New Tools for Monitoring Urban Sustainability
-
Challenges and Opportunities for Cities in the 2020s

Dissertation

zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.- Ing.) der Fakultät Raumplanung der Technischen Universität Dortmund

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Executive summary

Global migration and the expansion of the urban space, the two megatrends of the 21st century, pose new challenges for cities, influencing urban land use, urban quality of life and integration, and thus jeopardising the sustainable development of cities. Due to their innovation function, cities are where the problems of this decade are particularly manifested, but at the same time they are also where solutions are developed and applied. The German Advisory Council on Global Change, as well as other players from research, politics and planning practice, have recognised that cities play a key role in the discussion on sustainable development. Urban transformation is therefore an essential component of sustainability, to be permanently guided by spatial monitoring. In the face of the many problems and challenges that this decade poses, the so-called data revolution offers new opportunities for monitoring urban space. New highly up-to-date and freely available datasets allow dynamic developments in cities to be better captured and visualised. This thesis thus aims to investigate the potential of new (data-driven) technologies and how they can be used to develop new GIS-based tools for monitoring urban sustainability. Previous tools differ in their temporal and spatial resolution or their complexity, and there is currently no agreement within the scientific community on how such tools should be designed. Therefore, this thesis focuses on how new tools can improve the spatial monitoring of urban sustainability and why it is important to link research fields. In addition, the extent to which these tools can be transferred into planning practice and what limitations exist are examined.

Three main research foci serving as catalysts for sustainable urban development are selected, each examined within a specific sub-study: urban growth dynamics (sub-study 1), urban mobility structures (sub-study 2) and urban arrival spaces (sub-study 3). All three sub-studies have already been documented in respective journal articles constituting the pillars of this cumulative thesis. The dynamics of urban growth, one of the megatrends of the 21st century, are difficult to capture and analyse due to their complexity. The approach developed in this thesis, which links two decisive measures with land use efficiency and urban sprawl, allows these growth dynamics to be divided into four different development paths, classifiable in a simplified way as rather positive (compact & densely populated) or rather negative (dispersed & sparsely populated) development from a sustainability perspective. The examples of Paris and Chicago serve to illustrate the different development paths cities have taken in the last 40 years. Closely linked to the growth of cities is the question of mobility structures, whose interactions are not one-sided and simple, but complex and two-way. The mobility transition and the resulting shift away from cars are important drivers of sustainable urban development. However, there is a lack of valid information to monitor this shift. The development of a tool allowing the identification of the existing urban mobility structure can fill this gap. The classification into walkable neighbourhoods, neighbourhoods with access to high-quality public transport, and car-dependent neighbourhoods makes it possible to monitor the conditions for a mobility transition, but also to identify small-scale potential and problems. First applications of this tool were conducted for Paris, Portland and Melbourne, three very different cities that nevertheless all present

themselves as high walkable cities. Turning to the third research focus, the identification and typification of arrival neighbourhoods, this work ties in with the second megatrend of this century. The methodology developed allows us to identify global migration movements on a small scale in the urban fabric and to categorise these areas on the basis of their characteristics, for example diversity, socio-economic status or resources. Using the example of Dortmund, a West German city with a long history of migration due to its industrial past, different types of arrival neighbourhoods can be identified. In a long-term monitoring, this methodology allows us to observe changes in the social fabric of a city, e.g., ethnic or social segregation, gentrification.

Alongside the development of new tools for the three main research foci, the second empirical focus of this thesis investigates an integrative monitoring approach linking different sustainable urban development research fields. These cross-thematic analyses focus on three different research branches, drawing on the previously developed tools. The first analysis deepens the already mentioned close link between land use and mobility by using a simplified concept of the vicious cycle of car dependency. The second analysis combines the work from the research foci of mobility structures and arrival spaces to investigate the operationalisation of mobility poverty, while the last one examines the influence of urban sprawl on residential segregation. These three analyses present a simplified way of handling cross-thematic research branches, although there are some limitations compared to established complex models. However, it turns out that the tools are versatile due to the given conditions and their design. Thus, different research questions and fields can be addressed, but also different user groups served.

With regard to the questions posed, this thesis provides some important insights for the monitoring of urban sustainability. On the one hand, it became apparent that tools making use of new (data-driven) technologies allow local phenomena and problems in urban space to better analysed than existing monitoring systems have been able to do so far. In this context, a variable spatial level of analysis is crucial in order to answer spatially important questions and to understand urban problems. However, valid and small-scale information on the socio-economic structure of the population is difficult to access, but highly important for monitoring especially the social aspect of urban sustainability and the overall impact on the population. On the positive side, open data and open source are gaining importance in the development of new monitoring tools. This also relates to the spatial transferability of new methodologies, a factor essential for cross-border monitoring. However, these findings are not conclusive, but represent an intermediate state of research on new tools for monitoring urban sustainability based on analyses conducted in recent years. Future research should address the question of how new and comprehensive monitoring systems need to be structured and designed in order to be able to capture the dynamic developments in urban space in their entirety.

Kurzzusammenfassung

Die globalen Wanderungsbewegungen und die anhaltenden urbanen Wachstumstendenzen, die als die zwei Megatrends des 21. Jahrhunderts gelten, stellen die Städte vor neue Herausforderungen. Diese extremen und anhaltenden Veränderungen der demographischen Struktur beeinflussen auch die urbane Landnutzung, die Lebensqualität sowie die Integrationskraft und gefährden dadurch eine nachhaltige Entwicklung der Städte. Durch ihre Innovationsfunktion sind Städte die Räume, in denen sich die Probleme dieser Dekade besonders manifestieren, gleichzeitig aber auch die Räume, in denen Lösungen entwickelt und erprobt werden. So erkannte der Wissenschaftliche Beirat Globale Umweltveränderungen (WBGU), neben weiteren Akteuren aus Planung, Politik und Praxis, dass Städte ein zentraler Baustein der nachhaltigen Entwicklung sind. Die urbane Transformation ist daher ein wichtiger Bestandteil der Nachhaltigkeit, die dauerhaft mit Mitteln der Raumbeobachtung begleitet werden muss. Neben den vielen Problemen und Herausforderungen, die diese Dekade mit sich bringt, ergeben sich aus der sogenannten *Datenrevolution* einige neue Chancen für das Monitoring des urbanen Raumes. Neue, aktuelle und frei verfügbare Datensätze erlauben es, die hochdynamischen Entwicklungen in den Städten besser zu beobachten und zu erfassen. Daher hat diese Dissertation das Ziel, die neuen (daten-)technischen Potenziale zu nutzen, um neue GIS-basierte Instrumente für das Monitoring urbaner Nachhaltigkeit zu entwickeln. Bisherige Tools unterscheiden sich in zeitlicher und räumlicher Auflösung oder ihrer Komplexität, aber bisher gibt es keine Einigung in der Wissenschaft, wie diese Tools gestaltet sein sollen. Im Mittelpunkt dieser Dissertation steht daher die Frage, wie neue Instrumente das räumliche Monitoring der urbanen Nachhaltigkeit verbessern können und warum es wichtig ist, unterschiedliche Forschungsfelder der nachhaltigen Entwicklung miteinander zu verknüpfen. Darüber hinaus wird untersucht, inwieweit diese Instrumente in die Praxis übertragen werden können und welche technischen Limitierungen bestehen.

Um diese Forschungsfragen zu beantworten, wurden drei Schwerpunkte ausgewählt, die in der Debatte um eine nachhaltige Entwicklung der Städte einen bedeutenden Stellenwert einnehmen: urbane Wachstumsdynamiken (Teilstudie 1), urbane Mobilitätsstrukturen (Teilstudie 2), urbane Ankunftsquartiere (Teilstudie 3). Hierbei verfolgt jeder methodische Ansatz ein eigenes Ziel: Urbane Wachstumsdynamiken sind aufgrund ihrer Komplexität nur schwer in einer vereinfachten Form abzubilden. Der hier entwickelte Ansatz, der mit der Landnutzungseffizienz und der Zersiedelung zwei entscheidende Maße miteinander verknüpft, ermöglicht es, das Wachstum der Städte in vier unterschiedliche Entwicklungspfade einzuteilen. Diese sind aus nachhaltiger Sicht als positiv (kompakt und dicht besiedelt) oder als negativ (dispers und dünn besiedelt) einzustufen. Am Beispiel von Paris und Chicago wird hier verdeutlicht, welche unterschiedlichen Entwicklungen Städte in den letzten Jahrzehnten genommen haben. Das Themenfeld der urbanen Mobilitätsstrukturen ist inhaltlich eng mit der ersten Teilstudie verknüpft, deren Wechselwirkungen komplex und wechselseitig sind. Im Sinne einer nachhaltigen Transformation des urbanen Raumes ist die Mobilitätswende mit der dazugehörigen Abkehr vom privat motorisierten Verkehr von entscheidender Bedeutung. Im Bereich des Monito-

rings besteht derzeit das Problem, dass bestehende Tools größtenteils auf die aktuellen und zukünftigen Mobilitätspräferenzen fokussiert sind, ohne die bestehende Mobilitätsinfrastruktur innerhalb einer Stadt zu bewerten. Die Entwicklung eines methodischen Ansatzes, welcher es ermöglicht, die bestehende Mobilitätsstruktur im städtischen Raum zu identifizieren, kann diese Lücke schließen. Eine Klassifizierung in fußgängerfreundliche Räume, Nachbarschaften mit hoher qualitativer ÖPNV-Anbindung sowie autoabhängige Quartiere ermöglicht es, die Voraussetzungen für eine Mobilitätswende zu beobachten, sowie kleinräumige Potenzial- und Problemräume zu identifizieren. Erste Anwendungen dieses methodischen Ansatzes wurden für Paris, Portland und Melbourne durchgeführt. Mit der dritten Teilstudie, der Identifizierung und Typisierung von Ankunftsquartieren, deckt diese Arbeit auch den zweiten Megatrend dieses Jahrhunderts ab. Dieser methodische Ansatz erlaubt es, die globalen Wanderungsbewegungen kleinräumig im Stadtgefüge zu lokalisieren und diese Gebiete aufgrund ihrer Charakteristika zu typisieren, beispielsweise bezüglich der nationalen Diversität, des sozioökonomischen Status oder der Ressourcenausstattung. Am Beispiel der Stadt Dortmund können so unterschiedliche Typen von Ankunftsquartieren identifiziert werden. Im langfristigen Monitoring lassen sich mit diesem methodischen Ansatz Veränderungen im sozialen Gefüge beobachten (z.B. ethnische oder soziale Segregation oder Gentrifizierungstendenzen).

Neben der Entwicklung neuer Tools für die drei Forschungsschwerpunkte liegt der zweite empirische Fokus auf einem integrativen Monitoringansatz, der die unterschiedlichen Forschungsfelder der nachhaltigen urbanen Entwicklung miteinander verknüpft. Diese themenübergreifenden Analysen konzentrieren sich auf drei verschiedene Forschungszweige, die auf den zuvor entwickelten Tools aufbauen. Der erste Ansatz vertieft den bereits erwähnten engen Zusammenhang zwischen Flächennutzung und Mobilität und untersucht die Auswirkungen der Autoabhängigkeit auf eine nachhaltige urbane Entwicklung. Der zweite Ansatz kombiniert die Arbeiten aus Teilstudie 2 und Teilstudie 3 und widmet sich der Operationalisierung von Mobilitätsarmut, während sich der letzte Forschungszweig mit dem Einfluss der Zersiedelung auf die residenzielle Segregation befasst. Diese drei Analysen stellen einen vereinfachten Weg dar, themenübergreifende Forschungszweige zu analysieren, auch wenn es im Vergleich zu etablierten komplexen Modellen einige Einschränkungen gibt. Es zeigt sich jedoch, dass die Instrumente aufgrund der vorgegebenen Rahmenbedingungen und ihrer Konzeption vielseitig einsetzbar sind, wodurch unterschiedliche Forschungsfragen und -felder, aber auch unterschiedliche Nutzergruppen adressiert werden können.

In Hinblick auf die hier festgesetzten Fragestellungen konnte diese Arbeit wichtige Erkenntnisse für das Monitoring urbaner Nachhaltigkeit ableiten. Es wurde klar ersichtlich, dass die Anwendung innovativer (daten-)technischer Mittel es erlaubt, Phänomene und Herausforderungen im städtischen Raum präziser zu verorten, als es bisherige Monitoringssysteme vermochten. Hierbei ist insbesondere eine variable räumliche Analyseebene entscheidend, um raumbedeutsame Fragestellungen zu beantworten und Problemlagen zu verstehen. Allerdings sind valide und kleinräumige Informationen zur sozioökonomischen Struktur der Bevölkerung nur schwer zugänglich, jedoch wichtig, um besonders den sozialen Aspekt der urbanen Nachhaltigkeit und die Auswirkungen auf die Bevölkerung zu beobachten. Auf der positiven Seite ist zu vermerken, dass aufkommende Open-Data-Quellen und Open-Source-Algorithmen aufgrund ihrer Charakteristika in der Entwicklung neuer Instrumente für das Monitoring an Bedeutung gewinnen. Das bezieht sich auch auf die räumliche Übertragbarkeit von neuen methodischen Ansätzen, die für ein grenzüberschreitendes Monitoring essenziell sind. Diese Erkenntnisse sind natürlich nicht abschließend, sondern bilden anhand der in den vergangenen Jahren durchgeführten Analysen einen Zwischenstand der Forschung zu neuen Instrumenten für das Monitoring urbaner Nachhaltigkeit. Zukünftige Forschung muss sich auch mit der Frage beschäftigen, wie neue, vollumfängliche Monitoringsysteme aufgebaut sein müssen, um die dynamischen Entwicklungen im urbanen Raum in ihrer Gänze erfassen zu können.

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List of Abbreviations

BBSR Bundesinstitut für Bau-, Stadt- und Raumforschung

CBD Central Business District

DI Dispersion Index

ESPON European Spatial Planning Observation Network

GHSL Global Human Settlement Layer

GIS Geographic Information Systems

GTFS General Transit Feed Specification

LOD Level of Detail

LUI Land Use Inefficiency

MAUP Modifiable Areal Unit Problem

MDG Millenium Development Goal

MORO Modellvorhaben der Raumordnung

ORS Open Route Service

OSM Open Street Maps

POI Point of Interest

ROG Raumordnungsgesetz

RVR Regionalverband Ruhr

RWI Leibnitz-Institut für Wirtschaftsforschung

SDG Sustainable Development Goals

SHDI Shannon’s Diversity Index

TOD Transit Oriented Development

WBGU Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen

1 Introduction

Global migration and urban growth are the two 21st-century megatrends shaping cities and posing new challenges for planning, politics and research. The reasons behind these megatrends are manifold. As economic centres, cities offer agglomeration benefits affecting all aspects of life. Although the highest growth pressure is to be found in emerging countries in the Global South, European cities are also set to face the impact of these developments, with a wave of urbanisation impacting all spatial structures and functions. The first difficulties with a large and short-term influx arose during the refugee crisis of 2015 / 2016 when cities in particular became a place of refuge. Alongside these waves of immigration, we are seeing a steady migration from rural to urban areas in most European countries, with cities seemingly continuing to gain in attractiveness from a national perspective. These major demographic shifts are having lasting impacts on land use, the urban quality of life, ecology and a city's integrative power, thus jeopardising sustainable urban development. Though suffering from these global dynamics, cities are also key anchors of life, offering tremendous potential to shape this development. Driving social, cultural and technical innovations, they are at the origin of a shift in values, as seen in such developments as the sharing economy, urban gardening or car-free zones. Therefore, cities are the places where the problems of the 21st century originate, but also where their solutions are developed and established.

In its flagship report *Humanity on the move: Unlocking the transformative power of cities*, the German Advisory Council on Global Change (WBGU) recognised the importance of cities and placed them at the centre of a sustainable transformation. One product of this work is the so-called normative compass, intended to serve as a framework guiding the transformation. According to the WBGU, transformation can only succeed if there is interaction and a balance between the different dimensions of sustainability. The WBGU also sees striving for integrated solutions as an important principle here. Synergies should be sought, as any sector-by-sector handling of objectives can lead to further conflicts and jeopardise achievements in other fields. In addition to the normative compass with its long-term guidelines for urban transformation, the WBGU identified various fields of action with a high potential to drive the urban transition to sustainability (WBGU, 2016). One of its core recommendation is the setting-up of 'suitable data-collecting, monitoring and control structures in order to create social, political and economic indicators on urban transition bases on these data' (WBGU, 2016). However, this seems to be quite a challenge due to the overall complexity of topics, their interrelationships and the patchy data landscape.

At the same time this century - and this decade in particular - offers many new opportunities, as this is the age of digitalisation. All areas of everyday life are characterised by new technical achievements and digital innovations applying to both private and public life. These changes are having a lasting impact on our society and cities. New technical innovations and possibilities have also emerged in the field of spatial analysis and monitoring in the form of new processing mechanisms and innovative datasets. Increased computing capacities enable the processing of big data, as witnessed by the processing of earth observation data stemming for example from the Copernicus programme, or mobile phone datasets used to track movement patterns (Fina et al., 2021). In addition, there is a steadily increasing number of open datasets and open government initiatives making valuable datasets widely available. One pioneering example is Open Street Maps (OSM) which provides a wide variety of spatial data free of charge and which serve as the (data-) basis for many new methodologies. This so-called 'data revolution' (Kitchin, 2014) could be an important element in overcoming future challenges. While many urban developments are currently quantified and interpreted using simple indicators, there are now opportunities available to investigate complex and short-term spatial interactions in cities by developing new algorithms, spatial analysis methods or (impact) models based on GIS-techniques (Geographic Information System). Integrating these new methodologies into permanent monitoring can be very beneficial for exploring the urban space from different perspectives, though also poses a number of challenges. One of these is that there is no agreement on how these tools or methodologies should be designed. Ness et al. (2007) have shown that demands on such tools differ greatly. On the one hand, they should be simple and applicable to a wide range of users. On the other hand, there is the need for them to be able to map very complex processes and interrelationships. At the same time, it is important to have standardised tools fostering comparability over time and space. Moreover, certain scholars or planning practitioners need concepts matched to a particular space. All these requirements must be aligned with existing data and analysis potentials, as well as with current sustainable development issues. At the moment, many monitoring systems rely on simple indicators and stable time series to monitor urban space. But in many cases there is not enough information to understand why cities have taken certain development paths. One alternative in this context is geomonitoring which can be used to develop new explorative methods based on the intersection of new and innovative datasets (Fina et al., 2019). Following their critical review, such tools can be included in existing monitoring systems.

This thesis thus takes up the idea that such new possibilities in the data landscape allow deeper insights into urban processes and phenomena. The key objective here is to ascertain the (technical) potential of this decade to develop new tools for monitoring urban sustainability in the Global North based on spatial analysis methods. Based on technical possibilities, data availability and the thematic delimitation of the sustainability debate, the spatial framing will be explained in greater detail in the later stages of this thesis. In the context of this dissertation, the term tool refers to GIS-based methodologies able to help monitor developments in the urban space. This rough delimitation allows us to address the broad scope and complexity of the topic of urban sustainability in an open and at the same time focused manner. Within the scope of this work, however, it is not possible to set up a comprehensive system for monitoring urban sustainability. Based on three selected research foci, specific research questions are formulated which, together with the theoretical foundations, form the basis for the development of the tools. This is the main task of this cumulative dissertation and is therefore discussed intensively in three sub-studies. With this reduced but focused procedure, this thesis contributes to the discussion on the spatial monitoring of urban sustainability by answering four important research questions:

(1) How can new innovative tools improve the spatial monitoring of sustainable urban development?
The current state of research presents a host of methodologies and indicators able to describe and assess sustainable development in cities. However, new technical opportunities and an expanding data landscape allow us to look in greater detail at the potential of new monitoring tools. To narrow down this overarching research question, it is guided by four secondary questions which put the developed tools to the test. By answering these questions, this thesis aims to provide a clear picture of the value of the tools for research and planning in terms of urban sustainability.

- *1.1 What insights (for sustainable development) can be derived from the results achieved by the tools?*
- *1.2 What functions can the tools take on?*
- *1.3 What are their advantages compared to the tools and indicators used in established monitoring systems?*
- *1.4 How should the tools be designed to increase their impact?*

(2) Why is it worthwhile developing an integrative monitoring approach linking research fields related to sustainable urban development and exploring their intersections?
Besides the overall value of monitoring tools, the broad thematic scope of this work allows us to examine the intersections and overlaps of research foci, highlighting and exploring cross-thematic research fields. For these, the developed tools will be examined as to whether they enable new strands of analysis. Based on these results, the added value of an integrative monitoring approach will be discussed.

(3) What data and technical potentials / limitations are linked to the development of new monitoring tools?
It can be assumed that the increasing availability of new data and processing options is not the same for all research fields. Some fields are set to receive a major boost due to new technical possibilities, while others remain side-lined due to their minor importance in research and politics or statutory framework conditions. This thesis thus also examines the question of the potentials / limitations of the tools developed for different research foci.

(4) How can the tools be transferred into planning practice and in which contexts can they be applied?
In order to generate benefits not just for research but also for spatial planning, this thesis also examines the extent to which the tools can be transferred to planning practice. Such transfers are not to be taken for granted. There are some obstacles that need to be overcome before practitioners can use the tools. Two perspectives are considered here: technical transfers and content-related transfers. This means examining possible technical hurdles and which planning fields would benefit from the use of such new tools.

To answer these research questions, this cumulative thesis is structured as follows: To gain an overview of the state of research, **Chapter 2** looks at three issues. First, the theoretical and conceptual framework of urban sustainability is introduced, looking at the origin of and basic idea behind sustainability and the importance of cities in any transformation. The second part deals with the importance of urban data and technical innovations, while the third part is dedicated to spatial monitoring, looking at its foundations, legal basis and forms of organisation in Germany. **Chapter 3** introduces the research design and the methodological procedure in this thesis. Beginning with an outline of the selection process for the research foci and the identification of linkages and overlaps, I go on to discuss the requirements for the datasets and tools. The last part of this section establishes specifications for the research area and scale. After defining the framework, two empirical chapters demonstrate the main focus of this thesis. **Chapter 4** presents a summary of the publication-based findings in three sub-studies, including the importance of the research foci, the development of the tools as well as their application in case studies. The full versions of the journal papers are to be found in the appendix (see A.3). The second empirical part, **Chapter 5**, underlines the importance of an integrative monitoring approach. looking at cross-thematic research fields linking the three sub-studies. The discussion in **Chapter 6** brings together the different strands of research by discussing the overall results and answering the four research questions. This chapter also includes a section on the overall limitations of this work independent of the research questions. **Chapter 7** provides concluding remarks on this thesis, including its value for the reader, research gaps that still exist and what we can expect in coming years.

2 Geodata and monitoring as the foundation for a sustainable urban development

Identifying potentials in an emerging technology landscape, developing new tools and assessing their value for monitoring urban sustainability requires addressing conceptual and theoretical backgrounds. Starting from the idea that current technical improvements can provide a high-quality basis for monitoring urban sustainability, this chapter addresses the fundamentals of urban sustainability, (geo-)data and spatial monitoring.

2.1 Urban sustainability

The term (urban) sustainability has become the key issue in spatial planning. Despite its significance, the term remains fuzzy from a conceptual standpoint, often being used inaccurately or even deceptively to promote ideas and concepts as good. However, the basic idea behind this term is for it to be a guiding principle of urban development. This chapter aims to define a few basics necessary for better understanding what is meant by sustainable development. Presenting some core ideas, definitions, concepts and measurements, the aim is to highlight its significance for current research, politics and planning. Translating these broad ideas into a spatial and thematic context, the second part focuses on the transformation of urban space.

While the limited scope of this thesis does not allow a comprehensive and critical illumination of this concept, there are already other major works on this subject dealing critically with the buzzword sustainability (see e.g., Apetrei et al., 2021; James, 2014).

2.1.1 Fundamentals of sustainability

As a concept involving both social and economic elements, the term sustainability first appeared in the late 1970s (Caradonna, 2014). In the context of planning, sustainability is rooted in the 1987 Brundtland report, *Our common future*, which also established a widely accepted definition: 'Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs' (United Nations, 1987). To date, countless definitions of sustainability have been added, but they are all similar in their core statements. Most ideas and concepts focus on the three dimensions shown in Figure 1: Environmental protection, social equity and economic development. The image on the left highlights the need to consider all three dimensions equally in order to ensure sustainable development, while that on the right underlines the importance of environmental protection as the core of sustainable development, followed by social and then economic aspects. However, both the term and the definition are usually kept quite vague, meaning 'that sustainability is a broadly conceived philosophy' (Caradonna, 2014).

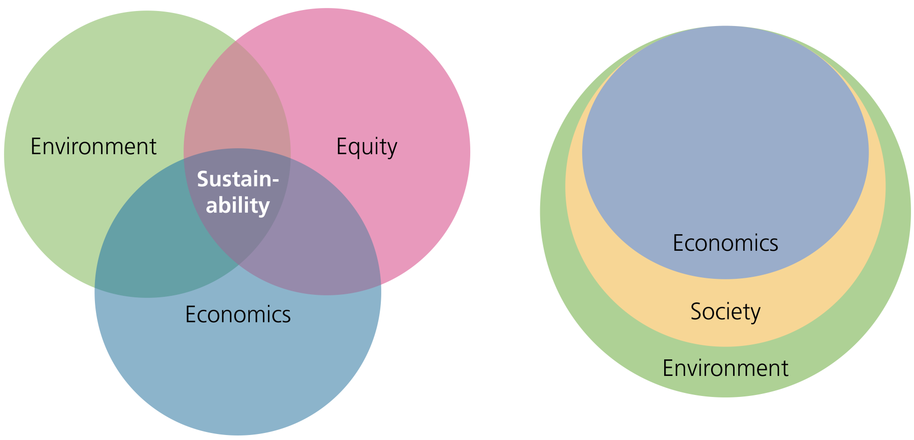


Figure 1: Concepts of sustainability (source: own elaboration, adapted from Caradonna, 2014)

Based on the broad definition of sustainability, the ambitious goal is to distribute social and economic resources evenly and sparingly so that future generations have the same opportunities. Thus, the call for sustainability is also a call for equity and solidarity, leading to the question of which guidelines and rules of living together need to apply in order to meet the call for sustainable development. In 2011 the WBGU introduced a global, but not legally binding, social contract setting out these normative principles. In view of the massive changes needed to fulfil this contract, the WBGU draws on the *Great Transformation*, the book published by economist Karl Polanyi in 1944. According to him, the transformation requires 'the modification of both the national and the global economy within these guard rails in order to avoid irreversible damages to the Earth system and its ecosystems, and the impact of these damages on humankind' (WBGU, 2011). Another global milestone in the history of sustainability is the 2030 Agenda signed by all UN member states in 2015 (United Nations General Assembly, 2015). Within the framework of this agenda, 17 *Sustainable Development Goals* (SDGs) with 169 targets are defined, setting guidelines for a sustainable future. Building on the successes and experiences of the *Millennium Development Goals* (MDGs), the WBGU are intended to further advance this debate through their concrete character and integrated approach (Schneidewind, 2018; United Nations General Assembly, 2015). Schneidewind highlights six of these goals as having outstanding significance in driving the great transformation:

- Achieve gender equality and empower all women and girls (SDG 5)
- Ensure availability and sustainability management of water and sanitation for all (SDG 6)
- Ensure access to affordable, reliable, sustainable and modern energy for all (SDG 7)
- Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (SDG 9)
- Make cities and human settlements inclusive, safe, resilient and sustainable (SDG 11)
- Ensure sustainable consumption and production patterns (SDG 12)

SDG 11 is of particular importance from the perspective of urban and spatial research and thus for this thesis. Furthermore, it is clear that the development goals overlap to a large extent, as seen in the handling of urban space. Moreover, a UN synthesis report emphasising the importance of cities calls for an integrative view of the goals (United Nations, 2018). Cities are this assigned an outstanding role in sustainable development due to their size and attraction. Inspecting this role, the following section focuses exclusively on the sustainable transformation of urban space.

2.1.2 Sustainable urban transformation

As early as 2011, the WBGU , in its report on the *Social Contract for Sustainability*, underlined that cities have a decisive role to play in this transformation. It called for '[...] joint research on urbanisation dynamics and their various sustainability implications' (WBGU, 2011). This work was further elaborated and intensified in the following years. The flagship report *Humanity on the move: Unlocking the transformative power of cities* put cities at the centre of sustainable development, as they are responsible for around 70% of the world's energy demand. Ongoing urbanisation, characterised by large waves of migration, is set to increase this share. Thus, the success of global sustainable development is inevitably linked to the success of urban transformation. To drive this process forward, the WBGU outlines several important guidelines that find their starting point in the three dimensions of the normative compass:

- *Sustain natural life-supports system*: Compliance with planetary guard rails to solve environmental problems and ensure environmental protection.

- *Inclusion*: Providing universal minimum standards to ensure substantiative, political and economic inclusion.
- *Eigenart*: Individual path to a sustainable future and property preservation.

The urban 'transformation can be achieved by a combination and balance of three dimensions' (WBGU, 2016). Moreover, the WBGU defines eight transformative fields able to support this process due to their highly influential and catalytic function: (1) Decarbonisation, energy and mitigation of climate change in cities, (2) Mobility and transport, (3) Urban form, (4) Adaption to climate change, (5) Poverty reduction and socio-economic disparities, (6) Urban land use, (7) Materials and material flow, (8) Urban health. In addition to defining important research fields, the WBGU also set some overarching goals, such as moderate densification, socially mixed districts, polycentric spatial development, affordable housing and access to basic infrastructures. Further objectives include the 'departure from the paradigm of the car-friendly city' or a 'suitable balance between densification and public green and open spaces' (WBGU, 2016). They stress that transformation should be seen as an integrated approach changing existing planning and regulatory frameworks as well as political and institutional structures, with the experts seeing windows of opportunities in the next two decades to implement it. Much of the urban infrastructure needs to be renewed or rebuilt, changing the physical shape of a city. This will be one of the most challenging processes, with a 'deep transition [...] unfolding across subsystems, organizational fields and policy domains' (Mikelsone et al., 2021). Schneidewind (2018) also refers to such an deep transition in his book *The Great Transformation*. According to him, this is not however an all-encompassing mega-process but the bringing together of many structuring turnarounds calling arenas. He defines seven major ones, including prosperity, energy, resources, mobility, nutrition, urban space and industry. In addition to these sources, there are many literature reviews analysing journal papers and defining important urban sustainability topics (see e.g., Cohen, 2017; Sharifi, 2021).

While the previous two sections have highlighted the overarching guidelines for sustainable development and which processes need to be initiated to achieve certain goals, it remains unclear what sustainable urban development means in detail. Which objectives apply in detail to the individual sustainable development research fields taken up in this work will be shown in the respective sub-studies.

2.2 (Geo-) Data

To set such processes in motion and to be able to implement and legitimise actions in a focused manner, a wealth of data is needed. The basis for any political or planning decision, quantitative analyses or monitoring systems are valid, intelligible, aggregate and linkable datasets. Kitchin (2014) describes the importance of data as follows: 'Data have strong utility and high value because they provide the key inputs to the various modes of analysis that individuals, institutions, businesses and science employ in order to understand and explain the world we live in, which in turn are used to create innovations, products, policies and knowledge that shape how people live their lives.' Demand for and availability of high-quality, up-to-date big data have risen sharply in recent years and decades, leading to a so-called 'data revolution' (Kitchin, 2022) offering both researchers and planners new ways of processing and generating data as well as developing new analytical approaches. This also supports the idea of data-driven science, where data is not only used in the empirical design of scientific work, but from the very beginning. In contrast to classical forms of deductive epistemology, initial hypotheses are generated from data, not from theory (Kelling et al., 2009).

One term that has particularly shaped this data revolution is big data. Though the research community has not yet agreed on a clear definition of this term, most researchers relate it to the 4V's: volume, velocity, variety and veracity (Favaretto et al., 2020). There are three important data types: survey data, administrative data and big data (Table 1). In general, big data allows us to conduct area-wide and small-scale analyses usually requiring a significantly higher computing effort. By contrast, survey and administrative data are often restricted to a single reference area and therefore less comparable.

	Survey data	**Administrative data**	**Big data**
Volume	Manageable volume	Manageable volume	Huge volume
Timeliness	Slower	Potentially faster	Potentially much faster
Cost	Expensive	Inexpensive	Potentially expensive
Geography / Extent	National, defined	National or extent of programme and service	National, international, potentially spatially uneven
Methods	Classical statistical methods available	Classical statistical methods available, depending on the data	Classical statistical methods not always available
Comparability	Weaker comparability between countries	Weaker comparability between countries	Potentially greater comparability between countries
Representativeness	Representativeness and coverage known by design	Representativeness and coverage often known	Representativeness and coverage difficult to assess
Scalability	Low to middling	Low to middling	High

Table 1: Characteristics of data (source: own elaboration, adapted from Kitchin, 2014, 2022)

However, there are also other ways to characterise data types like licensing, origin or availability. One approach used by the *Fraunhofer Institute* classifies urban data in three different layers: open data, commercial data and internal data (Schieferdecker et al., 2018). Internal refers to official or municipal data (e.g., registration data or police records) that is not published as raw data for various reasons (e.g., data protection or internal guidelines). Commercial data, on the other hand, is available for a fee, though its usage, processing and distribution is often restricted by licensing. A large segment covered by commercial data is geomarketing, where different socio-economic datasets and milieu data are used to identify market structures. The third layer, open data, is non-privacy-restricted and non-confidential, which 'anyone can freely, access, use, modify, and share for any purpose' (Open Knowledge Foundation, 2022). However, high demands are also placed on open data. The basis is a suitable license allowing its use, sharing and modification free of charge. The importance of open data has increased in recent years in the wake of the *Open Government Initiatives* and many other funding programmes. The benefits of open data are manifold: transparency of public processes, cost saving and higher efficiency (European Comission, 2022). As part of these initiatives, large amounts of internal, municipal data are checked for data privacy and made available as open data easily accessible for new monitoring approaches. This section shows only a small excerpt of the current data revolution. Readers will find a more detailed overview in (Kitchin, 2022). However, important concepts and trends were highlighted, to be taken up again in the following sections and in addressing the research questions.

2.3 Spatial monitoring

The following section on spatial monitoring links the two previous principles through focusing on three important aspects. First, the fundamentals and organisation of spatial monitoring, including key stakeholders, their objectives and the regulatory framework, are considered. The second part provides an overview of the important functions and tasks of monitoring as well as established systems. Finally, the last subsection deals with a special type of monitoring, the so-called geomonitoring, as well as an overview of new methodologies.

2.3.1 Fundamentals and competences

Spatial monitoring is the basis for several forward-looking urban development policies. To be able to monitor progress in solving the sustainable development issues outlined at the beginning, organisational and legal foundations are needed. To reduce the complexity and scope of this section, the following subsections focus on the European and German perspectives on spatial observation, starting with the latter.

In Germany, spatial monitoring (*Raumbeobachtung*) is performed permanently and comprehensively at federal, state (*Länder*) and local levels (Sturm, 2018), as regulated by the Spatial Planning Law (ROG). Starting from the bottom, local spatial monitoring is organised by the statistical offices as data providers, supported by planning departments. At the state level, it is further defined in the respective state planning laws and is mostly managed by state statistical offices. At federal level the *Federal Institute for Research on Building, Urban Affairs and Spatial Development* (BBSR) is responsible for such monitoring, with many different thematic areas and indicators within its scope (BBSR, 2022). For example, information on the labour market, social structure, finance or housing is provided, albeit mostly based on simple indicators at municipal level. However, there are also approaches within inner-city spatial monitoring that evaluate indicators below the municipal level. The results of this spatial monitoring are evaluated in regular spatial planning reports which give substance to the abstractly formulated principles of the Spatial Planning Law (ROG sect. 2). In an earlier version of the ROG, spatial observation was explicitly listed as an advisory instrument, whereas in the new version it is only an (in-)formal form of cooperation (sect. 14 para. 2 cl. 1). Some see this as a downgrading of spatial monitoring (Glatzweiler, 2011). However, the amended version provides legal backing to cross-border monitoring, thereby highlighting its importance (sect. 25 ROG) and creating new opportunities to reduce the existing deficits in its transnational organisation. The first model project MORO (dt. *Modellvorhaben der Raumordnung*) underlines the success of 'overcoming borders' (BBSR, 2019).

At European level, the *European Spatial Planning Observation Network* (ESPON) is the key player, as it is where the strands of the individual EU countries come together. Within the 2020 cooperation programme, one objective was to improve territorial observation and analysis. A number of significant projects have developed user-friendly and easily accessible tools relevant to both policy and planning practice. One of these projects is the *European and Macro-regional Territorial Monitoring Tool*, the MRS ESPON which provides indicators for a variety of thematic fields in a simplified way (ESPON, 2020).

2.3.2 Functions, tasks and established monitoring systems for urban sustainability

In general, monitoring includes all activities involving the collection, analysis and interpretation of important indicators as a basis for decision-making (Weick, 2007). But there are also other approaches dealing with the delineation of the two main tasks of monitoring: observation and controlling (Gnest, 2008). While observation refers to the provision of information, controlling is primarily concerned with the achievement of goals. In research and practice, however, such a distinction is usually not always possible or feasible. Therefore this thesis follows Hanusch's (2018) differentiation of seven main functions of monitoring:

- **Information function**: gaining and supplying information.
- **Analysis function**: evaluating the status.
- **Verification function**: verifying forecasts and assessments to counteract uncertainties.
- **Control function**: controlling the objectives of the various policies or measures.
- **Early warning function**: identifying and assessing risks at an early stage.
- **Transparency function**: improving the transparency of political and planning actions.
- **Learning function**: improving future planning processes.

The basis for all monitoring systems are analyses that map and assess sustainable development. In general, those assessments use one or more indices. These in turn result from the aggregation, combination or intersection of different indicators serving as a representative description of certain mechanisms or conditions in a complex (urban) system (Scholles, 2008a). There are several requirements that indicators must meet. Proposals have been made in this regard from various research directions, although most of them are similar in substance. This thesis uses the definition of Harger and Meyer (1996), which sets six minimum standards for indicators: simple, comprehensible, measurable, assessable, sensitive and timely.

