counted building points was compared to the total number of buildings in the area of interest. The results are displayed in table 3 as well as in appendix C.

Furthermore, the number of buildings that gained access was set in relation to the number of buildings without initial access. This enabled a better interpretation of the data presented in table 3 and is discussed in chapter 5.1. To accelerate the employed steps and their repetition for different amenity types, a model was created that can be found in the GitHub repository “Copenhagen_Bachelor-Thesis_Friedrich**”**. The input needed are the previously created dissolved isochrone layers of each amenity, as well as the building point layer, clipped to the area of interest.

[6] GitHub repository: online at https://github.com/jule-friedrich/Copenhagen_Bachelor-Thesis_Friedrich

4.3 Spatial Analysis Based on Grid Creation

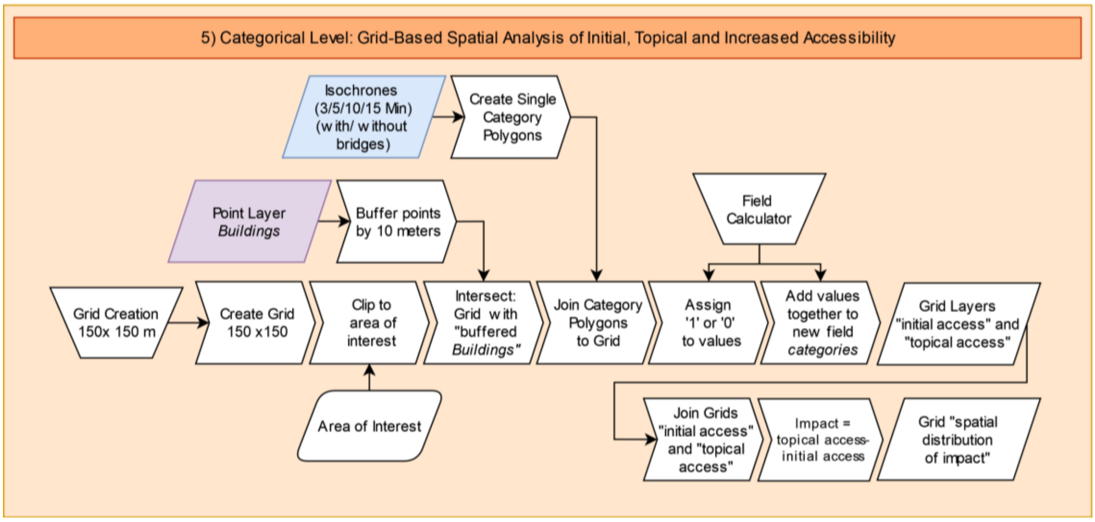

Figure 12: Workflow Segment 5) Categorical Level: Grid-Based Spatial Analysis of Initial, Topical, and Increased Accessibility

Workflow step 5 correlates with the description in chapter 4.3. The purple-coloured item was created in segment 3, the blue item as part of segment 4.

Regarding RQ2, it is necessary to gain a proper understanding of how well Copenhagen performs as a XMC within the different thresholds. Here the aim was to make areas identifiable that a) have a high accessibility and compliance with the XMC concept and b) areas that have a low compliance with the XMC concept for each threshold.

The second step was to assess RQ3; the aim was to detect the impact of the bridges on accessibility by identifying areas that improved in their XMC performance because of the bridges.

For both objectives, a suitable method of visualization needed to be applied. Here a grid-based methodology was chosen, which has been utilized by multiple studies (chapter 2.2). Grid cells in this work only present trip origins, and indicate the accessibility to categories for each individual cell.

First the size of grid cells needed to be chosen. Within the literature, sizes of grids varied strongly and were often determined by data sets, predominantly census data. The following sections will first justify the choice of grid cell sizes, and then describe the steps taken to achieve the final results of grids that show the spatial distribution of initial or topical accessibility, as well as the measured impact. An overview of the individual steps can be found in figure 12.

4.3.1 Justification of Grid Cell Size

In this work, the grid size was chosen as a compromise between cell sizes that are still recognizable in final visualization but are small enough to still offer specific information for accessibility levels of one single area. In addition, the travel speeds of cycling were incorporated in the final choice. The approach of selecting own grid sizes was also employed by Gorrini et al. (2023). The travel speed set by ORS for paved surfaces is 18 km/h, which entails a theoretical travel distance of 18.000 meters per hour or 300 meters per minute. It is essential for cells to remain identifiable, especially within the 3-minute threshold. Cells that are too small, however, would not be identifiable anymore. Since each cell only displays one value, large cells might yield misleading results that would only be true for a part of the cell. Therefore, a maximum travers time of 1 minute per cell was established. Given that streets are not always straight and may feature obstacles such as traffic lights, crossings, barriers, or other elements that could impede cyclists and extend travel distances, a preferred travel time of 30 seconds along each grid cell side was selected. This ensures that traverse times remain below the 1 minute maximum for most cells. Consequently, a grid cell size of 150m x 150m was chosen, a dimension also utilized by Abdelfattah et al. (2022).

4.3.2 Creation and Intersection of Grids

Having established the cell sizes, the grid was created with the vector research tool "create Grid," implemented in QGIS. The resulting grid was then clipped to the area of interest. Since the grid cells are representative of the trip origin and therefore residential buildings, the grid needed to only incorporate cells that functioned as residential area.

As shown in figure 13, when simply intersecting the grid with the *buildings* point layer, only cells that contained centroid points were included. However, several cells that contained building structures but not their centroids were not taken into consideration, entailing misleading results. To avoid that, the building points were buffered by ten meters before being intersected with the grid.

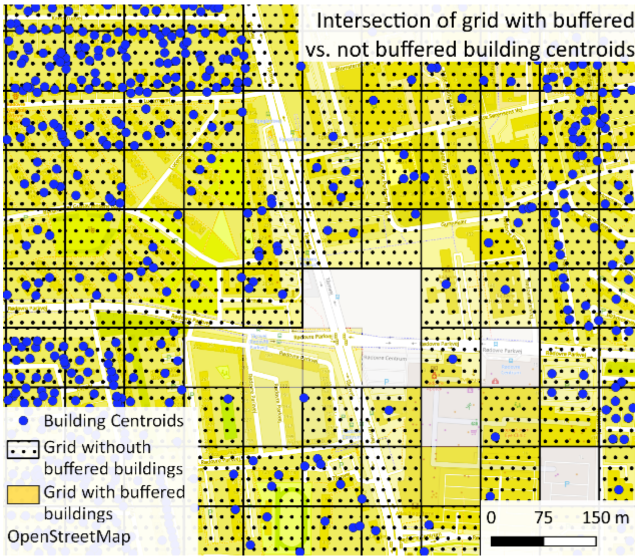

Figure 13: Intersection of Grid with Buffered and Not-Buffered Building Centroids

The figure displays that some areas that still contain building structures are not included in the grid "without buffered buildings", as the building centroids are not located in those cells. By buffering the centroids with 10 meters the left-out cells become included. Projection: WGS 84/Pseudo Mercator, EPSG 3857

The previously created amenity isochrone layers were combined for each category, following the rules of substitution displayed in table 2. For the term “AND”, layers were intersected with the geoprocessing tool “intersection”, resulting in the areas that access all amenities. For “OR”, layers were merged with the geoprocessing tool “union”, resulting in areas that can access at least one of the amenities. The result was eight polygon layers per category – two for each threshold of which one displayed the initial and one the topical accessibility.

Next a spatial join was conducted, joining the information of the category polygon layers onto the grid cells. Again, the spatial join parameter “one to one” was employed, so that the amount of grid cells was maintained.

The result were eight grids, again two for each threshold either containing initial or topical accessibility. Each of those grids contained the information of the seven category layers of the specific situation and threshold.

To facilitate grid creation a model was created: The model can be accessed in the aforementioned GitHub repository: “Copenhagen_Bachelor-Thesis_Friedrich**”** and relies on the input of the readily prepared grid and the individual category layers. To further accelerate computing times and reduce processing power, the utilization of models, the dissolving of layers and the creation of spatial indices is recommended.

4.3.3 Visualization of Results

Utilizing the field calculator, category values in the attribute table were set to either

‘1’ – people living in this cell are able to access all required amenities to fulfill the categorical need within the considered travel time threshold, or

‘0’ – people living in this cell do not have access to (all) amenities required to fulfill the need within the considered travel time threshold.

After updating all data, a new column was created, containing the sums of the category values of each row. This new field added a new value to each grid cell, which indicated how many categories a cell could access. Each cell therefore contained a value between

‘0’ – does not access any of the categories within the considered threshold” and

‘7’ – has access to all the categories within the considered threshold.”

Using the tool “categorize” in the symbology options, the values were classified and linked to a gradient colour scale. The resulting eight layers (initial and topical accessibility for each of the four thresholds) displayed the spatial distribution of access of each cell to ‘x’ categories, which was analysed in the discussion of chapter 6.2.1 that explored RQ2. The resulting initial accessibility distributions for the four thresholds are depicted in figure 14, chapter 5.1.

When examining the created grids, the differences between topical and initial accessibility distribution were difficult to detect. To address the issue, the two layers of each threshold were again spatially joined, and a new column was created that contained the differences of the topical and initial accessibility. The result was four layers, which visualize the spatial distribution of impact of the bridges on grid cells for each threshold. The layers can be found in figures 15-18. Their implications are discussed in 6.2.2 of this study with the aim to explore RQ3.

5 Findings

In this chapter, the results and findings of the previously described methodology is presented. This will be done in three subsections of which the first addresses the single amenities, the second the spatial distribution of the initial accessibility and the third section the topical state as well as the spatial impact that the bicycle bridges have had in Copenhagen.

First the effect of bridges on the accessibility of individual amenities will be presented. This seeks to explore RQ1, which will then be discussed more closely in chapter 6.1. To do so it will look at the four distinct aspects:

(A) the total numbers of buildings that can additionally access an amenity type within a certain threshold,

(B) the percentage of all buildings that have access to the individual amenities without using the bridges (initial accessibility),

(C) the results from (A) put into relation to the number of buildings without initial access, stating the percentage of impact on buildings for which improvement was still possible, and

(D) the relative impact of the additional buildings with access (A) in relation to the total number of buildings in the area of interest will be discussed. The data for (D) can be found in appendix C.