Several monitoring systems exist in the German and international context. Some systems, such as the aforementioned BBSR monitoring system, provide important key indicators and statistics on overall spatial developments in German cities (BBSR, 2022). There is also a subsystem, an inner-city spatial monitoring system, which provides comparatively few indicators on a smaller scale. A further system focused on monitoring SDGs at national level has been implemented (Statistisches Bundesamt, 2021; United Nations Statistics Division, 2021). Furthermore, UN-Habitat is working on an urban monitoring system 'that harmonizes existing urban indices and tools, and offers an agreed universal framework to track performance of the urban SDGs and the New Urban Agenda' (UN-Habitat, 2022). In addition, there are several non-governmental monitoring systems, such as the IÖR monitor (Leibnitz-Institut für ökologische Raumentwicklung, 2022) or the system for monitoring city regions (Institut für Landes- und Stadtentwicklungsforschung, 2022b), which provide new delimitation methodologies and more complex indicator calculations complementing existing basic data. This brief summary of existing monitoring systems is not intended to be a comprehensive listing but rather to show their variety: the spatial focus, the thematic focus and the complexity of the indicators. The latter aspect is of particular importance for this thesis and is discussed in greater detail in the next chapter.

2.3.3 Geomonitoring and new methodologies

One particular form of monitoring is geomonitoring. In contrast to the standardised monitoring approach used in spatial observation and primarily based on stable time series, geomonitoring combines new data sources and geodata, allowing the investigation of spatial development trends with new explorative methods (Fina et al., 2019). After testing and validation, these methods and tools can be transferred into established monitoring systems. Geomonitoring thus fits into the idea on 'data-driven science' (Kitchin, 2014) which generates research topics and questions from data. The origin lies in the modelling of environmental processes to detect changes at an early stage (Fina et al., 2018). Examples are early warning systems regarding soil erosion (Steinhoff-Knopp et al., 2019) or damage in former mining areas (Rudolph et al., 2020). One key characteristic of geomonitoring is the use of GIS, which also offers several advantages for assessing sustainability. The spatial intersection and (dis-)aggregation of indicators allows the creation of new indices and changes the level of analysis. Concepts for assessing sustainability already exist at regional (Graymore et al., 2009) or local (Pedro et al., 2019; Sharifi and Murayama, 2013) level. However, most of the studies use simplified indicators and are therefore unable to make the most of the current potential of quantitative assessment with GIS. By contrast, van Maarseveen et al. (2019) present more sophisticated approaches to different sustainability topics at municipal level (e.g., patterns of urban growth, urban quality of life or public transport). They thus show that the use of GIS for urban planning offers a higher quality of data analysis and therefore also a better and more valid basis for decision-making. However, there is no agreement on how such tools for assessing sustainability should be designed. They can vary in their spatial resolution (from local to national), in their temporal availability (from past developments to predictions), and in their complexity (from simple indices to complex algorithms). Several studies deal with the categorisation and comparison of sustainable measurement methods in terms of content and methodology (Kaur and Garg, 2019; Ness et al., 2007; Sharifi and Murayama, 2013). The preconditions are discussed in the next chapter.

3 Research design

3.1 Identification of research fields

To address the research questions and objects of this thesis, we need to identify research fields able to function as catalysts for sustainable urban development. This also allows us to narrow down the very broad spectrum of urban sustainability. A first overview of important topics was already presented in the previous chapter. Based on the work done by the WBGU (2016), Cohen (2017), Schneidewind (2018) and Sharifi (2021), a simplified overview of the main research fields of urban sustainability, their key sub-disciplines as well as the research branches are shown in Figure 2. I identified six key research fields of particular importance for the sustainability of urban space: (1) Decarbonisation & Climate Change, (2) Urban Health, (3) Socio-economic Equality & Migration, (4) Urban Form & Land Use, (5) Mobility & Transport, (6) Economy & Industry. Each of these research fields can be assigned a number of specific subdisciplines, presented here in excerpts. As examples, active mobility, accessibility, the dominance of private transport or eco-friendly transport are primarily *Mobility and Transport* topics. However, these subdisciplines overlap with other research fields, as e.g., accessibility provides the basis for supplying basic goods or participating in social life. It is thus difficult to clearly assign subdisciplines. Moreover, some research branches are clearly located at the intersection of multiple research fields. One example is walkability. This concept refers to the possibility of safely accessing key facilities on foot, an aspect which promotes the health of the urban population, but also brings environmental and economic benefits. Therefore, the topic is studied by various disciplines. A bibliometric analysis reveals that this topic is mainly addressed by researchers in the fields of health, medicine and mobility (Ramakreshnan et al., 2021), though there are also evident linkages in the fields of social, spatial or sports science. Figure 2 illustrates in a simplified form the initial problems of clearly positioning fields of sustainable urban development.

As mentioned at the outset, the research questions are addressed on the basis of three research foci. The selection should include topics of high importance for urban sustainability, but at the same time with overlaps and linkages to demonstrate the importance of an integrated monitoring approach. In line with the illustration above, the selection falls on the following three research foci covering a wide range of important topics:

1. **Urban growth dynamics**, combining different research fields from the topic of *Urban Form & Land Use*.
2. **Urban mobility structure**, as an overarching topic of active mobility, accessibility and the dominance of private transport, with strong linkages to many other research fields.
3. **Urban arrival spaces**, places where massive migration is concentrated and inequalities can emerge.

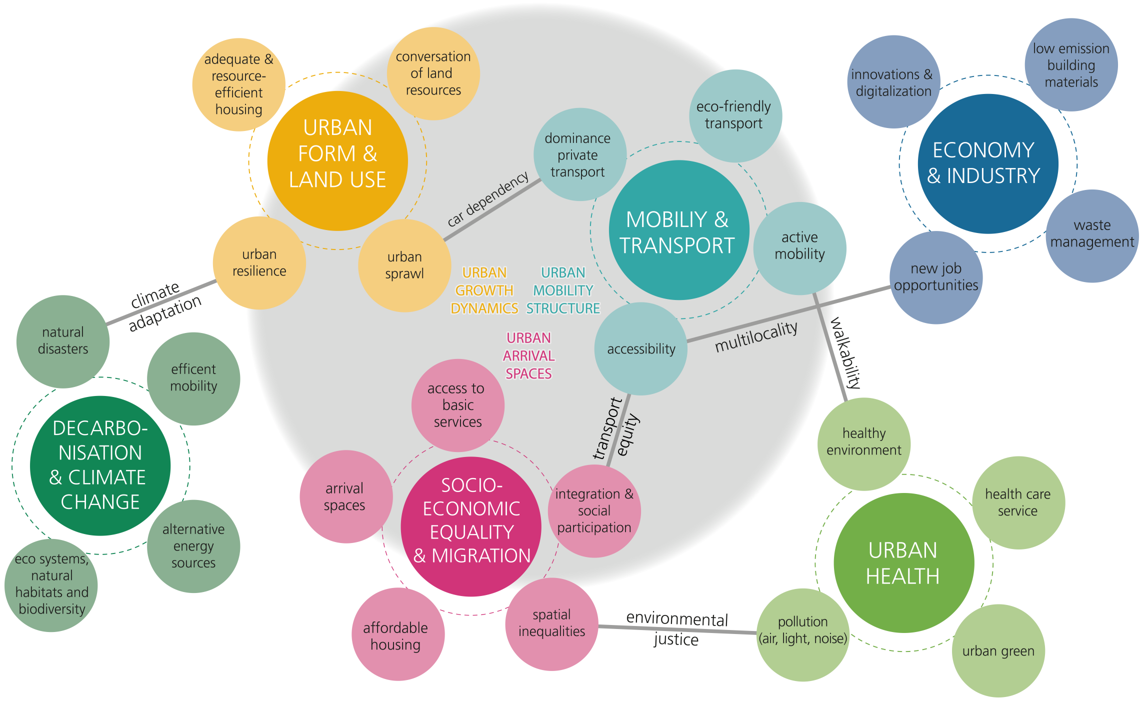


Figure 2: Research fields, sub-disciplines and research branches of urban sustainability (source: own elaboration)

3.1.1 Urban growth dynamics

Driven by strong (inter-)national migration, the physical expansion of cities has been steadily increasing for decades and has led to somewhat uncontrolled growth and sprawl in some parts of the world. The impact of this physical growth on society and the environment is very complex (Fina, 2013). Negative effects include losses of ecological diversity (Grimm, 2008), the sealing of fertile soils or increases in traffic with all its negative consequences (Zolnik, 2011). The aim therefore seems to be to shape land use in a way saving as many resources as possible and minimising the negative impacts. This target is pursued by many national and international strategies, such as the German sustainability strategy aimed at bringing land consumption down to 30 ha per day (Henger et al., 2010). Therefore, urban land use change, land consumption rates and the degree of urban sprawl are issues of high political, planning and social importance and a key element of sustainable development. These topics are subsumed in this thesis under the term urban growth dynamics. The high level of interaction with other sustainable development research fields makes it a very complex but also important subject of spatial research. This also applies to the quantification of growth dynamics. Current research offers a host of different approaches to conceptualise sustainable urban growth (e.g., Seto et al., 2011). One concept put forward by Cervero and Kockelman (1997) uses three dimensions or main characteristics of urban development: density, diversity and design. However, as yet there are few approaches able to map complex urban growth dynamics in a simplified way. Thus, the research focus of urban growth dynamics is dedicated to the following question: How can the complex growth dynamics of cities be presented and monitored in a simplified and comprehensible way?

3.1.2 Urban mobility structure

This research field occupies a special place in the discussion on sustainable development, as mobility can both promote and hinder urban transformation. Therefore, mobility is often labelled as a 'maker or breaker of cities' (Clark, 1958; Newman et al., 2016). Many experts see the ubiquitous dominance of private transport as the key problem of current urban mobility structures (Wiersma et al., 2021). Negative effects include environmental pollution, such as particulates or noise, or increased land consumption for parking spaces and roads. To drive the transition to sustainable mobility, three key elements must be taken into account: (1) a general reduction in traffic volumes, (2) a shift to more ecologically compatible modes of transport, (3) an increase in the efficiency of existing systems or converting to electromobility (Schneidewind, 2018). Needless to say, all three have been discussed for years in transport planning. From the perspective of spatial science, reducing overall traffic volumes and the use of private vehicles are two essential components for which planners are already coming up with solutions. Traffic avoidance can be achieved through smart, compact and multi-centre city design. Moreover, the past few years have shown that there is huge potential for new ways of working, such as telework or flexible work schedules. These are already leading to a significant reduction in commuter traffic (Wethal et al., 2022). This is where planning, but also the business world, can help boost the existing potential. Structural changes are also being made to encourage a switch from cars to more environmentally friendly modes of transport. Examples of this are initiatives to promote cycling, the expansion and enhancement of existing public transport infrastructures, or the provision of new sharing services. However, to be successful, these changes must be implemented structurally and extensively, i.e., including changing a city's physical structure. Currently there is a lack of reliable statistics on how the mobility transition is progressing as well as a lack of small-scale information on problem areas for supportive interventions. Furthermore, there are hardly any methodologies dealing with the topic of urban mobility structures. First attempts to conceptualise the relationship between urban design and transport systems include the theory of urban fabrics by Newman et al. (2016). Based on this concept, this research focus is dedicated to the question: How can urban mobility structures be classified to monitor the mobility transition?

3.1.3 Urban arrival spaces

Migration is a 21st-century mega-trend set to change the social and physical structure of cities in the long term: the physical form through ongoing urbanisation and massive in-migration, the social fabric through increasing diversity and growing economic disparities. The WBGU describes this as the biggest challenge for cities: 'This relocation of humanity could become the process of social change that has the most powerful impact in the 21st century' (WBGU, 2016). Previous waves of immigration in the last century showed that a high influx of new arrivals can (over-)stretch the integration capacity of cities, possibly leading to exclusion, social deprivation and persistent inequalities (Schillebeeckx et al., 2019). It is therefore important to identify and localise these processes in urban space. However, monitoring this process or making it quantifiable is highly complex, first because of the manifold influences of migration on a city, and second because there are so far few (data-related) concepts for doing so (existing concepts focus mainly on quantifying small-scale migration dynamics or socio-spatial inequalities). One approach combining different aspects of global migration is the so-called 'arrival space' or 'arrival city' concept (Saunders, 2011). Unlike other concepts on migrant neighbourhoods, these places of arrival are defined by such characteristics as the diversity of nationalities, arrival-related infrastructures, social networks or the physical structure. Saunders thus expands our understanding of 'ethnic enclaves' (Wilson & Martin, 1982) or 'urban enclaves' (Zhou & Portes, 1992). However, there are currently no tools or quantitative approaches able to capture these urban phenomena. Therefore, this last research focus is dedicated to the question: How can immigration flows be localised on a small-scale level to identify and characterise arrival spaces?

3.1.4 Linkages and overall research framework

Each research focus is framed by a specific research question, elaborated in the respective sub-studies. However, the previous sections have already shown that the research fields show strong linkages and overlaps. As this thesis also focuses on an integrative view - following the idea of the WBGU -, a further empirical chapter deals with cross-thematic research branches. The overall research design is presented in Figure 3.

At the intersection of land use and mobility, the **first** cross-thematic research branch looks at path dependencies in transport planning which influence a city's land use structure and overall design. This so-called *Vicious cycle of car dependency* is one of the biggest transformation obstacles to the mobility transition and resource-saving land consumption (Randelhoff, 2016) and leads to the following question: How can the interaction of transport and urban development be measured with regard to this vicious cycle of car dependency? The **second** cross-thematic research branch deals with inequalities in accessible mobility options, a branch at the intersection of *Urban Mobility Structure* and *Urban Arrival Spaces*. With equity in transport an important component of integration and participation in private and public life (Di Ciommo & Shiftan, 2017), the second cross-thematic question is raised: How is it possible to identify socio-spatial inequalities in the distribution of mobility options? Focusing on the influence of urban sprawl on residential segregation, the **third** cross-thematic research branch is at the intersection of *Urban Growth Dynamics* and *Urban Arrival Spaces*. Urban growth can have a significant impact on a city's social fabric when it comes to equal living conditions, segregation or environmental justice (Wei & Ewing, 2018), leading to the following question: How can we measure the influence of urban sprawl on residential segregation?

The overall research framework thus covers three research foci addressed in detail in the journal articles, and three cross-thematic research branches forming the second analytical part of this thesis. With regard to the latter, however, it should be noted that the analytical approaches selected here are intended to be based on the tools developed for the research foci. It is also important to mention that the questions relating to the individual research fields form the scope for the empirical work and thus provide the basis for answering the overall research questions presented at the outset.

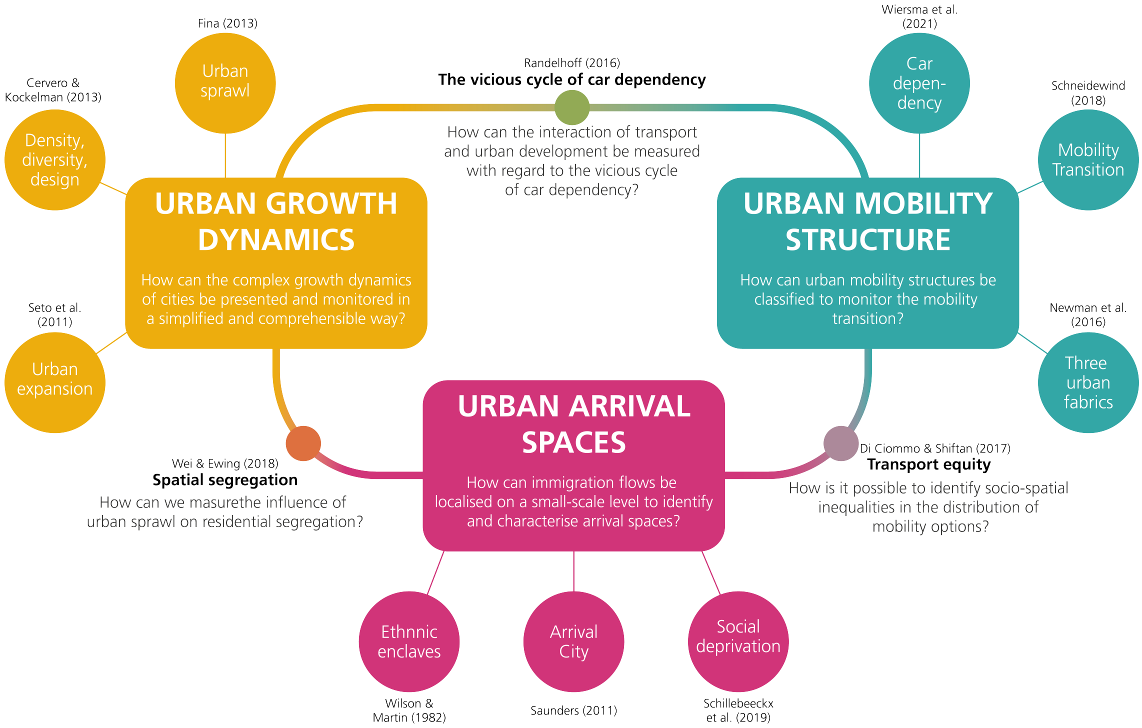


Figure 3: Research framework (source: own elaboration)

3.2 Requirements for the tools and datasets

In order to answer the questions of the individual research foci, we first need to establish some requirements for tool development and the required datasets. In general, there are several scientific criteria needing to be respected here. These include quality criteria, such as reliability, validity, reproducibility, comprehensibility and consistency (Scholles, 2008b), all of which are hard requirements for these tools. In particular, reproducibility is crucial for methodologies to be integrated into a continuous monitoring. To ensure reproducibility, it is a good idea to create or develop precise documentation or defined algorithms for the tools. However, I set some additional soft requirements for the tools which are essential for the elaboration of this thesis. One important feature is their spatial scalability. The term scale is simple to understand from a cartographic point of view, but in many other sciences it is often much more complex. This thesis follows the idea of Goodchild (2011), differentiating between scale components in GIS science: resolution and extent. Extent refers to the spatial (and sometimes temporal) extent of a study area, while resolution refers to the level of detail. Depending on the research field or research questions, it is necessary to analyse results on a smaller or larger scale. In general, analyses should proceed from the highest degree of detail, as aggregating spatial data is more accurate than disaggregating. Two important issues are the ecological fallacy (Walker, 2021) and the modifiable areal unit problem (MAUP; see e.g.,Nelson and Brewer, 2017). Since the aim of this work is to ensure the usability of the tools (almost) throughout the Global North, transferability is another essential requirement. This entails some technical (e.g., the spatial extent of geodata) but also content-related (e.g., validity of results) perspectives, as explained later. A key issue is the selection of (geo-)data. To make the tools usable for the general public, it is a good idea to use easily accessible, favourably licensed or open data. This also applies to software algorithms which should preferably also be open-source or at least widely known. Similar quality criteria, such as reliability and validity, apply here as well. To gain an initial overview of the technical possibilities, I conducted data and software research on the three research foci, differentiating between open-source, commercial and internal products. The result is presented in Figure 4. However, it should be emphasised from the start that this is not an all-encompassing and complete analysis, but merely intended to give a first impression of the availability of different types of data in the respective subject areas.

It quickly becomes apparent that the available data products and tools for the individual topic areas differ greatly. Many open datasets generated by remote sensing can be assigned to the field of urban land use and land consumption. These are mainly European products from the Copernicus programme, such as the Urban Atlas or Corine Land Cover, though there are also global datasets, such as the Global Human Settlement Layer (GHSL) which contains information on built-up and population development. OSM, an open user-generated dataset, also contains global land use information, but can be incomplete and does not contain stable time series. Local administrative datasets can be obtained from municipal land use and building registers. Under the open government Initiative, these datasets are also often available free of charge. Similarly, new 3D level-of-detail (LOD) building models are published as open data in some regions, enabling changes in spatial density to be detected. Although this topic is strongly associated with indicators and metrics, there are only a few widely known tools providing official, ready-to-use algorithms. By contrast, in the field of urban mobility infrastructures, several tools – both commercial and open-source – offer possibilities for calculating accessibility within transport networks, catchment areas or distance matrices. Information on the technical characteristics of a transport infrastructure can be obtained from datasets such as OSM or the official feeds of transport companies. However, it remains difficult to capture actual traffic behaviour. In the past, mobility surveys were conducted for this purpose, for example to record the modal split. In Germany, mobility behaviour is surveyed at regular intervals (Nobis & Kuhnimhof, 2019). Mobile phone data is now being increasingly used for this purpose, though is constrained by data protection problems, the size of the data and the high costs. These problems could also become relevant in the last research field dealing with urban arrival spaces. As data on this topic always concerns individuals, it is subject to ethical and privacy issues. In Germany, this concerns municipal migration and household registers, which are prepared by the statistical offices. These internal datasets are only available at an aggregated level. Open datasets are available from the (micro) censuses or other migration surveys. These may be complemented by other commercial geomarketing datasets containing information on the socio-economic status of a population, e.g., purchasing power. The sub-studies explain in detail how and why which datasets are used in the research fields under consideration.

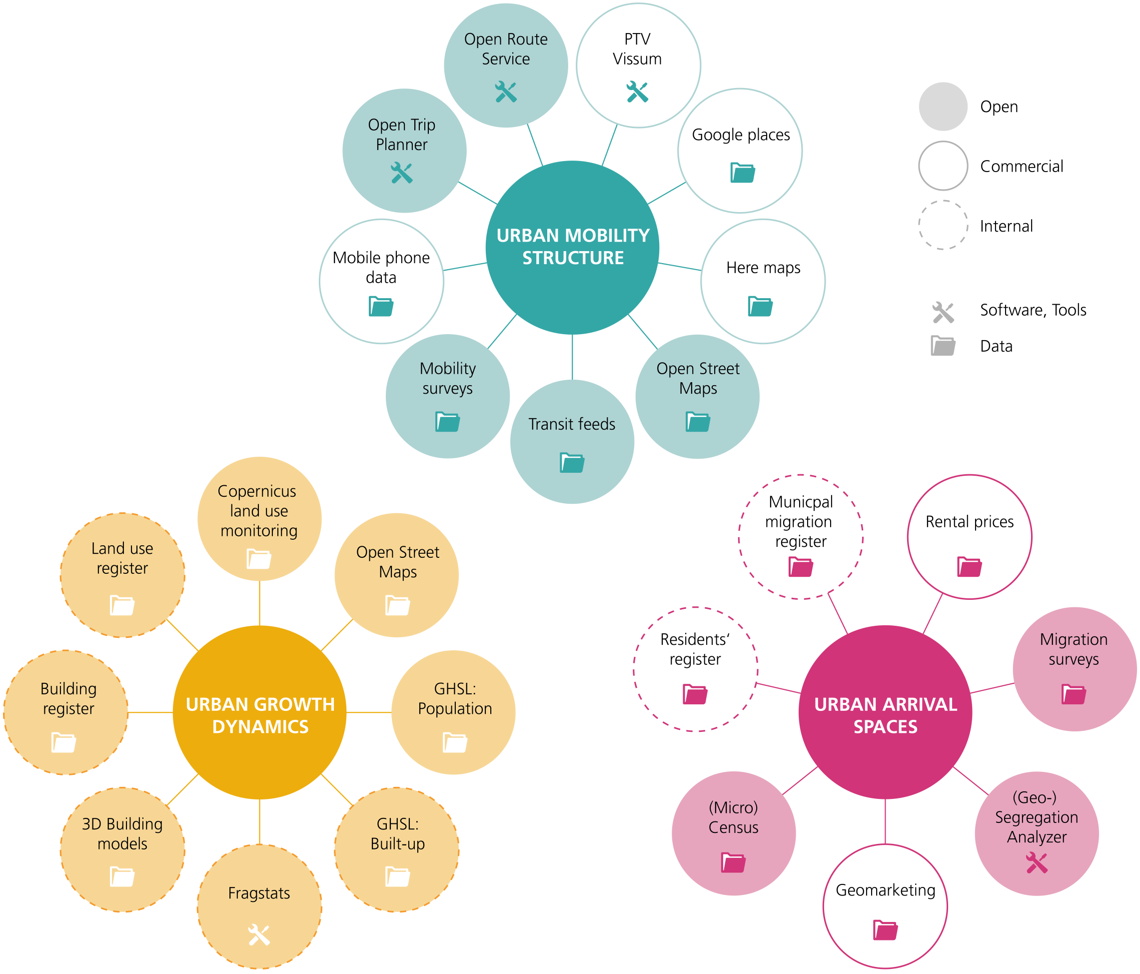


Figure 4: Datasets and tools for the identified research foci (source: own elaboration)

3.3 Study area and scale

With regard to the chosen research fields and scales, the requirements for the tools and datasets already define some parameters. One requirement is that the methodologies have a high degree of transferability to other regions. This means that the tools should use datasets available for a multitude of areas and regions or can be easily collected. In general, the prioritisation of goals to promote sustainable urban development varies greatly between regions of the world, which is why this thesis focuses on the Global North.

The spatial scale of the tools should be kept as flexible as possible, as users have different requirements. Researchers and planners with a regional perspective obviously have a different spatial focus than urban researchers or neighbourhood stakeholders. From a methodological point of view, however, the aim should be to process data on the smallest scale and to aggregate it at a higher level, thereby increasing accuracy and spatial flexibility. Wherever possible, common geographic geometries should be used to locate geospatial data to avoid transferability problems. One possibility is the harmonised *Inspire grid* which is available in different resolutions for the Pan European area. This offers multiple benefits in methodological processing, utilisation and dissemination. However, as these geometries have not yet been fully introduced in all institutions, other administrative units are still to be considered as standard. For some analyses and questions, for instance those focusing on building structures, the use of administrative units might be beneficial.

The choice of case studies for looking at these selected research fields and the available data and tools varies within this thesis. Therefore, the selection is strongly based on the thematic focus. The international case studies occupy a special position and have specific characteristics, as discussed in greater detail in the respective sub-chapters. By contrast, the cross-thematic research branches in Chapter 5 focus on one specific region, the Ruhr, Germany's former industrial heart. With over five million inhabitants, the Ruhr is one of the largest agglomerations in Germany. Formerly dominated by the coal and steel industry, the region has been undergoing restructuring for more than half a century, with the 2018 closure of the last coalmines a milestone (WBGU, 2016). The region's polycentricity and associated political and planning issues in particular make it an outstanding spatial research subject. One key feature of the Ruhr is its plurality, a term used to describe a number of medium-sized cities with no clear hierarchy (Burger & Meijers, 2012) and engendering a host of research topics and questions. Examples are the complex administrative and governance structures (Growe et al., 2012), methods of spatial-functional delimitations (Fina et al., 2018), as well as practical issues such as commuting patterns and the provision of key infrastructures (Wiechmann & Siedentop, 2018). As regards transformation research, this 'post-industrial metropolis' occupies a separate place due to its specific features, with the mobility transition listed here as a central obstacle (WBGU, 2016). As a delineation for the study area, this thesis is based on the official boundaries of the *Regionalverband Ruhr* (RVR), an administrative region covering 11 cities and 4 rural districts, along with a host of smaller and less populated municipalities (see Figure 5). The majority of the population is concentrated in the cities of Essen, Dortmund, Duisburg and Bochum, whereas the north and south of the region are mainly characterised by large agricultural areas and smaller settlements. These characteristics make the Ruhr region an ideal case study for cross-thematic analyses.

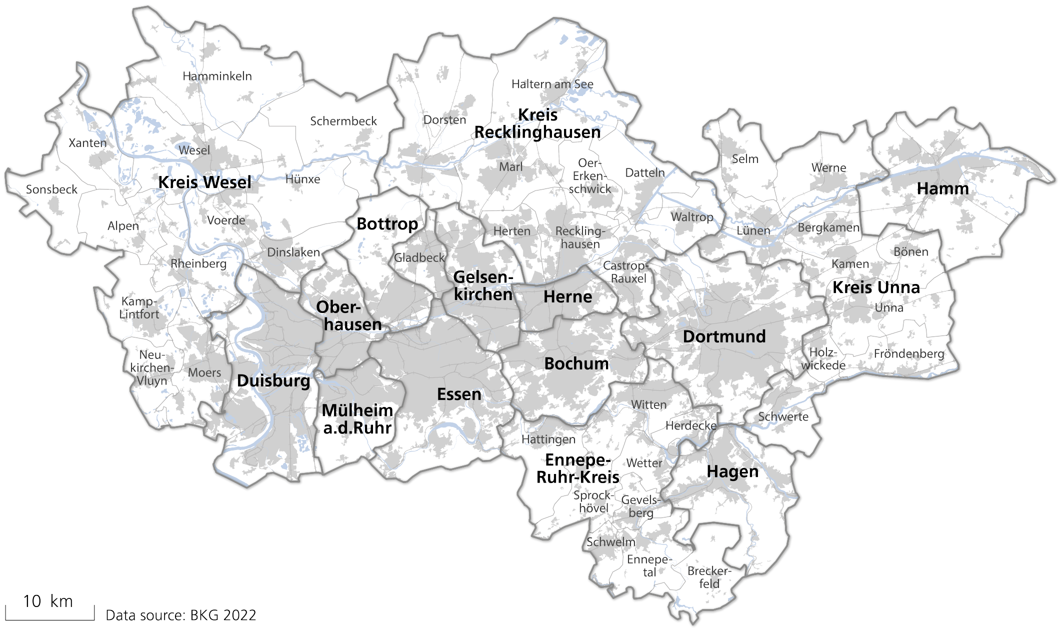


Figure 5: Administrative borders of the Ruhr with municipalities and rural districts (source: own elaboration)

4 Publication based findings: the development of new tools to monitor urban sustainability

The following chapter presents the three research foci and the related tools, as represented by the three published articles of this thesis. Chapter 4.1 deals with the questions of how the complex growth dynamics of cities can be monitored and presented in a simplified way. Gerten et al. (2019) discuss the potential offered by new remote sensing data to assess development trends based on their resource efficiency and land composition. In Chapter 4.2, Gerten and Fina (2022) present a new methodology for classifying urban mobility structures in urban areas, inter alia scrutinising buzzwords related to the mobility transition. Chapter 4.3 addresses the issue of inequalities and migration in the context of arrival spaces. Gerten, Hanhörster, et al. (2022) present a new methodology for the spatial identification and typification of arrival spaces. Finally, Chapter 4.4 presents interim results, summarising the main findings of this chapter.

4.1 Sub-study 1: Urban growth dynamics

The following section summarises the key results of the journal paper 'The sprawling planet- simplifying the measurement of global urbanization trends' by Gerten, Fina and Rusche published in Frontiers in Environmental Science in 2019. The full version can be found in Appendix A.3.1. The own contribution is listed in A.1.1.

As already mentioned at the beginning of this thesis, there are two megatrends shaping cities in the 21th century: ongoing urbanisation and increasing migration flows. Cities need to be prepared for significant population and settlement growth, as by 2050 nearly 70% of the global population is set to be living in urban spaces (Koceva et al., 2016). The many reasons why cities are so attractive for in-migration include educational and job opportunities, access to amenities, or richer cultural and social life. This is mostly the case in inner-cities, but not always in suburbia. If the latter is unable to take on urban functions or can only do so in part, dysfunctional and functionally segregated settlement areas will emerge, increasing commuting distances and infrastructure costs. These problems are often labelled 'urban sprawl' (Fina, 2013; Galster et al., 2001; Wei and Ewing, 2018). The (partly uncontrolled) growth of urban space brings with it threats to various ecosystem functions and conflicts with climate change mitigation strategies, thereby jeopardising sustainable urban development. The expansion of settlement areas should not be based on individual housing preferences or land market conditions. Instead, such decisions should be made strategically and with foresight with a view to saving costs and reducing the negative impacts on the environment and population. However, there is unanimity within the research community that some cities or regions are more successful in controlling urban growth dynamics than others (Fregolant & Tonin, 2015). But it remains unclear to what extent planning and urban growth management instruments successfully influence urban sprawl. What is clear however is that, despite various planning approaches and initiatives, the trends of high land consumption, land use changes and urban sprawl are set to continue to increase or at least remain stable (Angel et al., 2011). One main reason is increasing living standards which go hand in hand with higher land consumption per inhabitant.

To monitor these growth dynamics and evaluate specific policies, robust information able to capture the current status but also development trends is needed. Over the past three decades, researchers from the Global North have been working on theories and measurement frameworks to assess urban sprawl. Based on their *Three D's*, density, diversity and design, Cervero and Kockelman (1997) presented a concept looking at how travel demand is influenced by urban form. This idea has been taken up and further developed by many researchers to quantify land use patterns, with indicators such as continuity, concentration, clustering, mixed use or proximity used to assess urban land use, land use patterns and their distribution (Ewing and Rong, 2008; Galster et al., 2001). Pursuing different purposes, the approaches differ in terms of scale (from a city block to regional level), geographical datasets (from land use categories to the binary consideration of urban and non-urban land) and complexity, which can make internationally comparable analyses challenging (due to data availability).

With the emergence of new datasets and technical innovations, however, great potential now exists to monitor and assess urban growth dynamics. One of these new, innovative products is the GHSL which provides global information about population and built-up for 1975, 1990, 2000 and 2015 (Pesaresi et al., 2013). In combination with population information, this binary land use dataset allows the identification of global trends in urban growth. It was used in this thesis to develop a new methodology for monitoring and presenting urban growth dynamics in a simplified way by concentrating on two dimensions: land use (in-)efficiency and urban dispersion. Land use inefficiency (LUI) compares the growth rate in the built-up environment with population growth over time. A positive LUI means that the growth rate of the built-up area is higher, inferring a less dense urban structure and pointing to urban sprawl. Conversely when population growth is higher, the LUI is negative, indicating an increase in urban density and resource-saving land consumption. As an indicator in the SDG (11.3.1), this dimension also has high political and planning relevance. The second dimension, urban dispersion, deals with the configuration and size of built-up areas. Here, the decision was taken to use the dispersion index (DI), an index combining two spatial metrics, namely the largest patch and the number of patches (Taubenböck et al., 2019). The DI ranges from 0 to 100, with low values indicating a compact settlement structure and high values a dispersed one. To monitor development trends, the absolute change in the DI is used, whereby negative values indicate densification, positive values dispersion. Based on these two indicators, we can show the urban growth dynamics of cities in a two-dimensional matrix, resulting in four different development paths (see Figure 6).

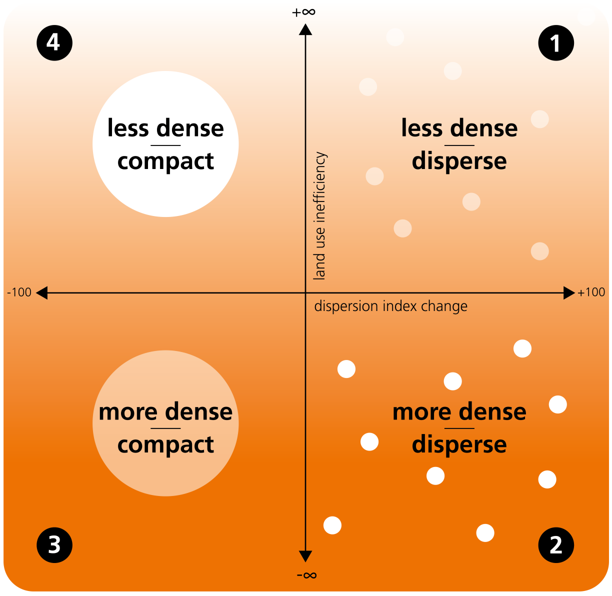


Figure 6: Growth matrix (source: own elaboration, adapted from Gerten et al., 2019)

Cities in the third quadrant feature positive urban growth from a sustainability perspective, as land consumption grows less than the population, meaning that the urban structure becomes more compact. There is thus no urban sprawl. The situation is different for cities located in the second and fourth quadrant, where one indicator each points to urban sprawl. Featuring less dense and dispersed development, cities in the first quadrant clearly show negative urban growth dynamics with strong signs of urban sprawl. To monitor developments not only over time but also spatially, administrative boundaries are not chosen as the area of investigation, but catchment areas based on travel time from the city centre. This approach offers several advantages, as suburbanisation or reurbanisation processes as well as spatial commuting relations are independent of defined administrative boundaries. The use of different travel time rings, so-called isochrones, helps delineate a city's different zones (from city core to the hinterland).

This methodology was applied in a two-stage process to assess its validity. In a first step, the global observation, we calculated the indicators discussed above for over 600 cities representing all continents and different city sizes. The analysis of the urban growth dynamics by continent revealed that the general trajectories were very similar. Almost all cities were located in the second quadrant, with a less dense but compact development in the first observation period from 1975 to 1990. However, the continents differ in their dynamics. While Asian cities showed a quite intense and dynamic development, values for European cities were comparable lower. These global dynamics can be explained by the strong expansion policies resulting from car-oriented suburbanisation tendencies common to large parts of the world. The strikingly high values can also be explained by some minor problems in the technical preparation and some general limitations of the 1975 dataset (European Commission Joint Research Centre, 2016). However, in the second (1990 – 2000) and third (2000 – 2015) observation periods, growth was less dynamic, though development paths diverged: while African cities continued to become less dense and compact, North/South American cities became denser but more dispersed and European cities less dense and dispersed. Only Asian cities seem to have become denser and more compact since 1990. Other researchers have come to similar conclusions, locating the growth peak for Europe as early as before 1975, while Asian, African or South American cities continue to grow (Angel et al., 2011; Seto et al., 2011). Testing these results statistically, we found out that the differences in land use (in-)efficiency between the continents were highly significant over the entire observation period. In the case of urban dispersion, this could only be verified for the first observation period. However, it is difficult to draw any clear conclusions from these results, as the growth dynamics in the respective cities can be affected by local, regional or national strategies and policies. Nevertheless, comparing individual cities or grouping them into different planning regimes offers the opportunity to evaluate growth management approaches.