Chapters 5.2 and 5.3 will present the results of the grid-based spatial analysis of the individual thresholds. Chapter 5.2 will assess the different grids that show category accessibility without the use of the bicycle bridges. This is crucial to gain an understanding of the initial situation that served as the foundation for the development of the other two grids.

Chapter 5.3 will assess the individual thresholds regarding the overall accessibility of categories including the bicycle bridges. This aims to investigate RQ2. Furthermore, the impact that the bicycle bridges had on accessibility within each threshold will be analysed. Taking into consideration both the initial conditions and subsequent improvements, the results aim to explore RQ3. RQ2 and RQ3 will then be discussed in chapter 6.2.

5.1 Amenity Level: Quantification of Impact on Building Numbers

Table 3 illustrates the results of the amenity-based measurements. It includes the assessed impact of bridges based on counted buildings that can additionally access an amenity within a certain threshold (A), The Percentage of buildings that have initial access to an amenity (B) and the Percentage of buildings without initial access that gained access (C). The Percentage of total number of buildings that gained access (D) can be found in appendix C.

Table 3: Results of Counted Buildings of Impacted Areas and Initial Access and Proportionality to the Number of Not Initially Accessed Buildings[7]

Category & -Subcategories-	Amenity	(A) Number of buildings that can additionally access an amenity				(B) Percentage [%] of buildings that have initial access to an amenity				(C) Percentage [%] of buildings without initial access that gained access			
		3 min	5 min	10 min	15 min	3 min	5 min	10 min	15 min	3 min	5 min	10 min	15 min
Education	Kindergartens	85	69	16	0	71,1	95,9	99,7	99,7	0,23	1,30	3,83	0,00
	Schools	149	16	8	4	73,8	96,2	99,7	99,7	0,44	0,33	1,86	1,14
Commerce													
-Food-	Super -markets	414	2	2	2	86,3	99,0	99,7	99,7	2,34	0,16	0,53	0,60
	Restaurant Food Courts	932	164	3	14	68,9	94,0	99,7	99,7	2,33	2,13	0,90	4,15
	Bakeries	105	202	16	4	66,5	96,2	99,7	99,7	0,24	4,07	4,71	1,17
- Retail-	Clothes	218	389	58	14	36,3	67,1	93,7	98,8	0,27	0,92	0,71	0,94
	Electronics	526	289	69	6	20,6	47,1	89,4	99,6	0,51	0,42	0,50	1,15
	Hardware	147	754	1.299	106	26,7	60,8	95,9	99,5	0,16	1,49	24,33	17,18
	Bike stores	229	142	14	5	71,3	96,1	99,7	99,7	0,62	2,80	3,74	1,46
	Shopping malls	165	1.718	1.021	21	12,4	44,2	94,6	99,6	0,15	2,39	14,74	4,45
	Chemists	137	261	350	7	33,1	69,2	99,2	99,7	0,16	0,66	35,14	1,94
-Economics-	Banks, ATMs	231	595	19	5	53,9	87,6	99,7	99,7	0,39	3,72	4,30	1,49
Healthcare	Healthcare Services	63	128	90	19	44,8	80,2	97,5	99,7	0,09	0,50	2,75	5,21
	Pharmacies	525	533	0	3	42,9	84,2	99,6	99,7	0,71	2,62	0,00	0,81
Entertainment and Social	Night life	199	344	19	1	57,6	84,3	99,6	99,7	0,36	1,70	4,16	0,30
	Cafes	64	0	20	9	77,4	99,2	99,7	99,7	0,22	0,00	6,04	2,74
	Playgrounds	172	5	1	1	91,1	99,2	99,7	99,7	1,49	0,50	0,28	0,30
	Cinemas	345	1.621	1.379	75	11,8	34,4	82,7	98,3	0,30	1,92	6,20	3,41
	Cultural Facilities	129	162	16	6	53,9	86,2	99,7	99,7	0,22	0,91	4,66	1,81
	Libraries	8	22	0	2	33,4	76,9	99,4	99,7	0,01	0,07	0,00	0,50
Leisure and Recreation													
-Green Spaces-	a- no grass	24	1	11	5	97,0	99,7	99,7	99,7	0,62	0,24	3,35	1,50
	b- all grass	24	1	11	5	97,0	99,7	99,7	99,7	0,62	0,24	3,35	1,50
-Sports-	Sport facilities	16	0	14	1	95,6	99,7	99,7	99,7	0,28	0,00	4,22	0,30
Civic Services	Post offices	71	99	0	9	78,4	92,9	99,7	99,7	0,25	1,08	0,00	2,69
	Nursing homes	396	158	79	232	7,0	23,8	75,7	95,5	0,33	0,16	0,25	3,98
	Police stations	13	92	82	45	6,4	24,6	76,0	96,7	0,01	0,09	0,27	1,07
Transportation	Bicycle Rental Stations	22	37	376	610	1,3	3,4	10,4	20,2	0,02	0,03	0,33	0,59
	Public Transport	4	0	8	2	99,0	99,7	99,7	99,7	0,32	0,00	2,42	0,61
Average		193	279	179	68	50,7	72,9	89,6	93,0	0,47	1,08	4,65	2,20
Total average		180				76,5				2,01			

[7] Column (D) "Percentage [%] of total number of buildings that gained access" can be found in appendix C

Looking at (A), the findings from the analysis revealed significant variations in the number of impacted buildings across different amenities and thresholds. For some amenities, no increase in accessibility for any building was achieved, denoted by an impact value of '0'. This was the case for *kindergartens* within 15 minutes, *pharmacies, libraries*, and *post offices* within 10 minutes as well as *cafes, sports facilities*, and *transportation* within 5 minutes.

Within 3 minutes, accessibility to all amenities was improved. Within that threshold, a small increase was observed in the case of four buildings gaining additional access to *public transportation*, while the largest increase occurred with 932 buildings gaining additional access to *restaurants and food courts*. This illustrates the significant variation in the number of buildings gaining additional access. The most strongly impacted amenity was *cinemas*. The bridges allowed 1.621 buildings to additionally reach *cinemas* within 5 minutes and 1.379 within 10 minutes. Further, 1.327 additional buildings achieved access to *hardware stores* within 10 minutes. Accessibility to *shopping malls* was increased for 1.718 buildings within 5 minutes and 1.021 within 10 minutes.

When considering (D) the impact rate on the total number of buildings in the area of interest (128.870 buildings), the highest increase rate was 1,33% for *shopping malls* within 5 minutes. No amenity reached a higher accessibility increase rate within any threshold than 1,33% of the total building count. The average increase was 0,29% within 3 minutes, 0,41% within 5 minutes, 0,27% within 10 minutes and 0,06% within 15 minutes. The lowest increase rate in relation to the total number of buildings was therefore measured for the 15-minute threshold. The full results of increase in relation to the total number of buildings can be found in the appendix C in column (D).

When looking at the initial accessibility rate, in other words the percentage of buildings that are able to access amenities without using the bicycle bridges, the average accessibility rate is 74,7%. The maximum percentage is 99,7%, prevalent for different amenities in the thresholds 5, 10 and 15 minutes. Within the threshold of 15 minutes, the accessibility rates are higher than 99% for all amenities except for *bicycle rental stations*, which have an initial accessibility rate of 20,2%. The average accessibility rate for all amenities within 15 minutes is 90,1%. In the 10-minute threshold, a decrease in accessibility rates without bridges in comparison to the 15-minute threshold is recognisable. However, apart from *bicycle rental stations* that have a rate of 10,4%, all other amenities can be accessed by at least 75,7% of buildings. The average initial accessibility rate to *bicycle rental stations* within 10 minutes is 87,0% and 17 of 28 amenities have an accessibility rate higher than 99%.

The next step was to combine the results of (A) and (B) by comparing the total building numbers of (A) with the number of buildings without initial access, resulting in the increase rate for the buildings, for which improvement was still possible, depicted in column (C). On average, bridges increased the accessibility for about 2,2% of buildings within 15 minutes, 4,65% within 10 minutes, 1,08% within 5 minutes and 0,47% within 3 minutes. Therefore, the highest increase in access to amenities for buildings without initial access was achieved within the 10-minute threshold. When considering individual amenities, the largest increase of accessibility for buildings without initial access was 35,14% to *chemists* within the 10-minute threshold. Other high increase rates occurred for *hardware stores* within 15 minutes for 17,18%, and within 10 minutes for 24,33%, as well as to *shopping malls* within 10 minutes for 14,74%. For the threshold of 5 minutes, increase rates rose as high as 3,2% in access to *banks and ATM's* and within 3 minutes for 2,34% in access to *supermarkets.*

5.2 Category Level: Spatial Distribution of Initial Category Access

The state of the initial accessibility in the XMC, shown in figure 14, correlates strongly with the findings presented in (B) in table 3. With increasing travel time thresholds, the number of accessible categories for cells also increases. Furthermore, the 15-minute threshold exhibits relatively high accessibility with an average access to 6,13 of 7 categories per cell. When comparing all four thresholds, a pattern of increased accessibility to more categories is detectable along an area extending from the sea in the East towards the West (figure 14).
This area, that will further be referred to as “high access area”, describes the area that displays access to all seven categories within the 15-minute threshold (figure 14). It contains the centre of Copenhagen, as well as the enclave of Frederiksberg.

Additionally, across all thresholds, a decrease in accessibility is evident in areas further away from Copenhagen's centre. Particularly areas in the buffered zone around the Copenhagen Municipality experience lower accessibility. The buildings with no accessibility within a 15-minute threshold primarily comprise islands for which ORS could not find bicycle access. This also explains the frequent result of the 99,7% accessibility rate of amenities within the 15-minute and 10-minute thresholds in column (B) of table 3, since approximately 0,3% of the buildings do not have bicycle access to the mainland, leaving them with no accessibility, regardless of the threshold. Depending on the islands and their structures, connecting them to the mainland via bridge might be a possible way to increase accessibility in these areas.