In a second step, the methodology was then applied to Chicago (United States) and Paris (France), two metropolitan cities featuring very high urbanisation rates from 1975 onwards. Figure 7 shows an excerpt of the results and the visualisation technique for Chicago. With over 9 million inhabitants living in the metropolitan region, Chicago has been the subject of several urban theory studies (Dear, 2004). We established a consolidation of the settlement structure over the entire period, with a compact structure in the inner city and a compaction of land use patterns on the outskirts. However, this was accompanied by a decrease in urban density across the entire observation area caused by out-migration to the suburbs (Angel et al., 2010). As one of the most important metropolitan regions in Europe, Paris has always been an attractive centre for large companies and government institutions. Due to its well-developed infrastructure, urban growth in Paris took place mainly along the main arteries to second-tier cities. Our analyses thus revealed slight densification in the city core, which is for the most part built-up, and a densification and compaction trend in the wider inner-city area. While development along the main arteries has led to a (temporary) dispersion of suburban space, it is set to become more compact in the future as settlement areas grow together. Although land use efficiency in this area is still negative and shows signs of urban sprawl, we are noticing positive developments towards suburban densification.

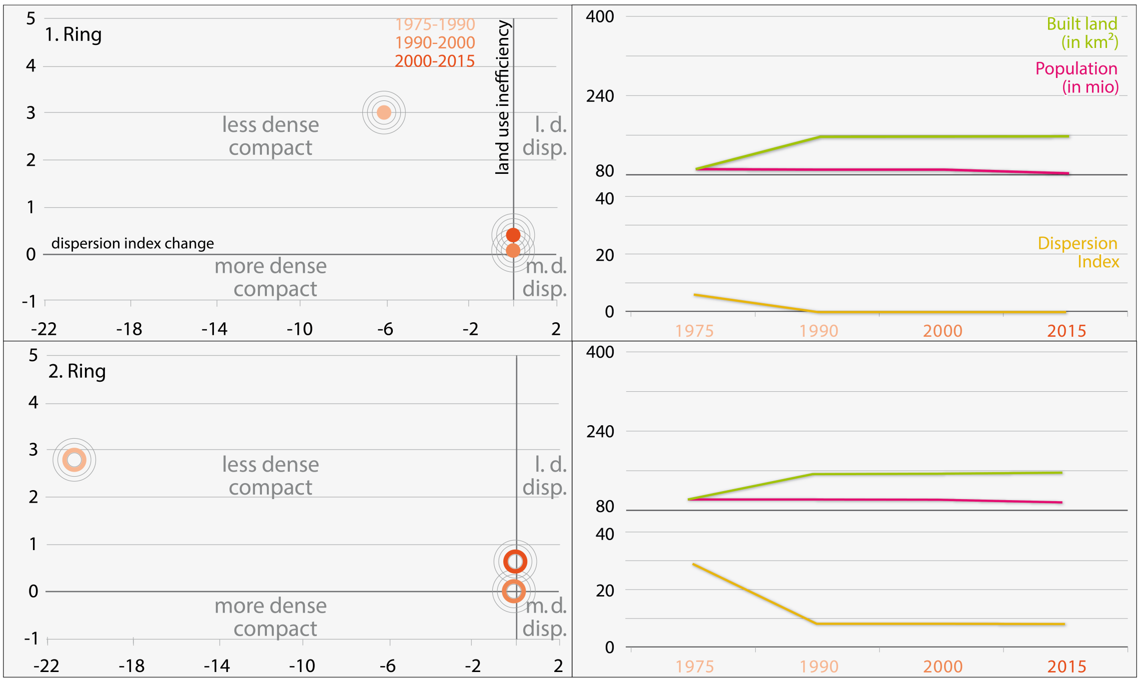


Figure 7: Exemplary presentation of the urban growth dynamics for Chicago (source: Gerten et al., 2019)

It is important to test new methodologies and datasets against well-studied case studies in order to validate technical and methodological strengths and weaknesses. This naturally has both advantages and disadvantages. In contrast to other assessment tools that make use of a wide range of indicators, we were able to combine the dimensions of population growth, land expansion and urban sprawl in one simplified tool. Although the logic and calculations behind this methodology may be complex, communicating the results is easier due to the graphical illustration and clear naming of the development path. Furthermore, this methodology requires only minimum input to describe urban growth dynamics: temporal information on building (binary) and population. This will allow us to replace the current input by future datasets with higher resolution, accuracy and/or up-to-dateness. Other approaches using a variety of indicators mean that any international comparison quickly runs into the problem of spatial and temporal data availability.

4.2 Sub-study 2: Urban mobility structure

The following section summarizes key results of the journal paper 'Scrutinizing the buzzwords in the mobility transition: The 15-minute-city, the one-hour metropolis, and the vicious cycle of car dependency' by Gerten and Fina published in Projections 16 - The power of urban metrics in 2022. The full version can be found in Appendix A.3.2. The own contribution is listed in A.1.1.

Urban mobility structures and transport systems are the arteries of cities, providing the infrastructure for the entire mobility of a city's population and the foundation of urban life and making them an essential component of sustainable urban development. In this context, mobility can be the 'maker or breaker of cities' (Clark, 1958). While sustainable forms of mobility can have a positive impact on the lives of a city's inhabitants, protect the climate and reduce land consumption, the dominance of cars is putting pressure on city environments far beyond the carrying capacity of environmental systems. This dominance is also seen as a main driver of many negative urban developments in terms of urban sprawl or dysfunctional areas (WBGU, 2016). This catalytic function makes mobility one of the most important research fields of this work. One overarching goal of any mobility transition is to redesign urban structures to support active forms of mobility. One prominent idea for such structures is the *15-minute city*, a concept that has gained traction in recent years. Under this concept, everyday necessities are accessible within walking distance (Pozoukidou & Chatziyiannaki, 2021). The current problem is the mismatch between sustainable mobility rhetoric and urban developments on the ground. This also applies to the use of digital planning tools, as these are able to reinforce path dependencies in transport planning. Future transport demand scenarios are usually modelled on the basis of today's mobility behaviour which, in a society characterised by growth and prosperity, means that capacity bottlenecks will arise due to increasing numbers of users (Dalvi, 2021). Consequently, future transport capacities must be enhanced. This 'induced demand' was also identified by Duranton and Turner (2011) in the United States, in their analysis of data on road capacity and traffic. Randelhoff's (2016) concept of growing car ownership and structural land use change, shown in Figure 8, adds some interesting components to the theory of 'induced demand'. He shows that increasing car ownership and car-oriented transport policies disadvantage alternative transport modes.

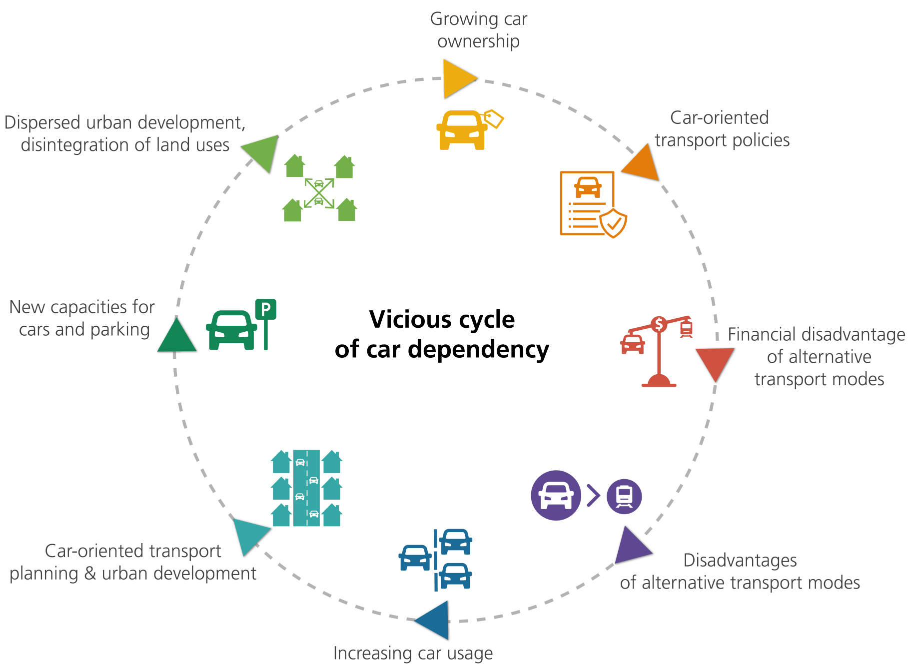


Figure 8: Cycle of car dependency and structural land use change (source: own elaboration, adapted from Randelhoff, 2016)

It has become clear that existing planning tools are highly focused on current and future mobility preferences without reviewing existing infrastructures. Therefore, the intention was to develop a new assessment tool able to classify a city's mobility structure in three different categories: the walking neighbourhood, the transit neighbourhood and the car-dependent neighbourhood. This approach adapts the concept of the three urban fabrics put forward by Newman et al. (2016) who propose a similar categorisation. In this tool, the walking neighbourhood, following the idea of the 15-minute city, is characterised by high walking accessibility to local services and amenities, while the transit neighbourhood relates to an excellent integrated public transport infrastructure. By contrast, the car-dependent neighbourhood is defined by 'the lack of alternative transport modes to the car in terms of time, cost and effort in accessing destinations' (Wiersma et al., 2021). To characterise the urban mobility structure and classify neighbourhoods, we used four indicators to assess walkability and one indicator for public transport (see Table 2).

	Indicator	Source
Walkability	Proximity of facilities and services Functional land use mix Green spaces Pedestrian network	OpenStreetMaps (OSM) OSM OSM OSM / OpenRouteService (ORS)
Public transport	Access to public transport with high frequencies	General Transit Feed Specification (GTFS) of the local transport authorities

Table 2: Walkability and public transport indicators to identify urban mobility structures (source: Gerten and Fina, 2022)

The local provision of key infrastructures, services and amenities is an essential feature of walkability. Most of the trips we undertake every day fall within the 'visit - life – work triangle' (Dovey & Pafka, 2017). While the locations of homes and workplaces are highly individual and difficult to capture, destinations of visit-trips are frequently (public) places of general interest. The importance of different types of amenities and services are taken into account through special weightings and varieties. However, as their supply cannot be mapped exclusively via points of interest (POIs), the functional land use mix is used as a complementary indicator. A high mix frequently reduces the need to travel longer distances. To rate this diversity, we make use of *Shannon's Diversity Index* (SHDI), which includes two important components, richness and evenness. One land use type, namely green space, is used as a separate indicator in the discussion of walkable neighbourhoods. The design, streetscape and attractiveness of a neighbourhood influence walkability to a great extent (Adkins et al., 2012; Frank et al., 2009). The share of green spaces is used as a proxy for such attractiveness. In addition to its function as a recreational resource, green spaces are positively associated with mental and physical health (Ward Thompson et al., 2012). As a final indicator of walkability, the directness and connectivity of the pedestrian network (related to the design of a neighbourhood) are analysed and evaluated. Here we make use of an indicator called pedestrian radius: the area within a 15-minute walking radius is set in relation to a static buffer representing the perfect design of a pedestrian network within a circle.

Access to high-frequency public transport is the only indicator used for assessing a transit neighbourhood. This is done using datasets provided by the local transport authorities. The geo-referenced positions, the mode of transport and the frequency with which a stop is served can be determined from the so-called General Transit Feed Specification (GTFS) datasets. Using this information, we define a service level quality that can be used to identify high-quality public transport stops. By combining the different indicators and scores, we are able to classify the urban mobility structure at neighbourhood level. Though the scale of analysis is freely definable, it should correspond to an appropriate neighbourhood size. This information can then be linked with population and building data to calculate further indicators, such as the number of people living in a neighbourhood or emerging settlement areas in car-dependent neighbourhoods.

For a first application of this new tool, we chose three cities supporting the idea of a 15-minute city: Paris, Portland and Melbourne. For the empirical part, we selected two different analytical approaches to map the distribution of inhabitants in different neighbourhood types. We started by assessing the urban mobility structure on a 500 x 500 m grid within the administrative boundaries of the cities, allowing an evaluation of transport policies or a review of mobility targets. We then used travel time polygons to analyse the urban mobility structure from the core city to the suburban area, i.e., representing urban-rural relationships. In all three cities we found highly walkable inner-city centres and central business districts (CBDs). However, the results for the three cities differed greatly, the further one moved away from the city centre. Due to its longstanding development as a high-density metropolis, Paris has a mature urban fabric with highly walkable structures (Figure 9). With only a small share of its inhabitants living in car-dependent neighbourhoods, Paris is very close to its goal of being a 15-minute city. Outside the core city, transit neighbourhoods dominate due to the well-developed public transport network. In this context, we were also able to observe high population growth in these areas, probably due to the strategically favourable location and the focus on transit-oriented development (TOD). Melbourne similarly records a very low number of people in car-dependent areas, but also a lower share of people living in walking neighbourhoods. Nevertheless, with more than three-quarters of the urban population living in walking neighbourhoods, Melbourne also seems very close to being a 15-minute city. Similar to Paris, the outskirts of the city are dominated by transit neighbourhoods. This is also a result of Melbourne's strategic plans to strengthen sustainable mobility and in particular public transport, which also includes TOD. The US city of Portland offers a structurally different picture. As already mentioned, the city centre, like some other urban neighbourhoods, is highly walkable. Deficits in the provision of sustainable mobility options are particularly visible on the outskirts of the city. Whereas in Paris and Melbourne an extensive public transport system serves the outer suburbs, in Portland people are very much dependent on their cars in these areas. Urban growth is also concentrated in these areas. Although this goes against the city's self-perception (City of Portland, 2010), our findings are consistent with observations on car dependency in other US cities (Newman & Kenworthy, 1999).

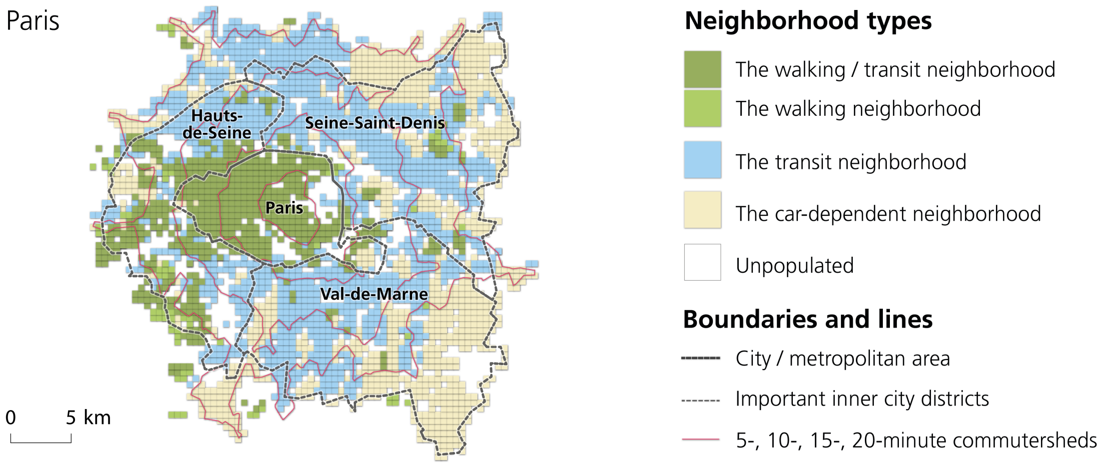


Figure 9: Exemplary presentation of the urban mobility structure for Paris (source: Gerten and Fina, 2022)

Although our results seem to be robust and consistent with other research findings, we need to mention some important points and limitations of this tool. The analyses focus only on the structural conditions for mobility, without including individual preferences (which is not a limitation but rather a help in understanding the results). A simultaneous advantage and disadvantage lies in the simplified structure of this methodology. While this allowed the tool to be built entirely on open-source and open data, thereby making it transferable to other spaces without major problems and making the results easy to understand, only the three most important means of transport are covered, while some important options are missing, e.g., cycling or other sharing options. Furthermore, the indicator for determining transit neighbourhoods is simplified compared to the four indicators used for assessing walkability. Here, the assumption is that a highly frequented stop also has good connectivity. Nevertheless, this sub-study presents an initial approach contributing to the current discussion on implementing a mobility transition. Long-term monitoring is needed to observe these developments and provide information on where strategic approaches can be implemented at a small-scale level.

4.3 Sub-study 3: Urban arrival spaces

The following section summarizes key results of the journal paper 'Identifying and typifying arrival spaces in European cities – a methodological approach' by Gerten, Hanhörster, Hans and Liebig published in Population, Space and Place in 2022. The full version can be found in Appendix A.3.3. The own contribution is listed in A.1.1.

The global intensification of migration and mobility is accelerating urbanisation and posing challenges to the social fabric of cities due to increasing social and ethnic diversity and issues of socio-economic inequalities, integration and social cohesion (Heider et al., 2020; WBGU, 2016). The majority of immigrants first settle in specific urban areas characterised by affordable and accessible housing, but often described as ethnically segregated and deprived neighbourhoods

(Ostendorf & Musterd, 2011). Back in the 1920s, the Chicago School described these areas as 'urban transition zones' where immigrants arrive and social mobility starts (Park & Burgess, 1925). In the following decades, scholars have come to different conclusions about the role of these spaces in the integration process: the disintegrative effect of living in ethnic communities, the advantages of 'ethnic enclaves' (Wilson & Martin, 1982), 'immigrant enclaves' (Portes & Manning, 1986) or 'urban enclaves' (Zhou & Portes, 1992). With the concept of 'arrival cities' or 'arrival spaces', Saunders (2011) steered the discussion towards the local factors contributing to the social mobility of immigrants. This new research landscape considered arrival spaces to be characterised by high in-migration from abroad and population fluctuation, whereby the socio-economic status and ethnic diversity of such a neighbourhood can vary (Hanhörster and Wessendorf, 2020; Meeus et al., 2019). Further studies characterise these neighbourhoods as ethnically very diverse but with a constantly changing composition (Biehl, 2014), as neighbourhoods affected by social disadvantage and poverty (Schillebeeckx et al., 2019), or as having a high concentration of arrival-related opportunity structures, such as services (e.g., money transfer), places of worship (e.g. mosques) or social infrastructures (Hans & Hanhörster, 2020). The variety of literature assigning different characteristics to these urban areas illustrates the difficulties of a quantitative consideration of arrival spaces. Up to now, various methodologies have been used to measure in-migration from abroad or segregation and disadvantage, though none present a transferable approach to identifying and typifying arrival spaces in European cities. There is thus a lack of suitable methods to identify arrival spaces regardless of their social status and diversity on a small-scale level and to typify them on the basis of certain characteristics. Analysing neighbourhoods in a three-step procedure (see Figure 10), our methodology attempts to fill this research gap.

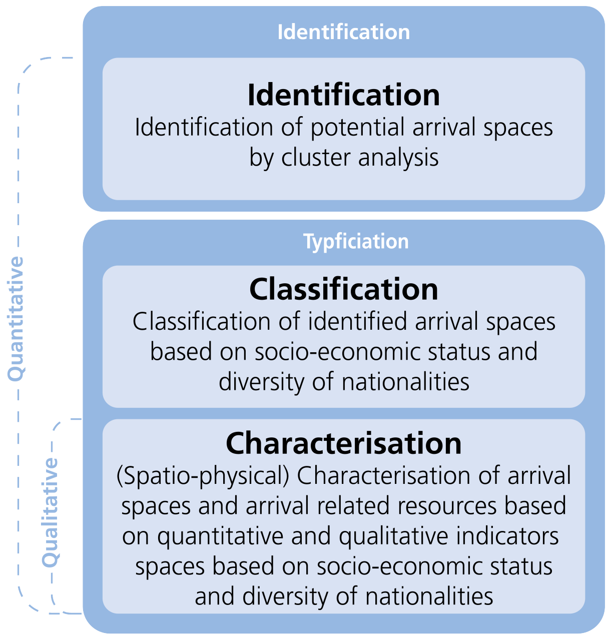


Figure 10: Step-by-step procedure to identify and typify arrival spaces (adapted from Gerten, Hanhörster, et al., 2022)

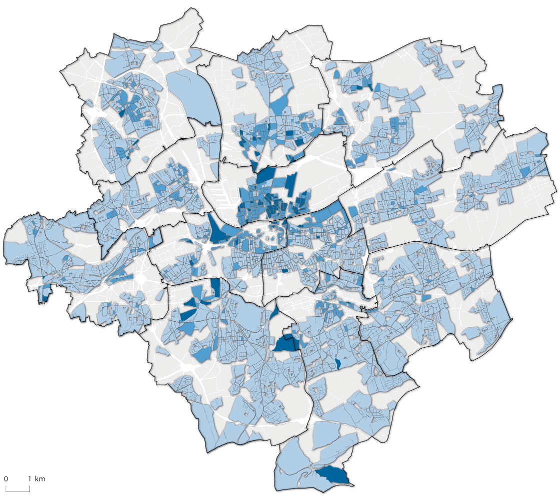
Identifying potential arrival spaces is the first step. Based on three key indicators characterising arrival spaces, we initiate a first explorative filtering using a hierarchical cluster analysis. This helps us to deal with the very different demographic compositions and conditions in European countries without defining thresholds. In contrast to other methodologies, we refrain from using economic indicators in this first step. The first indicator, the share of foreigners, refers to the migration background of a neighbourhood. As arrival spaces are home to earlier immigrants, newcomers can rely on existing infrastructures and resources (Hans & Hanhörster, 2020). The second indicator, population exchange, represents the high turnover of migrants within an arrival space. Such spaces are often the first place of residence and only a 'stop-over' before moving on to other cities or districts (Meeus et al., 2019). To shed light on the important function as places of international migration, the third indicator, arrivals from abroad, includes all movements into the city from abroad. The following applies to all three indicators: the higher the value, the higher the probability that the respective area is an arrival space. The individual clusters can thus be assigned a high to no potential as arrival spaces. In the next two steps, the neighbourhoods identified as potential arrival spaces are typified in more detail.

The second step involves classifying the spaces on the basis of their inhabitants' national diversity and socio-economic status. To quantify the national diversity, we make use of the SHDI to rate the richness and evenness of different nationality groups. The socio-economic status should be represented by appropriate statistical values, such as income, social welfare quota, employment rate or poverty risk. For both indicators we assign the values to four quantiles, distinguishing between *below average* (first quantile), *average* (second and third quantile) and *above average* (fourth quantile). This allows us to classify the arrival spaces in low/medium/high diversity and low/medium/high social status.

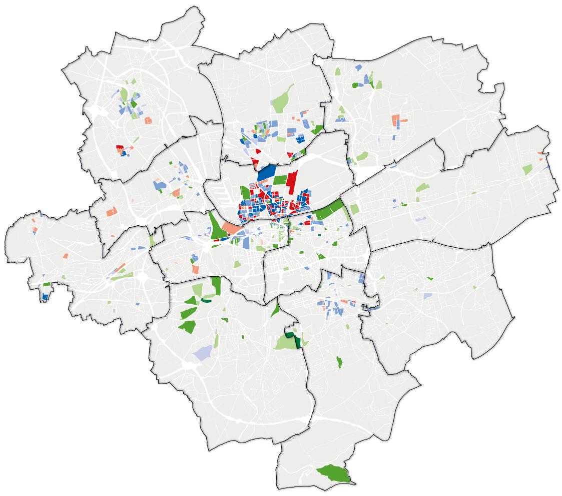
The last step, the spatio-physical characterisation, is intended to draw conclusions on the (arrival-related) resources, including urban structure, access to important arrival infrastructures, rent levels, and the location within the city. The urban structure is analysed by the construction volume, the proportion of residential building and population density. Following Saunders (2011), arrival spaces are highly dense and crowded spaces with ground-floor shops offering opportunities and services to new immigrants. Specific arrival-related infrastructures offer important resources to immigrants, such as money transfer or translation services, migrant associations or integration courses. These help newcomers in their integration by offering social interactions and the exchange of information. The density of these infrastructures also determines whether an arrival space is well-established or quite new. Additional information on access to affordable housing and participation in urban life can be derived from rent levels and the location of the space or respectively its distance to the city centre.

However, it quickly becomes apparent that quantitative analyses reach their limit when typifying arrival spaces in detail. Therefore, our methodology includes qualitative analyses, in which the urban structure and the foreign languages in the (semi-)public space are recorded and qualified by photo documentation. The analysis of the 'linguistic landscape' (Landry & Bourhis, 1997) gives an impression of spatial use, power relations, language diversity and intercultural networks (Kurtenbach et al., 2019). In addition, the distribution and intensity of foreign languages can be an indication of the languages spoken in an area, the ethnic diversity of the residents and whether an arrival area is well-established or quite new. Since this step requires an on-site visit and a lot of resources, interesting areas should first be selected on the basis of quantitative analyses.

As a first application of this methodology, we chose the city of Dortmund. The identification and classification results are presented in Figure 11. Located in the Ruhr, Dortmund has a longstanding migration history due to its former coal and steel industry, a magnet for waves of immigration. This makes Dortmund a suitable case study for analysing various layers of arrival. In the first step, we identified a large cluster of building blocks located in the inner city, namely Innenstadt-Nord. Characterised by high ethnic diversity and a low socio-economic status, this district has been the subject of various quantitative and qualitative studies (Gottschalk and Tepeli, 2019; Hans and Hanhörster, 2020). But we also identified other areas in the urban core and the outskirts as potential arrival spaces. However, especially in the outer areas, these were concentrated in a few contiguous but spatially isolated blocks with a comparatively higher social status and lower diversity. In general, however, it is noticeable that especially in the urban areas there are many large potential arrival neighbourhoods.



Cluster No.	Cluster Name	Share of foreigners (in %)	Population exchange (in %)	Arrivals from abroad (in %)	No. of city blocks
1	High Potential	++ (54.6)	++ (71.2)	++ (15.5)	120 (3.8 %)
2	Potential	+ (31.7)	+ (36.5)	+ (3.1)	446 (14.1 %)
3	No Potential	- (7.6)	- (18.7)	- (0.5)	2,608 (82.1 %)
Average values		(16.0)	(25.8)	(2.1)	3,174 (100 %)



Potential Arrival Spaces			Diversity: Shannon Index (low ← medium → high)		
			1.0 - 3.0	3.0 - 4.2	> 4.2
Social status:	Rating		-	o	+
		Quantil	1	2 3	4
Social welfare quota: high	0 - 15 %	- / 1	83 (14.7 %)	64 (11.3 %)	3 (0.5 %)
medium	15 - 28 %	o / 2 3	46 (8.1 %)	157 (27.8 %)	68 (12.0 %)
low	> 28 %	+ / 4	13 (2.3 %)	61 (10.8 %)	71 (12.5 %)

Figure 11: Identified and characterised arrival spaces in Dortmund (source: Gerten, Hanhörster et al., 2022)

The last step of the analysis provides the opportunity to describe the identified neighbourhoods in more detail. We were able to identify four different types of arrival spaces for our case study: the traditional arrival space, the suburban arrival space in high-rise buildings, arrival spaces for highly qualified immigrants and specially created arrival spaces. The traditional arrival space is located in the inner city, has a high population density, an urban building structure, high ethnic diversity and a low overall social status, although rents correspond to the city-wide average. We observed a high density of arrival-related infrastructures and foreign languages, indicating that these spaces are well-established. Such established arrival spaces have also been found in other cities such as Antwerp (Schillebeeckx et al., 2019), Düsseldorf (Heidbrink & Kurtenbach, 2019) and Leipzig (Haase et al., 2020). Suburban arrival spaces in high-rise buildings are characterised by their location and building structure, with density, social status and diversity comparable to the inner city. However, due to their location in suburban areas, less visible languages and less access to arrival-specific infrastructures, and their morphological characteristics, they constitute a unique type of arrival space. Studies from East Germany (El-Kayed et al., 2020) or Italy (de Vidovich & Bovo, 2021) have also identified this type. The third type are arrival spaces for highly qualified immigrants. These feature significantly different characteristics: a higher socio-economic status, higher rents, a slightly lower ethnic diversity and lower population density. One such space is located near the university in Dortmund. We can assume that the influx relates primarily to highly qualified immigrants studying or working there. However, similar structures can also be found in inner-city locations close to high-quality public transport, a feature attractive for highly qualified migrants (Maslova & King, 2020). The last type we identified is the specially created arrival space. We found two areas on the outskirts of Dortmund where people live in refugee housing rented from the city authorities. Distribution policies explain the isolated and peripheral location. However, this type can also occur in other forms, such as former military bases or purpose-built camps for people in the low-wage sector. Only a few studies consider this type, although it can be interesting to observe whether new arrival spaces are emerging nearby, established by former residents. Overall, it is very important to integrate this methodology into long-term monitoring. On the other hand, other urban phenomena can be observed due to the appearance or disappearance of arrival spaces. For example, potential arrival spaces can become attractive to socio-economically privileged groups, triggering gentrification processes (Haase et al., 2020). Furthermore, only four different types were identified in this observation area. An analysis over a longer period or the application of the methodology to a different study area may expand the variety of types.

It should be noted that this first attempt to identify and typify arrival spaces is not without limitations. However, the importance of small-scale monitoring of this issue has become particularly apparent in in recent times due to successive waves of refugees. Unfortunately, this importance does not go hand in hand with the current availability of data: small-scale, socio-demographic and -economic data are often subject to data protection legislation and thus difficult or impossible to obtain. This also applies to detailed movement data for analysing mobility patterns. Thus, not all social developments and phenomena in the city can be mapped and explored.

4.4 Interim results I

Each of the previous sections was dedicated to a research focus highly relevant for sustainable urban development. Based on important research questions for the respective sub-studies (see Figure 3), three tools were developed to explore and analyse urban space from different perspectives, considering growth dynamics, mobility structures and arrival spaces. To ensure their validity and quality, they were applied to different case studies. During processing, it became apparent that all three tools focused on different methodological aspects related to the research questions:

- **Chapter 4.1** focuses on drawing urban growth development paths for different zones of a city.
- **Chapter 4.2** presents a classification of urban mobility structures on a small-scale level reaching from the city core to the hinterland.
- **Chapter 4.3** illustrates a modular approach to identifying, classifying and typifying arrival spaces at neighbourhood level.

Although their design differs greatly, all tools meet the methodological requirements mentioned in Chapter 3.2. These served as a guideline but also as an orientation for the development of the methodologies. A review reveals that the tools meet nearly all requirements, though there are some constraints (see Table 3). The reproducibility – one of the hard requirements – of the methodology for identifying and characterising urban arrival spaces is partly limited. However, this only affects the qualitative part of the characterisation and typification of arrival spaces, as this process follows no defined algorithm. This also applies for one soft requirement, transferability, which somewhat complicates the procedure presented here. Furthermore, the limited availability of data on the small-scale socio-economic structure of the population and information on migration patterns makes it difficult to transfer the methodology to other areas. Overall, all the tools discussed in this thesis meet the requirements (almost) in full.

Requirements		**Urban growth dynamics**	**Urban mobility structure**	**Urban arrival spaces**
Hard	Reliability	x	x	x
	Validity	x	x	x
	Reproducibility	x	x	(x)
	Comprehensibility	x	x	x
	Consistency	x	x	x
Soft	Transferability	x	x	(x)
	Spatial scalability	x	X	x

Table 3: Requirements for the tools and their compliance (source: own elaboration)

However, it appears that, despite the focus on individual research areas, there are major overlaps and intersections. Based on three selected research branches connecting the different research foci, the next chapter deals with the vicious cycle of car dependency, transport equity and spatial segregation.

5 Cross-thematic research branches

The identification and elaboration of the research foci have already made it clear that the three sub-studies have significant overlaps despite their different thematic spotlights. A major advantage of the tools developed in this work is their small-scale analysis level and their spatial scalability, allowing the intersection of different indicators and a detailed view of the thematic overlaps. This additional empirical framework highlights the advantage of an integrative monitoring approach, as demonstrated by three examples in the research framework. The first section deals with the interaction between transport and land use, combining the research described in sub-study 1 and 2. A simplified concept of the vicious cycle of car dependency is used for this purpose. The second section explores the question of how to quantify inequality in a population's access to mobility. This includes ideas and methods derived from sub-studies 2 and 3. Finally, the third section deals with spatial segregation, combining the work and ideas from the research foci *Urban Growth Dynamics* and *Urban Arrival Spaces*. In contrast to the sub-studies, which analysed different case studies, the following two approaches focus on a single reference area, the Ruhr. Its characteristics and historical development have already been explained in detail in the description of the case study (see Chapter 3.3).

5.1 Measuring the interactions of transportation and urban land use: the example of the vicious cycle of car dependency

As already pointed out in this thesis and also in many other scientific works, there is a close interaction between transport and urban development that 'is not simple and one way but complex and two way' (Wegener, 2014). Several complex models address making correlations, dependencies and impacts measurable and transparent (Wegener & Fuerst, 2004). These use many different input factors and indicators, such as employment density, neighbourhood design, travel time or travel costs. The aim of this chapter is not to develop a complex interaction model, but to explore whether it is possible to measure the interaction of transport and land use using existing tools and spatial analysis techniques. The basis is the methodology used to classify urban mobility structures, as applied for the Ruhr. One main characteristic of this region, its polycentricity, is also reflected in the distribution of different mobility structures, as seen in Figure 12. The region's urban core, stretching from Duisburg to Dortmund, is characterised by consistently good public transport accessibility, with some highly walkable areas in the city centres. Car-dependent areas are mainly located on the outskirts of the cities, although in Mülheim, Bochum, Essen and Dortmund they are concentrated in the southern part. This urban core is surrounded by more rural towns and districts characterised by car-dependent cells. Due to the generally low population density, are only small local supply areas, while high-quality public transport stops are few and far between. For example, the districts of Wesel and Unna feature (visually) no pedestrian-friendly zones. This leads to the conclusion that a major urban-rural divide exists in the provision of mobility options, a conclusion backed by research into mobility and the provision of essential infrastructures (Regionalverband Ruhr, 2017).

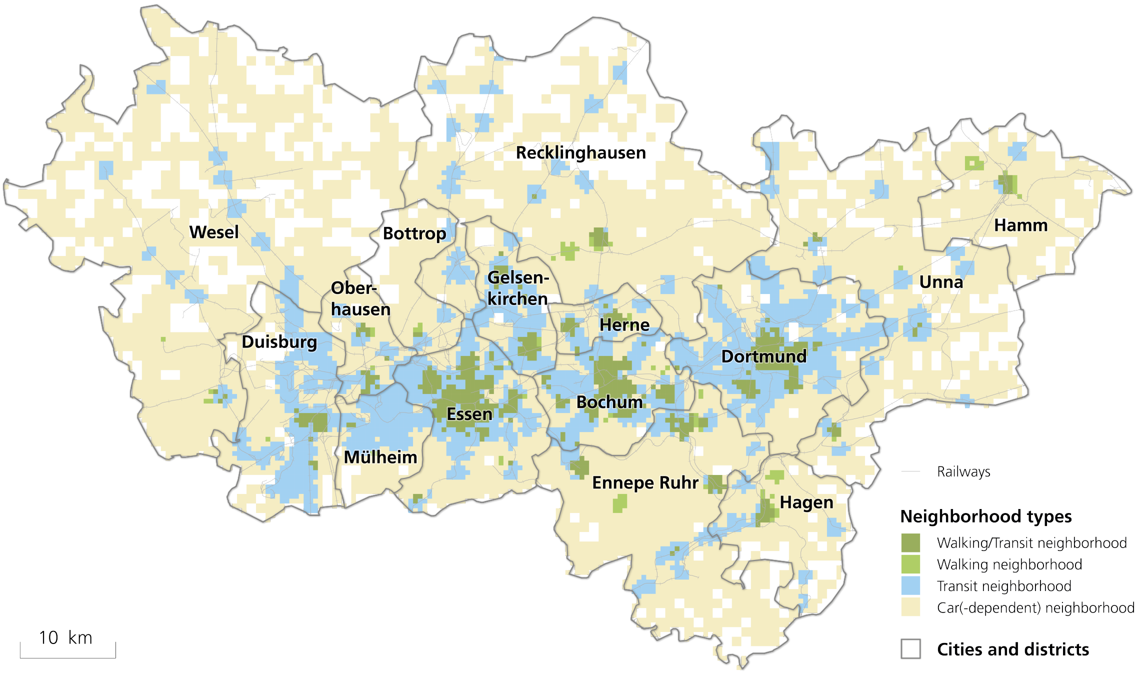


Figure 12: Urban mobility structure in the Ruhr on a 500 x 500 m grid (source: own elaboration)

One concept that deals with the interaction between transportation and urban land use was already introduced in the previous chapters: the vicious cycle of car dependency. Put in simple terms, this concept illustrates that increasing car ownership disadvantages alternative transport modes, and ultimately leads to a dispersed urban development, thus cementing car dependency. Since many of the steps in this concept involve very complex urban processes and political decisions without spatial reference, I use a simplified concept, focusing on four important but quantifiable indicators (see Figure 13).

- **(1) Change of car-density**: Car ownership is an important mobility indicator as it reflects the potential number of car users and gives an indication of the current transport infrastructure. This information derives from a 1 x 1 km grid used by the*Leibniz Institute for Economic Research* (RWI) and microm. The period 2005 – 2018 was selected (Breidenbach & Eilers, 2018).
- **(2) Share of car-dependent inhabitants**: This indicator represents the disadvantages of alternative transport modes and the dominance of cars in cities. High values indicate problems in the accessibility of alternative and environmentally-friendly forms of mobility, while low values point to a good public transport system and/or highly walkable areas. The value is generated at the intersection of the urban mobility structure and population data derived from RWI and microm. Due to a lack of data, no time series could be built up. Therefore, only the current status is calculated for this indicator.