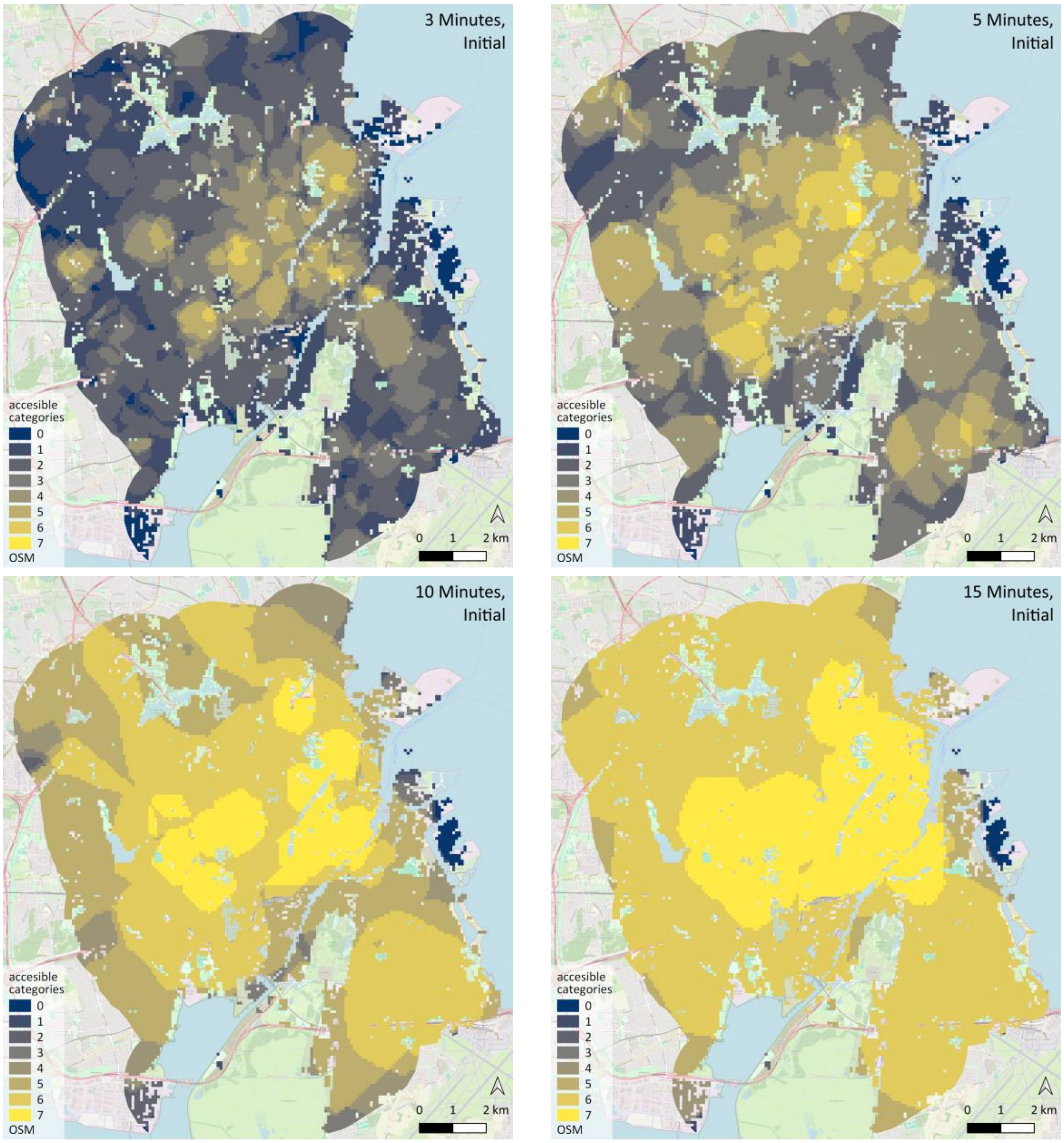

Figure 84: Spatial Distribution of Initial Accessibility for the 3-, 5-, 10- and 15-Minute Threshold

A "high access area" is depictable in the 15 minute threshold that has access to all seven categories.
Mean topical accesibility per cell:3 Mintues: ⌀ 2,26; 5 Mintues: ⌀ 3,69; 10 Mintues: ⌀ 5,53; 15 Mintues: ⌀ 6,13.
Projection: WGS 84/Pseudo Mercator, EPSG 3857

5.3 Category Level: Spatial Distribution of Topical Access and Impact Rates

Detecting the differences between the grid displaying initial accessibility and the grid displaying topical accessibility appeared to be difficult. Therefore, a separate layer was created which depicts the impact that the bridges have had.

After examining initial accessibility in chapter 5.2, the study will now assess the spatial distribution of topical accessibility in Copenhagen, exploring RQ2, Further, the impact that the bridges had within each individual threshold will be assessed, exploring RQ3. To do so, the study will look at the grids displaying spatial distribution as well as the quantified data extracted from the grid's attribute tables for each threshold individually.

3 Minutes

Within the threshold of 3 minutes, cells have on average access to 2,28 categories. However, the accessibility levels between individual cells vary significantly. As shown in figure 15, the centre of Copenhagen and Frederiksberg display mostly high accessibility to six or seven amenities within 3 minutes. Hot spots of high accessibility are located within the in 5.2 described "high access area". Around these hotspots, the number of accessible categories decreases, especially towards the North, Northwest, and South of the centre. Apart from the islands without bicycle access, some areas located on the buffer around Copenhagen Municipality display accessibility to 0 categories within 3 minutes.

When looking at the impact of bridges, on average each cell gained access to an additional 0,018 categories. However, only 1,57% of cells were affected, while the majority experienced no increase. The cells that were affected are located near the bridges, especially in and south to the centre, where bridges cross the canals and river and connect the South and North. Cells that initially had low accessibility, for instance access to only one category, experienced an increase of up to three more categories and can now access three or four categories. In addition, accessibility was increased by the bridges to the East of Copenhagen's centre. In total 262 cells, around 1,57% of the residential area experienced improvements.

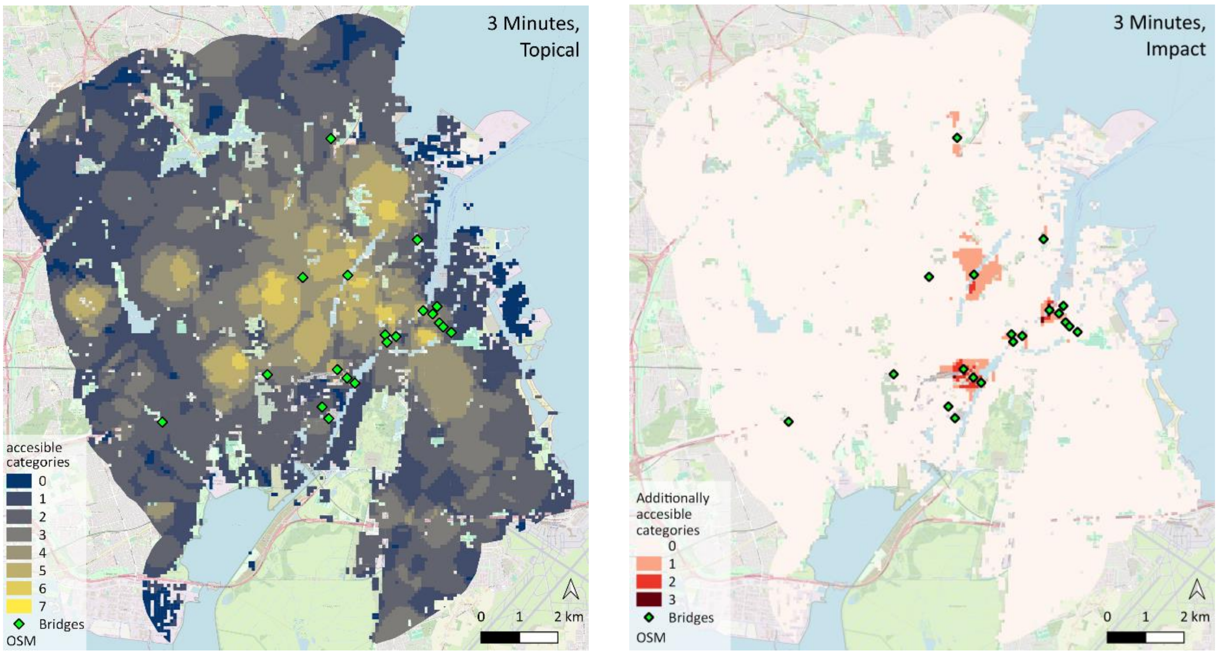

Figure 95: Spatial Distribution of Topical Accessibility (Left) and Accessibility Increase (Right) in Copenhagen for the 3-Minute Threshold

Mean topical accesibility per cell: ⌀ 2,28 categories, mean increase per cell: ⌀ 0,018 categories, ratio of impacted area :1,57%
Projection: WGS 84/Pseudo Mercator, EPSG 3857

5 Minutes

Within the threshold of 5 minutes, cells have on average access to 3,72 categories, with an average increase per cell to 0,031 categories due to the bicycle bridges. The high accessibility hotspots, assessed within the 3-minute threshold (figure 15), are still present. However, they are widened and less concentrated (figure 16). Substantial parts of the South have increased access and the cells with access to no categories have mostly disappeared. Apart from the areas with no bicycle access, as well as a few cells located in the far South, every space has access to at least one category. However, the lower accessibility rates in the North and South prevail.

When comparing increase rates across the different thresholds, the 5-minute threshold displays the highest increase rates in both average increase per cell and percentage of increased area. In total 430 cells, so 2,58% of the residential area, were positively impacted by the bridges. Similarly to the 3-minute threshold, impacted areas are located close to the bridges. Moreover, some cells in the Northwest gained accessibility as well, even though the bridges are all located further away. These cells of low or medium access between two to four categories gained access to one more category.

The main impact was assessed near the bridges crossing the canals and river in the centre of Copenhagen. The impact zones were widened, especially towards the South. Here cells of medium access to three or four categories were increased by up to three more categories, gaining high accessibility to six or seven categories.