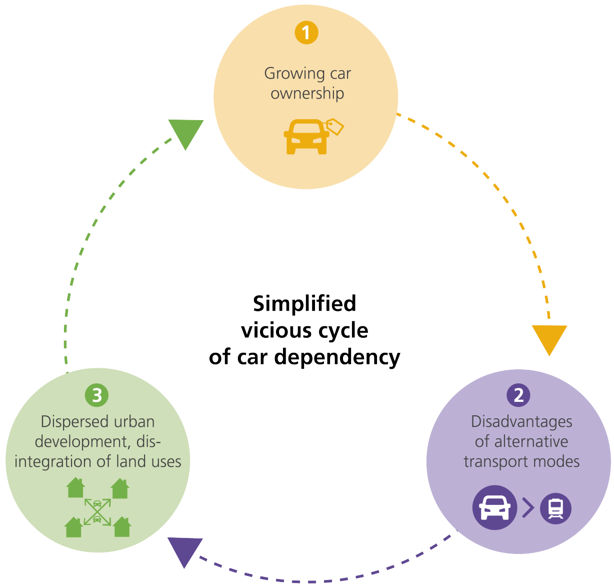


Figure 13: Simplified concept of the vicious cycle of car dependency (source: own elaboration)

- **(3a) New, car-dependent areas**: The share of new-builds in car-dependent neighbourhoods is indicative of a perpetuating car-dependent development and non-integrated settlement structures. Low values reveal a concentration of new urban developments in areas with good infrastructure, while high values demonstrate the opposite. Information on new-builds from 2000 to 2014 is derived from the GHSL.
- **(3b) Change of Dispersion Index (DI)**: As already shown in Chapter 4.1, the change of DI represents how (in)compact cities have grown. Negative values indicate compact growth, while positive values are indicative of urban sprawl. Within the vicious cycle of car dependency, dispersed urban development and the disintegration of land uses result from car-oriented transport planning and the creation of new capacities for cars and parking. A rising DI, as a sign of increased dispersion, can in turn lead to increasing car ownership and car density. Similar to the previous DI analyses, the GHSL for the period from 2000 to 2014 is also used here.

Figure 14 shows the results of the analyses calculated at city / district level. The following applies to all indicators: the lower the value, the less the cities are exposed to the structural problems associated with car dependency. When interpreting the results, however, the value ranges of the indicators should be considered. While (2) and (3a) refer to percentages from 0 to 100, the change rates of (1) and (3b) range from $-\infty$ to $+\infty$. Therefore, the latter are usually somewhat lower.

The change of car density indicator reveals interesting tendencies in relation to the structural conditions of the study area, as there seem to be no clear trends for urban and rural areas. In the cities of Bochum (-10.9%) and Mülheim (-7.8%), car density is decreasing, while it has increased significantly in other major cities (e.g., Duisburg 14.6% or Herne 12.3%). The rural districts of Wesel (10.2%), Unna (6.1%) and Recklinghausen (10.0%) have registered moderate

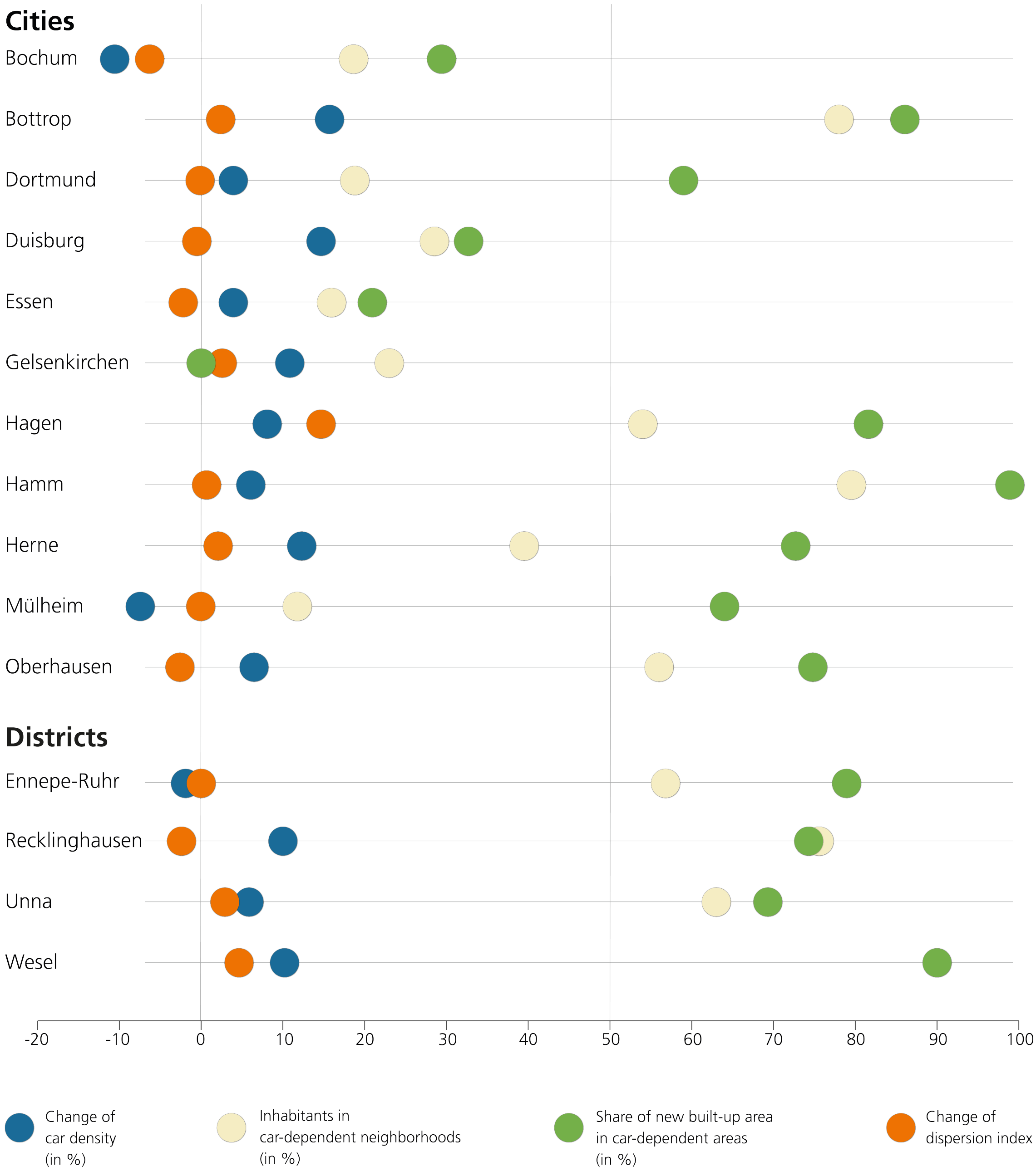


Figure 14: Indicators representing the vicious cycle of car dependency for the Ruhr (source: own elaboration)

to high growth in car ownership. Surprisingly, this does not apply to the Ennepe-Ruhr area, where car density has fallen by around 2%. However, it should be noted here that initial values in the rural areas were significantly higher. The first visual impression of the distribution of mobility options in the Ruhr area is confirmed by the crossing this mobility data with population data: in cities like Dortmund (19%), Bochum (19%), Essen (16%) or Mülheim (12%), only a small percentage of the population lives in car-dependent neighbourhoods. By contrast, the rural districts of Recklinghausen (79%) and Wesel (77%), but also more sparsely populated cities such as Hamm (79%), are significantly more car-dependent. With these trends in mind, let us now turn to the indicators dealing with dispersed urban development, starting with the share of new built-up area in car-dependent neighbourhoods. This indicator is very high in almost all cities and districts (Ø 63%), with a maximum of 99% in Hamm. Lower values can be identified in Bochum (30%), Duisburg (32%), Essen (21%) and particularly Gelsenkirchen (0.1%). However, the results are associated with a certain bias, as potential open spaces for built-up development are mostly located in car-dependent outskirts. This is particularly noticeable in more rural, predominantly car-dependent areas. Furthermore, densification in existing built-up areas is disregarded due to data limitations. But in terms of sustainable development and the economical use of land, this indicator remains suitable. As already mentioned, the value range for the last indicator, the change of dispersion, is lower. But there are also some interesting observations to be made. In total, only five cities show a reduction in the DI, i.e., an increase in the compactness of settlement areas, including major cities like Bochum (-6.3), Duisburg (-0.5) or Essen (-2.2). Surprisingly, Recklinghausen (-2.6), a rural district, is also affected. A major increase in dispersion is registered in the city of Hagen (14.5) and the rural districts of Unna (2.9) and Wesel (4.5). In all other observation areas, the settlement composition has changed only slightly.

Overall, it becomes apparent that, although city characteristics such as location, size or density, seem to have an influence on transport and settlement development, other factors also seem to play a decisive role in the interaction of land use and transport. Bochum, as a positive example with a low share of car-dependency, a reduction of car density, a comparably low share of new car-dependent settlement areas and an increasingly compact settlement structure, shows no signs of deepening car dependency. Negative examples in the sample are the two rural districts of Unna and Wesel. Both are quite car-dependent and have experienced a growth in car density, major developments in car-dependent areas and a dispersed settlement development. Therefore, there is a high probability that these two areas are locked into the vicious cycle of car dependency. From a spatial structure perspective, these results are not surprising, as both rural districts are located on the outskirts of the polycentric region. The opposite is true for Bochum which, while growing very compactly in the centre of the Ruhr, also has a well-developed public transport network.

5.2 Transport equity: socio-economic inequalities in the access of mobility options

The second important cross-thematic issue is transport equity, dealing with the socio-economic inequalities in access to various mobility options. This research branch is derived from the work in sub-studies 2 and 3. In the context of transport, the term equity is strongly related to the distribution of goods (van Wee & Geurs, 2011). The fact that groups of people do not always have the same or equal access to certain infrastructures or workplaces is obvious and not necessarily a problem. But it becomes a problem when this inequity persists for certain groups of people and leads to systemic disadvantage. Di Ciommo and Shiftan (2017) identified six features of population groups, that are relevant when considering transport equity: income, car availability, age, gender, household composition and place of residence. Another work defines mobility-related exclusion or mobility poverty as the 'process by which people are prevented from participating in the economic, political and social life of the community because of reduced accessibility to opportunities, services and social networks, due […] to insufficient mobility in a society and environment built around the assumption of high mobility' (Kenyon et al., 2003). In total, they identified eight dimensions of exclusion, including economic (e.g., unemployment), living space (e.g., geographical isolation), personal political (e.g., poor access to information) and societal (e.g., poor educational opportunities). The fact that social exclusion and mobility are strongly connected is evident when looking at the case of (un-)employment. Jobseekers with poor access to public transport and without a car are very restricted in terms of potential job opportunities. This makes transport equity an important cross-thematic issue. A broad overview of key components, framings and metrics is provided by Martens et al. (2019). Although there are many theoretical concepts of transport equity, the literature reveals only few methodologies for measuring it. Examples are provided by Lucas et al. (2016), who performed geostatistical analyses to operationalise equitable accessibility, or Falavigna and Hernandez (2016), who used different indicators to illustrate public transport affordability.

In line with the work done in the third sub-study, this analysis concentrates on deprived neighbourhoods characterised by a low socio-economic status. To measure inequalities in access of mobility options, the analysis needs additional input alongside information on access to different mobility options. I chose three key indicators describing socio-economic status: purchasing power per inhabitant, the unemployment rate and car density. Although the latter gives only a limited indication of a neighbourhood's economic strength, car density offers insights into access to mobility, especially regarding the question of mobility poverty. Similar to the last analysis, the information is derived from the 1 x 1 km grid provided by RWI and microm. To identify deprived neighbourhoods, this analysis follows a simple logic: where the most negative values of all three indicators overlap, the highest level of disadvantage exists. For this purpose, all three indicators are divided into four quantiles. Deprived neighbourhoods are those found in the 1st quartile of purchasing power and car density and the 4th quartile of unemployment rate (see Figure 15). These areas are concentrated in the northern cities of the Ruhr, particularly affecting Duisburg, Gelsenkirchen and Herne. Concentrations are also to be found in the smaller cities of Hamm and Hagen. Isolated pockets also exist in some rural areas (e.g., Recklinghausen or Unna). Overlaps between car-dependent and socio-economically disadvantaged areas are shown in Figure 15: they are mainly to be found in the transition zones between cities and their outskirts. However, it is unclear how much of the population is affected.

By linking these two analyses, a new key indicator of transport equity can be derived. Besides the presented indicator on the share of inhabitants living in car-dependent neighbourhood, we can calculate the share of inhabitants living in deprived neighbourhoods. The combination of the two is shown in Figure 16. Beginning with the share of inhabitants living in deprived neighbourhoods, the visual impression of the map is reflected in the values. The highest shares are concentrated in urban areas such as Gelsenkirchen (81%), Herne (74%), Duisburg (64%) or Oberhausen (47%), while they are lowest in the rural regions of Recklinghausen (20%), Ennepe-Ruhr (13%), Unna (12%) and Wesel (5%). Surprisingly, Bottrop and Mülheim have a

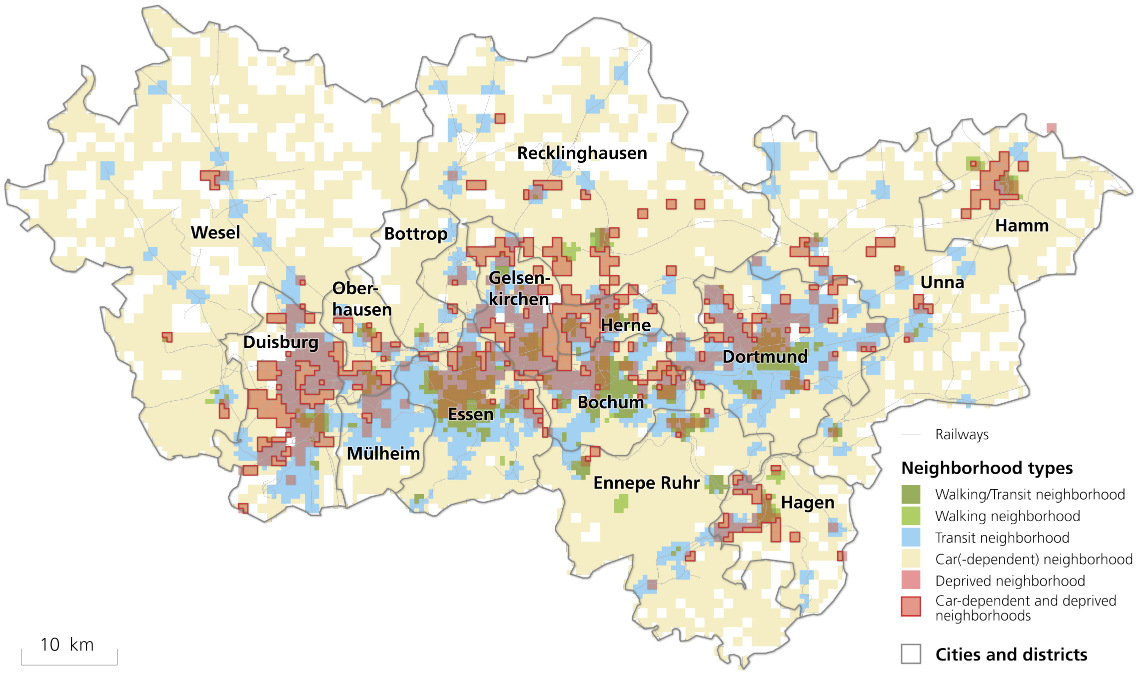


Figure 15: Urban mobility structure and socio-economic deprivation in the Ruhr (source: own elaboration)

similarly low value. Crossing these values with the information on car-dependency reveals the inequalities. At first glance, there is no significant difference between the cities and rural districts. The highest rate is found in Herne (28%), followed by Hamm (19%), Gelsenkirchen (18%) and Oberhausen (16%). We thus observe two general but common trends: urban areas have socio-economic problems, while rural areas have mobility problems. Moreover, transport equity primarily affects urban areas, but in a much more diverse way.

As stated in the presentation of the case study, poverty is concentrated in certain urban areas of the Ruhr region, primarily to the north of A40, a motorway also known as the 'social equator' (Kersting et al., 2009). However, these are mostly not the areas affected by mobility poverty or car dependency. One example is Gelsenkirchen, where around 80% of the population live in deprived neighbourhoods but only around 18% also in car-dependent areas. Already examined in detail in this work, another example is Dortmund's Nordstadt, a deprived area in socio-economic terms but with a high level of supply due to its urbanity. Therefore, the share of inhabitants affected by transport poverty in Dortmund is very low (5%). But even such low values are not to be ignored, as the residents of these areas area are highly restricted in participating in society, whether privately, publicly or at work. Therefore, this analysis serves as an indication of potential urban problems in the distribution of mobility options that can be reduced or resolved through targeted action.

Figure 16: Indicators representing transport equity in the Ruhr (source: own elaboration)

5.3 Spatial segregation: the influence of urban sprawl on residential segregation

In line with the research framework (see Figure 3), the last cross-thematic branch, combining the research foci of urban growth dynamics and urban arrival spaces, deals with the topic of spatial segregation. The causes and effects of segregation have already been considered in the concept of arrival spaces (see Chapter 4.3), but also in the framework of the work on the 15-minute city (see Appendix A.3.2), discussing the criticism of Edward Glaeser (London School of Economics and Political Science, 2021). Therefore, this section considers the relation between urban sprawl and residential segregation, starting from the question of whether it is possible to measure the influence of the former. A few years ago, Wei and Ewing (2018) asked what impact urban sprawl has on equitable development (regarding segregation, spatial mismatch, digital divides or environmental justice) at different spatial scales. Although there has been a strong focus on the environmental consequences and monetary costs of urban sprawl in recent decades, one strand of research has focused on these inequalities (see e.g., Jargowsky, 2002; Le Goix, 2005; Lee et al., 2018). This literature also reveals different methodologies for addressing the research question quantitatively. Examples are analysis of variance (Wheeler, 2006), regression analysis (Monkkonen et al., 2018) or agent-based modelling on income segregation (Guo et al., 2019). Conclusions differ: while some papers identified no influence (Wheeler, 2006), others found a negative correlation (Glaeser & Kahn, 2003) and still others a positive correlation (Jargowsky, 2002).

The question now arises as to whether similar results can be produced for the Ruhr with the tools developed in this work. As shown in Chapter 5.1 (and also 4.1), the growth trends of cities in terms of their compactness or diversity can be illustrated by changes in the DI. The situation is different with regard to residential segregation. As mentioned in Chapter 4.3, small-scale socio-economic data is scarce, especially when it comes to area-wide information. Therefore, this chapter draws on a secondary analysis by Helbig and Jähnen (2018) who calculated ethnic and social segregation indices for 74 cities in Germany. While their work does not allow comprehensive analyses, it covers at least part of the study area: 9 cities for social segregation and 6 for ethnic segregation. Besides the changes in the DI (from 2000 to 2015), my analysis includes the two indicators calculated by Helbig and Jähnen (2018): the development of social segregation (welfare recipients) from 2005 to 2014 and that of ethnic segregation (persons with foreign citizenship) from 2002 to 2014. Taking up the idea of the growth matrix from Gerten et al. (2019), Figure 17 compares the development of urban sprawl and segregation. This reveals four different types of development: (1) more segregated and dispersed, (2) less segregated and dispersed, (3) less segregated and compact and (4) more segregated and compact. Starting with social segregation, the analysis shows that the segregation index in all cities increases at different levels during the observation period. At the same time, their growth dynamics differ. Herne, Dortmund, Gelsenkirchen (low dispersed development) and Duisburg (low compact development) show few dynamic changes in urban sprawl and segregation. In Essen, Mülheim and Oberhausen, social segregation has increased sharply, while the settlement structure has become slightly more compact or is stagnating (Mülheim). Bochum and Hagen are outliers, with Hagen having the highest values of all cities. As far as ethnic segregation is concerned, the development trends have hardly changed, possibly due to the smaller number of cities. A less segregated development with a low urban sprawl tendency can be observed for Duisburg and Dortmund. The highest ethnic segregation tendencies are found in Mülheim.

Overall, however, the figure shows no clear, visualisable influence of urban sprawl on residential segregation. This is in line with the research mentioned above: there is no consensus on the influence or on any correlation between urban sprawl and spatial segregation. This is probably also due to the different methodologies and data sources used. Depending on the selection of the spatial level of analysis, indices and data basis, results can vary greatly (see e.g., Wong, 2004). Due to the small sample and methodological limitations, the analysis shown above is also not suitable for making conclusive statements on the correlation of urban sprawl and residential segregation. However, this analysis still offers some potential: cities with very dynamic and out-of-line developments, such as Hagen, can be considered in more detail, ex-

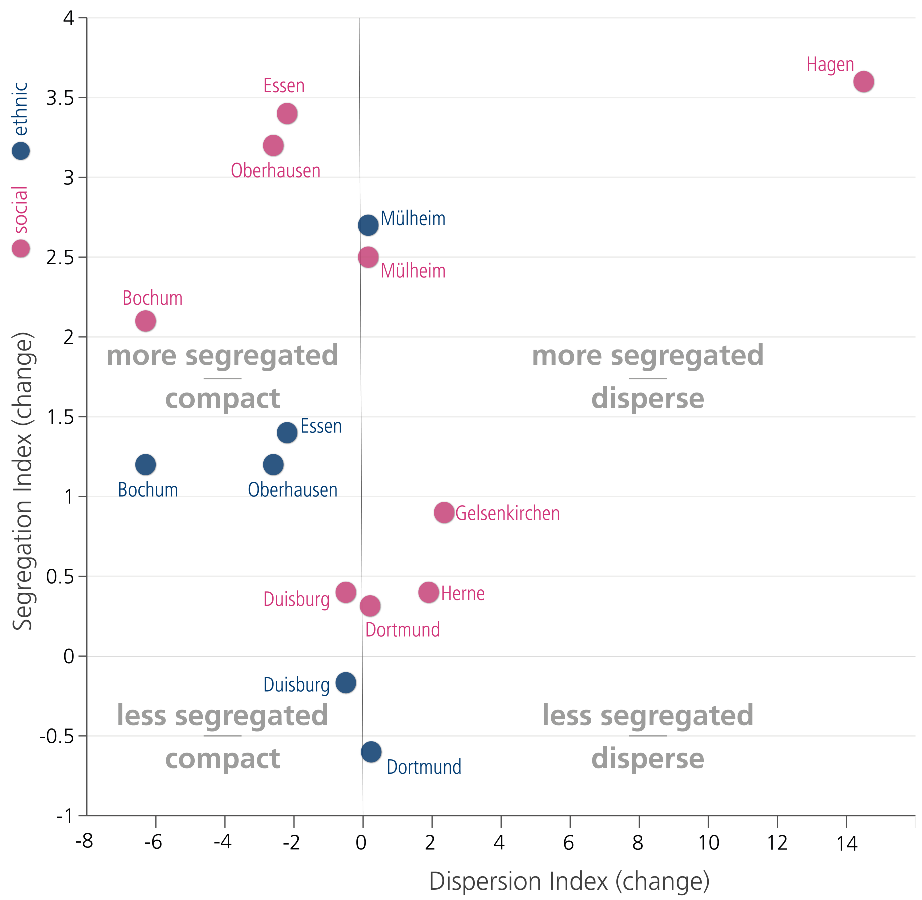


Figure 17: Comparison of segregation index and DI for the Ruhr (source: own elaboration)

amining the reasons for this. Indeed, the combination of the work done by Helbig and Jähnen (2018) and the analytical approach visualised in Figure 17 could provide new insights for this topic in further research considering a larger sample of cities.

5.4 Interim results II

This chapter presented the important analytical approaches for three different research branches derived from the selected main research foci. Based on the questions raised in this thesis, three simplified methodologies were outlined to measure (1) the interaction of land use and transportation using the vicious cycle of car dependency, (2) inequalities in access to mobility options and (3) the influence of urban sprawl on spatial segregation. In general, the three previous sections have again shown in detail that the thematic overlaps are of high scientifical and societal relevance. At the same time, however, it became clear that the tools developed in this work could only partially support these branches of research. The elaboration for transport equity worked particularly well, with Chapter 5.2 presenting a simplified but suitable way of defining a new indicator. This can be integrated into long-term monitoring to identify persisting negative processes, while at the same time the small-scale analyses offer opportunities to identify problem areas. Planning can implement targeted short-term measures by providing financial support or alternative mobility options. In the long term, however, these areas should also be strengthened in terms of infrastructure in the spirit of the mobility transition. Turning to the first analysis, Chapter 5.1 lists a body of literature investigating the relation between land use and transport and also existing quantitative concepts like the land use interaction models which include e.g., migration and population forecasts, land and housing market or economic forecasts (Wegener, 2014; Wegener and Fuerst, 2004). While these approaches or models are very accurate and multidimensional, they are also highly complex, resource-intensive and require a lot of information and input data. Therefore, such models are not suitable for long-term and transnational monitoring. By contrast, the cross-thematic analyses presented in this work offer simplified approximations using existing tools and indicators. In contrast to transport equity, no separate indicator has been developed to show the negative interactions of car dependency and dispersion, as the effects of the various factors are too complex and multifaceted. Instead, this approach relies on an overview of different indicators representing different facets of the vicious cycle of car dependency. The previous section, considering the influence of urban sprawl on residential segregation, had to rely on secondary analyses due to the poor availability of small-scale socio-economic information. This meant that the analyses could only be completed for part of the study area. In this thematic field, there are many different and more accurate approaches that can shed more light on the correlation and interactions. Ultimately, complex modelling, simulations and geostatistical analyses can generate significantly more insights for the research questions defined here. However, as already mentioned, these are often based on specific datasets and only applicable to certain areas. The choice is therefore between simple but variable analyses and complex and (mostly) location-based analyses.

However, the findings of this analyses are broadly consistent with work already done on the Ruhr region in research and planning practice. As a polycentric region struggling with structural transformation, the Ruhr faces enormous challenges that also affect the research branches analysed in this chapter. Bringing the strands of analysis together in a single observation area also helps complete the picture of a region, i.e., its strengths, but also its weaknesses. Besides the required structural changes in the economic sectors, the Ruhr also needs to promote the mobility transition for a sustainable urban transformation (Danielzyk et al., 2011). The analyses in Chapters 5.1 and 5.2 have shown that a shift away from cars to ecologically sustainable modes of transport can have a positive impact on land use and land consumption, as well as on inequalities in the urban space. An influence of those growth dynamics on social and ethnic segregation could not be verified. However, these processes should be intensively monitored for the Ruhr region.

6 Discussion

At the beginning of this thesis, it was shown that cities are facing enormous challenges. There are countless fields of action and tasks to support sustainable urban development, requiring efficient cooperation between planning, politics and research. At the same time, research players such as the WBGU have identified important levers for driving this process forward, calling for new datasets and indicators to monitor development dynamics in urban space. One fundamental aim of this thesis was to use the emerging data potentials and technical innovations to develop new tools for monitoring urban sustainability. As outlined at the beginning, it was not feasible to design a comprehensive monitoring system within the scope of this work. Instead, this thesis set the focus on three important research topics playing a leading role in the discussion on sustainable urban development: urban growth dynamics, urban mobility structures and urban arrival spaces.

All tools presented use currently available (data-)technical possibilities to investigate and answer important research questions within the thematic focus of sustainable urban development. Picking up the main research questions of this thesis, the next section deals with the question of how these tools can improve the spatial monitoring of sustainable urban development. Due to the broad scope, this chapter is divided into four sections. Chapter 6.2 deals with the importance of an integrative monitoring approach, taking up the insights of the previous chapter. Chapter 6.3 takes a critical look at the development of the tools, closely examining the current technical potentials and limitations of the data and software landscape. Chapter 6.4 examines the possibilities of transferring the tools into planning practice by looking at technical hurdles and reference points in the daily work of planners, while Chapter 6.5 deals with the overall limitations of this thesis.

6.1 Contribution of new tools for monitoring urban sustainability

Research question 1: How can new innovative tools improve the spatial monitoring of sustainable urban development?

The previous chapters used different perspectives to show which possibilities we currently have to explore urban space with the help of new spatial analysis tools. As mentioned in the introduction, this first part of the discussions is guided by four secondary research questions which, taken as a whole, provide an overview of the contribution that the tools can make to monitoring urban sustainability.

Research question 1.1: What insights (for sustainable development) can be derived from the results achieved bx the tools?

The respective sub-studies as well as the interim results in Chapter 4 have already sketched the opportunities offered by the tools for exploring and monitoring urban space. This section digs deeper, looking at which insights can be gained from their application for research and planning in general and specifically for monitoring urban sustainability.

- **Monitoring urban growth dynamics:** The methodology presented in Chapter 4.1 considered the DI and LUI as two key indicators for simplifying and capturing urbanisation trends. By combining these two indicators in a matrix, urban growth dynamics can be classified in four different development paths: (1) dense and compact, (2) dense and dispersed, (3) less dense and compact, (4) less dense and dispersed. In line with existing guidelines and objectives on land use and land consumption, these four trends can be assessed as negative or positive developments. The tool therefore allows information to be generated from past growth periods and assessing targets for land-saving and efficient land-use. Understanding how and why cities have grown is an essential part of spatial science. This methodology can be used to trace the effects of urbanisation processes (e.g., sub- or reurbanisation) or to study theories (e.g., zone models or central place). Moreover, it allows benchmarking with other cities and enables comparisons of (international) policies or planning systems. Integrating this approach into a monitoring system can also provide further insights into the negative impacts of urban growth dynamics on a city's social, environmental and physical fabric.

- **Monitoring the urban mobility structure:** The second methodology discussed in this thesis deals with the determination of urban mobility structures. Based on various indicators of walkability and the quality of public transport, the tool classifies neighbourhoods in three structural types: the walking neighbourhood, the transit neighbourhood and the car-dependent neighbourhood. Using this classification, various insights into urban (mobility) structures could be gained. Car-dependent areas are of particular importance for sustainable urban development and for making progress in the mobility transition. These neighbourhoods have infrastructure deficits and are therefore disadvantaged from a mobility perspective. By crossing this information with population data, strong indicators emerge which allow conclusions to be drawn on the car-dependent population. Observing this in a time-series with information on actual travel behaviour, e.g. modal split or mobile phone data, offers new ways to evaluate whether progress is being made in the mobility transition. The results of the analysis of mobility structures also allow statements to be made on the different structural types of cities. Through looking at structures beyond a city's administrative boundaries or in travel time isochrones, this analysis enables the identification of sub-centres. Combining this information with other conceptual frameworks on polycentricity (Krehl, 2017) or other zone modals could allow deeper insights into urban development processes.
- **Monitoring arrival spaces:** Used to identify and typify arrival spaces, the third methodology differs clearly from the first two for several reasons. In contrast to urban growth dynamics and urban mobility structures, no direct quantitative targets are pursued with regard to arrival spaces. Therefore, it is not easy to derive any positive or negative significance from the appearance or disappearance of arrival spaces – at least at first glance. However, changes in individual indicators such as socio-economic status or access to arrival-specific infrastructures can reveal problems in the social fabric of a neighbourhood or an entire city. At the same time, a shift or clustering of neighbourhoods can predict or indicate different processes such as increase in ethnic segregation (Ostendorf & Musterd, 2011), poverty concentration (Schillebeeckx et al., 2019) or gentrification (Haase et al., 2020), all of which contribute to shaping a city's social fabric.

These three short sections have shown what insights can be gained for the three main research foci. Ultimately, however, it is important to emphasise that urban development trends cannot be viewed in exclusively positive or negative terms with regard to their impact on urban sustainability. This takes me back to the problem of the ambiguity of the term sustainability or sustainable development mentioned at the beginning. James (2014) argues that many principles of sustainable planning ('planning for density is good', 'inclusion is an essential good') are insufficiently qualified. Instead, strict criteria would have to be set for when something has a positive or negative impact on sustainability: for example 'Planning for density is good only when it is based on good planning and when the conditions for increased density are well designed' (James, 2014). Especially the last methodology (for identifying urban arrival spaces) shows that the aim is not only to assess urban processes, but also to develop an understanding of their causes and effects and to interpret them in the context of the city as a whole system. Unachieved targets or milestones are easier to explain if one recognises the cause-and-effect relationships in space. This is also the subject of the next subsection, which takes a closer look at the functions of the tools.

Research question 1.2: What functions can the tools take on?

The second question relates to the functions that the tools can take on within a monitoring system. The three tools have specific characteristics due to their special thematic foci and the underlying research questions. This also applies to certain monitoring tasks. As outlined in Chapter 2, monitoring is versatile and an essential component of sustainable urban development. It is performed for various reasons, e.g., to gain information or as an early warning system. However, not all these tasks are equally important for all sustainable development research fields. As seen, the three research foci concentrate on different monitoring tasks. Following the work of Hanusch (2018), Table 4 illustrates which tasks the individual tools can perform in detail. As mentioned above, all three tools can provide valuable information for the research fields, analyse the current status, add transparency to planning and policy actions and aid learning. However, none allow forecasting and its verification. This would greatly increase their complexity due to the assumptions that have to be made. Instead, the tools for measuring growth dynamics and mobility structures allow objectives and milestones to be monitored. In contrast to the methodology used to assess urbanisation trends, which primarily refers to past developments, the other two methodologies can also be used as an early warning system. However, by adapting the datasets and time periods, this function can also be integrated into an assessment of urban growth dynamics.

Research question 1.3: What are their advantages compared to tools and indicators used in established monitoring systems?

To specify the potential of innovative approaches to monitoring urban sustainability, we also need to clarify the advantages that these have over the methodologies and indicators used in existing systems. The latter often rely on simple statistics and indicators to build up time series without any small-scale spatial reference. This means that information is usually only available at the level of the municipalities or higher. Examples include the SDG Tracker (Ritchie et al., 2018) or the Sustainable Development Report (Sachs et al., 2022) which track SDG achieve-

	Urban growth dynamics	Urban mobility structure	Urban arrival spaces
Gaining information	x	x	x
Analysing the status		x	x
Verifying forecast			
Controlling objectives		x	x
Early warning	x	x	
Transparency	x	x	x
Learning	x	x	x

Table 4: Monitoring tasks of the individual tools (source: own elaboration)

ments at federal state level. These offer less explanatory content as they are mainly used to check progress in achieving targets. This similarly applies to the BBSRs spatial monitoring, briefly introduced in the background section. In addition to some specific topics (e.g., housing market and Corona dashboards), the BBSR provides indicators at district or municipal level and smaller-scale data for larger cities in Germany. Although the data repertoire is very comprehensive, any indicators are simply generated from official statistics. Particularly for complex sustainable urban development topics, these have only limited explanatory value, as illustrated by the example of urban mobility (structures). While a number of accessibility-related indicators (for example, distances to supermarkets or train stations, car and population density) can be found here, there is little information on car dependency or the status of the mobility transition – in particular because such information is only available at municipal level. Therefore, researchers or decision-makers only have a blinkered view of reality, without being shown the spatial causes and circumstances. In contrast to the indicators used in existing monitoring systems, the approaches developed here offer more information and explanations for urban phenomena and developments. Basically, there are thus two key problems with established monitoring systems:

1. The indicators are too simple or only use basic data, meaning that only little information can be extracted.
2. The spatial level is too high, meaning that small-scale problems are not identified.

The localisation of spatial problems, changes in space over time, the overlapping and intersection of seemingly disjunct indicators - all this offers a more differentiated view on cities. Urban spaces are not always what they seem at first glance. New innovative methods thus allow us to look at spaces in different ways and to explore and quantify previously unknown phenomena. For researchers or decision-makers, this means a significantly expanded picture of spatial problems and correlations. However, there are other monitoring systems, such as the city regions monitoring (Institut für Landes- und Stadtentwicklungsforschung, 2022b) or the IÖR-Monitor (Leibnitz-Institut für ökologische Raumentwicklung, 2022), which use a mix of established and new, explorative indicators addressing various research fields and user groups. Such systems are well suited for integrating the tools developed in this thesis. However, it is important to note that all these systems were created for different reasons, on the basis of different legal foundations and for different user groups. As already mentioned at the beginning of this thesis, spatial monitoring is only superficially regulated in German planning law. In the longer term, it will be important to strengthen the legislation surrounding spatial monitoring. Furthermore, the publication of simple indicators and raw data is of high importance for research, policymaking and society to create transparency, in line with the spirit of the Open Data initiatives.

Research question 1.4: How should the tools be designed to increase their impact?
As already mentioned at the beginning of this thesis, there is no general agreement on how tools or methodologies for monitoring urban sustainability should be designed (Ness et al., 2007). Therefore, the last part of this overarching research question deals with their design and configuration. Many researchers have already shown that requirements for such tools vary greatly. The degree of complexity, the interpretability and visual reproduction of the results, temporal and spatial characteristics – these are just a few points that can increase or decrease the number of use cases and the impact on research. Some of these properties are difficult to classify and evaluate objectively, as all monitoring tools pursue different goals and therefore use different design and transfer approaches. However, all tools should meet the hard requirements listed in Chapter 4.4. Besides these hard requirements essential for their development, there are two decisive soft requirements: transferability and spatial scalability. Both are greatly affected by the choice of spatial analysis methods but also by the choice of (geo-)data. Due to their transferability, application of these tools in different regions of the Global North enables cross-border monitoring not constrained by administrative boundaries. As already stated, initial scientific project approaches have already demonstrated the benefits of such monitoring (BBSR, 2019). In general, it is important to be able to observe processes and developments over a large area, as these usually do not stop at administrative borders. The second soft requirement, spatial scalability, allows us to study and explore cities from different spatial perspectives, as different questions require different levels of spatial detail. To guarantee a high degree of flexibility and thus increase the impact of the tools, spatial scalability is important. However, there are some limits here in terms of content and the interpretation of the results (e.g., regional questions on growth dynamics should not be answered at neighbourhood level), but also technical limits related to the use of accurate datasets (e.g., socio-economic information at neighbourhood level should not be disaggregated to household level). Looking at the development of the tools, this thesis underlines the importance of ensuring that research questions are addressed and answered at the appropriate scale.