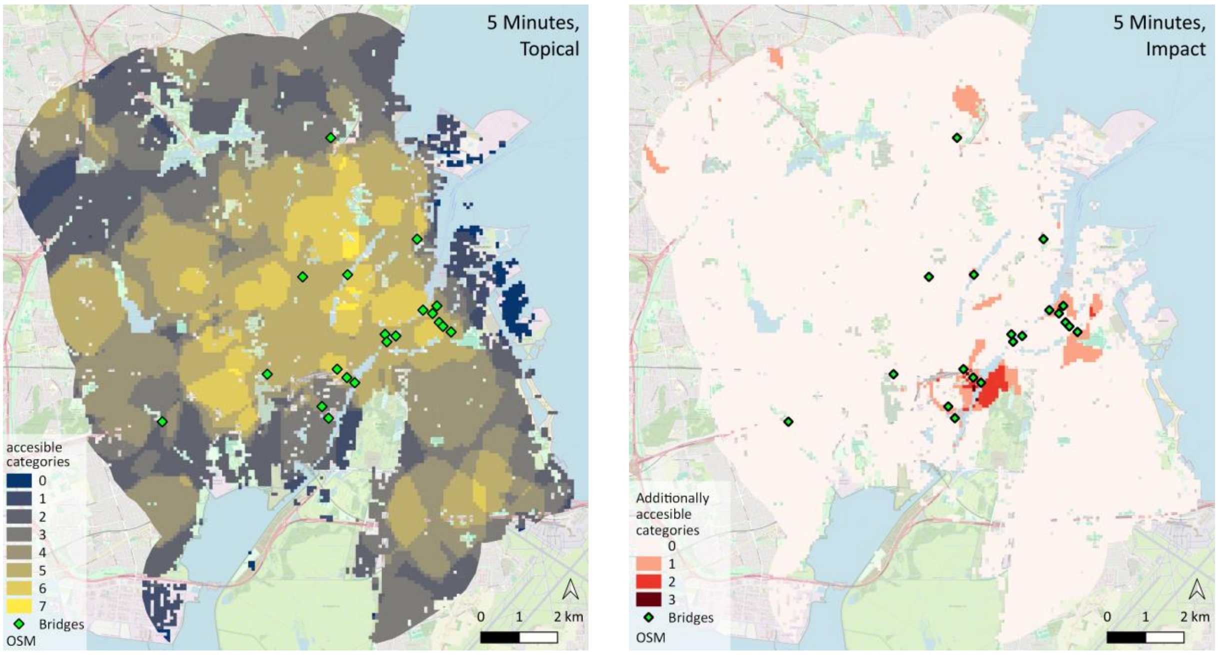

Figure 106:Spatial Distribution of Topical Accessibility (Left) and Accessibility Increase (Right) in Copenhagen for the 5-Minute Threshold

Mean topical accesibility per cell: ⌀ 3,72 categories, mean increase per cell: ⌀ 0,031 categories, ratio of impacted area 2,58%
Projection: WGS 84/Pseudo Mercator, EPSG 3857

10 Minutes

Within the 10-minute threshold, cells have on average access to 5,56 categories. Most areas have access to at least five categories, which only few cells on the edge of the area of interest fall below (figure 17). As part of the “high access area”, Frederiksberg and the centre of Copenhagen stand out, with high values of six or seven accessible categories. Lower values especially occur in the buffer zone around the municipality as well as to the South of the centre. Looking at the river that cuts through Copenhagen, a disparity between the areas north (higher values) and south (lower values) to the river becomes apparent.

When looking at the increase rates, 422 cells, so 2,53% of the residential area, gained higher accessibility because of the bridges. Some areas of impact still occur nearby bridges, though multiple zones of impact are located further away. For instance, in the far North, a strip of land gained access to one more category, increasing its access from four to five categories. Areas south of the centre experienced an increase of accessibility to 5 categories.

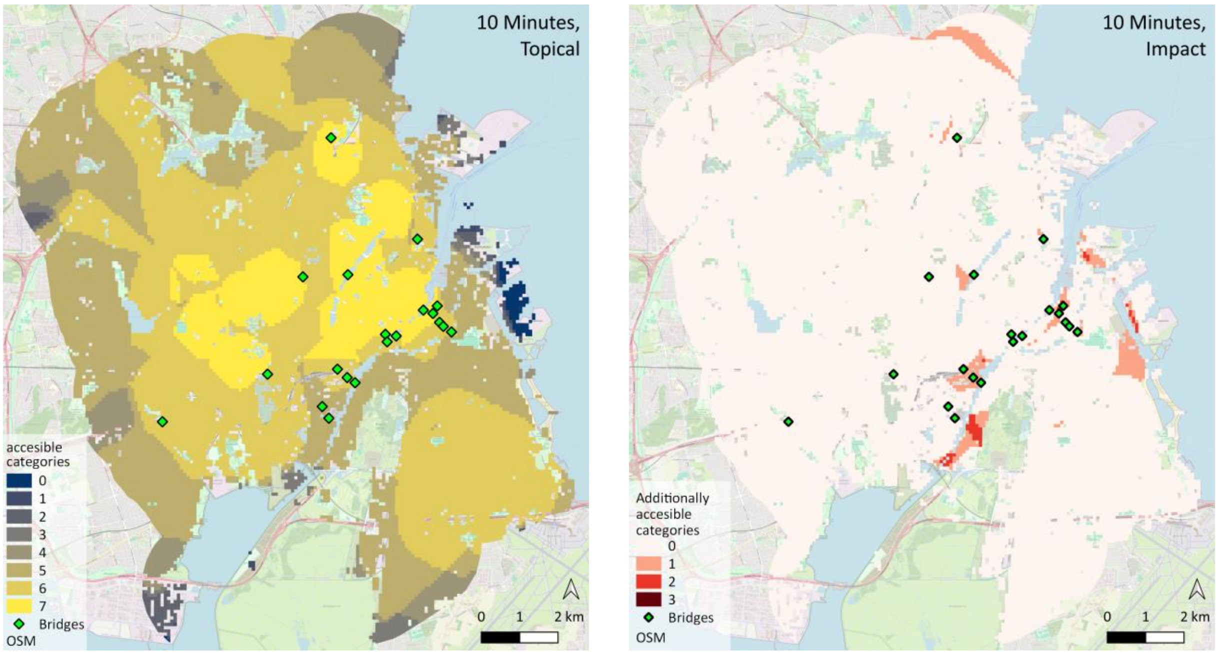

Figure 117: Spatial Distribution of Topical Accessibility (Left) and Accessibility Increase (Right) in Copenhagen for the 10-Minute Threshold

Mean topical accesibility per cell: ⌀ 5,56 categories, mean increase per cell: ⌀ 0,028 categories, ratio of impacted area: 2,53%
Projection: WGS 84/Pseudo Mercator, EPSG 3857

15 Minutes

As mentioned before, the correlation to the results found in (B) table 3 for single amenities is especially true for the threshold of 15 minutes (figure 18). As shown in table 3, the average initial accessibility for each amenity is 90,1% within 15 minutes.

This is reflected in the spatial distribution and categorization, where on average each cell can initially access 6,13 (figure 14), and topically access 6,15 out of seven categories (figure18). Access to six or more categories makes up for 92,1% within the threshold of 15 minutes. Towards the edges, in some spots, access rates decrease to 5 accessible categories. Apart from the non-accessible island cells, almost no cells have lower accessibility rates.

This is reflected in the comparably low increase numbers of the 15-minute threshold. As most areas already exhibited high accessibility rates without the bridges, only 259 cells, or 1,55% of the residential area, gained additional accessibility.

Again, areas near the bridges south of Frederiksberg and to the East of the centre gained access to one more category, enabling them to access all seven categories. However, apart from these areas, only a few cells experienced increased accessibility in the North and West of the interest area. Overall, the 15-minute threshold exhibited the lowest increase rates among all four thresholds.

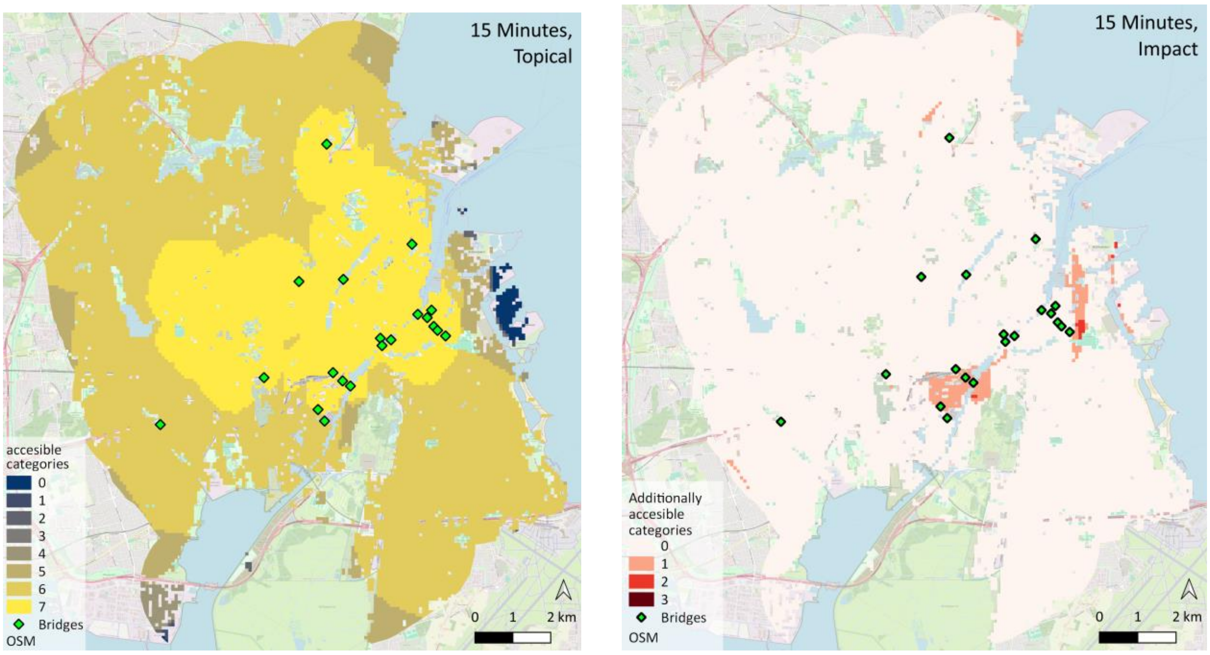

Figure 128: Spatial Distribution of Topical Accessibility (Left) and Accessibility Increase (Right) in Copenhagen for the 15-Minute Threshold

Mean topical accesibility per cell: ⌀ 6,15 categories, mean increase per cell: ⌀ 0,016 categories, ratio of impacted area :1,55%
Projection: WGS 84/Pseudo Mercator, EPSG 3857

6 Discussion

The discussion chapter will analyse the results presented in chapter 5. It will first discuss the findings presented in chapter 5.1 that were based on individual amenities as well as the number of buildings accessed, addressing RQ1. It will then discuss the findings of chapter 5.2 and 5.3 that were based on the spatial distribution of access and impact, visualized in grids, addressing RQ2 and RQ3. Having investigated the research questions, the methodology described in chapter 4 will be reviewed in relation to the literature presented in chapter 2.2. Lastly, limitations and opportunities for further research based on this study will be addressed.