Overall, this section has used four research questions to demonstrate how new innovative tools can improve the spatial monitoring of sustainable urban development. New solutions are becoming available to expand (not replace) established monitoring systems and basic indicators, allowing deeper insights into sustainable urban development processes. Nevertheless, we should bear in mind that the tools presented in this thesis do not constitute ’quick fixes’ for the challenges currently facing cities. They are neither tools for direct use in planning, nor do they simulate or forecast future developments. Their greatest potential is as an information tool for assessing and exploring past and current urban development trends

6.2 Importance of an integrative monitoring approach

Research question 2: Why is it worthwhile developing an integrative monitoring approach linking research fields related to sustainable urban development and exploring their intersections?
This work has already shown that separating the research foci is quite complex due to the large overlaps and intersections. Similarly, there are many other research branches and questions that cannot be assigned to one overarching thematic field. In this context, integrative monitoring is becoming increasingly important, as it strives for an overarching approach to urban sustainability, as backed the statements of the WBGU (2016) and the United Nations (2018). However, there are currently no approaches as to how such a monitoring system should be designed. Although this thesis does not offer an explicit solution for the design of such a system, it has the goal of highlighting the value of an integrative approach by presenting three simplified, but important cross-thematic analyses using GIS techniques (Chapter 5). The first part explored possibilities to quantify the interaction of land use and transport based on the concept of the vicious cycle of car dependency. The second part combined the research fields of mobility and socio-economic inequalities to measure the degree of transport equity, while the third part analysed the influence of urban sprawl on residential segregation. These analytical strands are all based on indicators and tools developed in this thesis to address the question of the value of integrative monitoring. It could be shown that crossing existing data enables further branches of research to be explored. At the same time, the analyses have also revealed some disadvantages compared to existing concepts due to the simplified structure.

However, it is important to mention that analyses located between several research fields are not novel. Entire research branches, such as walkability, have been studied for many years in mobility research but also in public health or psychology. But such approaches are often neglected in monitoring. Although there are quite some existing integrative monitoring systems, such as the IÖR-Monitor (Leibnitz-Institut für ökologische Raumentwicklung, 2022) or the monitoring city region (Institut für Landes- und Stadtentwicklungsforschung, 2022b), there are hardly any covering cross-thematic topics or research branches. In many cases, these are isolated analyses or newly developed approaches, but without a long-term basis. This for example applies to TOD, an approach already introduced in this thesis. Combining the topics of land use and transport, it can help monitor the mobility transition and resource-saving land use, as already demonstrated in the works of Eichhorn et al. (2020) and Eichhorn et al. (2021) on the operationalisation of TOD. The analysis of urban mobility structures identifies areas in which the potential for land development should be realised as a matter of priority. This important issue for a city's sustainable growth is currently not adequately monitored. In addition to whole research branches, individual aspects of an integrative approach provide new insights and perspectives on specific topics. One example are the mobility options of arrival spaces, an aspect that has so far received little attention in the conceptual elaboration. As regards further characteristics of arrival spaces, their location has already been discussed in Chapter 4.3 and the corresponding journal paper (Appendix A.3.3). However, accessibility of mobility options is a very important aspect when discussing integration and the disadvantages of such neighbourhoods. With regard to the location of newly created arrival spaces on the outskirts of Dortmund, it appears that these are more or less dependent on cars. Especially for those migrants without the freedom to choose their place of residence, they should at least be given mobility options, as otherwise their participation and integration in society is at risk. Such examples of integrative analyses and monitoring approaches can provide new insights for urban research.

Overall, cross-thematic research shows how important it is to observe a city from different perspectives, thereby also promoting explorative monitoring. Following the logic of data-driven science, an integrative view of urban sustainability offers new insights into (as yet unexplored) urban phenomena. Especially in the current situation characterised by many challenges and dynamic developments, it is important to look at urban space in its entirety, not only in parts.

6.3 Potentials and limitations of tool development

Research question 3: What data and technical potentials / limitations are linked to the development of new monitoring tools?

It can be assumed that the increasing availability of data sources and processing options is not homogenous across all research fields. Some are gaining a major development boost through new technical achievements, while others are restricted due to their minor importance in research and politics or statutory framework conditions. The analyses presented so far and the impression from the overview in Figure 4 show that the availability of data sources and software is not homogenous across all research fields, meaning that the development and application of the tools are based on different preconditions. As the potentials and limitations of the developed concepts and tools have already been discussed in the respective chapters, this section serves to discuss an overall view thereof. One tremendous technical challenge to monitoring is the availability of valid data and time series. While this has no influence on the development of tools, it should be taken into consideration in their application. This applies not only to individual datasets, but also to linking and combining different datasets. Most of the datasets are not available annually but only at specific regular intervals (e.g., Copernicus land use data), for a specific year (e.g., census data) or for a specific point in time (e.g., OSM), or are very recent and thus not available historically (e.g., GTFS). This is a major limitation, especially when monitoring and building up time series. However, these data limitations vary depending on the research field.

Even in the first exploratory data search, a large number of interesting sources were found for the field of **Urban Growth Dynamics**. Until a few years ago, official land use registers or cadastral information were one of the most important sources in Germany for quantifying land use and land consumption. However, problems have arisen with the validity and continuity of the datasets. Adjustments to land use classes, massive changes in survey methodologies and a generally spatially and temporally inconsistent processing mean that the datasets are not fully comparable over space and time (Schmitz et al., 2021). There is thus a strong interest in up-to-date and comparable data bases in both science and planning practice. One way of circumventing these problems and establishing robust monitoring is the use of remote sensing. The data now offered by the *Copernicus programme*, together with enhanced ways of processing big data, are opening up new opportunities for this research field. Two projects demonstrating the benefits of these new technologies are the *Atlas of Urban Expansion* (Angel et al., 2016) and the *Incora Dashboard* (Institut für Landes- und Stadtentwicklungsforschung, 2022a). Nevertheless, even the remote sensing datasets have some problems in terms of accuracy, scale and validity. However, it can be assumed that these will decrease with further technical progress.

The research field of **Urban Mobility Structure** has also seen some technical progress in recent years, especially in transportation network analysis and public transport assessments. We identified tremendous potential created by the many open data initiatives of local transport associations making transit feeds available free of charge in different readable and processable data formats. These can be evaluated with the corresponding expertise but also integrated into other commercial or open-source tools, enabling multi-modal transport analyses. Furthermore, non-commercial projects and dashboards collect these datasets (see e.g., Interline, 2022). The sub-discipline of walkability has also experienced an enormous development surge in terms of technology and data in recent years. Now well established, the *WalkScore®* or *Walkability Index* provide new methodologies for quantifying pedestrian friendliness, with a range of tools, plugins or libraries made available through various commercial and open software to calculate these values. One example is the OS-WALK EU, completely made up of open-source components (Fina et al., 2022). However, the availability of data on infrastructures and Point of Interests (POIs) remains a problem. Although commercial providers such as Google or various geo-marketing companies offer this data for purchase, in addition to the usually high costs, the licensing conditions often go against any continuous and comprehensive monitoring. However, OSM offers a free and licence-friendly alternative which, although problematic in parts in terms of validity, is sufficient for many purposes, especially in urban areas. Moreover, we have seen a significant boost in data quality over the last few years, a trend set to continue. Slight problems, on the other hand, are still evident in the evaluation of bicycle-friendliness. Especially in cities, the availability and quality of data on cycling infrastructures are quite poor.

The greatest data availability problems and limitations are to be found in the field of **Urban Arrival Spaces**. One major problem is the poor availability of small-scale socio-economic data, such as purchasing power, unemployment rates or welfare quotas. This applies primarily to small-scale analyses, as data is often available at municipal or city district level. Obtaining data at the level of building blocks or small grid cells often entails great effort on the part of statistical offices and is subject to strict data protection regulations. However, this applies first and foremost to Germany, while other countries, such as the USA, have much more flexible ways of handling sensitive data, e.g., on ethnic concentrations (Portland State University, 2020). Indeed, Germany's very strict data protection laws are the cause of many monitoring problems, with the result that researchers often lack important data when addressing socio-economic disparities in depth and on a small scale. This in turn makes transnational analyses or even a monitoring system much more complicated, as comparable indicators are hardly available. The same applies to migration data. Due again to strict data protection regulations and low case numbers for certain immigrant groups, small-scale localisations or migration matrices are only possible with great effort. As shown in the analysis, different nationalities have to be grouped together in order to make this problem manageable. But new technical innovations may also help in this research field as well, for example through tracking migration using mobile phone data (Deville et al., 2014). By crossing such data with municipal data, new possibilities arise for modelling small-scale migration movements. But even here, there will probably be similar discussions over data protection.

In general, this thesis shows that we now have a variety of opportunities to further enhance the monitoring of urban sustainability. This is mainly due to new technical innovations and data, albeit not evenly distributed among the research fields. Following the concept of Schieferdecker et al. (2018), this work mainly used one layer of urban datasets, open data and open source, for the development of the tools. This was primarily done for two reasons: availability and transferability – as area-wide monitoring requires area-wide data. Besides the topic of open data, there are further emerging forces in the technical landscape. Big data, user-generated data, real-time data, simulations and forecasts in particular, are set to make fresh leaps forward due to the new analytical capacities, thereby offering new capabilities. One big problem at the moment is the insufficient availability of socio-economic data which makes it difficult to identify small-scale problems such as mobility equity, poverty segregation or environmental justice. After all, the effects of unsustainable development ultimately affect all inhabitants of a city. Without reliable data on them, monitoring faces almost insurmountable problems.

6.4 Transfer to planning practice

Research question 4: How can the tools be transferred into planning practice and in which contexts can they be applied?

The previous discussion about the benefits of the tools, their structure as well as their technical limitations leads to the question of who can or should use them. While the research community critically examines, applies and adapts them for its own activities, they can also help planning departments in their daily work. Therefore, the last research component of this thesis is dedicated to the question of how the tools can be transferred into planning practice and in which context they can be used. It must first be stated that the use of GIS, data and quantitative methods are already well-established in planning practice. Therefore, this chapter is not an appeal for planners to use GIS tools for the analysing and visualising urban problems. We have already seen other important works pointing out the potential, but also the problems, of GIS in planning-related practice (see e.g., Berchtold, 2016). Instead, the aim is to show in detail why and where the tools can be used. Transferability is thus examined from two perspectives: technical and contextual transferability. The technical aspect includes the use of the tools in planning practice. One fundamentally important point has already been mentioned in the requirements in Chapter 3. To foster transferability, open datasets and software should be used as far as possible, as this boosts independence from commercial products and allows the maximum number of users from planning practice to access the tools. Göçmen and Ventura (2010) highlight funding and knowledge as two main barriers to the use of GIS in urban planning. Although this study is somewhat outdated, it can be assumed that these reasons continue to play a significant role. More recent research has focused on the challenges of the new generation of data: 'However, with new methodologies come rising challenges related to the processing of data, data analysis, and how to build models that can accurately characterize complex city environments' (Ahn et al., 2022). Therefore, planning practice should prepare for these new technical challenges.

The second part of this section on transferring tools to planning practice examines where they can be used and what importance they can have there. The methodology for measuring urban growth dynamics presented in Chapter 4.1 can be used at both regional and local level. In particular, planning principles and objectives can be evaluated by using the matrix of growth dynamics and the related indicators. One example of this is the guiding principle of developing previously used land within a city in preference to further land-take on a city's outskirts (in German: 'Innentwicklung vor Außenentwicklung'). By using the matrix, we can track whether these principles are being followed. In this way, goals in different land-use plans can be assessed. However, it is also possible to derive information by considering just one part of the matrix. Expenditure on infrastructure can be contrasted with changes in settlement structures in terms of their compactness or dispersion. In the process of SDG tracking, municipalities can use the matrix to monitor land use efficiency (11.3.1). First applications of these indicators at regional level have already been discussed with experts from regional planning practice (Gerten, Boyko, & Fina, 2022). The results showed that compiling the indicators was somewhat complex, but comprehensible and in line with the expertise and experience in the case studies. In the field of urban mobility structures, the concept developed in this thesis offers some possibilities for its practical application. In their mobility plans, many cities adopt guidelines at an early stage for the development of different modes of transport or for the design of transport space. While the methodology cannot fully monitor target achievement or the impact of these plans, it can provide important information, for example, changes in the population of car-dependent neighbourhoods or visual insights into disadvantaged areas. At the same time, however, it also offers the possibility of using the tool quantitatively with a view to legitimising urban initiatives or projects. Examples of this are innovative ideas such as traffic calming, the removal of parking spaces, new forms of transport management or a general redesign of streets in favour of active forms of mobility. Results can be linked with information on actual travel behaviour or existing models of transportation forecasting. The research focus on urban arrival spaces also offers many options for planning practice, especially for social reporting and social space monitoring. This refers to the issues of immigration, refugees, segregation and deprivation, all of which have become increasingly important in recent years. In this context, small-scale analyses also enable selective measures such as neighbourhood management and other supporting contact points. This in turn facilitates integration in certain neighbourhoods. Similarly, issues such as socio-spatial segregation, gentrification tendencies and displacement processes are essential features of monitoring social space. Especially in this field where data for research is hard to come by, planning departments and municipalities have much better opportunities.

Although the last sections have shown that there are many links to the daily work of practitioners and presumably only low technical obstacles, it is very challenging to implement new methods and contents in practice. Reporting in planning practice is often based on existing and long-established indicators and topics with which stable time series can be formed and changes monitored. Therefore, most reporting uses simple indicators that can be generated from official statistics. However, there are already a few examples from practitioners that show that certain concepts and methods from research mentioned in this work have already been taken up in German cities. One is the concept of walkability and the development of an index for Munich (Sedlmeier, 2022). Others deal with the identification of arrival spaces in Düsseldorf (Heidbrink & Kurtenbach, 2019) and Munich (Hanslmaier & Kaiser, 2019) or the segregation of and discrimination against certain population groups (Stadt Frankfurt, 2021). Discussion forums or networks can make an important contribution to bringing new concepts closer to planning practice. This is where scientists can exchange ideas with practitioners and define framework conditions for a transfer. Finally, transfers are not to be taken for granted. This chapter shows that the path of new technical tools from their development in research to their application in practice can be extremely arduous. Both sides must be held accountable here: research must provide the appropriate methods and adapt them as needed, and practitioners must critically engage with them.

6.5 Limitations of this work

Overall, this thesis has certain limitations. The broad thematic scope chosen meant that the basic concepts and theories of the individual research foci could only be examined selectively. For this purpose, important literature was referenced at appropriate places and thematic boundaries drawn. As a result, the work walks a tightrope between the added value of a cross-thematic and overarching monitoring approach while not responding to important questions. Ultimately, however, I think the research agenda has usefully narrowed the scope of this work. In line with this, however, the selection of research foci is also a general limitation of this work. Only a small excerpt of the overall work on urban sustainability could be covered through the three research foci and three cross-sectional analyses. For example, the topics of urban economy or climate change were not directly addressed. However, the focus topics show their importance for monitoring urban sustainability. The development of a comprehensive and overarching monitoring system requires significantly more resources. The establishment of further indicators to cover a broader range of topics is itself a matter for further research. Another minor limitation concerns the development of the tools: the aim was to develop tools with a clear and easy design, thereby opening them up to a wide range of users in the Global North. This meant that the full potential of the current technical landscape could not be leveraged. One example of this is the use of certain datasets likely to have lower validity (e.g., open data rather than data from commercial providers / built-up data instead of building volume) or algorithms that require less performance (e.g., isochrones instead of accurate distances), as discussed in the full journal papers (see Appendix A.3). However, tool design can be adapted in terms of the algorithms and input datasets used. It should also be noted that the methodologies discussed in the cross-thematic research branches are not fully developed. The aim of this chapter was more to demonstrate the importance of an integrative monitoring approach and the versatility of the developed tools. Therefore, these topics and related analytical concepts deserve more attention in further research. However, despite the limitation mentioned here, this work is a valuable contribution to research on monitoring urban sustainability.

7 Concluding remarks and need for further research

This thesis has contributed to determining the potential of new methodologies and their relevance for monitoring urban sustainability. At its beginning, I elaborated major challenges for cities in terms of a sustainable development, but also showed the opportunities that this decade offers. This potential lies primarily in the new technical achievements and the expansion of the data landscape, giving a boost to new monitoring applications. Based on this idea, I identified three important research fields playing a leading role in the discussion on sustainable urban transformation: urban growth dynamics, urban mobility structure and urban arrival spaces. The sub-studies were concerned with the development of new methodologies to explore urban problems and understand urban space from new perspectives. In the first empirical part, a methodology able to represent complex growth dynamics in a simplified form was presented (Gerten et al., 2019), while the second sub-study presented a tool enabling the identification of urban mobility structures and allowing conclusions to be drawn on the mobility transition (Gerten & Fina, 2022). The last empirical section was dedicated to a methodology to identify, classify and typify arrival spaces (Gerten, Hanhörster, et al., 2022). All methodologies have shown the added value they offer for monitoring urban sustainability and why they have some advantages over applications and indicators in established monitoring systems. Based on these cornerstones, the second empirical part was dedicated to three cross-thematic analyses located between the main research foci. Two main insights were gained: (1) cross-thematic analyses are important because they often deal with less researched branches of spatial science, (2) well-designed tools can be used for different purposes and research questions. Overall, some important lessons can be learned from this work:

- Newly developed tools (of this thesis), in contrast to established monitoring systems, enable the exploration of urban phenomena and problems.
- Variable-scale analyses are essential for exploring and understanding urban problems because of their flexible use (e.g., intersection or aggregation).
- Valid and easily accessible information on socio-economic structures is of enormous importance but difficult to obtain.

- Open data and open source are gaining importance in the development of tools, as they generally increase flexibility and transferability.
- Transferability of applications to other spaces is crucial for monitoring developments across administrative borders.

However, there is a need for further research or prospects for further development on several points in this work. One point concerns the biggest limitation, namely the broad scope of application. Although the importance of new tools for monitoring urban sustainability could be demonstrated with the three main research foci, further insights can be gained through the implementation of additional research fields and indicators. This would also offer new perspectives for the integrative monitoring approach, which could be illuminated in this work, but still has significant dormant potential. Although it was possible to show the benefits of monitoring cross-thematic research branches, no statement could be made here about how future integrative monitoring systems should be designed. Ideally, new systems based on data-driven science will allow the free overlapping of indicators from different thematic areas – but this will require further technical development and content improvement. Furthermore, the instruments developed in this thesis should also be evaluated in more detail after their first application in research and planning practice, as it is necessary to calibrate the tools. Finally, it is important for me to emphasise again that this thesis does not offer a solution to the problems mentioned at the beginning. With the urban transformation, cities are facing a complex upheaval that requires support from many parties. But this thesis can at least make a small contribution to support this process. The tools developed for monitoring urban sustainability offer research, planning and politics new bases for decision-making and the opportunity to locate problems in the urban space.

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A Appendix

A.1 Formalities

A.1.1 Requirements for a cumulative dissertation

This dissertation is cumulative, i.e. the empirical basis is derived from three published journal papers. All journal papers meet the requirements of §10 of the PhD Regulations as revised in 2018:

1. All journal papers contain at least 30,000 characters of the doctoral candidate's own work.
2. All journal papers are published.
3. All journal papers are closely thematically related.
4. All journal papers have first authorship.
5. All journal papers have no substantial overlaps.

Parts of this cumulative dissertation are:

1. Gerten, Christian; Fina, Stefan; Rusche, Karsten (2019): The Sprawling Planet: Simplifying the Measurement of Global Urbanization Trends. In: Front. Environ. Sci. 7, Artikel 140. DOI: 10.3389/fenvs.2019.00140.
2. Gerten, Christian; Fina, Stefan (2022): Scrutinizing the buzzwords in the mobility transition: The 15-minute-city, the one-hour metropolis, and the vicious cycle of car dependency. In: Projections 16: Measuring the City: The Power of Urban Metrics). Retrieved from: https://projections.pubpub.org/pub/g7vtbyns/release/1.
3. Gerten, Christian, Heike Hanhörster, Nils Hans, and Simon Liebig (2022): How to Identify and Typify Arrival Spaces in European Cities—A Methodological Approach. Population, Space and Place. https://doi.org/10.1002/psp.2604.

All three journal papers are published in peer-reviewed journals, are closely related but have no substantial overlaps. All three journal papers are co-authored, with first authorship and main responsibility in the hands of the PhD student. In the case of the three papers mentioned above, the own contribution is similar: the basic idea, the content and technical conception of the article and the implementation of the empirical study were in my area of responsibility. When writing the papers, the work of the co-authors focused on compiling the theoretical background (section 2 of each paper). Thus, for all papers mentioned above, the personal contribution was more than 30,000 characters. The approximate number of characters per paper and section (without spaces) can be found in the following table:

Paper	**(1)**	**(2)**	**(3)**
1. Introduction	9,000	3,000	4,000
2. Theory & Background	11,000	11,000	5,000
3. Research design (Data & Methods)	15,000	11,000	15,000
4. Results / Application	16,000	8,000	10,000
5. Discussion	8,000	8,000	7,000
6. Conclusion	2,000	2,000	2,000
Total	61,000	43,000	43,000

A.1.2 Eidesstattliche Versicherung

Gemäß § 11 der Promotionsordnung Fakultät Raumplanung der Technischen Universität Dortmund (in der Neubekanntmachung von 2018) erkläre ich:
Ich versichere hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Titel „New Tools for Monitoring Urban Sustainability – Challenges and Opportunities for Cities in the 2020s“ selbstständig und ohne unzulässige fremde Hilfe angefertigt habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie wörtliche und sinngemäße Zitate kenntlich gemacht. Die Arbeit hat in gegenwärtiger oder in einer anderen Fassung weder der TU Dortmund noch einer anderen Hochschule im Zusammenhang mit einer staatlichen oder akademischen Prüfung vorgelegen.

Ort, Datum	Christian Gerten

A.2 Additional publications supporting the idea and technical basis of this dissertation

1. Eichhorn, Sebastian; **Gerten, Christian**; Siedentop, Stefan; Rönsch, Jutta; Diller, Christian (2020): Baulandpotenziale an Haltepunkten des schienengebundenen Regionalverkehrs in Nordrhein-Westfalen - Umfang, Qualität und Perspektiven. Dortmund (ILS-Working Paper, 3). Retrieved from: https://www.ils-forschung.de/files_publikationen/pdfs/ils-working-paper3.pdf.

2. Eichhorn, Sebastian; **Gerten, Christian**; Diller, Christian (2021): Bewertung und Klassifizierung von Bahnhaltepunkten in Nordrhein-Westfalen. Ein methodischer Ansatz zur Operationalisierung von *Transit-Oriented Development*. In: RuR 79 (1), S. 21–38. DOI: 10.14512/rur.28.

3. Fina, Stefan; **Gerten, Christian**; Gehrig-Fitting, Katinka; Rönsch, Jutta (2019): Geomonitoring und die große Transformation – Methoden zur kritischen Bewertung von nachhaltiger Raumentwicklung. Dortmund ILS-TRENDS [extra].

4. **Gerten, Christian**; Boyko, Dmitry; Fina, Stefan (2022): Patterns of Post-socialist Urban Development in Russia and Germany. In: Front. Sustain. Cities 4, Artikel 846956. DOI: 10.3389/frsc.2022.846956.

5. Otsuka, Noriko; Wittowsky, Dirk; Damerau, Marlene; **Gerten, Christian** (2021): Walkability assessment for urban areas around railway stations along the Rhine-Alpine Corridor. In: Journal of Transport Geography 93, S. 103081. DOI: 10.1016/j.jtrangeo.2021.103081.

6. Taubenböck, Hannes; **Gerten, Christian**; Rusche, Karsten; Siedentop, Stefan; Wurm, Michael (2019): Patterns of Eastern European urbanisation in the mirror of Western trends – Convergent, unique or hybrid? In: Environment and Planning B: Urban Analytics and City Science 46 (7), S. 1206–1225. DOI: 10.1177/2399808319846902.

7. Fina, Stefan, **Gerten, Christian**; Pondi, Brian; D'Arcy, Lorraine; O'Reilly, Niamh; Vale; David Sousa; Pereira. Mauro; Zilio, Samuele (2022). OS-WALK-EU: An Open-Source Tool to Assess Health-Promoting Residential Walkability of European City Structures. Journal of Transport and Health 27:101486. https://doi.org/10.1016/j.jth.2022.101486.

A.3 Journal papers meeting the requirements of a cumulative dissertation

In the following sub-chapters, the reader will find the three journal articles that form the basis of this work. In order to maintain the layout and design of the overall work, these articles have been revised, but their content is identical to the published versions. The original versions can be accessed online via the respective link / DOI:

1. A.3.1 The Sprawling Planet: Simplifying the Measurement of Global Urbanization Trends
(Link: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00140/full)

2. A.3.2 Scrutinizing the Buzzwords in the Mobility Transition: The 15-Minute-City, the One-Hour Metropolis, and the Vicious Cycle of Car Dependency
(Link: https://projections.pubpub.org/pub/g7vtbyns/release/1?readingCollection=41f24860)

3. A.3.3 How to Identify and Typify Arrival Spaces in European Cities- A Methodological Approach
(Link: https://onlinelibrary.wiley.com/doi/10.1002/psp.2604)

A.3.1 The Sprawling Planet: Simplifying the Measurement of Global Urbanization Trends

The Sprawling Planet: Simplifying the Measurement of Global Urbanization Trends

Authors: Christian Gerten*, Stefan Fina, Karsten Rusche

Journal: Frontiers in Environmental Science

Section: Land Use Dynamics

Published: 25 September 2019

DOI: https://doi.org/10.3389/fenvs.2019.00140

Citation: Gerten C, Fina S and Rusche K (2019). The Sprawling Planet: Simplifying the Measurement of Global Urbanization Trends. Front. Environ. Sci. 7:140. doi: 10.3389/fenvs.2019.00140

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Abstract: Recent decades have been characterized by a rapid and steady urbanization of the global population. This trend is projected to remain stable in the future and to affect land use patterns in multiple ways. Monitoring and measurement concepts for urbanization processes have presented difficulties with the multitude of driving forces and variations in urban form as well as the assessment of outcomes of sometimes contradictory objectives for economic, social, and environmental policies. The monitoring frameworks that are employed with the aim of assessing the land use changes related to urbanization break down this complexity into singular dimensions that can be measured with individual indicators. Such monitoring allows planners and policy analysts to assess new urban growth against sustainable development criteria. Examples include compact city policies that allow urbanization to happen in suitable locations rather than laisser-faire urbanization that can happen regardless of environmental impacts and resource efficiency. In this context, we note that monitoring methods are most often designed for case studies in Europe or North America where urban structures are rather mature and consolidated. However, such monitoring can provide crucial information on urban development at a phase at which structures are currently evolving and can potentially still be modified. This is frequently the case in developing countries. Given this background, this paper presents an approach to simplifying the measurement of the land use changes related to urbanization with a new methodology. This paper condenses the needed measurement components into two dimensions: land use inefficiency and dispersion. The method can be used globally based on the newly available Global Human Settlement (GHS) layer that is available from the European Commission at no cost. In an initial application of the method to over 600 cities worldwide, we show the land use trends related to urbanization by continent and city size. In summary, we observe a consolidation of urban centers worldwide and continued sprawl on the outskirts. In European cities, a consolidation phase of urban structures began earlier, and cities are more mature and develop less dynamically compared to those in other regions of the world. More in-depth analyses of case studies present results for Paris, France, and Chicago, United States. In the case of Paris, the method helps to illustrate the growth pressures that led to massive urban sprawl on the outskirts with a continued densification of the inner city. In the case of Chicago, we observe a type of urban sprawl that goes along with the waves of suburbanization with population loss in the inner city and continued urban sprawl on the outskirts that are consolidated over time.

Keywords: urban land use change, urban sprawl, density, dispersion, global human settlement

Contents

1 Introduction

Urbanization has been a megatrend of global land use change that can be observed in all parts of the world. By 2050 close to 70 % of the global population will live in cities (Eurostat, 2016). The reasons that explain why the global population is more attracted to city life than ever have been widely discussed in the literature (see for example Adli, 2017). Many lines of argumentation suggest the so-called “urban advantage” that drives urbanization: city life is associated with better prospects for prosperity and progress, access to services, education, and amenities, as well as a richer cultural life. However, from a sustainability point of view, this promise may only hold true for the most attractive inner city locations where the distances between destinations are walkable, public transportation is good, and there is a density of people and activities result in what is perceived as urbanity. As a matter of fact most urban growth happens in the surrounding areas: We are living on a 'suburban planet' and are trying to 'make the world urban from the outside in' (Keil, 2018). These processes are not uniform though, the dichotomy between spatial categories has increasingly been contested over the last years. Suburbanization can have functional subcenters of high urbanity, peri-urban areas can consolidate over time to dense urban fabric, rural areas have centers with urban cores, and a high level of centrality and service quality (Hugo and Champion, 2017). The continuum between urban and rural areas becomes even more blurry in polycentric regions, where networks of cities form large metropolitan areas that exhibit a diverse set of land uses and urban functions (Danielzyk et al., 2016). It is increasingly becoming difficult for applications in urban land use monitoring to delineate functional urban areas in order to report on land use policies and related objectives. One such objective is to combat excessive forms of urban land take. This can be frequently observed in suburban areas, where the influx of people and the building activities that are needed to accommodate increased residential, industrial, and business land uses give rise to what is often labeled urban sprawl. The term 'urban sprawl' has not yet been clearly defined. The term basically describes a form of urban growth whereby residential areas and social classes are highly segregated and dispersed over space, distances to amenities and workplaces can be comparatively long, and architecture lacks diversity (Galster et al., 2001; Wolman et al., 2005; European Environment Agency, 2006; Soule, 2006; Couch, 2008; Frenkel and Ashkenazi, 2008; Wei and Ewing, 2018). Urban theory concerned with sustainable planning has identified this form of urban growth as problematic. Expansions of urban areas should not be subject only to demand factors such as the housing preferences of the urban population or land market conditions. Planning regimes must manage urbanization with more foresight before unsustainable and irreversible urban sprawl structures are established to prevent the impacts of inefficient and environmentally harmful urban land use (Soule, 2006). Examples of such planning include urban containment policies or regional planning approaches that work with spatial concepts to optimize land use change (i.e., transit-oriented development or nodal growth, see Calthorpe and Fulton, 2010). Evidence-based policy aims to increase urban densities along development axis and nodes of good public transport accessibility and high quality service provisions, strengthening the links between the urban core and subcenters in such concepts. Favoring urban development in such a way is complemented by development restrictions in the interspaces between development axes. The objective of spatial planning in this line of thinking is to minimize the environmental impact of land conversions to sealed surfaces and ensure good outcomes for resource efficiency, accessibility and mobility and at the same time to prevent social imbalances with mixed-use urban design and affordable housing areas. The monitoring of these processes, however, is complex, since it is almost impossible to assess the causalities of land use change between the effects of spatial planning policies and global trends. Another difficulty is that such functional relationships are difficult to assess when analyzing land use change. Dedicated indicators that measure different aspects of dispersion, density, concentration, and other features of urban land use structures are typically employed to overcome this problem (Tsai, 2005; Herzig et al., 2018).

Early attempts to conceptualize sustainable urban development have identified three main characteristics, which are referred to as the three D's of urban development (diversity, density, and design, Cervero and Kockelman, 1997). Other researchers have enhanced this view and presented measurement concepts for urban sprawl. The work of Siedentop and Fina (2010), for example, takes a similar approach and focuses on the state and trends of land use in terms of surface features (urban land use change), patterns (urban land use structure), and density (population or business density). To date, the implementation of such measurement concepts has mainly been conducted in study areas in the Global North, using advanced geodata structures and population registers to calculate indices. Most scholars agree that there cannot be one combined index to measure urban sprawl. One must approach the topic with multiple criteria and indicators that capture the complexity of the different aspects that drive the land use change related to urbanization (Frenkel and Ashkenazi, 2008; Fina, 2013).

Global measurement concepts for urbanization have been studied in a meta-analysis by Seto et al. (2011). The authors look at 326 studies and applied four indicators of land expansion and population growth. In the results they identify the countries with the highest urbanization rates and analyzed correlations with factors like GDP growth or locational aspects. Zhang and Seto (2011) present an innovative way to display urban expansion in their research by using multi-temporal night-time light data. This method allows for the differentiation between stable and highly dynamic urban areas, potentially defining urban growth rates for different countries. A more recently published way to present global urban growth is the Atlas of Urban Expansion (2019). Scientists from the New York University, the Lincoln Institute of Land Policy and UN Habitat developed an online visualization of urban land use for 200 cities worldwide. The project website contains information and visualizations of indicators suitable to differentiate between different types of urban form based on extent, density, and the composition of newly developed area. In our study we would like to conceptually advance and test such measures of urban form with a simplified approach that can be applied for multi-temporal data worldwide. Our main interest is to contribute toward monitoring concepts that detect and evaluate trends in urban development for global and regional land use dynamics.

In this context, this paper aims to use the knowledge generated by urban sprawl researchers in selected study areas and extend it to a global dataset that has only recently become available for a time series from 1975 to 2015. We use the global human settlement layers (GHSL) provided by the European Space Agency to calculate representative indices to measure urban growth worldwide. Based on these data, we establish a large database for each country with more than 5 million inhabitants. We apply the processing procedures for indicator calculations to the catchments of the cities with the highest urban land expansion rates in the observation period. To determine a valid logic for comparative analysis, we structure our sample by the selection of the fastest growing city regions in the classes of large, medium, and small cities (in terms of population size). We can thus assess some of the worldwide trends of land use change related to urbanization for growing cities. City borders are modelled using network analysis, taking travel times of up to 1 h in 15 min intervals as threshold values. This approach allows us to model catchments without arbitrary delineations of urban areas based on administrative boundaries. Monitoring applications for the largest urban regions in Germany conducted by the authors have shown that such delineation would not be realistic given the increasingly diverse mobility patterns of commuters. This is particularly true for polycentric city regions where the diversity of urban functions is increasingly becoming detached from theoretical conceptualizations of an urban-rural dichotomy (Fina et al., 2019). This methodology enables us to analyze the resulting land use characteristics in a comparative way, although some data inconsistencies explain deviations from the general logic.

These data and indicators provide the possibility of comparing the indicator results for world regions, planning regimes, or any other grouping logic in which urban researchers might be interested. However, the wealth of information is difficult to communicate and present. This paper therefore suggests a simplification procedure for urban growth assessments that concentrates on the dynamics of two dimensions: land use inefficiency and urban dispersion. We explain how the logic of this method was inspired by the discussion of existing quantification methods for urban sprawl represented in the literature. Subsequently, we apply the methodology in global observation and in two sample implementation areas (Paris, France, and Chicago, United States), including descriptions of the city selection procedure and indicators used. For the first applications of our methodological approach, we focus on the growth of cities and portray how the urban land use change has progressed in growing cities. We discuss interpretation prospects, methodological potentials and limitations as well as concepts for further research. By doing so, we hope to initiate discussion on the value of such a monitoring approach. In addition, the suggested approach could be a contribution to the spatial monitoring. Our two dimensional approach simplifies the measurement of urban form and provides policy makers and planning practitioners new information about regional and urban development trends, especially in terms of sustainable city development (United Nations, 2018).

2 Background

The growth of urban land use is a worldwide trend that threatens a range of ecosystem functions through the loss of vegetation and biodiversity, habitat functions, agricultural resources, and soil (Hasse and Lathrop, 2003; Haase et al., 2018). Such growth conflicts with climate change mitigation strategies in coastal locations that are susceptible and vulnerable to the effects of sea level rise and the higher frequency of extreme events (McGranahan et al., 2007). The actual impact of these effects varies; geographic conditions and specific sets of drivers of urban growth on global, regional and local scales as well as regulatory planning each play a role. There is a large consensus in the research community that some cities are more successful in terms of urban growth management than other cities (Fregolent & Tonin, 2015). In this respect, Tosics et al. (2010) classified the regulatory regimes of Europe in terms of land use controls and related it to the topic of urban growth. The authors basically consider the governance system to be either fragmented or consolidated and the planning policy system to have either strong or weak control at the regional or national governance levels. The findings of that study are instructive in comparing current planning systems across Europe but do not relate the findings to actual assessments of land use change in terms of urban growth. The influence of planning thus remains unknown, with some authors arguing that it may not be sufficiently effective to remedy the power of other driving forces in the context of urban sprawl. In this context, Angel et al. (2011) found that despite all planning efforts to control urban sprawl, such as compact city policies and urban growth management initiatives, urban land use change will continue to increase worldwide. The main reason for this increase is a rise in living standards that goes along with more land consumption per person. It is very rare that citizens dispense with less space for living and activities over time, although quite a few initiatives promote this way of thinking where high inner city density is proclaimed to be a factor for quality of life (see for example the OECD compact city policies, OECD, 2012). Besides the problems of decreasing densities in growing cities, Wolff et al. (2018) detected this process also in shrinking urban areas. As the demand (e.g., for infrastructure) decreases, shrinking cities are more challenged with dedensification than their growing counterparts. These efforts, however, are outmatched by a strong global trend for more land consumption. The most recent population prospects published by the United Nations shows that the main driver for more urban land, population growth, is expected to bring the global population from 7.7 million people in 2019 to 9.7 million in 2050, a 26% increase. This growth is expected to occur with varying rates across world regions, ranging from 99% increase in Sub-Saharan Africa to only 2% in Europe and North America. As a matter of fact, more than half of the projected growth is expected in only nine countries: India, Nigeria, Pakistan, the Democratic Republic of the Congo, Ethiopia, the United Republic of Tanzania, Egypt, and the United States of America. In contrast, 27 countries or areas are already experiencing population decline today, including the most populous country, China. Fertility rates are decreasing worldwide, so that population growth can actually reverse over the generations. The increase of life expectancy compensates for some of this dynamic, and some countries will see a high increase in elderly people over the next decades (United Nations, 2019).