6.1 Amenity Based Analysis (RQ1)

The discussion of the findings presented in chapter 5.1 seeks to put the results of the increased rates of accessibility in the context of initial accessibility, based on the counted buildings in both scenarios. Doing so, it seeks to explore RQ1: “Regarding individual amenities: Which have seen improvements, what factors determined that, and how does substitution of amenities affect accessibility on a categorical level?”

Chapter 5.1 presented the effect of bridges on the accessibility of individual amenities by quantifying buildings with initial or additional access. More precisely, the work assessed the number or percentage of buildings with access to each amenity for four different scenarios:

(A) the number of buildings that additionally gained access,

(B) the percentage of buildings that initially had access,

(C) the percentage of buildings with no initial access that gained access, and

(D) the percentage of the total number of buildings that gained access.

The results for each scenario were described, focussing on the smallest and largest results within each scenario for different amenities and thresholds. Key findings were varying results for the number of buildings gaining access (A), generally low rates for total increase rates (D), high rates for initial accessibility (B) as well as generally low but varying numbers for the increase rates of buildings with no initial access (C).

The analysis also provided insights on which types of amenities lack accessibility and could benefit from redistribution or the emplacement of additional facilities. As the accessibility of *bicycle rental stations* is relatively low, in most areas people who don’t possess bicycles cannot access locations in the way presented in chapter 5.3. The low rates for *bicycle rental stations* further affected the results, as the need of *transportation* is only met when both *public transportation* as well as *bicycle rental stations* are accessible from a residential location. Therefore, areas with good access to *public transportation,* but outside of the *bicycle rental stations service area,* were unable to reach access to all 7 categories.

On the other hand, the notably high initial accessibility rates (B), averaging 93% in the 15-minute threshold, indicate that Copenhagen already functions as a 15-minute city for the majority of buildings and thresholds without the bridges. This validates the hypothesis by Stariccio (2022) presented in chapter 2.2, which stated that the 15-minute timeframe is unsuitable as a goal in European cities. As the results showed, this is especially true when choosing cycling as mode of transportation, since it entails substantially larger travel distances within a time frame of 15 minutes.

It further correlates with the significantly lower accessibility rates of *bicycle rental stations*, as isochrones were calculated with the walking profile, entailing significantly smaller access isochrones. Given the substantial differences in results between walking and cycling accessibility, this disparity further underscores the necessity for research and evaluation of cycling.

Regarding the impact on building numbers in relation to all buildings in the area of interest (D), no significant increase could be measured as all values were under 1,29%. The result of a 0% increase rate in relation to the total number of buildings (D) can be caused by two different scenarios:

(1) the distribution and accessibility levels of the amenity within that threshold is already satisfactory without the bridges, or
(2) the bridges could not enable better accessibility since the increase of travel distance caused by the bridge was either not big enough, or within the additionally accessible areas were no amenities located to fulfill further needs.

To investigate this phenomenon, the percentage of buildings reached without the presence of bridges (B) was used to explore scenario (1). Further the relative percentage for each amenity in relation to buildings without initial access (C) was determined to explore scenario (2).

Here, the high initial accessibility rates to most amenities (B) explain why the bridges show such minor impact within the 15-minute threshold. As most of the buildings already had access to the amenities without the bridges, the total number of buildings with access could, in most cases, not be significantly improved. Therefore, the modest increase rates observed across the thresholds are not only due to poor bridge placement, but also to an already satisfactory pre-existing condition. Due to the correlation between amenities and their overarching categories, categories that include amenities with a 0% increase (chapter 5.1) did not show any increase within the spatial distribution of category access either (chapter 5.3).

Regarding the increase of accessibility rate for buildings with no previous access (C), all thresholds fall below the average of 5%. In other words, in most thresholds 95% of the buildings without previous access did not experience any increase of accessibility caused by the bridges. When looking at individual amenities, some of them achieved comparably high increase rates (C). However, the importance of the amenities achieving comparably high improvement scores (*chemists, banks and ATMs, hardware stores,* and *shopping malls*) might be considered as relatively low. Potentially, an increase in accessibility to other amenities of higher importance might have been preferrable. However, the definition of which amenities are important, and which are not, has not yet been sufficiently discussed within the research to date.

When comparing the initial amenity accessibility presented in chapter 5.1 (B) with the spatial distribution in chapters 5. 2 and 5.3, the category *transportation* appears to be most affected by the choice of substitution. By combining *public transport* with *bicycle rental stations,* the accessibility to this category significantly decreased. Isochrones for *bicycle rental stations* were computed on the basis of walking, causing them to be significantly smaller than the isochrones created on the basis of cycling. Therefore, the large area that *public transportation* could cover was majorly clipped to the smaller area that could access *bicycle rental stations*. The recorded hotspots addressed in the 3-minute threshold mostly align with the locations of the *bicycle rental stations* that are predominantly found in the centre as well as in the highest access areas of the 15-minute threshold. This shows that the inclusion or substitutional relations of one single amenity can majorly affect the outcome of the recorded accessibility distribution. It also suggests that by adding more *bicycle rental stations* in the North and South of the municipality, Copenhagen could significantly improve their XMC scores across all thresholds.

6.2 Analysis of Grid Methodology and Spatial Distributions

Chapters 5.2 and 5.3, presented the results and information generated from the spatial distribution of impact, as well as initial and topical accessibility. The following discussion aims to contextualize the findings from these chapters in order to explore RQ2: “Considering bicycle usage: To what extent has the city of Copenhagen implemented the XMC concept across 3-, 5-, 10-, and 15-minute thresholds and how is accessibility spatially distributed?” The second part, 6.2.2, will address RQ3: “What impact did the newly constructed bicycle bridges have on the spatial distribution of accessibility for the XMC concept in Copenhagen overall and across different thresholds?”

6.2.1 Topical Distribution of Access (RQ2)

When looking at the spatial distribution of accessibility to categories in Copenhagen, the majority of the lowest scores were located at the edges of the area of interest as well as the islands that have no recorded bicycle access. Lower accessibility rates were especially found in the North, Northwest, and South of the Copenhagen Municipality. Therefore, better infrastructure or an increase of POIs in those areas might help improve overall accessibility scores.

While it was vital to expand the area of interest to include the buffer zone for the purpose of assessing the spatial impacts of the bridges, the low access rates observed in the newly created buffer zone are not a part of the Copenhagen Municipality and therefore are not included in the plan of achieving the 5-minute city concept. The average scores recorded in only the municipality would consequently be higher than the scores assessed in the entire area of interest. For instance, when looking at only the cells within the municipality within the 5-minute threshold, the average accessibility is 4,06, whereas for the entire area of interest, the average accessibility is 3,72. The Copenhagen Municipality is therefore closer to the goal of becoming a 5-minute city than presented in the data above.

In contrast, when taking into consideration that the 3-minute threshold is partially representative for the 10–15-minute walking threshold, as described in chapter 4.2.1, the results for Copenhagen as XMC based on walking are less favourable. A sizeable portion of the municipality is left with lower accessibility rates, with only specific hotspots offering good access to most categories within a 3-minute walking distance.

6.2.2 Distribution of Impact (RQ3)

Higher accessibility rates were achieved, since the bridges allow cyclists to travel further and reach more areas, including amenities that were previously inaccessible to them. Structures such as bridges can therefore help shorten travel distances to amenities. The majority of bridges were constructed along the river and the canals cutting through Copenhagen, nearby the city centre. Depending on the thresholds, bridges increased the accessibility of areas close by or further away. With increasing thresholds, impacted areas were found further away from the bridge locations. However, across all thresholds, zones with the highest increase rates were found near the bridge locations.

Furthermore, bridges that cross rivers and bodies of water seemed to have a higher impact than bridges crossing highways or train tracks. This could be due to there being more crossings options or tunnels available for highways and train tracks.

The findings presented in chapters 5.2 and 5.3 suggest that although the bridges did increase accessibility in certain areas, the overall impact rates are notably modest, and can therefore not be considered as a pivotal factor of the XMC concept in Copenhagen. The limited impact rates primarily stem from the construction of bridges in areas where initial accessibility is already relatively high without the bridges. Conversely, in regions with generally lower accessibility rates such as the Northwest of the Copenhagen Municipality, either no bridges were constructed or only few were added.

When comparing impact rates between different thresholds, notable differences were found. Within the 5- and 10-minute thresholds, the average impact was 0,031 and 0,028 category access per cell with 2,6% and 2,5% of the residential areas being positively impacted. Whereas within the thresholds of 3- and 15-minutes, the average rates were 0,018 or 0,016, and only 1,5% of residential spaces were impacted.