With regard to the consequences of population growth for urbanization, any regulatory approach must be based on robust information about the current state and development trends of urban land use change. Beginning in the 2000s, a line of research focused on this topic with studies that have given considerable research attention to land use dynamics. Cervero and Kockelman (1997) showed how to identify the influential factors of urban form with a view toward travel demand. The landmark study by these authors on the influence of the 'density, diversity, and design' of urban neighborhoods (the so-called 'three D's') inspired subsequent studies to work with multiple indicators to quantify urban land use patterns. In this line of thinking, authors such as Galster et al. (2001), Wolman et al. (2005), and Ewing and Rong (2008), established theories and measurement frameworks for urban sprawl assessments in the United States. These studies consider the drivers of urban sprawl and acknowledge the fact that the assessment of urban areas is very complex in terms of urban land use change. For example, Galster et al. (2001) identify eight criteria (density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, proximity) related to land use and its distribution over an urban area for urban sprawl assessment in the United States. The criteria can be measured individually and are used in that study as inputs for a factor analysis to apply a form of multicriteria assessment for the ranking of US cities. Such rankings are useful for comparative analysis of development paths between cities but provide no normative information on the success of planning interventions or the criticality of urban sprawl in terms of its impacts. For such purposes, time series in monitoring frameworks dedicated to the testing of policy interventions are needed. In this context, the European Environment Agency inspired further research with a technical report on urban sprawl in 2006 in which it identified the challenges of measuring urban sprawl with a matrix of drivers that are differentiated by topic (land, transport, governance, economy, society) and scale (global, regional, local) (European Environment Agency, 2006). Subsequent state-of-the-environment studies adopted these ideas by applying a so-called pressure-state-response model to the assessment of undesirable land use changes, resulting in rather alarming qualitative assessments of urban sprawl perspectives for the near (five-plus years) and more distant (20-plus years) future (European Environment Agency, 2011; European Environment Agency, 2015). The measurement approach considers the interrelationships among the current state of land use, the driving forces that exert pressure on the system (for example, population growth), the actual impacts on ecosystem functions (in a normative assessment), and the effects of policies. Other work that was later taken up by the European Union to report on landscape fragmentation with a view toward urban sprawl adopted measurement methods based on landscape metrics. The aim was to assess the configuration and patterns of urban land use using geographic information systems (Siedentop, 2005; J. Jaeger and Bertiller, 2006; J. A. Jaeger, Bertiller, Schwick, and Kienast, 2010; Siedentop and Fina, 2010; European Environment Agency, 2011; Fina, 2013; Behnisch et al., 2018).

Our interpretation of the literature is that the US literature seems to focus more on economic urban functions and their resource efficiency within cities (e.g., Galster et al., 2001) whereas the European literature is more concerned with the environmental impacts of urban sprawl (e.g., European Environment Agency, 2006). However, there is no clear research agenda that explains this observation, and there are certainly many overlapping areas. A range of indicators are presented in the literature to measure the degree of urban sprawl that are applied to geographic datasets on different scales, from a binary view of urban vs. non-urban land, to the study of the building blocks of different land uses, to analysis at the level of street addresses and types of households and enterprises. There are too many indicators to discuss in this paper. However, the common denominator of most measurement concepts is the use of selected indicators that represent different dimensions of urban land use change. In this context, the study by Galster et al. (2001) mentioned above was able to operationalize eight dimensions based on census block data in the United States. Such data structures are not available for international comparative analyses on such a detailed level. Some authors have therefore employed simplified measurements, grouping the dimensions with the most essential indicators. A research group from Switzerland worked with only three indicators to determine the amount of urban structures in a study area ('degree of urban permeation'), their locational setup ('degree of urban dispersion') and the intensity of use that might justify a higher urbanization level ('sprawl per capita'; J. A. Jaeger, Bertiller, Schwick, Cavens, and Kienast, 2010). These authors combined the indicator values for their study area to only one measure ('total sprawl'). Frenkel and Ashkenazi (2008) work with three dimensions of urban sprawl ('density', 'scatter', 'mixture of land uses'), to which they refer as configuration and composition parameters. The indicators to operationalize these dimensions are as follows: population density, irregularity of the shape of the central built-up area boundary, fragmentation, land-use segregation, and land-use composition. Both of these studies require datasets that are not available everywhere. Similarly, a study from an environmental government institution in the German state of Baden-Württemberg suggested a measurement based on three dimensions that can be translated as density, efficiency, and quality of urban land use. This concept places explicit emphasis on indicators that detect changes over time in addition to indicators that measure the state of urban land uses at the beginning of an observation period (Raith, 2007).

Another example is the theoretical framework by Siedentop and Fina (2010) (see Supplementary Figure 1). This framework differentiates three dimensions of urban sprawl as being subject to singular indicator assessments. These dimensions include (1) surface characteristics, such as the amount of urban land use and its increase over time, the sealing degree of different urban land uses or the amount of urban green spaces and mixed land use functions. The resulting land use pattern (2) is the second dimension and addresses the configuration and position of different land uses toward one another as being dispersed or compact, fragmenting open space or forming planned and optimized structures, such as transit-oriented development or nodal growth. Urban density (3) considers the number of users in a given residential population, for example, based on their reliance on certain urban land uses, such as public transportation. In that case, more users would create a higher demand for such services, which would improve cost-efficiency.

The framework attributes certain impacts of urbanization to the sphere of influence of these dimensions (e.g., the loss/degradation of farmland, urban heat islands). Subsequent attempts to operationalize this concept have resulted in a challenging demand on data availability and time series consistency. The indicators that were implemented as representative are urban density; change in urban density; greenfield development rate (dimension: density); effective share of open space; patch density; mean shape index; openness index (dimension: pattern); and share of urbanized land and new consumption (dimension: surface). A full description would exceed the scope of this paper; however, references can be found in Siedentop and Fina (2010).

Nevertheless, it is important to note that the pattern indicators are especially complex study objects in themselves. For example, the effective share of open space as a measure of landscape fragmentation is employed to reflect the value of habitat size for the health of flora and fauna. The resulting value is higher for large habitats and smaller for small habitats based on complex procedures to geographically extract habitat sizes among urban areas for a given study area and to assess the remaining connected size (Ackermann & Schweiger, 2008). The important aspect to note here is that many of the indicators presented in these studies can only be operationalized in administrations with advanced capacities to provide detailed geographic objects on urban land use and statistical data (e.g., on population development) on small-scale urban units. The results are convincing and promising; however, they cannot be extended to other regions with limited data availability. From this viewpoint, it is regrettable that monitoring methods are being designed in regions of the world with advanced data structures in rather mature and consolidated environments that cannot be easily applied where they are needed most, namely, in regions where urbanization is still very dynamic and information on the alarming trajectories of land use change could be used in crucial decision-making processes and adjustments to land use policies. In this context, Wei and Ewing (2018) recently published a call for new research efforts on the topic with a view toward capturing the variety of urban land use change worldwide. The following sections present a dataset that we tested in this context. These are worldwide data, and they provide a consistent time series from 1975 to 2015.

3 Materials and Methods

3.1 Land Use and Population Data

We use the GHSL as our main source for the analysis. This source, which is based on Landsat satellite and census data, is a dataset that is available worldwide. This dataset covers built land areas (built-up layer) and population data (population layer) for 1975, 1990, 2000, and 2015 (Pesaresi et al., 2013). The GHS built-up layer, with a high resolution of 38 m, provides the opportunity to monitor changes in urban land use and the resulting patterns using indicators that are applicable in a global context. In addition, we have information on population development from the GHS population layer on a 250m cell size so that we can report on the demographic impact on urban growth. This data is available for 1975, 1990, 2000, and 2014 and stems from population estimation and disaggregation models (Freire et al., 2016). There are some caveats that come with the use of the dataset, although we generally assess it to be a unique source for the observation and analysis of global urban developments in the future. In their research, Pesaresi et al. (2016) described challenges and problems with the GHSL and its validation. A relevant issue for our study is that, due to a lack of available image data for 1975, there are problems in identifying built-up areas for this year. As the information of population is a result of the census data and the built-up layer, we also expect inaccuracies in the population dataset (see for the example of the German city of Pirmasens in Supplementary Table 25). We documented such inconsistencies found during data processing in the population (Supplementary

Table 25) and in the remote sensing data (Supplementary Figure 2). This led to an exclusion of possible cities to analyse and to a drop in sample size (see Supplementary Table 3).

3.2 City Selection Procedure

To find a representative dataset of the most growing cities from different world regions, we defined a specific selection procedure. In a pre-analysis step, we used a 60 km buffer around every city centroid as a typical catchment for cities. The source is a point dataset provided by Esri and Garmin (Esri Word Populated Places), which contains a centroid for the administrative boundaries of every city with more than 50,000 inhabitants. This distance can generally be managed in 1 h travel time by car, which represents a maximum commuting time in Europe (Eurostat, 2019). We are aware that this not applicable for every country or city, but we need equal distances for our selection procedure. In comparison to the delimitation of functional urban areas of the urban audit, which includes employment and population data, we could identify similar catchment areas for the larger cities (Eurostat, 2013). As the research focus is set on cities with increasing urbanized areas, we concentrate on two kinds of city: those with most absolute growth and most relative growth in built-up land in city regions. The calculation of growth makes use of the GHS change layer of built-up areas and identifies the time period with the largest values from 1975 to 2015. Considering the fact that the most populated cities are often also the most growing cities, we decided to divide cities into three size classes: category A (over 500,000 inhabitants), category B (100,000–500,000 inhabitants) and category C (50,000–100,000 inhabitants). The information about the population classes is also part of the ESRI world populated places with 2017 as reference year.

We also applied two filtering steps. The first approach eliminates the dataset entries for smaller countries, giving effect to the assumption that the growth of cities in small countries, such as Liechtenstein or Luxembourg, is highly influenced by neighboring metropolitan regions in other countries and does not provide the number of cities to present a solid selection base (e.g., small island country states, such as Samoa or Cape Verde). As a result, we excluded countries with fewer than 2 million inhabitants from this part of the research. To avoid agglomeration and overlap effects in polycentric urban regions- cities affecting the growth of catchments of neighboring cities - such as in the Ruhr area in Germany or the east coast of China, we implemented the second filtering rule: the cities of category A are not subject to any special restrictions. The cities of category B cannot be in a radius of 60 km from a city of category A.We dropped the cities of category C from the sample if they are in 60 km proximity to a larger city from categories A and B. Excluded cities remain part of the larger city region. Subsequently, the sample for a specific city category is filled with the next entry in the ordered list of growing cities in its category. For example, if a city of category B is part of the catchment of a city from category A, it will be part of the analysis for the larger city and will no longer be considered individually. Then, the city that is next in rank in category B is taken into consideration for spatial analysis. In its final state, the database contains a maximum of six cities per country, with the exception of smaller countries where many cities are geographically close to one another and affected by the application of filtering rules. As a result, some city categories are missing in such countries. For a total overview of all of the selected cities (see Supplementary Table 4).

Table 1 shows the resulting cities for the example of France. Of the largest cities, Paris had the highest absolute growth in hectares (4,614 km2 from 1975 to 2015), which is certainly due to its extraordinary size compared to the next-largest cities. However, in relative terms, Reims had a higher growth rate in percentage terms (150 % from 1975 to 2015). For cities with 100,000–500,000 inhabitants, Lille had the highest absolute growth rate, Avignon had the highest relative growth rate. In category C (under 100,000 inhabitants) Saint Quentin had the highest absolute growth and Beziers the highest relative growth.

City/Growth	Absolute	Relative
A (more than 500,000 population)	Paris (4,614 km^2)	Reims (150 %)
B (between 100,000 and 500,000 population)	Lille (3,554 km^2)	Avignon (221 %)
C (more than 500,000 population)	Saint Quentin (1,208 %)	Beziers (271 %)

Table 1: Cities with the highest urban development dynamics in France, by population class (in brackets: absolute and relative change of urban land)

3.3 Processing and Analysis

Our logic for delineating catchments for cities uses travel time areas from the city centers as its core element. This approach reflects the functional relationships between the city center and its surroundings better than linear rings or squares. Processes of urbanization (e.g., sub- or re-urbanization) and related phenomena (i.e., commutersheds) rely on street networks. Indicators that measure such processes are therefore better calculated in alignment with network geographies. In particular, the analysis of urban growth will provide more realistic and comprehensible results in this context. Topographic features such as mountains, water surfaces, forests, or conservation areas are usually not accessible by road and were therefore intentionally excluded from the research area. If frozen boundaries were used, inaccessible or unconnected areas would also be part of the analysis. However, defining the catchment areas by travel time polygons also contains some deficiencies. Although indicators for cities can be compared, they are based on different geometry sizes in contrast to static squares or circles. We have to consider this in the interpretation of the results.

The resulting polygons represent so-called isochrones (polygons of equivalent travel time for the centroid) or spatial units such as those shown in Figure 1. The travel time polygon for the city of Innsbruck in Austria runs through the valley locations to the east, south, and west. Northern parts in the alpine valleys are more difficult to reach and thus take longer. Another example is shown on the right-hand side, which is located in the desert. The isochrones of Hafar al Batin in Saudi-Arabia span the first two rings, the outer rings are singular radial roads, which are officially labeled as highways, and other parts are not accessible by sealed roads (excluding dirt tracks). Unaffected by any topographic restrictions, the city of Dusseldorf in Germany approximates circular travel time rings, albeit with some deviations.

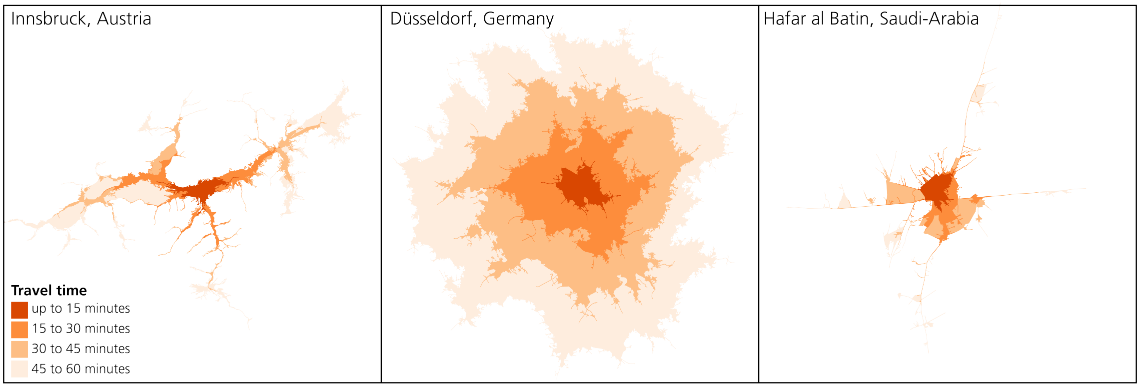


Figure 1: Examples of travel time polygons

For our analysis of individual cities, we calculated isochrones for car travel times of 15, 30, 45, and 60 min to the city center. Data basis for the analysis is the ESRI ArcGIS Online network analysis services, which delivers "up-to-date" road data by HereMaps. With an almost world-wide available routing network, this source ensures our requirements for the analysis with a given reference year of 2018 (Esri, 2019). We use the resulting isochrones for all observation years to make the results comparable. For the application on the global level in section Global Observation, we simplify and aggregate the database by reducing the research area to a single catchment ring per city category. The travel time used to create the rings relies on city size. For the cities of category A (over 500,000 inhabitants), we assigned a travel time of 45 min; for the cities of category B (between 100,000 and 500,000 inhabitants), we assigned a travel time of 30 min; and for the cities of category C (100,000 inhabitants), we assigned a travel time of 15 min. Restrictions such as toll roads or unpaved roads are ignored for this purpose because they prevent general accessibility and would have yielded unrealistic and complex isochrones, including islands, and possibly disconnected polygons. Such restrictions are therefore set to the minimum in the software we used, the ESRI ArcGIS Online network creation tool. Excluding toll roads or unpaved roads also leads to better results in the US and rural parts of Asia and Africa, where a large number of roads are actually unpaved. The only restriction we considered is the use of ferries to avoid areas that are inaccessible by car. Despite its good usability, there are some limitations in the use of ESRI service areas. In general, there are problems in countries, such as North Korea, Afghanistan or Yemen, where the street network data do not seem to be very reliable and yielded inconclusive results (mainly visible in the form of the resulting polygons). In addition, there are potential problems when calculating drive time areas in smaller cities in Asia, Africa and South America, most likely also due to deficiencies in the available street network data. Countries and cities with inconclusive results had to be excluded from the city selection to avoid unrealistic indicator calculations. It is important to note that especially smaller cities in the named continents have outer rings with smaller areas. We suspect that the definition problems in street hierarchy and connectivity in rural areas are responsible for this issue.In the interpretation of the results, it is crucial to check the forms of the catchments to reflect the topographic conditions in the area. It is also important to note that the isochrones are valid for the recent past when the street network we used was in place. Therefore, for the previous years of our observation period, we may have potentially overestimated accessibility. From a methodological point of view, this is a necessary specification and provides a solid framework for the analysis of trends from the past. For future monitoring purposes, such fixed spatial units could impose restrictions when excessive growth renders these polygons outdated.

3.4 Indicators

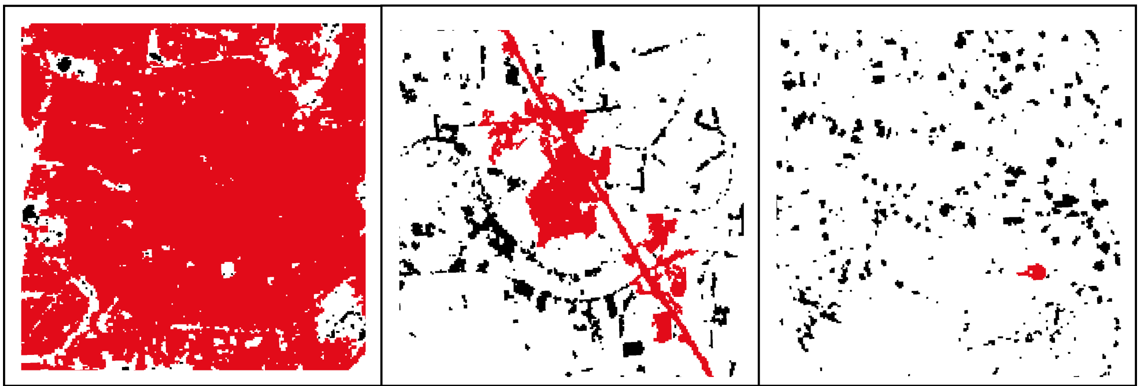
As shown in the literature review the measurement and analysis of urban land use trends requires a multitude of indicators. According to the framework depicted in Supplementary Figure 1, multiple indicators are selected to represent the three dimension of growth (see Table 2): change of land surface characteristics (dimension 1), change of urban density (dimension 2), and change of land use patterns (dimension 3). The indicators we selected for our study can be implemented with the GHSL. With this background, we condensed the three dimensions of urban sprawl to only two dimensions: the dimensions of land use (in-) efficiency and dispersion.

- Land use inefficiency: we borrowed this concept from a range of reporting tools on urban form but could not identify who published the idea first [*]; however, it is a simple comparison of population growth vs. urban area growth. If the population growth is higher, the urban footprint will become denser. If the population growth is much lower, the urban structure will become less dense, which is typical for urban sprawl. This dimension therefore measures the economic use of land resources over time in light of population development. This approach is sometimes labeled as land use efficiency, a term we adopt but invert the logic in terms of land use inefficiency to make our results more accessible in light of the indicator values. Land use efficiency is also an indicator in the United Nations Sustainable Development Goals and therefore highly relevant for policy formulation (Number 11, see United Nations, 2018; Florczyk et al., 2019). Put simply, land use inefficiency covers the dynamics of the surface and density dimensions.

- Dispersion: we monitor and assess the pattern dimension with the changes observed for the so-called 'dispersion index'. The methodology for this indicator was first presented by Taubenböck et al. (2019) with a very simple binary analysis of settlement and non-settlement areas. Dispersion index derives two spatial metrics from these land use classes, the largest patch, and the number of patches (Macgarigal, 2015), and it positions these metrics in relation in one another. The share of the largest settlement patch in the entire area represents the dominance of one patch in a landscape. The number of patches equals the total number of all patches in the landscape. By normalizing the values of the number of patches and the largest patch, we obtain equal ranges from 0 to 100 (see

[*] See for example the planning tool 'Vitalitätscheck' [vitality check] for rural settlements in Bavaria, Germany at t http://www.stmelf.bayern.de/landentwicklung/dokumentationen/059178/index.php

Figure 2). Low values indicate a compact settlement structure, and high values indicate dispersion.



LPn 99.2 % NPn 0.4 %	**DI 0.6**	*LPn 57.1% NPn 8.4 %*	**DI 25.6**	*LPn 3.3 % NPn 26.1 %*	**DI 61.4**

Figure 2: Examples of urban land use patterns and the corresponding largest patch index (LPn), and dispersion index (DI) values (urbanized land in black, largest patch in red

Based on these indicators, we can portray the development of a city in a two-dimensional matrix. On the y-axis, we translate the surface and density dimension of our measurement concept into a value for the land use inefficiency as a result of land consumption and population growth in a given time period. If the population and urban land use grow at similar rates, the land use inefficiency remains constant (see Figure 3). Urban land use change that exceeds population growth considerably is an indication of wasteful land use management and a decrease in urban density ('less dense' in Figure 3, upper two quadrants). If the population grows much more than the urban land use, we obtain densification and higher efficiency ('denser', lower two quadrants).

In other words, land use inefficiency measures the difference of built-up area growth in relation to population growth and indicates whether urban density is increasing or decreasing. The x-axis, in contrast, is defined by the development of the dispersion index over time. If urban areas grow from a very patchy (or 'sprawling') condition to more compact structures, the values will be negative ('more compact', two quadrants toward the left). Accordingly, if new patches of urban land are built in isolation from existing urban areas, the dispersion (and urban sprawl) will increase (positive values), placing the value of the dispersion index change further to the right (two quadrants on the right-hand side).

Based on this idea, we can now depict the development of urban areas in terms of land use inefficiency and the change in the dispersion index in combination. A positive land use inefficiency value refers to less dense growth with a higher consumption of land; a negative land use inefficiency value refers to denser growth in the particular period. The objective of this approach is to portray the urban land use changes for the three time periods from 1975 to 1990, 1990 to 2000, and 2000 to 2015. To present the results on the full time series (1975 to 2015), we use the geometrical mean as the average of the growth rates between single time periods (e.g., 1975–1990, 1990–2000, 2000–2015). The complete mathematical definitions of the single indicators required to fill the land use inefficiency and dispersion index change matric is shown in Table 2.

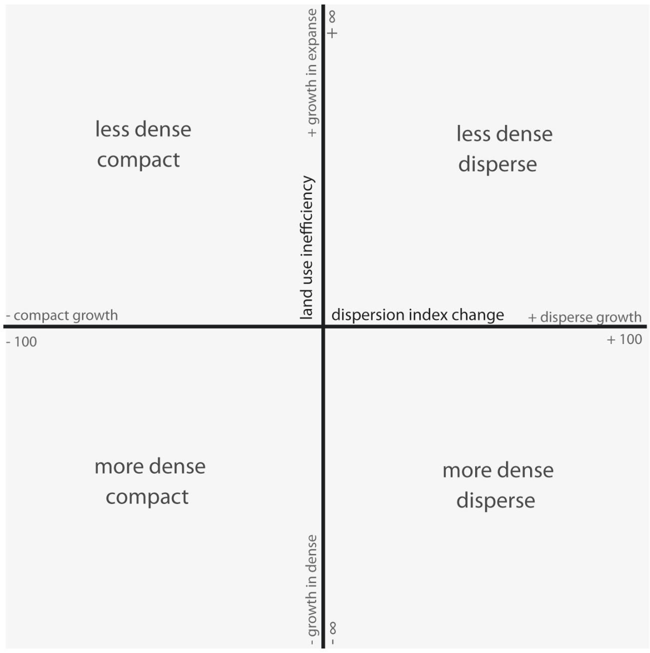


Figure 3: Trends of urbanization, divided into the four quadrants

Indicator	Range	Calculation
Growth rate of built land per year (n) (BuiltGR)	(–1) to (+1)	$BuiltGR = (\sqrt[n]{\frac{StartBuilt}{EndBuilt}} - 1) * 100$
Growth rate of population per year (n) (PopGR)	(–1) to (+1)	$PopGR = (\sqrt[n]{\frac{StartPopulation}{EndPopulation}} - 1) * 100$
Land use inefficiency (LUI)	(–1) to (+1)	$LUI = BuiltGR - PopGR$
Dispersion index change (DIC)	(-100) to (+100)	$DIC = EndDI - StartDI$
Dispersion index (DI)	0 to 100	$DI = \frac{NPn + (100 - LPn)}{2}$
Largest patch (normalized) (LPn)	0 to 100	$LPn = \frac{LP - \frac{1}{\sum_{j=1}^{n} a_{ij}}}{100 - \frac{1}{\sum_{j=1}^{n} a_{ij}}} * 100$
Largest patch (LP)	0 to 100	$LP = \frac{\max_{i=1}^{n} a_i}{\sum_{j=1}^{n} a_{ij}}$
Number of patches (normalized) (NPn)	0 to 100	$NPn = \frac{NP-1}{(\sum_{j=1}^{n} a_{ij} - 1)} * 100$
Number of patches (NP)	0 to +1	$NP = NP(absolute)$

Table 2: Overview of indicators and their calculations

4 Results

In the first step, we apply the introduced methodology on a global observation level. For this purpose, we work with only one catchment ring, simplifying outputs to one value for a city per year, categorized by city size classes.

4.1 Global Observation

The overview in Figure 4 shows the average values for urbanization trends by continent, taking the mean indicator values for each city type. The general development trajectories of urban land use change are comparable. Every continent exhibits a highly dynamic, less dense, and compact growth in the first period with some specific deviations. The growth development in Asia is more intense than, for example, in Europe, Australia and Africa. North and South American cities are characterized by a development compaction where the existing sprawling structures have been filled with new built-up areas over time; thus, urban footprints consolidate over the observation period and become denser. The time periods from 1990 to 2000 and 2000 to 2015 suggest that the growth dynamics on every continent have accelerated. Differences can be observed when examining the location of the darker red points in the quadrants of Figure 4. The growth dynamics in African cities do not lead to the same densification as on other continents, i.e., the land use inefficiency increases on the y-axis. At the same time, the growth curve in Asia moves across the quadrants to the 3rd quadrant, illustrating a compaction and densification of the urban footprint. In Australia, built areas change from being less dense and dispersed to denser and more compact. European urbanization since 1990 is characterized by a starting point that is already quite consolidated, i.e., closer to the zero points of the x- and y-axis in Figure 4.

The above findings are typical for mature urban development with comparatively slow dynamics; however, the results show urban areas steadily becoming less dense and more dispersed due to fewer people on average using and increasing amount of urban land. In North and South America, the growth patterns can be described as becoming denser but dispersed over time, with a slowing dynamic in the most recent observation period from 2000 to 2015. In this context, it would be of great value to enhance this analysis with ring structures, which we demonstrate in further analyses for Paris and Chicago in the next section. The presence of rings around the inner city allows for a differentiation of urban structures from the historical core to the latest phases of urban extensions and for the monitoring of the land use inefficiency and dispersion dimensions for each ring. This analysis could be conducted for all of the cities in the sample if the validity of the measurement concept can further be substantiated in future studies.

For the time being, we would like to highlight that the interpretation of the results presented here follows the movements of points from paler shades of red to the location of the darkest red point. This dark red point symbolizes the end of our observation period. The values very close to the zero point of both axes show a decreasing dynamic that we interpret as a mature level of

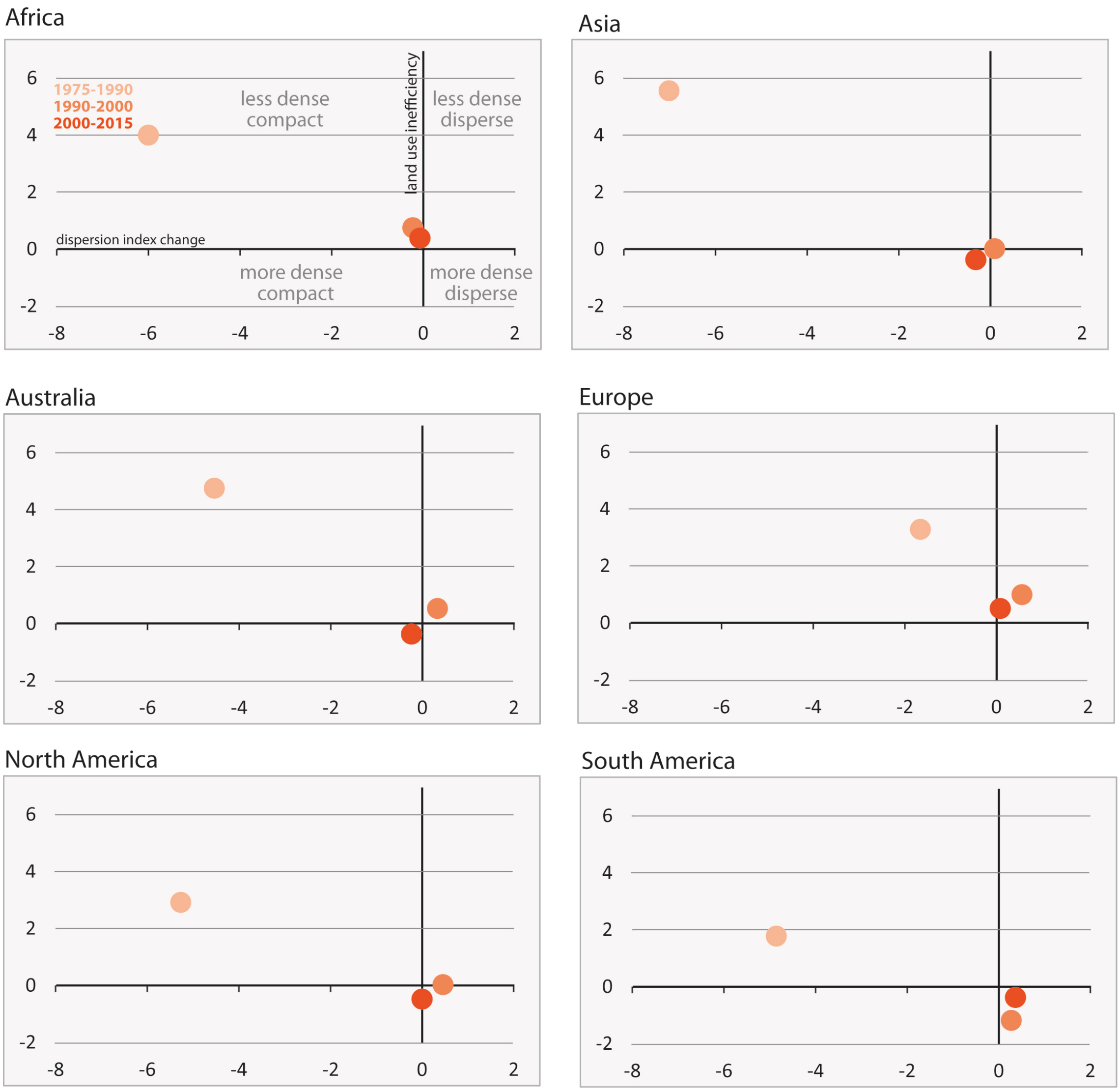


Figure 4: Urbanization trends for the continents

consolidation for urban development. The analytical value of this observation lies in the future monitoring of these points across the four quadrants. Once policies for urban containment and land saving densification are in place, one can detect progress toward policy objectives using this method.

In order to examine the difference of indicator results between the continents we apply the Kruskal-Wallis-Test (Vargha & Delaney, 1998) to all city regions in the sample, grouped by continent. The calculations were done in the SPSS statistical software package. Complete tables for the summary results presented here can be found in Supplementary Tables 5–24. If the value of the asymptotic significance p of the test is <0.05, there is a difference in the central tendency, otherwise the sample is homogenous. We computed these numbers for the various time periods and the two indicators. If there is indeed a difference, a post-hoc-test determines which continents exhibit significantly different values. In such cases we use the Dunn-Bonferroni-Test df (Cohen, 1992; Dinno, 2015). The results are presented in Tables 3, 4, including the Qui-Square values as context information.

In the first time period the values for both indicators in the sample are not significantly related, the urban development paths are therefore heterogeneous. The pairwise comparison in the post-hoc-test shows that this result is mainly due to the large difference between urban development paths of South America in comparison to Asian city regions. The medium effect size of $r = 0.45$ shows that the land use inefficiency deviates significantly, the data shows that it is Asian cities that densify over time, South American cities much less. The heterogeneity of the dispersion index change can mainly be attributed to the difference between Asia and Europe ($r = 0.32$, medium effect size) and Asia and Africa ($r = 0.32$, medium effect size). In contrast, the continents in the subsequent periods are homogenous with regards to the dispersion index change. For the land use inefficiency we can also identify differences in the central tendency in the more recent observation periods. For 1990–2000, we see a multitude of relations that emphasize the inequality of urban development paths across continents. The effect size is small and varies between 0.23 and 0.29. In the last period the inequality can mainly be attributed to the difference between Europe and North America ($r = 0.23$, small size effect), Europe and South America ($r = 0.29$, small size effect) as well as Europe and Asia ($r = 0.21$, small size effect).

In addition, we can aggregate the data on the city size level with the same methodology as above. Figure 5 presents the results for the three city categories A, B, and C. The results are similar to the comparison by continent. From 1975 to 1990, the growth dynamic was higher in the smaller cities. The cities in categories B and C develop in a less dense and compact fashion on average at this point as well as in the succeeding time periods. The largest category, cities over 500,000 inhabitants, moves from the quadrant with less density but a compaction of development (upper left) to the denser but dispersed quadrant on the lower right. We interpret these effects as maturing urban development where urban sprawl in the 1980s was followed by a densification and consolidation of suburban areas in the more recent observation periods.

Similar to city region groupings by continent we also conducted the Kruskal-Wallis-Test for city region groupings by city category. For the dispersion index change we identified homogeneity in the sample for the first two decades.However, the asymptotic significance value p for 1990–2000 is close to the level of significance and in the last period it falls under the threshold. This is due to major differences between cities of city category A and the smaller city categories, effect sizes are small. In contrast, we see a continuous heterogeneity between the size classes in terms of land use inefficiency. In all time periods we determine differences in the central tendency between major cities (City A) and the smaller cities (City B and C). Checking for the position of the city size. A symbol in the matrix of Figure 5 which is closer to the x and y axis we can conclude that large cities over 500,000 population have experienced less dispersion and dedensification than smaller cities in the observation period.

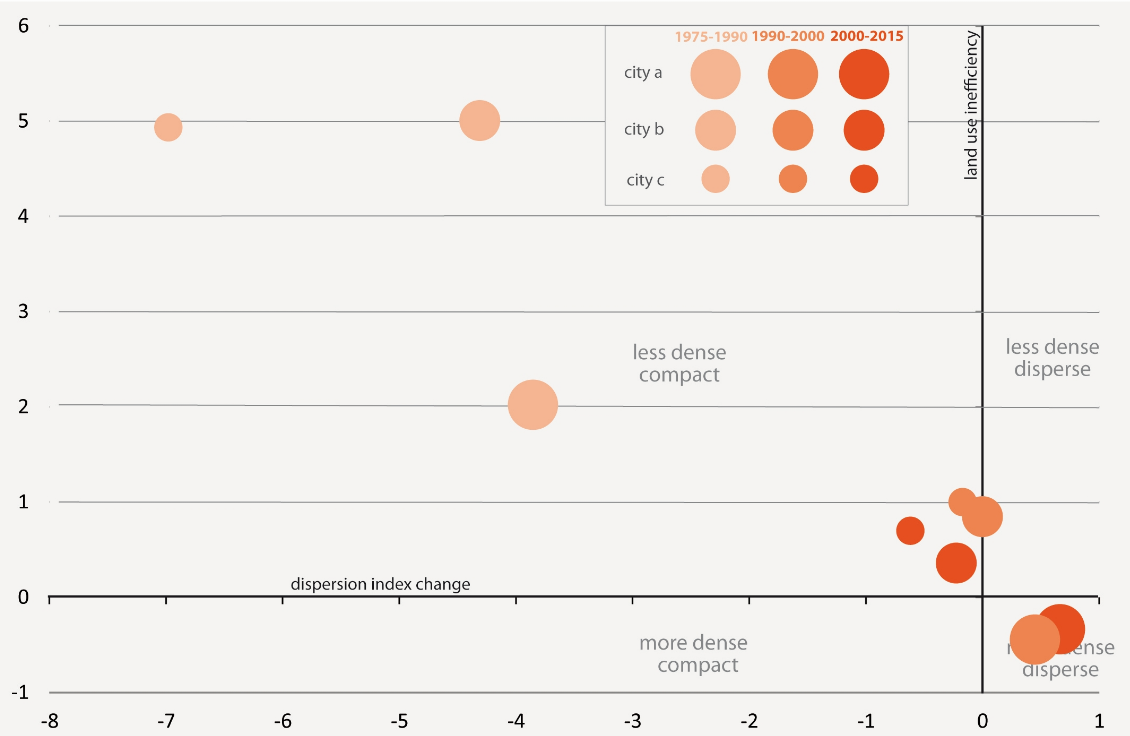


Figure 5: Urbanization trends by city size

	1975-1990		1990-2000		2000-2015	
	LUI	**DIC**	**LUI**	**DIC**	**LUI**	**DIC**
Qui-square	17,566	32,185	41,513	2,223	29,345	2,149
Dunn bonferroni test (df)	5	5	5	5	5	5
Asymptotic significance (p)	0.004	0.000	0.000	0.817	0.000	0.828

Table 3: Results of the Kruskal-Wallis-test (continents)

	1975-1990		1990-2000		2000-2015	
	LUI	**DIC**	**LUI**	**DIC**	**LUI**	**DIC**
Qui-square	22,873	4,245	29,605	5,759	28,131	14,173
Dunn bonferroni test (df)	2	2	2	2	2	2
Asymptotic significance (p)	0.000	0.120	0.000	0.056	0.000	0.001

Table 4: Results of the Kruskal-Wallis-test (city-size)

4.2 Urbanization Trends for Selected Cities

To apply this new methodology for individual cities, we selected Chicago and Paris. Both cities have similar populations (city category A), and they show the largest increase of total urbanized land in their respective countries, the United States of America and France (for more detailed information on city statistics see Supplementary Tables 1, 2). In addition, we can reflect on the urbanization trends for these two cities based on a rich body of literature on their historical development and influential factors (e.g., Dear, 2004; Hudson, 2006; Angel et al., 2010). Such knowledge is valuable in testing new measurement concepts such as the one we present here.