This discrepancy can be attributed to two key factors: Firstly, for smaller travel times as within the 3-minute threshold, travel distances are naturally shorter. Therefore, the smaller a threshold is, the closer to the bridges are the impacted areas, indicating that only structures within reach of areas with low accessibility will be able to improve the XMC standards. In the case of Copenhagen, most bridges are located in areas with high initial accessibility, and their impact zones did not extend into areas of low accessibility. As a result, almost no increase in accessibility could be assessed in low accessibility areas within the 3-minute threshold.

Secondly, large thresholds like the 15-minute threshold entail larger travel distances, enabling travellers to access the majority of the area from any starting point within a 15-minute travel time. This leads to high initial accessibility. As most areas within the 15-minute threshold already exhibited high accessibility rates without the bridges, there is less room for improvement, resulting in comparatively low impact rates.

Therefore, if a city aims to improve a relatively low XMC threshold, they should improve or place structures and POIs directly in neighbourhoods with low accessibility. The accessibility impact of bridges peaks at a threshold of 5 minutes, as the slightly longer travel time allows impact zones to reach more spaces of lower initial access. Moreover, initial accessibility levels are not yet as high, so that improvements caused by the bridges still affect the accessibility scores. Given Copenhagen's ambition to become a 5-minute city (State of Green, 2016), the enhancements within this threshold are undoubtedly of significant interest to the city itself.

6.3 Evaluation of Methodology, Limitations and Future Research

When comparing this work to the literature presented in chapter 2.2, there are several factors that set the applied methodology and findings apart.

The findings of this study offer a different view on structural impact on the XMC concept than other previously conducted work. Knap et al. (2023) looked at the impact of planned bicycle bridges by considering supply-demand patterns and found that the construction of bridges would lower accessibility rates, due to the increase of request with stagnating supply. The methodology used in this study provides an approach that considers accessibility to any category on the basis of opportunity for need of fulfillment. Hence, the approach used in this work assesses a considerably different research question.

In addition to the research question, the grid-based approach used in this work visualizes accessibility of residential cells that perform as trip origins. Cell sizes were, in contrast to other works, not determined by the size and shape of the input data. This had the advantage that they could be chosen in accordance with the travel speed of the chosen travel method. Furthermore, the uniform size of grid cells can be effortlessly compared with each other. Moreover, the evaluation and comparison of area sizes can be easily accomplished by comparing the relevant cells to the total number of cells within the study area.

Because of the availability of open data on a global scale, the methodology used in this work allows for much easier replication. Most importantly, the methodology can be adjusted to the needs and characteristics of each study case and area, as amenities and categories can be included or excluded, cell and area sizes can be changed, means of transportation can be adjusted and the impact of structures of all kinds can be measured.

Apart from the advantages that the presented methodology offers, there are several factors that need to be taken into consideration when applying the methodology. These might also present opportunities for further research.

When looking at the impact, the measurement of “average increase of accessibility” can be misleading. In all four thresholds the majority of cells did not display any impact whereas few cells were impacted with access to multiple categories. Therefore, a different measurement should be added. Hence, this study employed the “percentage of impacted cells”.

While the usage of grid cells is a viable choice to visualize spatial distribution, it does not offer information on the number of buildings within each cell, nor does it visualize the size of each building or the number of its inhabitants. To gain a more realistic and detailed representation of how many citizens are affected by high or low accessibility, further research could add different weighting to the cells, based on the number of buildings contained in each cell.

Similarly, the definition of which amenities are less or more important have not yet been sufficiently examined. Most papers that applied weights to their amenity types, employed local questionnaires on amenity importance and created weightings based on their findings. This approach does, however, not align with the aim of this work, which was to create a methodology that is easy to reproduce and can be applied on a global level. To solve this, a more general definition of importance of individual amenities and categories would be needed.

While most of the chosen amenities do simultaneously function as job opportunities, the study presented did not specifically include *work* as a category, due to its ambivalence (chapter 4.1.3). While the study did incorporate a variety of different amenities that appeal to different age and social groups, it did neither discuss social distribution and possible further needs connected to that, nor did it incorporate information on distribution of wealth, age, and heritage of the citizens. Future research could include such information to examine patterns and correlations between areas with varying accessibility levels and the demographic characteristics of their residents. This approach could reveal disparities and disadvantages experienced by certain population groups.

Similarly, the study did not include distinct cycling behaviours for different demographic groups. The study conducted by Weng et al. (2019) included distinct walking profiles. Further research could therefore use a similar approach and create distinct profiles for different cycling behaviours.

In addition, the presented study focuses only on bicycle usage. Although there now is a wide range of bicycles available, making cycling accessible to many individuals, some citizens still cannot utilize cycling as a mode of transportation. Future research could hence explore the accessibility of spaces for wheelchairs and other mobility aids, for instance by employing multimodal routing systems.

It also needs to be noted that the non-accessible areas on islands might already have implemented systems such as ferries or might in general not be accessed by many bicycles. Therefore the 0,3% of buildings that cannot access any amenities, found in table 3 column (B), might lead to misleading results that, depending on the aim of the research, may want to be taken out of the equation.

Regarding the usage of the 3-minute cycling threshold as a representation of a 10–15-minute walking threshold, it is important to acknowledge that the transfer of grid data does not realistically represent the accessibility characteristics for walking, as they are influenced by different factors and in different ways than cycling. Additionally, the thresholds for *bicycle rental stations* were calculated based on walking criteria, resulting in a representation of a 3-minute walking score instead of the 10–15-minute walking threshold. Consequently, the grid data of the 3-minute cycling threshold can only serve as an approximation of what the 10–15-minute walking score might resemble. To assess walkability more accurately, utilizing a walking score assessment, as commonly employed in various other studies, would yield more precise results.

Lastly, as presented in the introduction, the modal bicycle share in Copenhagen is significantly higher than in other cities. This increases the relevance of the results, as many citizens cycle on a regular basis. However, in other case studies, attitudes towards cycling might differ significantly. To ensure the relevance of cycling as transportation mode within an area, researchers could employ questionnaires on the “willingness to cycle”, similar to how Gaglione et al. (2022) assessed the “willingness to walk”.

7 Conclusion

This study embarked to investigate the XMC concept within the urban landscape of Copenhagen, with a special focus on the impact that 20 bicycle bridges had on initial accessibility across thresholds of 3, 5, 10, and 15 minutes. The study had two primary objectives: Firstly, to assess the increase rates produced by the bridges as well as general compliance of Copenhagen with the XMC concept across the four thresholds, and secondly to visualize the spatial distribution of accessibility and increase rates.

To achieve that, increase rates were first quantified by counting the number of affected buildings in the initial access as well as in impact zones, based on different thresholds and individual amenities. Secondly, the spatial distribution of accessibility rates within Copenhagen were displayed using a grid-based method to visualize both initial and topical distribution of access, as well as the spatial distribution of impacted areas. The methodology aimed to measure the compliance of spaces with the XMC concept while relying only on open-source and globally available data and tools, facilitating replications, and making it adjustable to fit different case studies.

Addressing the research question, several key insights became evident. Firstly, the rates of initial as well as increased accessibility vary significantly across amenities and thresholds. The two components further display correlation, as a high initial access allows for less improvement and therefore entails lower increase rates than amenities with low initial accessibility. The work discussed average measurements as well as several individual amenity types with comparably low or high increase rates. It concluded that the lack of determination of importance of these amenities calls for a more foundational definition of what is considered important. In addition to that, it became evident that individual amenities can have significant influence on the final distribution of access based on categories. This underscores the need of understanding the interplay and substitutional relations between amenities, to realistically portray the diverse needs of urban populations. Furthermore, as single amenities can significantly affect the outcome of final categories, it is recommended to look at both levels (amenity and categorical) in order to understand the reason for low access categories and spaces and identify the needed amenity types. Lastly, the chosen mode of transportation significantly influences the resulting accessibility, as scores for walking were substantially lower than for cycling.

Considering topical access scores, Copenhagen exhibits relative success within the 15-minute threshold. This aligns with the hypothesis of 15 minutes as an unsuitable goal for cycling, as it allows for significantly larger travel distance than walking. In contrast to the nearby surrounding areas, the accessibility within the Copenhagen Municipality is comparably high across all thresholds. However, the city still faces challenges, particularly in the northern and southern areas, as it strives to become a 5-minute city. The smaller the threshold the more areas of low access and hotspots of high accessibility can be detected, with the number of accessible categories decreasing when moving further away from the centre.

Regarding the impact of the newly constructed bridges, findings indicate that while they did enhance accessibility within their immediate vicinity, their overall impact on citywide accessibility rates was relatively low. This can be attributed to the fact that many bridges were built in areas with already high initial accessibility levels. Impact scores proved to be higher for medium thresholds of 5 and 10 minutes, whereas the thresholds of 3 and 15 minutes displayed lower overall impact. On the one hand, this might be caused by the short travel distances, confining the impact zones around bridges in the 3-minute threshold to the initially high access spaces. On the other hand, it might be related to the relatively high initial accessibility, limiting the possibility for improvement within the 15-minute threshold. In either case the impact was determined by how many cells of low impact could reach the bridges. Across all thresholds the highest impact was achieved within the 5-minute threshold. Finally, bridges crossing bodies of water seemed to achieve higher impact than bridges crossing highways and train tracks, which might be due to more numerous crossing alternatives.

The findings indicate that in order to improve accessibility for lower thresholds, cities are best advised to look into the individual amenities displaying lower accessibility and to enhance low categorical access by either rendering infrastructural changes or employing more of the amenities as close to the areas in need as possible.

Additionally, the findings suggest that opting for walking over cycling yields significantly different results, underscoring the necessity for further research that prioritizes cycling as the mode of transportation. This research should account for the resulting characteristics, such as increased travel speed, and accordingly adjust the thresholds to yield more meaningful outcomes.

When contrasting the approach used in this study with existing literature (chapter 2.2), notable distinctions in methodology and findings emerge. Unlike previous work, this study seeks to assess impacts of structural differences on the basis of cycling. Even though similar research has previously been conducted by Knap et al (2023), the approach utilized in this study is quite different. While Knap et al. (2023) focused on the impact that planned bicycle bridges and tunnels would have on accessibility rates due to supply-demand dynamics, this study approached accessibility from a broader perspective, considering the opportunity for need fulfillment across various categories.