4.2.1 Urbanization Trends in Chicago

With over 2 million inhabitants in the core city and over 9 million in the metropolitan area, Chicago is one of largest cities in the United States. Located at the Western edge of Lake Michigan, Chicago is subject to specific growth conditions that have been a prominent subject of research in urban theory for a long time (Dear, 2004). Waves of suburbanization and reurbanization have changed and enlarged the outskirts of Chicago and have placed pressure on land resources and changes in land rents (McMillen, 2003; Hudson, 2006). To measure the resulting growth patterns since 1975, we have delineated the expansion area toward the west with travel time rings formed as semicircles around the city core, not covering the water area of Lake Michigan. Figure 6 shows that the main areas of rings 1 and 2 were covered by builtup land before 1975. Urban land built between 1975 and 1990 closed the gaps in rings 1 and 2. Urban land extended toward the existing built-up areas in rings 3 and 4. New urban land that was developed after 1990 is mainly located in the outer two rings. Some parts extended new settlement areas in ring 2.

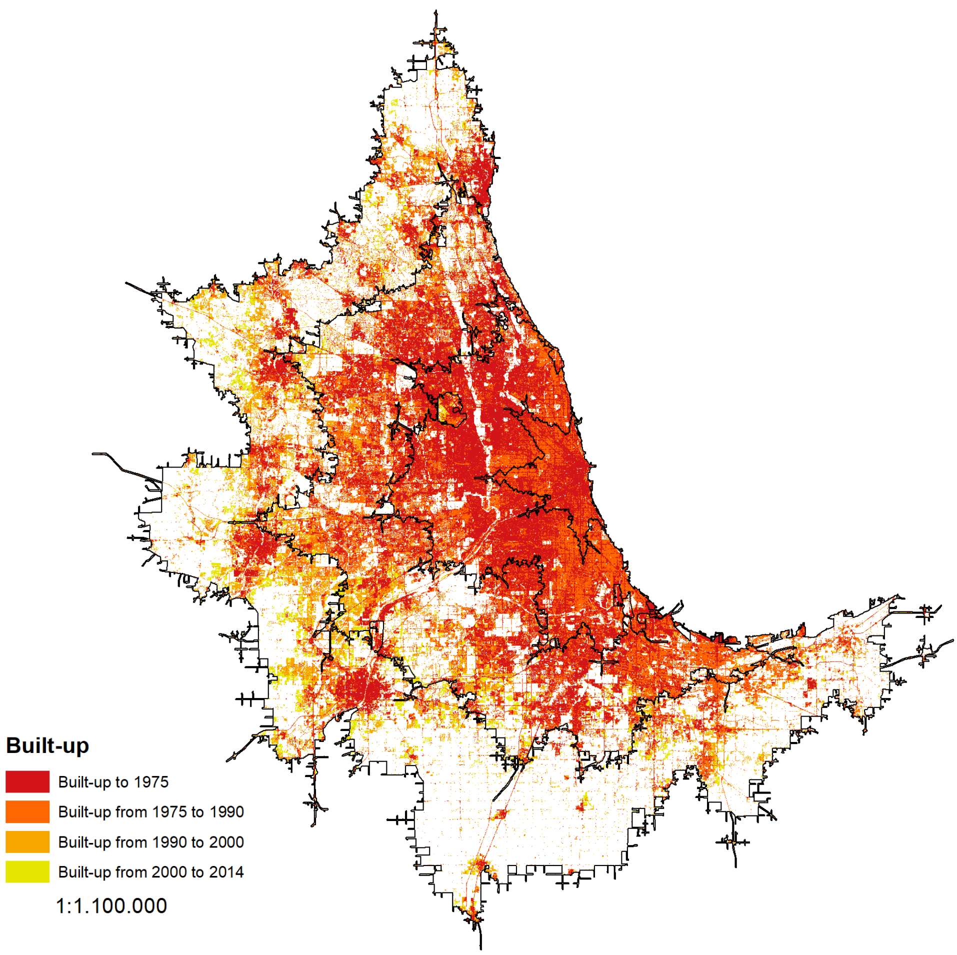


Figure 6: Urbanization periods in Chicago, based on the GHSL

Figure 7 illustrates urban land use change in Chicago for the three time periods subdivided into the different rings (graphs on the left). To put the values into context, additional graphs on the right show the development of built-up areas (green graph) and population growth (red graph) since 1975. The values are indexed and normalized for the starting value in 1975, which is set to 80. Subsequent developments show the deviation from 80 for the different years after 1975 on the x-axis. This information is complemented by the absolute change of the dispersion index (dark yellow graph) from 1975 to 2015. It is important to note that all of the values represented here are calculated as change rates based on the starting point in 1975.

The resulting graphs on the left-hand side show that the inner core ring represents high growth dynamics in the first time period from 1975 to 1990. This trend reflects a compaction of urban form with a loss of urban density and can be seen as a consequence of the strong suburbanization in this time period during which large shares of the affluent population fled the inner city problems of industrial pollution and crime in deprived neighborhoods (also known as 'white flight') (Boustan, 2010; Boustan and Margo, 2013). The following two periods indicate a further consolidation of the built-up area in the first ring with a decreasing value for the dispersion index change. The decrease in population in the city core continued, leading to a less dense settlement structure during the whole research period. Similar trends can be seen in ring 2. From 1975 to 1990, the total built area increased by 50 %, while we find no significant changes in the population numbers and a strong decrease in the dispersion index change. Development is found to be less dynamic in the following time periods. We can see a form of stagnation from 1990 to 2000 and decreasing urban density in the last time period due to a shrinking population base. The exterior rings 3 and 4 are similar in their development paths.

Overall, we determine an increasing population in these zones, extraordinary growth rates of built-up land that are typical of suburbanization (graphs on the right-hand side) and shrinking dispersion from 1975 to 2015. Here, the development path during the first period was less dense and very compact. This development is a reflection of continued development in formerly dispersed land use patterns that are typical for the outskirts of large cities. In both outer rings, the second time period from 1990 to 2000 shows a temporal increase in dispersion until 2010, probably a result of newly developed built-up land in isolated locations. However, this trend reversal does not continue in the last given period from 2010 to 2015, where we find a decreasing dispersion index and, therefore, a compaction of urban land use patterns. In this sense, the indicator values in Figure 7 suggest a convergence of the urbanized land in the outer rings.

In summary, we can characterize the urbanization in Chicago as a form of urban consolidation with compact development in the inner rings, and a subsequent compaction of dispersed land use patterns in the outer rings. This is a typical form of suburbanization. The example of Chicago lends itself to the application of this new monitoring concept that provides information about dispersion and land use inefficiency for such urban sprawl conditions. The trend analysis for Chicago shows that the growth in urban land was accompanied by a continuous decrease in urban density over all rings in the research area. We attribute this result to a massive migration of the inner city population to the outer rings in the wake of suburbanization, largely surpassed by the tremendous growth of urbanized land in rings 3 and 4.

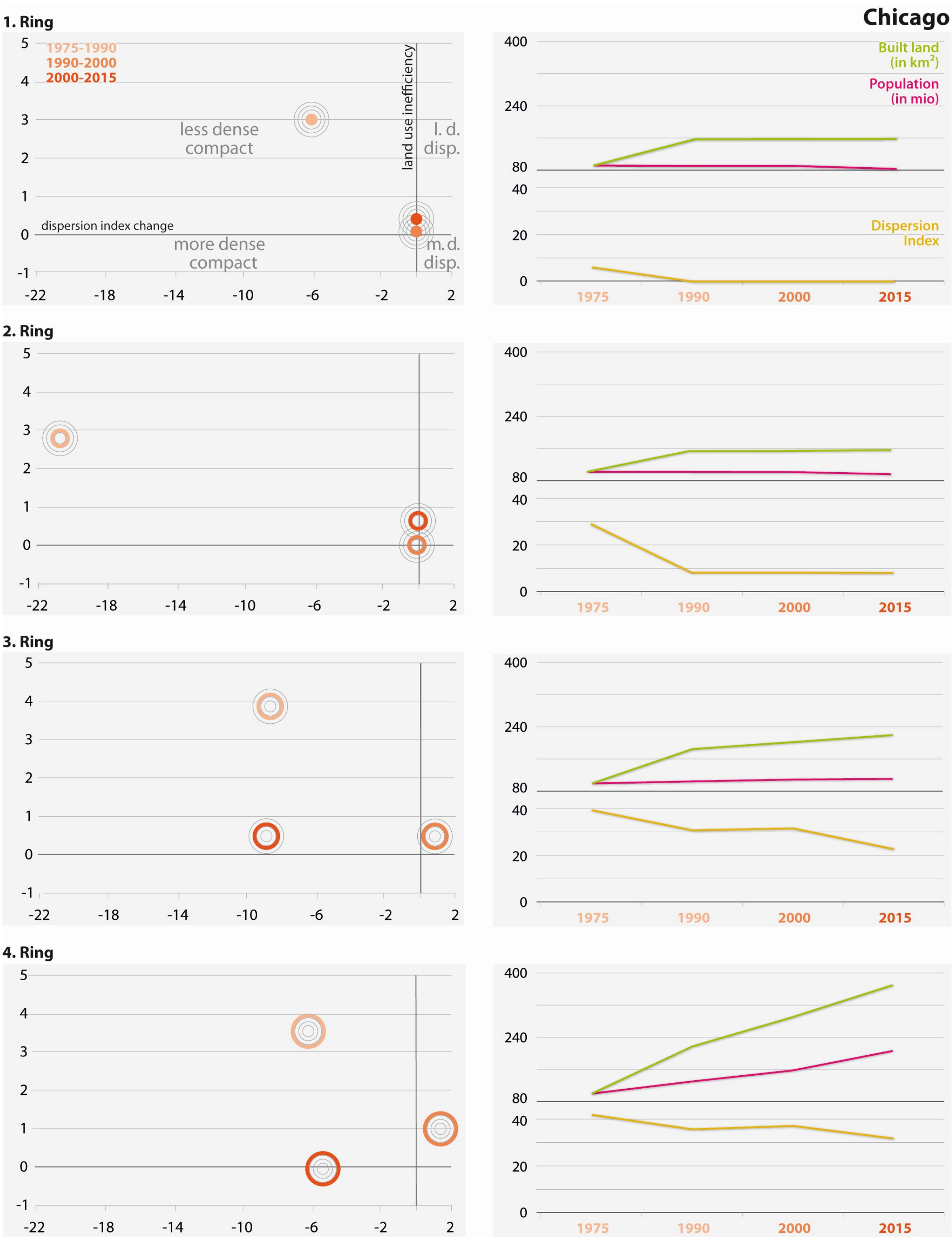


Figure 7: Urbanization trends for Chicago divided into the four rings. The line charts illustrate the corresponding development of built-up land, population, and dispersion index over time

4.2.2 Urbanization Trends in Paris

In contrast to Chicago, our second test case, the city of Paris, has no substantial topographic or natural restrictions for urban growth around the city. This lack of restrictions is why Paris has equal travel time rings in a radial growth pattern around the city core, with strong concentrations of newly built urban land along the major transport routes into the hinterland. As the capital of France, Paris has historically attracted urban growth with a concentration of government and business functions for centuries, dominating spatial development with strong transportation linkages to second-tier cities in France. It is therefore not surprising that Figure 8 shows the inner rings as already vastly built-up at the beginning of our observation period in 1975. Newer urban growth mainly occurred in the third ring along the main transportation axis. Ring 4 contains some smaller separated settlement areas in 1975, which we identify as formerly self-contained cities that attracted new growth in our observation period. The urban areas that were created after 1990 extend existing settlements, visible here in the orange and yellow patches of new urban land in rings 3 and 4.

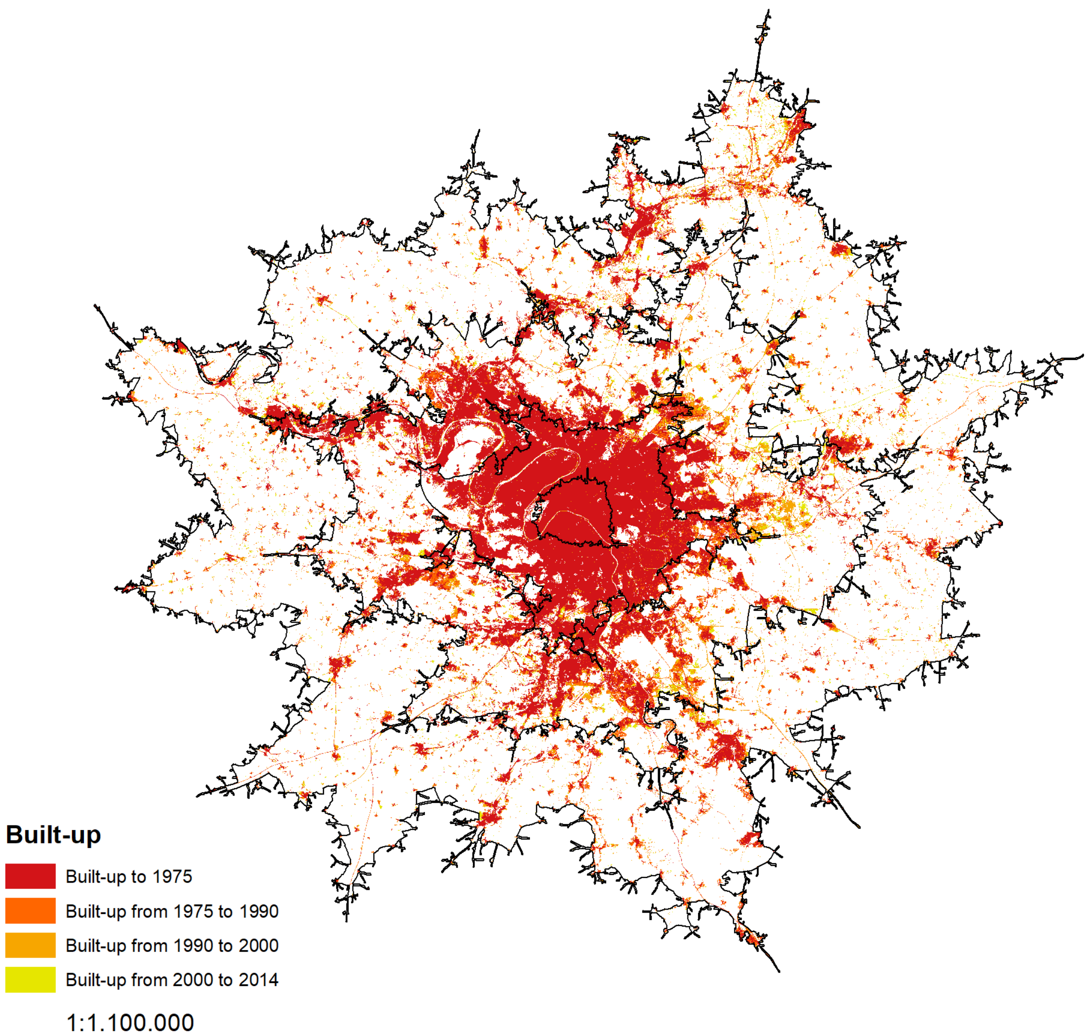


Figure 8: Urbanization periods in Paris, based on the GHSL

In the city core, the existing urban layout did not allow for much compaction in our observation period; it was already built-up. Our measurement concept reflects this observation accurately: the built-up land and subsequent dispersion remain constant, and the added area of 1.1 sq km of urban land in 39 years of our observation period is marginal considering the area. Nevertheless, we identify continuous population growth in the first ring and therefore a denser settlement structure. The popularity of Paris for city dwellers obviously led to new infill development or perhaps denser forms of living arrangements on average. The second ring, also part of the inner city of Paris, is characterized by dense and compact growth based on the negative land use inefficiency (e.g., population growth exceeding the growth of urban land) and development trends for the dispersion dimension. Figure 9 presents a shift over the time periods from 1975 to 1990, 1990 to 2000, and 2000 to 2015 along the x-axis to the zero point of the dispersion index change dimension.

We interpret these changes as a form of spillover effect from the first ring to the second ring where continued population pressure led to a compaction of neighboring suburbs. In contrast to the urban center of Paris, the third ring exhibits a different development path.We can observe increasing values of population and urbanized land but also a growing dispersion in the first two periods. Because we find a higher growth in built-up areas than in population in ring 3, we can assume a form of sprawling suburbanization with less dense and dispersed growth in the first two time periods. However, this trend was reversed in the third time period where population growth exceeds the built-up area growth. The land use inefficiency shows the effect along the y-axis, and the result is a gain of urban density. This minor trend of densification and dispersion in the last period could be a result of densification policies in the city-region (Touati-Morel, 2015). The exterior ring follows this trend with higher dynamics. Notable is the change in the urbanized land, which increases by a factor of 2.5 since 1975 and promotes the dispersion and the decrease in urban density in the fourth ring. We suspect that advantages in land rents and accessibility for commuters shifted the suburbanization from the city core further out to rings 3 and 4 of the research areas. This phenomenon is a typical process for European cities where historically compact cities have seen massive forms of urban sprawl on the outskirts. This is an observation that is often overlooked in theories on urban form that falsely idealize European cities as blueprints for compact city policies (European Environment Agency, 2006).

In summary, in Paris, we can identify different trends from rings 1 through 4. The city core is very compact and can only grow in density; ring 2 experiences a consolidation of urban form as a consequence since 1975. The low value for the dispersion index change in 2015 suggests that this process is largely completed, and the urban form is fully built-up. The developments in rings 3 and 4 have been subject to massive processes of suburbanization and urban sprawl in our observation period, with less dense and disperse growth of urban land and very high land consumption rates.

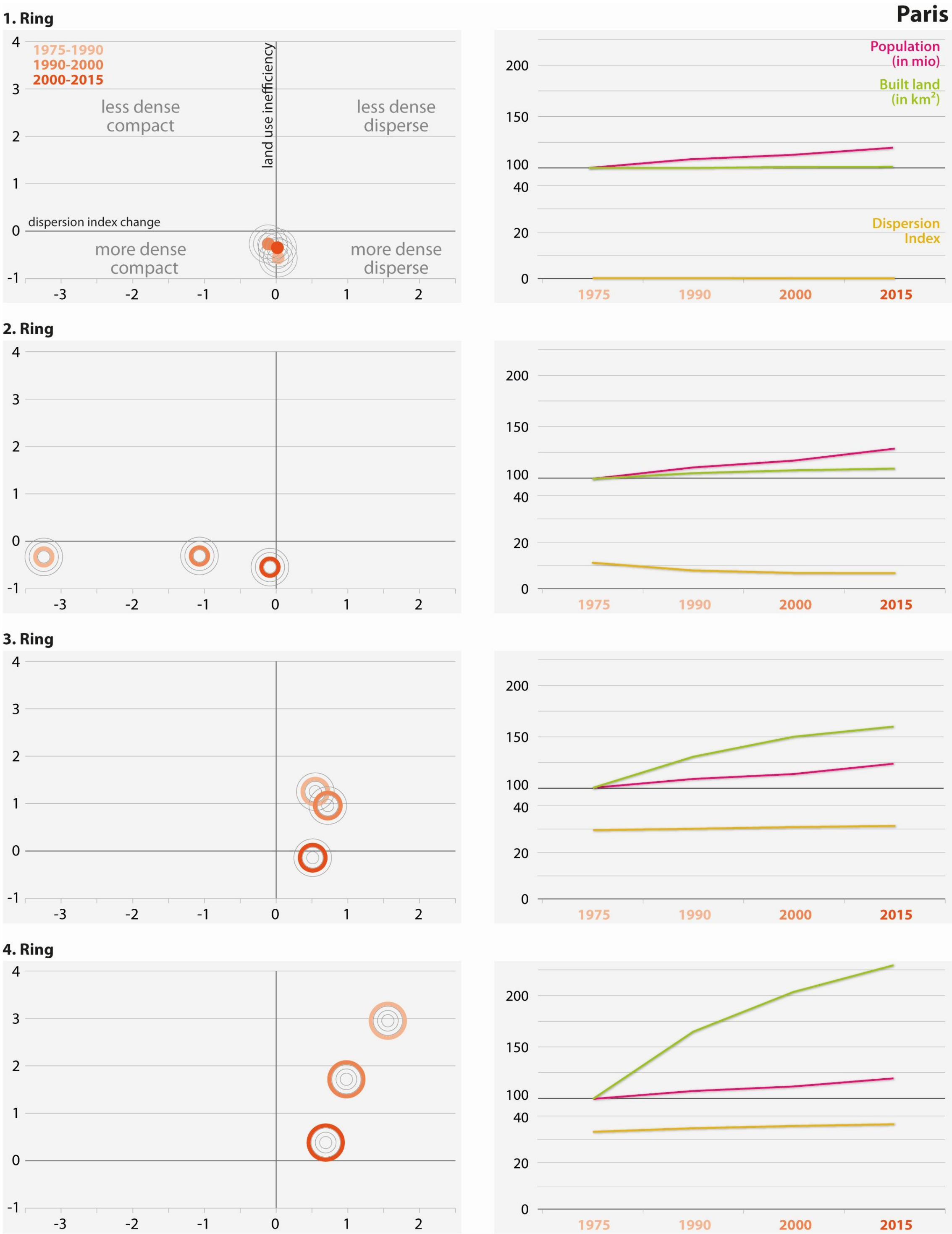


Figure 9: Urbanization trends for Paris divided into the four rings. The line charts illustrate the corresponding development of built-up land, population, and dispersion index over time

5 Discussion

The main results of our study inform about global urbanization trends and new monitoring methods based on remote sensing data. In terms of selected examples on urbanization we show that the highest growth dynamics occurred in the period from 1975 to 1990. In most world regions, this result is typical for the expansive building policies in the wake of the automobile oriented suburbanization that dominated urban development from the 1950s onward for some decades. This trend is global, although with variations in timing and scale (MacLean, 2008). Our results deliver additional evidence for such variations for selected cities and city groupings in this time period. In the following periods, from 1990 onwards, we see a general compaction of urban development.We attribute this compaction to a consolidation of suburban developments over time with new built-up areas. However, the results of densification or land use inefficiency are not as clear. Most of the cities in our sample show densification in the inner rings and later in the outer rings. Generally, cities exhibit a time lag between the growth of built-up areas and the influx of inhabitants that leads to higher densities. The dichotomy between urban and rural areas becomes blurry. The additional results of our analysis indicate the following urbanization patterns in the study areas:

- Chicago shows a decreasing density that is in line with the results obtained by Angel et al. (2010) from the early 1950s onwards. According to the results of that study, the share of urbanized land increased from 1970 to 2000 from 50 to 100%. We can verify this result with the urbanization shown in Figure 7 that illustrates a steadying trend of increasing land consumption per inhabitant.
- Due to the historically established high density in the urban core of Paris, the growth of urbanized land occurred in the outer rings, although the inner city is still growing in population. As a typical characteristic of this process, the settlement patterns aremost compact in the city core, and they become more dispersed in the outer rings, following the main transport routes. In the outer rings, the settlement density decreases as a consequence of the high land consumption rate, which is typical for urban sprawl.
- Angel et al. (2011) already showed that the growth of urbanized areas in European cities had already peaked before 1975. In contrast, cities in Asia, Africa and South America are still experiencing high growth rates, after 1970 and continuing until the last year of data availability in 2015. These trends were also identified by Seto et al. (2011). Figure 4 shows these differences in land use inefficiency and dispersion dimensions. The results of the statistical analysis present a major difference in the dispersion index change between the continents for the first time period. Since 1990 the sample seems to be more equal. In comparison, the differences of the land use inefficiency for the continents are tremendous for the complete observation time.

From a methodological point of view, our findings show that monitoring methods need to be complemented by validation procedures to test for data reliability. Future analysis must work with ground truth data and more in-depth case studies to assess the accuracy of monitoring results. This aspect is important due to doubts about data quality. As explained in the section on data, we cannot rule out that the limited data quality for the 1975 data is responsible for the large deviations of this time period compared to the trends of the whole observation period. This warning especially applies to the population data presented in section Land Use and Population Data. In terms of land use we expect an improvement of data reliability for more recent years based on the introduction of higher quality sensors and classification procedures.Due to our city selection procedure, our interpretation results on the global level refer only to growing cities. Therefore, we cannot comment on shrinking or stagnating cities. Other methodological findings are:

- The differentiation of growth trends according to city size is affected by the cities' catchment areas. For cities with more than 500,000 inhabitants, we used a 45 min travel time polygon as the research unit, which may also include suburban and rural areas in cities with a high density gradient. This area is mostly where urban sprawl happens, namely, at the outskirts along motorways, often as a result of suburbanization processes. In these cities, the urban density can increase in the core. On the outskirts, the urban patterns become more sprawled due to newly developed settlement structures. This effect is evidenced by major differences in land use inefficiency and dispersion between city size categories. Statistical analysis shows that large cities with more than 500,000 inhabitants have consolidated dispersed and inefficient sprawling conditions much more over time than smaller sized cities.
- Our analysis of cities by continent does not obtain clear differences for interpretation. Grouping cities by continent obviously mixes too many specific city types with unique development paths, and the resulting average values disguise the analytical power of a single portrayal of development trends such as those we presented for Chicago and Paris. To extract more analytical value from city classes, we aim to concentrate on planning regimes and other characteristic properties of cities for future groupings and the inclusion of different rings of observation.

In essence, we used this study to test a new methodology for a rich database. Our initial results show that the results can be conclusive and reflect global urbanization trends in a new and simplified way. In comparison to other global assessment methodologies (e.g., Seto et al., 2011; Zhang and Seto, 2011) that utilize more measures, we manage to combine the dimensions of population, land expansion, and urban sprawl in one measurement approach. The strength of this methodology is in the analysis of the individual cities and their different catchment areas, which can be adapted for further analysis. Thus, we can assign the development in the individual city rings to different trends of urban land use change. The delineation of cities and their catchments remains a problem for monitoring applications. Our approach to use network analysis and the most recent street network to model multiple rings around an urban core provides the flexibility to analyze urban development phases over time. Based on this approach we can capture land use changes in the rings without relying on the stability of administrative areas.

In addition, we do not have to differentiate arbitrarily between urban fringes, suburbia and the rural hinterland, categories that have changed highly dynamically in many city regions of our observation period. In addition, we can customize our methodology. With far-reaching methodological changes of our previous dataset, we are able to exchange the GHSL with similar data sources. The minimum requirements include small-scale information about population and built-up land. Such requirements also apply to our indicators as long as the new indicators are based on the same theoretical and methodological foundations. However, we have also identified limitations in the methodology. To interpret and compare the results additional information such as the initial absolute values of the indicators are useful. Further, our selected indicators also have strengths and weaknesses. As already determined, the application of the dispersion index does not consider the intensity of urban land use or functional centrality (Taubenböck et al., 2019). The indicator focuses on adjacent cells, where minimal inaccuracies in the dataset can break topological adjacency. However, we assess this problem as a minor inaccuracy that is acceptable with a view toward capturing general trends. It is also clear that aspects like urban density could be more accurate when using construction volume or 3D-building data. However, our approach is designed to work with data that is available worldwide, which is not the case for 3D data (e.g., Jahn et al., 2015; Krehl et al., 2016). For future analysis, it would be interesting to compare the results of our simplified analysis to a more complex and detailed measurement. For the time being we can validate the results based on the literature on urban development trends. Future analysis on drivers and impacts will certainly demand additional indicators and qualitative assessments.

We are aware that this idea initially requires some effort to conceptualize. However, once it has been understood and established as a monitoring concept, we expect benefits from its continuous use. In addition, this idea can be a relatively accessible and easy-to-communicate approach for the measurement of urban land use change. The advantage we envisage is that the data requirements are by far not as demanding as in most other measurement concepts. We also expect that further research is needed to make the analytical power more accessible to planning practitioners. Such research must include working with advanced visualization techniques and incorporating other reference data to validate the results. For example, further research could consider planning regimes or economic conditions to obtain information about the development paths of land use change. Such analysis will be left to future endeavors once we have established, communicated, and received feedback on the explanatory value of our methodological approach.

6 Conclusion

This study was designed to extend measurement methods on urban land use change for worldwide assessments of cities by city size. To achieve this goal, we explored several methods and produced a simplified framework based on the previous studies in Western countries. The idea of this framework is to condense the dimensions of urban land use change suggested in the literature without compromising the analytical depth. Our new approach combines the dimension of urban area, land use patterns, and urban densities into a unified measurement model on two axes: land use inefficiency (built-up area growth divided by population growth) and dispersion of urban patches in the research area.

Overall, the portrayal of global development based on this method provides a first glimpse into the analytical potential of both the method and dataset. Indicator results can be used as single measurements or in the combined analysis of the land use inefficiency and dispersion matrix. Future analysis will provide more insight into the actual development trends by using several rings and other groupings of cities, for example, with a view toward the planning culture or other specific dynamics. For the time being, we introduce this new analytical concept for discussion in the research community. Ideally, we would like to see such analysis used in monitoring applications in planning practice to inform decision makers about urban development paths. Put simply, our recommendation is to capture the starting point of the urban footprint in terms of density and compactness, formulate appropriate objectives, and then begin to monitor development paths with this new method.

The understanding of how cities have grown is an essential facet of the spatial sciences. Newly available, small-scale population and built-up area data serve as the basis for innovative but conceptually challenging analysis options. It is up to the scientific community to improve planner's abilities to effectively employ such data. In this sense, the results presented here deliver on the call of Wei and Ewing (2018) for the development of new monitoring methods for urban land use change.

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A Supplementary Tables

City	Year	Ring	Population	Urbanized land (in km^2)	LPn	NPn	DI
Paris	1975	1	1,938,168	96.1	99.4	0.0	0.3
Paris	1975	2	4,073,981	641.8	77.9	0.2	11.2
Paris	1975	3	2,743,855	656.6	41.2	0.6	29.7
Paris	1975	4	1,078,480	271.6	34.5	1.0	33.2
Paris	1990	1	2,101,314	96.2	99.4	0.0	0.3
Paris	1990	2	4,523,646	677.7	84.3	0.1	7.9
Paris	1990	3	2,979,668	856.4	40.0	0.6	30.3
Paris	1990	4	1,161,538	450.0	31.4	1.0	34.8
Paris	2000	1	2,183,985	97.1	99.5	0.0	0.2
Paris	2000	2	4,792,815	695.5	86.4	0.1	6.9
Paris	2000	3	3,114,306	984.2	38.5	0.5	31.0
Paris	2000	4	1,209,774	555.5	29.4	0.9	35.8
Paris	2015	1	2,319,620	97.3	99.5	0.0	0.2
Paris	2015	2	5,263,156	705.1	86.5	0.1	6.8
Paris	2015	3	3,392,364	1,049.1	37.5	0.5	31.5
Paris	2015	4	1,295,223	626.4	28.0	1.0	36.5
Chicago	1975	1	1,199,914	124.4	88.2	0.4	6.1
Chicago	1975	2	3,107,628	683.5	42.5	0.5	29.0
Chicago	1975	3	2,286,943	771.8	21.7	0.9	39.6
Chicago	1975	4	995,545	378.0	17.5	1.2	41.8
Chicago	1990	1	1,190,199	192.8	100.0	0.0	0.0
Chicago	1990	2	3,097,171	1,034.5	83.6	0.1	8.2
Chicago	1990	3	2,402,215	1,429.3	38.6	0.3	30.9
Chicago	1990	4	1,294,960	821.4	29.5	0.8	35.6
Chicago	2000	1	1,185,962	193.1	100.0	0.0	0.0
Chicago	2000	2	3,094,371	1,041.1	83.7	0.1	8.2
Chicago	2000	3	2,502,370	1,563.2	36.9	0.3	31.7
Chicago	2000	4	1,568,481	1,097.0	26.5	0.7	37.1
Chicago	2015	1	1,111,546	193.7	100.0	0.0	0.0
Chicago	2015	2	2,921,853	1,055.0	83.9	0.1	8.1
Chicago	2015	3	2,546,623	1,698.7	54.7	0.2	22.7
Chicago	2015	4	2,050,395	1,398.3	37.1	0.5	31.7

Supplementary Table 1: Data table for Paris and Chicago (static)

City	Time Period	Ring	Population Growth Rate	Built Land Growth Rate	Land Use Efficiency	DI-Change
Paris	1975 - 1990	1	0,54	0,01	-0,53	0,02
Paris	1975 - 1990	2	0,70	0,36	-0,34	-3,24
Paris	1975 - 1990	3	0,55	1,79	1,24	0,56
Paris	1975 - 1990	4	0,50	3,42	2,93	1,56
Paris	1990 - 2000	1	0,39	0,09	-0,30	-0,10
Paris	1990 - 2000	2	0,58	0,26	-0,32	-1,06
Paris	1990 - 2000	3	0,44	1,40	0,96	0,70
Paris	1990 - 2000	4	0,41	2,13	1,72	0,98
Paris	2000 - 2015	1	0,40	0,01	-0,39	0,01
Paris	2000 - 2015	2	0,63	0,10	-0,53	-0,07
Paris	2000 - 2015	3	0,57	0,46	-0,12	0,51
Paris	2000 - 2015	4	0,46	0,86	0,41	0,69
Chicago	1975 - 1990	1	-0,05	2,97	3,02	-6,1
Chicago	1975 - 1990	2	-0,02	2,80	2,82	-20,7
Chicago	1975 - 1990	3	0,33	4,19	3,87	-8,7
Chicago	1975 - 1990	4	1,77	5,31	3,54	-6,2
Chicago	1990 - 2000	1	-0,04	0,01	0,05	0,0
Chicago	1990 - 2000	2	-0,01	0,06	0,07	-0,1
Chicago	1990 - 2000	3	0,41	0,90	0,49	0,8
Chicago	1990 - 2000	4	1,93	2,94	1,00	1,4
Chicago	2000 - 2015	1	-0,43	0,02	0,45	0,0
Chicago	2000 - 2015	2	-0,38	0,09	0,48	-0,1
Chicago	2000 - 2015	3	0,12	0,60	0,48	-8,9
Chicago	2000 - 2015	4	1,80	1,75	-0,05	-5,4

Supplementary Table 2: Data table for Paris and Chicago (dynamic)

(1) Andorra	(39) Liechtenstein
(2) Afghanistan	(40) Liberia
(3) Antigua and Barbuda	(41) Luxembourg
(4) Barbados	(42) Latvia
(5) Bangladesh	(43) Monaco
(6) Bahrain	(44) Montenegro
(7) Bermuda	(45) Marshall Islands
(8) Brunei Darussalam	(46) Myanmar
(9) Bahamas	(47) Mongolia
(10) Bhutan	(48) Montserrat
(11) Belize	(49) Malta
(12) Cook Islands	(50) Mauritius
(13) Cabo Verde	(51) Maldives
(14) Cyprus	(52) Nauru
(15) Djibouti	(53) Niue
(16) Dominica	(54) New Zealand
(17) Estonia	(55) Pakistan
(18) Fiji	(56) Pitcairn
(19) Falkland Islands (Malvinas)	(57) Palau
(20) Micronesia (Federated States of)	(58) Solomon Islands
(21) Faroe Islands	(59) Seychelles
(22) Grenada	(60) Saint Helena, Ascension and Tristan da Cunha
(23) Guernsey	(61) San Marino
(24) Gibraltar	(62) Suriname
(25) Greenland	(63) Sao Tome and Principe
(26) Gambia	(64) Syrian Arab Republic
(27) Equatorial Guinea	(65) Eswatini
(28) South Georgia and the South Sandwich Islands	(66) Turks and Caicos Islands
(29) Guinea-Bissau	(67) Timor-Leste
(30) Guyana	(68) Tonga
(31) Iran	(69) Trinidad and Tobago
(32) Jersey	(70) Tuvalu
(33) Kiribati	(71) Holy See
(34) Comoros	(72) Saint Vincent and the Grenadines
(35) Saint Kitts and Nevis	(73) Virgin Islands
(36) Korea (Democratic People's Republic of)	(74) Vanuatu
(37) Korea, Republic of	(75) Samoa
(38) Saint Lucia	(76) Yemen

Supplementary Table 3: List of excluded countries (street-network problems)

Supplementary Table 4: List of selected cities per country

Country	City A (absolute)	City A (relative)	City B (absolute)	City B (relative)	City C (absolute)	City C (relative)	Count
Albania	Tiran						1
Algeria	Algiers	Oran	Medea	BouSaada	Sourel Ghozlane	Messaad	6
Angola	Luanda	Benguela	Malanje	Lucapa	Soyo		5
Argentina	Buenos Aires	San Miguel de Tucuman	Corrientes	San Luis	Rafaela	SanFrancisco	6
Armenia	Yerevan		Vanadzor	Gyumri			3
Australia	Brisbane	Gold Coast	Geelong	Alice Springs	Ballarat	Toowoomba	6
Austria	Vienna		Linz	Innsbruck			3
Azerbaijan	Baku		Mingecevir	Ganca			3
Belarus	Minsk	Homyel	Brest	Mazyr	Maladzyechna	Svyetlahorsk	6
Belgium	Antwerp	Brussels	Brugge	Liege			4
Benin	Porto Novo	Cotonou	Bohicon	Aplahoue	Save	Nikki	6
Bolivia	Cochabamba	Santa Cruz	Oruro	Potosi	Riberalta		5
Bosnia And Herzegovina	Sarajevo		Tuzla	Banja Luka	Bihac		4
Botswana	Francistown		Gaborone				2
Brazil	Campinas	Brasilia	Piracicaba	Franca	Peruibe	Ijui	6
Bulgaria	Sofia		Ruse	Pleven			3
Burkina Faso	Ouagadougou		Bobo Dioulasso		Garango		3
Burundi	Bujumbura						1
Cambodia	Phnom Penh		Batdambang	Siemreab			3
Cameroon	Yaounde	Douala	Mbouda	Mokolo	Guider	Bafia	6
Canada	Mississauga	Calgary	Abbotsford	London	Sarnia	MedicineHat	6
Central African Republic	Bangui				Carnot		2