While the grid-based approach employed in this study is a common choice to visualize the spatial distribution of accessibility, cells sizes in this work were not determined by the input data allowing for tailored selection based on travel speed. The uniformity in grid cells facilitates a comparison of results and a direct evaluation of area sizes relative to the total study area.

The methodology's usage of globally available open data enhances its replicability and adaptability to diverse study cases and regions. Key advantages include the ability to include or exclude categories and amenities, change cell and area size, choose a variety of transportation modes, and measure the impact of diverse structural changes. This flexibility underscores the methodology's utility and potential for diverse application scenarios.

The findings of this study could benefit city planners and policymakers in Copenhagen, as the insights into areas of low accessibility and suggested strategies for improvement could be useful in increasing accessibility and, as a result, the overall compliance with the XMC concept. The methodology could further be replicated and adjusted to identify said factors in various other case studies.

While the study utilized grid cells effectively to visualize spatial distribution, it did not provide information on building counts or population density within individual cells. Incorporating such data could offer a more realistic representation of the population affected by accessibility changes. Furthermore, the definition of which amenities are considered important has not been thoroughly examined, requiring a more generalized approach for global applicability. The discussion of different social groups and demographic characteristics of residents is limited to the incorporation of various amenity types. Further studies could look deeper into social distribution across the assessed space which could unveil disparities in accessibility among different population groups. Moreover, the study primarily focuses on bicycle usage, neglecting accessibility for individuals who cannot utilize cycling as a mode of transportation. Other studies could therefore further explore accessibility of those relying on wheelchairs or mobility aids. In contrast to the 15-minute city concept by Moreno, this study did not incorporate *work* as a category. Lastly, the methodology's transfer of grid data from 3-minute cycling thresholds to 10–15-minute walking thresholds does not accurately portray walkability and can merely be used as an idea of what the accessibility might look like. For more precise information a walkability measurement should be used.

Appendices

Appendix A: Complete Flowchart

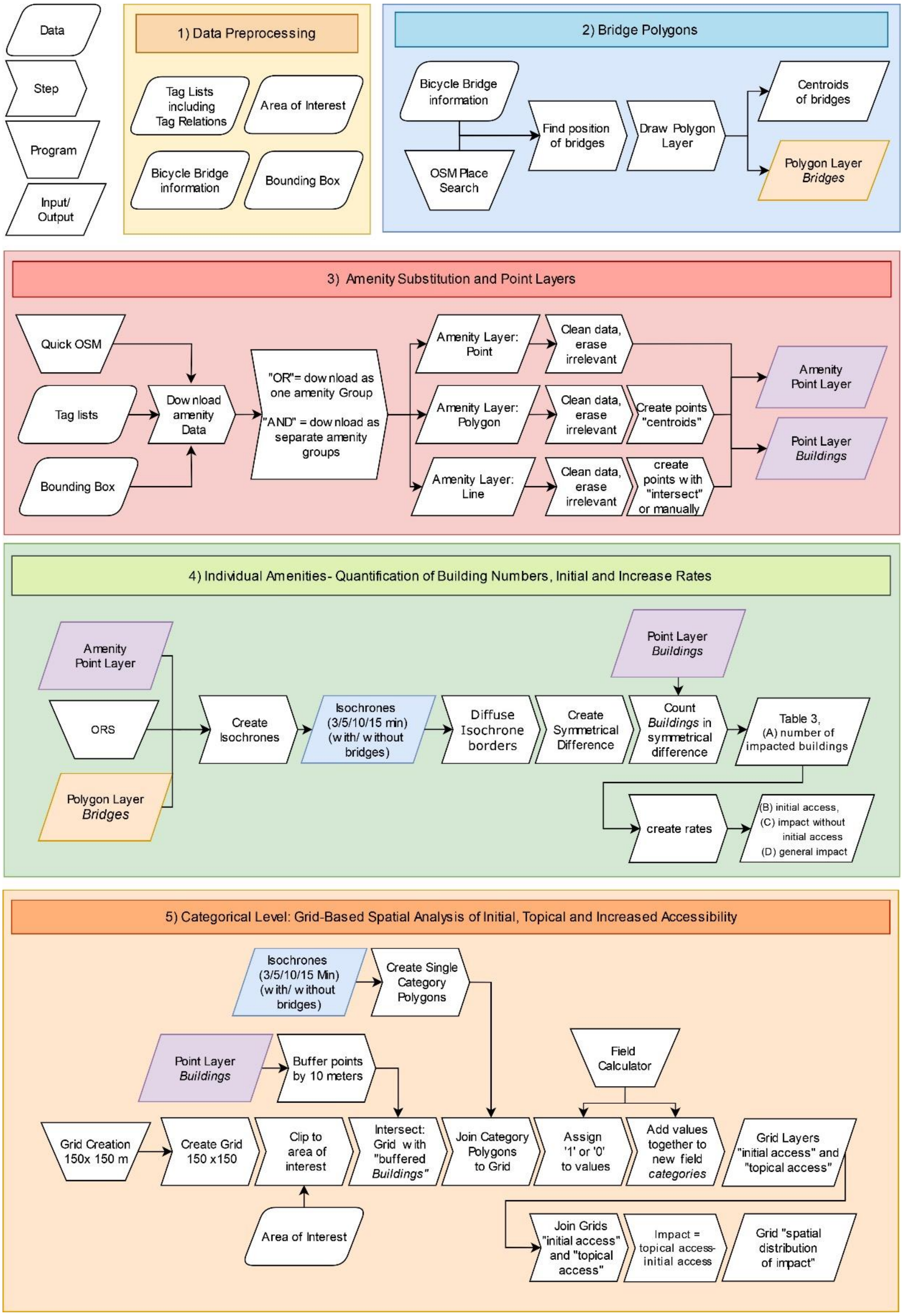

Figure A1: Complete Flowchart

Appendix B: Detailed Category Descriptions and Justification

Living

Living is a distinct category, since its items function as trip origins, not destination. As described in Moreno et al., *living* serves as the starting point from which all other essential needs should be reached (Moreno *et al.*, 2021). To assess the category *living,* the work relied on OSM data that had mapped *buildings.* Because of its high feature count, the data for *buildings* was retrieved with HOT. After data preprocessing, the obtained point layer functioned as countable items to measure the effect of the bridges on the access of *buildings* to specific amenities. Results for this are depicted in table 3. The *buildings* layer did further provide the basis for the grid layer, for which the *building* points were buffered, as described in 4.3.2.

Education

Especially for children, adolescents as well as families with young kids, *educational facilities* are an essential part of everyday life as they need to be visited on a daily basis. Therefore, short distances to *educational facilities* can positively impact family's and children's lives.

When looking at the findings of Papadopoulos, Sdoukopoulos and Politis depicted in figure 8, within the category *education* amenities with clear prevalence were different school types (*primary or elementary school, middle school, high scho*ol) as well as *kindergartens*. These were then established as theoretical amenities for this work. The data obtainment was however limited, since OSM tags do not differentiate between school types. Therefore, the overarching tag *amenity= school* as well as *amenity =kindergarten* were chosen. Because of the age differences in kids attending *schools* and *kindergartens,* the two do not function as substitutes for each other.

Not considered were the amenities *educational facilities*, *school for adults* and *seniors colleges/schools*, as they are not prevalent in many studies. Furthermore, *universities* were excluded as they function on an urban, not a neighbourhood level.

Commerce

The umbrella category *commerce* consists of three subcategories: *Food, retail,* and *economics*.

Food incorporates *groceries, bakeries*, and *restaurants*. *Groceries* is a frequent need, which needs to be accessed at least once if not multiple times a week. As the transportation of *groceries* by bike can be challenging, especially when they are meant to serve an entire family, short distances to a *grocery store* can increase the life quality of citizens. Therefore, the need for *groceries* nearby is essential.

Bakeries serve the need of *baked goods.* However, *bakeries* are often available in *grocery stores* as well. Therefore, if there is no *bakery* within the threshold, but there is a *supermarket*, the need *baked goods* is still considered as fulfilled. Here it is important to note that while a *supermarket* can replace the need for a *bakery*, a *bakery* cannot replace a *supermarket*. Therefore, within the subcategory *food,* the layers of *bakeries* and *supermarkets* cannot simply be merged but need to be treated as "*supermarket* AND (*bakery OR supermarket)*." This differentiation between *supermarkets* by itself and *bakeries* OR *supermarkets* for *baked goods* did not change the spatial distribution of category accessibility in grids. It might however have impacted the results found when analysing single amenity accessibility, shown in table 3.

Lastly, across the literature reviewed*, restaurants* are not only found in the category *food* but also in *entertainment* or *nightlife* - for instance in combination with *cafes* or *bars* (Papadopoulos, Sdoukopoulos and Politis, 2023). There seems to be no consensus and *restaurants* may as well be included in other categories. This work will treat them as part of *food*.

The need for *retail* incorporates a variety of different *shops* that provide citizens with various goods, essential to their daily lives. *Shops* considered were *clothing, electronic stores, chemists* and *shopping centres or malls*. *Since shopping malls* in most cases incorporate the previously named amenities, they were considered as a replacement of the individual *shops*. *Hardware stores* and *bicycle (repair) shops* were considered essential as well since they are essential to the cycling functionality and availability of bicycles.

Lastly, as part of *economic facilities*, *banks* and *ATMs* were included and are treated as substitutes. The subcategory was included, following the suggestion of Papadopoulos, Sdoukopoulos and Politis shown in figure 8. As the need for cash decreases in many countries, future research might want to exclude *economics.*

Healthcare

Healthcare as part of the everyday life is a necessity, which aligns with the common prevalence of the category in figure 8. Especially when needed urgently, short travel distances are highly preferable.

Included in *healthcare* are on the one hand facilities that provide healthcare services, here *hospitals, clinics,* and *doctors*, and on the other hand facilities that provide healthcare substances, here *pharmacies*. The two types of facilities were treated as not interchangeable. Because of its low occurrence in studies (figure 8), *dentist offices* were not included.

Entertainment and Socialising

Entertainment and socialising describes the need for enjoyment and social encounters. It is meant to enrich the lives of citizens by providing opportunities for activities or social spaces and to improve their mental health and everyday life (Moreno et al., 2021). There are significant differences in what citizens find entertaining and what places they prefer to socialize in. Since the XMC concept aims to satisfy people of various demographic and social groups, a variety of facilities and amenities *for entertainment and socialising* were chosen. Subcategories of *diverse cultural facilities*, *cafes, libraries, nightlife* and *playgrounds* were defined and treated as not interchangeable.

Leisure and Recreation

The need for *leisure and recreation* is understood to be fulfilled by areas that allow people to gather, rest, or to be physically active. *Leisure and recreation* was further subdivided into *natural spaces/ parks* and *sports*. Items within subcategories are treated as substitutes. The two subcategories are treated as not interchangeable.

Natural spaces/ parks contains a variety of natural spaces such as *forests, bays* and *parks* that are all accessible free of charge. However, the OSM tag *landuse= grass* presented difficulties, as the size of found grass areas varied from big grass lands to green strips next to roads, of which the latter would of course not satisfy the need for *recreation and leisure*. No justification for a specific size of what should or should not be included could be found. As a consequence, the impact of the incorporation of all *grass*, as well as the exclusion of all *grass* was assessed. As the results in table 3 show, no difference could be detected. Therefore, whether *grass* is taken into consideration or not does not make a difference in the case of Copenhagen. However, in urban spaces with less *natural and green spaces*, it might be sensible to further assess this issue and establish a limit for minimum grass area sizes.

Similarly, the treatment of the item *vineyard* might vary when looking at different regions. In Copenhagen one item for *vineyard* was retrieved. After further investigation, the vineyard in question was found to have no public access and was therefore excluded.

Furthermore, as explained in 4.1.4, some extracted areas of natural spaces occurred to be relatively large, so that the method of using centroids to measure accessibility would have led to misleading results. To avoid this, access points to those areas were selected manually. This could have also been accomplished by intersecting the boundaries of large spaces with a road network layer.

The second subcategory *sports* enables citizens to be physically active. The selection of sports facilities presented a challenge because of the prevalence of highly specialized sports that appeal to only a small portion of the population. As a solution, only sports facilities such as *fitness centres* or *sport pitches*, that serve a variety of people of different ages and heritages, were considered. However, this of course excluded many amenities that provide special sports forms and does take away the variability.

Furthermore, the tag *leisure= track* was retrieved as line strings. The transformation of them to points was accomplished by manually selecting access points to running tracks. It could have also been accomplished by intersecting *running tracks* with a road network.

Civic Institutions

The category of *civic institutions* subsumed different amenities, which provide various public services. Amenities considered were *police stations, post offices* as well as *nursing homes*. *Public administration offices* were excluded due to the low prevalence in literature (Papadopoulos, Sdoukopoulos and Politis, 2023).

Transportation

Even though *public transportation* is not an active mode of transport, and therefore does not align with the criteria of the XMC concept introduced by Moreno et al. (2021), many studies as well as the Parisian XMC concept included it as a mean of transportation (Papadopoulos, Sdoukopoulos and Politis, 2023; Ville de Paris, 2022). *Public transportation* is needed to extent the access of citizens of the neighbourhood scale onto the city scale, without entailing the need for a car. Papadopoulos, Sdoukopoulos and Politis (2023) therefore suggests an inclusion of *public transportation* as needed service, despite it presenting only intermediate points in trip chains rather than final destinations.

In the data collection process, diverse types of *public transportation* were grouped together, since slower means of transportation such as *busses* often connect to faster public transit with a higher capacity such as *trains*.

In addition, *bicycle rental stations* were chosen as essential need since they provide access to bicycles for people who do not possess one themselves. However, the incorporation of them on the basis of cycling is of course unrealistic, since not many people would ride a bike to a *bicycle rental station*. Therefore, in this specific case the routing operations were completed on the basis of walking.

Appendix C: Table C1 Including Results of (D): Impact Rates on Total Amount of Buildings

Table C1: Results of Counted Buildings of Impacted Areas and Initial Access and Proportionality to the Total Number of Buildings and Not Initially Accessed Buildings

Category, *Subcategories*	Amenity	(A) Number of buildings that can additionally access an amenity				(B) Percentage [%] of buildings that have initial access to an amenity				(C) Percentage [%] of buildings without initial access that gained access				(D) Percentage [%] of total number of buildings that gained access			
		3 min	5 min	10 min	15 min	3 min	5 min	10 min	15 min	3 min	5 min	10 min	15 min	3 min	5 min	10 min	15 min
Education	Kindergartens	85	69	16	0	71,1	95,9	99,7	99,7	0,23	1,30	3,83	0,00	0,07	0,05	0,01	0,00
	Schools	149	16	8	4	73,8	96,2	99,7	99,7	0,44	0,33	1,86	1,14	0,12	0,01	0,01	0,00
Commerce																	
Food	Supermarkets	414	2	2	2	86,3	99,0	99,7	99,7	2,34	0,16	0,53	0,60	0,32	0,00	0,00	0,00
	Restaurants, Food courts	932	164	3	14	68,9	94,0	99,7	99,7	2,33	2,13	0,90	4,15	0,72	0,13	0,00	0,01
	Bakeries	105	202	16	4	66,5	96,2	99,7	99,7	0,24	4,07	4,71	1,17	0,08	0,16	0,01	0,00
Retail	Clothes	218	389	58	14	36,3	67,1	93,7	98,8	0,27	0,92	0,71	0,94	0,17	0,30	0,05	0,01
	Electronics	526	289	69	6	20,6	47,1	89,4	99,6	0,51	0,42	0,50	1,15	0,41	0,22	0,05	0,00
	Hardware	147	754	1299	106	26,7	60,8	95,9	99,5	0,16	1,49	24,33	17,18	0,11	0,59	1,03	0,62
	Bike stores	229	142	14	5	71,3	96,1	99,7	99,7	0,62	2,80	3,74	1,46	0,18	0,11	0,01	0,00
	Shopping malls	165	1718	1021	21	12,4	44,2	94,6	99,6	0,15	2,39	14,74	4,45	0,13	1,33	0,79	0,02
	Chemists	137	261	350	7	33,1	69,2	99,2	99,7	0,16	0,66	35,14	1,94	0,11	0,20	0,27	0,01
Economics	Banks, ATMs	231	595	19	5	53,9	87,6	99,7	99,7	0,39	3,72	4,30	1,49	0,18	0,46	0,01	0,00
Healthcare	Healthcare Services	63	128	90	19	44,8	80,2	97,5	99,7	0,09	0,50	2,75	5,21	0,05	0,10	0,07	0,01
	Pharmacies	525	533	0	3	42,9	84,2	99,6	99,7	0,71	2,62	0,00	0,81	0,41	0,41	0,00	0,00
Entertainment and Social	Night life	199	344	19	1	57,6	84,3	99,6	99,7	0,36	1,70	4,16	0,30	0,15	0,27	0,01	0,00
	Cafes	64	0	20	9	77,4	99,2	99,7	99,7	0,22	0,00	6,04	2,74	0,05	0,00	0,02	0,01
	Playgrounds	172	5	1	1	91,1	99,2	99,7	99,7	1,49	0,50	0,28	0,30	0,13	0,00	0,00	0,00
	Cinemas	345	1621	1379	75	11,8	34,4	82,7	98,3	0,30	1,92	6,20	3,41	0,27	1,26	1,07	0,06
	Cultural Facilities	129	162	16	6	53,9	86,2	99,7	99,7	0,22	0,91	4,66	1,81	0,10	0,13	0,01	0,00
	Libraries	8	22	0	2	33,4	76,9	99,4	99,7	0,01	0,07	0,00	0,50	0,01	0,02	0,00	0,00
Leisure and Recreation																	
Green Spaces	a- no grass	24	1	11	5	97,0	99,7	99,7	99,7	0,62	0,24	3,35	1,50	0,02	0,00	0,01	0,00
	b- all grass	24	1	11	5	97,0	99,7	99,7	99,7	0,62	0,24	3,35	1,50	0,02	0,00	0,01	0,00
Sports	Sport facilities	16	0	14	1	95,6	99,7	99,7	99,7	0,28	0,00	4,22	0,30	0,01	0,00	0,01	0,00
Civic Services	Post offices	71	99	0	9	78,4	92,9	99,7	99,7	0,25	1,08	0,00	2,69	0,06	0,08	0,00	0,01
	Nursing homes	396	158	79	232	7,0	23,8	75,7	95,5	0,33	0,16	0,25	3,98	0,31	0,12	0,06	0,18
	Police stations	13	92	82	45	6,4	24,6	76,0	96,7	0,01	0,09	0,27	1,07	0,01	0,07	0,06	0,03
Transportation	Bicycle Rental Stations	22	37	376	610	1,3	3,4	10,4	20,2	0,02	0,03	0,33	0,59	0,02	0,03	0,29	0,47
	Public Transport	4	0	8	2	99,0	99,7	99,7	99,7	0,32	0,00	2,42	0,61	0,00	0,00	0,01	0,00
Average		193	279	179	68	50,7	72,9	89,6	93,0	0,47	1,08	4,65	2,20	0,12	0,01	0,01	0,00
Total average		180				76,5				2,01				0,14			

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I hereby declare that I have written this paper without any help from others and without the use of documents and aids other than those stated in the references. I have mentioned all the sources used and I have cited them correctly according to established academic citation rules. Moreover, the topic or parts of it are not already the object of any work or examination of another course. The paper format and electronic version of the paper are the same.

In the work presented here, I have used ChatGPT or another Artificial Intelligence as follows:

[] not at all

[] for brainstorming

[] for creating the outline

[] for creating specific sections, totalling ...% of the entire text

[] for developing software source code

[] for optimizing or restructuring software source code

[x] for proofreading or improving

[] Other, namely: ...

I confirm that I have fully disclosed all uses. Missing or incorrect information will be considered an attempt to deceive.

_________________________, ______________________

Name **Date**