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Supplementary Table 4: List of selected cities per country (Continued)

Chad	NDjamena		Moundou	Sarh			3
Chile	Santiago	Puente Alto	Quilpue	Talca	Los Andes	San Antonio	6
China	Wuxi	Hefei	Zhuzhou	Joeshou	Yuantan	Dongcheng	6
Columbia	Bogota	Medellin	Villavicencio	Quibdo	Caucasia	La Dorada	6
Congo	Brazzaville	Pointe Noire	Dolisie			Kayes	4
Costa Rica	SanJose						1
Cote D'ivoire (Ivory Coast)	Abidjan	Yamoussoukro	Daloa	Soubre	Duekoue	Guiglo	6
Croatia	Zagreb		Rijeka		Pula		3
Cuba	Havana	Santiago de Cuba	Matanzas	Sancti Spiritus	San Cristobal	Jaguey Grande	6
Czech Republic	Prague		Ostrava	Plzen	Most		4
Democratic Republic of the Congo	Kinshasa	Bukavu	Goma	Bunia	Mbanza Ngungu	Bukama	6
Denmark	Copenhagen		Arhus	Alborg	Esbjerg		4
Dominican Republic	Santo Domingo Este	Santiago de los Caballeros	LaRomana	Higueey			4
Ecuador	Quito	Guayaquil	Ibarra	Loja	La Libertad		5
Egypt	Shubraal Khaymah	PortSaid	Al Ismailiyah	AlArish			4
El Salvador	San Salvador		San Miquel				2
Eritrea	Asmara						1
Ethiopia		Jima	Awasa	Mekele		DebreBirhan	4
Finland	Helsinki		Oulu	Lahti	Kotka		4
France	Paris	Reims	Lille	Avignon	SaintQuentin	Beziers	6
Gabon	Libreville		Port Gentil				2
Georgia	Tbilisi		Zugdidi	Kutaisi			3

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Supplementary Table 4: List of selected cities per country (Continued)

Germany	Duesseldorf	Dresden	Aachen	Regensburg	Fulda	Passau	6
Ghana	Kumasi	Accra	Koforidua	Cape Coast	Nkawkaw	Bawku	6
Greece	Athens	Thessaloniki	Patrai	Larisa			4
Guatemala	Guatemala City		Quetzaltenango				2
Guinea	Labe	Nzerekore	Kindia	Kissidougou			4
Haiti	Portau Prince		Gonaives				2
Honduras	Tegucigalpa		ElProgreso	San Pedro Sula			3
Hungary	Budapest		Gyor	Debrecen	Sopron	Nagykanizsa	5
Iceland	Reykjavik						1
India	Ghaziabad	Bhavnagar	Puruliya	Balasore	Beypore	Contai	6
Indonesia	Surakarta	Semarang	Purwokerto	Pati	Bojonegoro	Tuban	6
Iraq	Baghdad	As Sulaymaniyah	Al Hillah	Samarra	Khanaqin	Tuzkhurmatu	6
Ireland	Dublin		Letterkenny	Athlone	Castleblayney	Westport	5
Israel	Tel Aviv Yafo	Jerusalem	Haifa				3
Italy	Milan	Florence		Foggia	Carrara	Lamezia Terme	5
Jamaica	Half Way Tree	Kingston					2
Japan	Saitama	Utsunomiya	Isesaki	Hitachi Naka	Maizuru	Miyako	6
Jordan	Amman		Irbid	Al Aqabah			3
Kazakhstan	Almaty	Astana	Qaraghandy	Qyzylorda	Shchuchinsk	Tuerkistan	6
Kenya	Nairobi	Mombasa	Kisumu	Nakuru			4
Kuwait	Kuwait City						1
Kyrgyzstan	Bishkek		Osh		KaraBalta		3
Laos	Vientiane		Savannakhet	Pakxe			3
Lebanon	Beirut		Tripoli				2

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Supplementary Table 4: List of selected cities per country (Continued)

Lesotho	Maseru						1
Liby		Banghazi	Sabratah	Yafran	Nalut		4
Lithuania	Vilnius		Kaunas	Panevezys			3
Macedonia	Skopje						1
Madagascar	Antananarivo		Toliara	Antsirabe			3
Malawi	Lilongwe	Blantyre	Mzuzu				3
Malaysia	Ampang	Kuching	AlorSetar	KotaBharu	Keningau	Semporna	6
Mali	Bamako		Segou	Sikasso	Koutiala	San	5
Mauritania	Nouakchott		Nouadhibou				2
Mexico	Ciudad Lopez Mateos	Chihuahua	Cuautla Morelos	Cordoba	Martinezde La Torre	Linares	6
Moldova	Chisinau		Balti	Tiraspol	Ribnita		4
Morocco	Casablanca	Fes	Settat	Khenifra	Benguerir	Youssoufia	6
Mozambique	Maputo	Matola	Cidadede Nacala	Chimoio	Angoche	Chokwe	6
Namibia	Windhoek		Oshikuku				2
Nepal	Kathmandu		Birganj	Biratnagar			3
Netherlands	Rotterdam	Amsterdam	sHertogenbosch	Zwolle			4
Nicaragua	Managua		Chinandega	Leon			3
Niger	Niamey		Maradi	Zinder	BirniNKonni	Arlit	5
Nigeria	PortHarcourt	Abuja	IjebuOde	Bama	Idah	Biu	6
Norway	Oslo		Bergen	Trondheim	Fredrikstad	Porsgrunn	5
Oman	Salalah	Masqat	Al Buraymi	As Suwayq			4
Palestine	Ramallah	Ghazzah					2
Panama	Panama City						1
Papua New Guinea	Port Moresby						1

Continued on next page

Supplementary Table 4: List of selected cities per country (Continued)

Paraguay	Asuncion		CiudaddelEste		Colonia Presidente Franco	Caaguazu	4
Peru	San Martinde Porras	Chiclayo	Tacna	Puno	Jaen		5
Philippines	Caloocan	Davao	Angeles	Malaybalay			4
Poland	Krakow	Warsaw	Tychy	Bialystok	Tarnobrzeg	Ostroleka	6
Portugal	Porto	Lisbon	Coimbra	Leiria			4
Qatar	Ad Dawhah		Madinatash Shamal				2
Romania	Bucuresti		SatuMare	Iasi	Birlad	Hunedoara	5
Russian Federation	Moscow	Orenburg	Sergiyev Posad	Yakutsk	Kamensk Shakhtinskiy	Ishim	6
Rwanda	Kigali						1
Saudi Arabia	Riyadh	Hail	Al Mubarraz	Hafar al Batin	Rasal Khafji	Qalat Bishah	6
Senegal	Dakar		Mbour	Kaolack			3
Serbia	Belgrade		Prizren	Pristina	NoviPazar		4
Sierra Leone	Freetown		Sefadu				2
Singapore	Singapore						1
Slovakia	Bratislava		Kosice		Trencin	Poprad	4
Slovenia	Ljubljana		Maribor				2
Somalia	Mogadishu	Hargeysa	Jawhar	Boorama			4
South Africa	Tembisa	Bloemfontein	Rustenburg	Richards Bay	Stanger	Louis Trichardt	6
South Sudan	Juba		Malakal	Waw	Gogrial		4
Spain	Leganes	Madrid	Vigo	Lleida	Ponferrada	Talaveradela Reina	6
Sri Lanka	Sri Jayewardenepura Kotte	Colombo	Kandy	Jaffna	Dambulla		5
Sudan	Khartoum North	Kadugli	Wad Madani	Sannar			4

Continued on next page

Supplementary Table 4: List of selected cities per country (Continued)

Sweden	Stockholm	Goeteborg	Uppsala	Vasteras	Norrkoeping		5
Switzerland	Zuerich	Geneva					2
Tajikistan	Dushanbe		Qurghonteppa		Kulob		3
Tanzania	DaresSalaam	Njombe	Kigoma	Mbeya	Newala	Ifakara	6
Thailand	Bangkok	Phra Nakhon	Chon Buri	Watthana Nakhon	HuaHin		5
Togo	Lome		Kpalime	Sokode			3
Tunisia	Tunis		Sousse	Kairouan			3
Turkey	Istanbul	Bursa	Izmit	Usak	Cizre	Aksehir	6
Turkmenistan	Asgabat		Dasoguz	Nebit Dag	Gyzylarbat		4
Uganda	Kampala		Jinja	Busia			3
Ukraine	Kiev	Odesa	Alchevsk	Bila Tserkva	Stryy	Pryluky	6
United Arab Emirates	Sharjah	Abu Dhabi	Al Ayn	Rasal Khaymah			4
United Kingdom	Manchester	Belfast	Reading	Ipswich	Carlisle		5
United States	Chicago	Colorado Springs	Corona	McAllen	Sandy Springs	Casper	6
Urugay	Montevideo						1
Uruguay			Salto		Santanado Livramento		2
Uzbekistan	Tashkent	Bekobod	Andijon	Nukus	Kattaqorgon	Zarafshon	6
Venezuela	Caracas	Ciudad Guayana		Maturin	ElTocuyo	Vallede La Pascua	5
Vietnam	Ho Chi Minh City	Hai Phong	Thai Nguyen	Vinh			4
Zambia	Lusaka		Kitwe	Kabwe	Mazabuka		4
Zimbabwe	Harare	Bulawayo	Kwekwe	Kadoma	Hwange	Zvishavane	6
Total	131	71	116	97	72	50	537

	Continents	N	Mean Rank
LUI	Africa	147	260,01
	Asia	123	287,78
	Australia	6	328,83
	Europe	145	253,52
	North America	42	236,69
	South America	50	190,96
	Total	513	
DIC	Africa	147	243,12
	Asia	123	216,51
	Australia	6	231,17
	Europe	145	313,17
	North America	42	238,10
	South America	50	253,49
	Total	513	

Supplementary Table 5: Kruskal-Wallis Ranks – Continents 1975 to 1990

	LUE	DIC
Chi-Quadrat	17,566	32,185
df	5	5
Asymp. Sig.	,004	,000

Supplementary Table 6: Kruskal-Wallis Ranks – Continents 1975 to 1990

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
South America-North America	45,730	31,027	1,474	,141	1,000
South America-Europe	62,557	24,311	2,573	,010	,151
South America-Africa	69,054	24,268	2,845	,004	,067
South America-Asia	96,820	24,862	3,894	,000	,001
South America-Australia	137,873	64,045	2,153	,031	,470
North America-Europe	16,827	25,975	,648	,517	1,000
North America- Africa	23,323	25,936	,899	,369	1,000
North America-Asia	51,090	26,492	1,929	,054	,807
North America-Australia	92,143	64,695	1,424	,154	1,000
Europe- Africa	6,496	17,350	,374	,708	1,000
Europe-Asia	34,263	18,171	1,886	,059	,890
Europe-Australia	75,316	61,756	1,220	,223	1,000
Africa -Asia	-27,767	18,114	-1,533	,125	1,000
Africa -Australia	-68,820	61,739	-1,115	,265	1,000
Asia-Australia	-41,053	61,975	-,662	,508	1,000

Supplementary Table 7: Kruskal-Wallis Pairwise comparison (LUI) – Continents 1975 to 1990; each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same; asymptotic significances (2-sided tests) are displayed; the significance level is ,05

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
Asia-Australia	-14,654	61,970	-,236	,813	1,000
Asia-North America	-21,583	26,490	-,815	,415	1,000
Asia- Africa	26,607	18,113	1,469	,142	1,000
Asia-South America	-36,978	24,860	-1,487	,137	1,000
Asia-Europe	-96,660	18,170	-5,320	,000	,000
Australia-North America	-6,929	64,690	-,107	,915	1,000
Australia-Africa	11,952	61,734	,194	,846	1,000
Australia-South America	-22,323	64,039	-,349	,727	1,000
Australia-Europe	-82,006	61,751	-1,328	,184	1,000
North America-Africa	5,024	25,934	,194	,846	1,000
North America-South America	-15,395	31,024	-,496	,620	1,000
North America-Europe	75,077	25,973	2,891	,004	,058
Africa-South America	-10,371	24,266	-,427	,669	1,000
Africa -Europe	-70,053	17,349	-4,038	,000	,001
South America-Europe	59,682	24,309	2,455	,014	,211

Supplementary Table 8: Kruskal-Wallis Pairwise comparison (DIC) – Continents 1975 to 1990; each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same; asymptotic significances (2-sided tests) are displayed; the significance level is ,05

	Continents	N	Mean Rank
	Africa	147	285,99
	Asia	123	215,66
	Australia	6	280,50
LUI	Europe	145	303,59
	North America	42	212,05
	South America	50	196,98
	Total	513	
	Africa	147	252,45
	Asia	123	262,96
	Australia	6	256,83
DIC	Europe	145	251,51
	North America	42	266,14
	South America	50	283,20
	Total	513	

Supplementary Table 9: Kruskal-Wallis Ranks – Continents 1990 - 2000

	LUE	DIC
Chi-Quadrat	41,513	2,223
df	5	5
Asymp. Sig.	,000	,817

Supplementary Table 10: Kruskal-Wallis Test Statistics – Continents 1990 – 2000

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
South America-North America	15,066	30,862	,488	,625	1,000
South America-Asia	18,677	24,546	,761	,447	1,000
South America-Australia	83,519	64,348	1,298	,194	1,000
South America-Africa	89,012	23,914	3,722	,000	,003
South America-Europe	106,612	23,979	4,446	,000	,000
North America-Asia	3,611	26,698	,135	,892	1,000
North America-Australia	68,452	65,199	1,050	,294	1,000
North America-Africa	73,946	26,118	2,831	,005	,070
North America-Europe	91,545	26,178	3,497	,000	,007
Asia-Australia	-64,841	62,458	-1,038	,299	1,000
Asia-Africa	70,335	18,227	3,859	,000	,002
Asia-Europe	-87,935	18,313	-4,802	,000	,000
Australia-Africa	5,493	62,212	,088	,930	1,000
Australia-Europe	-23,093	62,237	-,371	,711	1,000
Africa-Europe	-17,600	17,456	-1,008	,313	1,000

Supplementary Table 11: Kruskal-Wallis Pairwise comparison (LUI) – Continents 1990 to 2000; each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same; asymptotic significances (2-sided tests) are displayed; the significance level is ,05

	Continents	N	Mean Rank
LUI	Africa	147	264,97
	Asia	123	243,57
	Australia	6	195,33
	Europe	145	305,97
	North America	42	202,52
	South America	50	206,77
	Total	513	
DIC	Africa	147	269,49
	Asia	123	258,40
	Australia	6	238,33
	Europe	145	247,51
	North America	42	255,50
	South America	50	272,55
	Total	513	

Supplementary Table 12: Kruskal-Wallis Ranks – Continents 2000 - 2015

	LUE	DIC
Chi-Quadrat	29,345	2,149
df	5	5
Asymp. Sig.	,000	,828

Supplementary Table 13: Kruskal-Wallis Test Statistics – Continents 2000 – 2015

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
Australia-North America	-7,190	65,325	-,110	,912	1,000
Australia-South America	-11,440	64,472	-,177	,859	1,000
Australia-Asia	48,239	62,567	,771	,441	1,000
Australia-Africa	69,633	62,332	1,117	,264	1,000
Australia-Europe	-110,639	62,357	-1,774	,076	1,000
North America-South America	-4,250	30,921	-,137	,891	1,000
North America-Asia	41,049	26,722	1,536	,125	1,000
North America-Africa	62,442	26,169	2,386	,017	,255
North America-Europe	103,449	26,228	3,944	,000	,001
South America-Asia	36,799	24,564	1,498	,134	1,000
South America-Africa	58,193	23,960	2,429	,015	,227
South America-Europe	99,199	24,025	4,129	,000	,001
Asia-Africa	21,394	18,222	1,174	,240	1,000
Asia-Europe	-62,400	18,308	-3,408	,001	,010
Africa-Europe	-41,006	17,489	-2,345	,019	,286

Supplementary Table 14: Kruskal-Wallis Pairwise comparison (LUI) – Continents 2000 to 2015; each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same; asymptotic significances (2-sided tests) are displayed; the significance level is ,05

	City Category	N	Mean Rank
LUI	City A	202	225,77
	City B	211	292,15
	City C	119	290,15
	Total	532	
DIC	City A	202	282,24
	City B	211	262,66
	City C	119	246,60
	Total	532	

Supplementary Table 15: Kruskal-Wallis Ranks – City category 1975 to 1990

Supplementary Table 16: Kruskal-Wallis Statistics – City category 1975 to 1990

	LUE	DIC
Chi-Quadrat	22,873	4,245
df	2	2
Asymp. Sig.	,000	,120

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
City A – City C	-64,379	17,764	-3,624	,000	,001
City A – City B	-66,379	15,132	-4,387	,000	,000
City C – City B	2,000	17,623	,114	,910	1,000

Supplementary Table 17: Kruskal-Wallis Pairwise comparison (LUI) – City category 1975 – 1990

	City Category	N	Mean Rank
LUI	City A	202	222,67
	City B	211	289,11
	City C	119	308,57
	Total	532	
DIC	City A	202	286,56
	City B	211	250,10
	City C	119	270,57
	Total	532	

Supplementary Table 18: Kruskal-Wallis Ranks – City category 1990 - 20000

	LUE	DIC
Chi-Quadrat	29,605	5,759
df	2	2
Asymp. Sig.	,000	,056

Supplementary Table 19: Kruskal-Wallis Statistics – City category 1990 to 2000

Supplementary Table 20: Kruskal-Wallis Pairwise comparison (LUI) – City category 1990- 2000

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
City A – City B	-66,435	15,228	-4,363	,000	,000
City A – City C	-85,892	17,758	-4,837	,000	,000
City B – City C	-19,457	17,600	-1,106	,269	,807

Supplementary Table 21: Kruskal-Wallis Ranks – City category 2000 - 2015

	City Category	N	Mean Rank
LUI	City A	202	224,34
	City B	211	288,59
	City C	119	308,74
	Total	532	
DIC	City A	202	301,41
	City B	211	250,88
	City C	119	246,98
	Total	532	

Supplementary Table 22: Kruskal-Wallis Test Statistics – City category 2000 – 2015

	LUE	DIC
Chi-Quadrat	28,131	14,173
df	2	2
Asymp. Sig.	,000	,001

Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
City A – City B	-64,250	15,239	-4,216	,000	,000
City A – City C	-84,396	17,791	-4,744	,000	,000
City B – City C	-20,146	17,617	-1,144	,253	,758

Supplementary Table 23: Kruskal-Wallis Pairwise comparison (LUI) – City category 2000 to 2015; each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same; asymptotic significances (2-sided tests) are displayed; the significance level is ,05

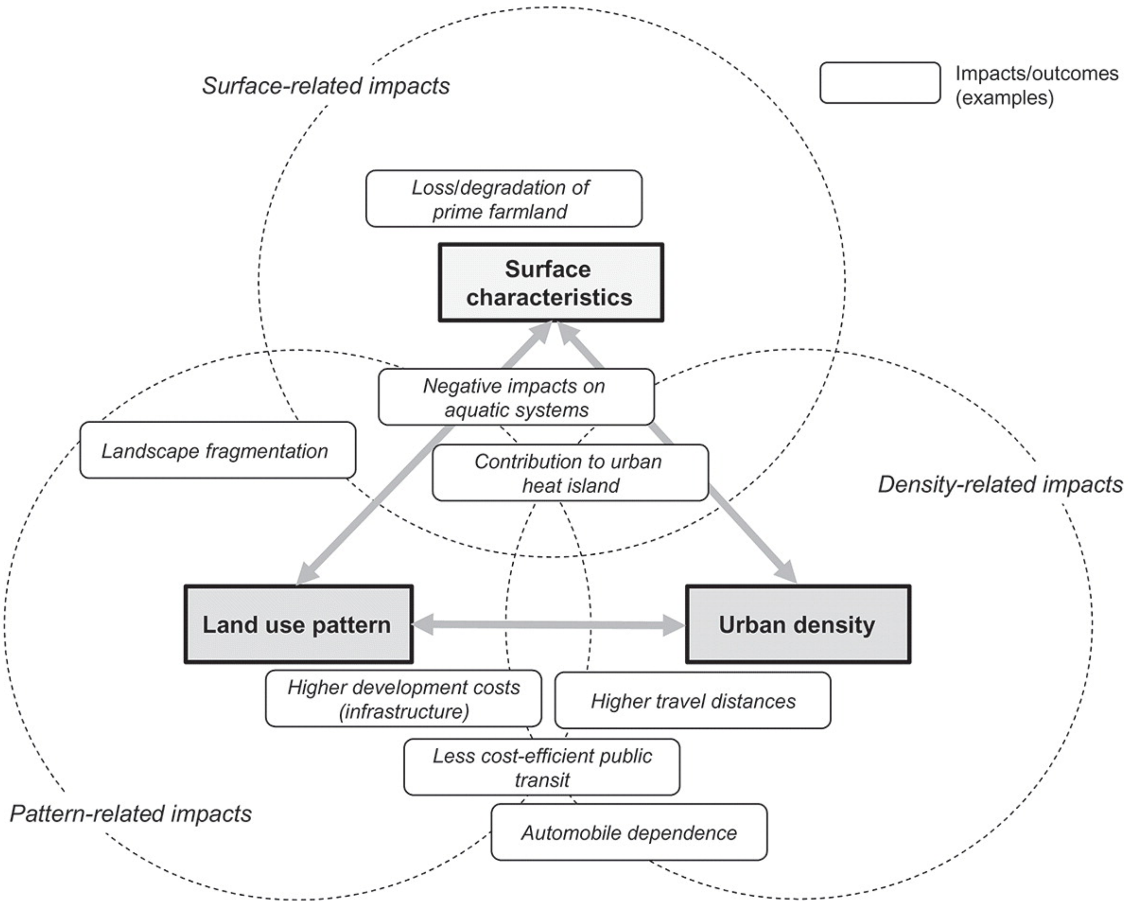
Sample 1-Sample 2	Test Statistics	Std. Error	Std. Test Statistics	Sig.	Adj. Sig.
City A – City B	-64,250	15,239	-4,216	,000	,000
City A – City C	-84,396	17,791	-4,744	,000	,000
City B – City C	-20,146	17,617	-1,144	,253	,758

Supplementary Table 24: Kruskal-Wallis Pairwise comparison (LUI) – City category 2000 to 2015; each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same; asymptotic significances (2-sided tests) are displayed; the significance level is ,05

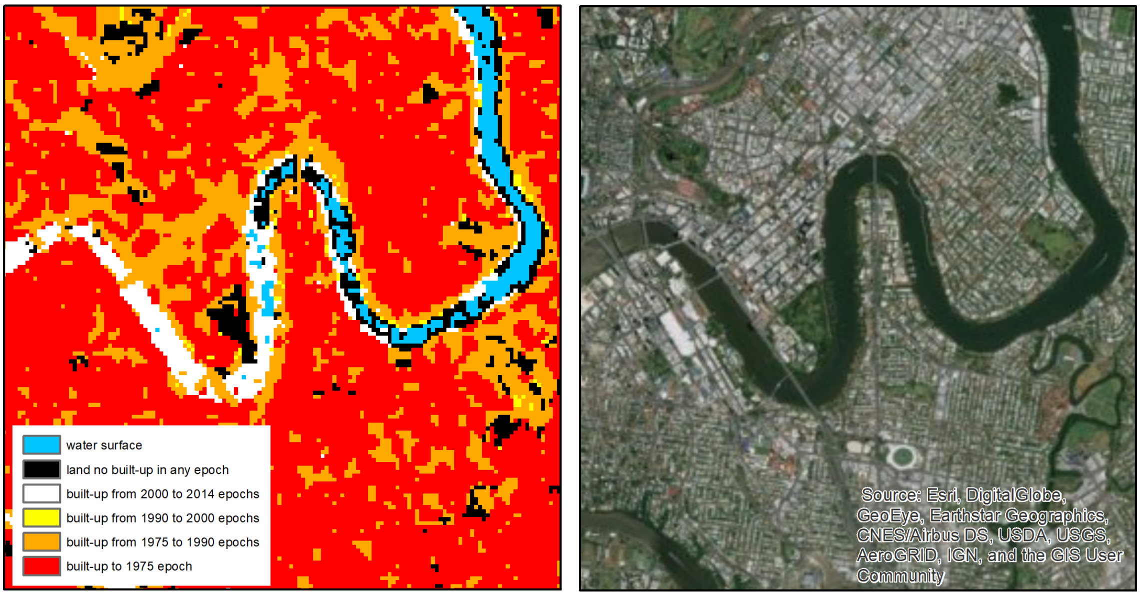
Year	Population (GHSL)	Year	Population (official statistics)
1975	11,464	1970	57,773
1990	19,362	1987	47,997
2000	28,277	2000	45,212
2015	46,105	2015	41,614

Supplementary Table 25: Comparison of GHSL and administrative population data from German statistical offices for the City of Pirmasens, Germany (Source: Federal Agency of Statistics Germany). In analyzing our results, we identified excessive developments in population growth, especially in the time period between 1975 and 1990, which we could not validate. An example is the population of Pirmasens in Germany. The GHSL dataset portrays a minor but growing population for 1975, 1990 and 2000 (see table 1). However, the official statistics show a higher initial value in 1970 and a shrinking population curve. This observation leads to a high underestimation of the population for 1975, 1990 and 2000 and a moderate overestimation of the population in 2015. We attribute minor deviations to the aggregation of the population raster to the city boundaries. The residual inconsistency could also be a result of inaccuracy in the GHSL

B Supplementary Figures



Supplementary Figure 1: Theoretical framework for the measurement of urban sprawl (Siedentop and Fina 2010, p. 79)



Supplementary Figure 2: Problems in coverage of urban land (example of Brisbane). A test has shown that the Brisbane River in Brisbane, Australia, (see figure 2) was not classified correctly. Some parts of the river were identified as water surface and other parts as nonbuilt or built-up from 2000 to 2014. We suspect that the quality of earlier satellite scenes with limited resolution and frequencies from the 1970s were more prone to such errors compared to the increasingly robust remote sensing products available for the more recent years.

A.3.2 Scrutinizing the Buzzwords in the Mobility Transition: The 15-Minute-City, the One-Hour Metropolis, and the Vicious Cycle of Car Dependency

Scrutinizing the Buzzwords in the Mobility Transition: The 15-Minute-City, the One-Hour Metropolis, and the Vicious Cycle of Car Dependency

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Abstract: In 2020, the mayor of Paris announced the ambitious goal to redesign the city for pedestrians to reach amenities and facilities for daily use within a 15-minute walk. Other cities, such as Melbourne or Portland, have also set themselves this goal. This objective has propelled older initiatives to improve the walkability and pedestrian friendliness of cities to the influential sphere of the tabloid press, giving a new boost to sustainable urban planning paradigms that emphasize the long-neglected importance of active mobility. In this context, researchers in public health and spatial sciences have worked on measurement tools of walkability for almost two decades now. Based on the widely acknowledged theories of the three Ds (density, diversity, and design), multicriteria indices, such as the IPEN walkability index, have shown how city structures can be assessed for their framing conditions for people to walk for a large share of activities. Such tools, however, have been difficult to operate for urban planners due to demanding requirements for data sources and software methods, including GIS network analysis capabilities. Therefore, this paper aims to provide a new assessment method for the three current foci of research on the mobility transition: the 15-minute city, the one-hour metropolis, and car-dependent structures. Based on an open-source tool, we could classify the prevailing mobility structure on the neighborhood level. The application of this tool allows for data-driven management to implement and evaluate plans and urban design policies to identify and assess the *15-minute city*. We will showcase for the cities of Paris, Melbourne, and Portland how outcomes of the tool help to unearth formerly unseen city live dimensions and legitimize urban design projects to mitigate and monitor deficiencies.

Keywords: sustainable mobility, walkability, public transport, car-dependency, mobility assessment

Contents

1 Introduction

Urban mobility structures and transport systems are of central importance for sustainable development. On the one hand, they are the 'maker and breaker of cities' (Clark, 1958) when they support or limit the mobility of people and transportation of goods. On the other hand, the dominance of motorized forms of transport is causing stress to city environments far beyond the carrying capacity of environmental systems. This applies to local emissions as well as cumulative downstream effects contributing to climate change. As a side effect, people's health suffers from exposure to air pollution and noise as well as inactive lifestyles (WBGU, 2016; Naess, 2006).

The ubiquitous dominance of private motorized mobility is determined as a driver for negative urban developments in terms of urban sprawl and functionally segregated areas (WBGU, 2016; Kosonen, 2015). The redesign of urban structures to support nonmotorized and active forms of travel is therefore a dominant objective for a socioecological mobility transition in the twenty-first century. To this end, transport planning is increasingly adopting a comprehensive understanding of mobility as a complex sociotechnical system. Political, academic, and civic initiatives advocate a redesign of urban structures for people-friendly forms of transport. At the same time, critical researchers point to a mismatch between the sustainable mobility rhetoric and actual developments on the ground. This is obvious when measures such as carbon emissions per person continue to increase in cities trumpeting their sustainable development policies. The effects are more difficult to assess when showcase examples of sustainable neighborhoods focus on privileged local conditions and neglect their embeddedness in a regional and national transport system.

Against this background, our paper introduces new assessment methods for the three current foci of research on the mobility transition: the 15-minute city and the one-hour metropolis with a positive association and car-dependent structures with a negative association (see, e.g., Kosonen, 2015). Whereas the 15-minute city is largely concerned with local neighborhood access to services and amenities by active modes of mobility (walking, cycling), the one-hour metropolis relates to mode integration based on an excellent public transport infrastructure for a city region. Car dependency, by contrast, is defined by 'the lack of alternative transport modes to the car in terms of time, cost and effort in accessing destinations' (Wiersma et al., 2021).

The opening sections describe the need for assessment methods based on a critical review of existing concepts and theories in the literature and in planning practice. This review is accompanied by a description of technical innovations in spatial analysis and supporting data infrastructures to advance measurement approaches. The following sections show sample implementations and interpret the results of a new measurement approach targeting pioneers of the 15-minute city idea: Paris, Melbourne, and Portland. The paper concludes with a critical discussion of the objectiveness of this approach in evaluating the policy objectives with regards to urban mobility structures in these cities.

2 Do digital planning tools reinforce path dependencies in transport planning?

Digital tools in transport planning have evolved substantially since their conception in the famous Chicago and Detroit transportation studies of the 1950s. At the time, pioneering models in the United States (and later in the United Kingdom) were mostly concerned with infrastructure demand for a rapidly increasing number of automobiles that required new infrastructure. Refined software packages for transport modeling evolved in due course, with a focus to integrate all transport options in order to comprehensively predict transport demand for future mobility needs. The main inputs were observed activities across spatial units of different land uses (e.g., residential, business, recreational, mixed use) that entail the movement of people and goods and the characteristic properties of such units to attract trips of various purposes (e.g., working, shopping, education, living) and at different times (morning and evening peaks, weekends, vacation periods). The data is sourced from household surveys where people state their current mobility patterns, which in turn is used to calibrate transport modeling scenarios for future transport demand (Boyce and Williams, 2015).

This latter point is crucial in understanding why such modeling approaches potentially lead to problematic path dependencies in transport planning: under quasilinear conditions of growth and increasing wealth, application of today's mobility preferences to a growing number of users must ultimately lead to capacity shortages and a requirement to enhance capacities in the future. Transport modeling software either acts on this requirement with incremental infrastructure interventions until an equilibrium between demand and capacity is achieved or introduces assumptions on behavioral change to acknowledge the limits to extrapolate behavioral patterns of the past into the future (Dalvi, 2021).

In this context, an article by Duranton and Turner (2011) comparing detailed data on road capacities and corresponding traffic numbers sparked a wide debate on path dependencies in transport planning. The authors' intention was to empirically test the *induced demand* hypothesis in transport planning postulated as early as 1972 (Koppelman, 1972). This hypothesis states that any road widening that increases capacity generates new demand and will be consumed shortly thereafter. Duranton and Turner (2011) found significant evidence for the United States that this is the case: 'people drive more when the stock of roads in their city increases; commercial driving and trucking increase with a city's stock of roads; and people migrate to cities that are relatively well provided with roads'.

Interestingly,Duranton and Turner (2011) also found evidence in their analysis that investments in public transport do not provide the expected road system relief targeted by corresponding transport policies: while 'public transit serves to free up road capacity by taking drivers off the roads and putting them in buses or trains', vehicle drivers who change to buses or trains simply make room for new drivers and vehicles (i.e., demand is induced).

Duranton and Turner (2011) mention people's relocation to places attractive for motorized transport as a possible cause for their observations. They also hint at misconceptions in influential transport policies that one-sidedly continue to argue for more road space and public transport options to relieve congestion. Following this line of thinking, a model designed by Randelhoff (2016) adds additional explanatory value. His *cycle of structural land use change with increasing car ownership* attributes the *induced demand* to increasing distances and mobility needs that have developed over time (see the highlighted text in Figure 1). Car ownership and the car-oriented transport policies of the past have resulted in a path-dependent competitive advantage for motorized transport. *Induced demand* can therefore be seen as a self-reinforcing cyclical dynamic between the land use structures made possible by motorized transport and the continued demand for new transport infrastructure (UN-Habitat, 2013).

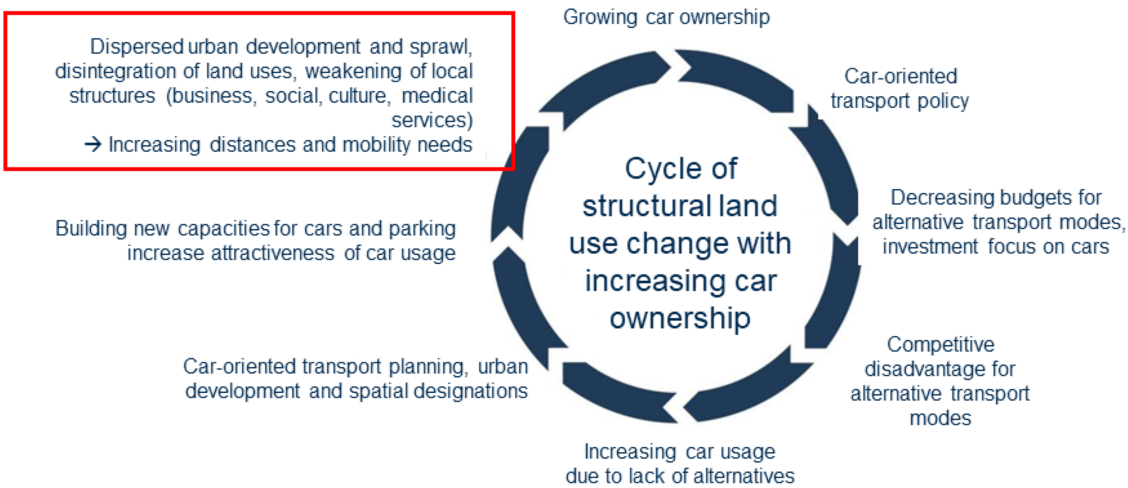

Figure 1: Path dependencies in transport planning (Randelhoff, 2016)

Litman (2017) uses two revelatory citations by influential transport officials to pinpoint the root causes of such vicious cycles. Paradigms of the past that are still deeply ingrained in road engineering guidelines frequently follow the logic of 'increasing highway capacity is equivalent to giving bigger shoes to growing children'. This stance is contrasted by a view that acknowledges limits to growth when 'widening roads to ease congestion is like trying to cure obesity by loosening your belt' (Litman, 2017). Such contrasting viewpoints can be seen as value-oriented interpretations of priorities for the role of transport in a socio-technical system. The choice of digital planning tools can reinforce such priorities in decision-making processes, for example when providing path-dependent planning options for deliberation without further consideration of alternatives. Where critical views on path-dependent growth are clearly on the rise (Banister, 2008), the role of digital planning tools is only starting to become the subject of critical reflection. Authors such as Pavlovskaya (2018) point to an underexposed proliferation of future development options with neoliberal logics but also emphasize the potential of spatial ontologies in maps to facilitate social transformation.

In this context, advocates of socioecological transformation are calling for a fundamental mobility transition to a transport system that attaches high value to social equity and sustainably mitigates adverse health and environmental impacts (Banister, 2018; Schneidewind, 2018). Showcase examples of sustainable mobility in new local developments are frequently cited as blueprints for people-oriented mobility in cities such as Freiburg, Germany (Barton, 2016). Critical commentators, however, find this praise misplaced. It ignores significant rebound effects, such as the dynamics of displacement and the heightened segregation of transport-inducing land uses in the city region (Mössner et al., 2018).

This point highlights the contradictions between academic descriptions of sustainable mobility and their current impact, looking beyond prototypical best-case examples. A recent contribution by Nikolaeva et al. (2019) points to the logics of scarcity as a driver of mobility planning, where savings of oil, finance, space and time motivate transport policymakers in Western countries to call for greener, smarter, and cheaper mobilities. Such scarcities could theoretically be managed by an austerity approach aimed at redistributing remaining mobility options fairly, giving highest priority to carbon reductions and just transitions. In reality, however, opposing viewpoints attributed to neoliberal politics lead to *lock-in* situations in democratic decision-making processes, with path-dependent mobility patterns prevailing. A new alternative advocated by Nikolaeva et al. (2019) is the *commoning* approach: 'commoning mobility can [...] be understood as a process that encompasses governance shifts to more communal and democratic forms while also seeking to move beyond small-scale, niche interventions and projects'. The authors argue that this is necessary for a truly transformative mobility transition where the relationship between humans and mobility is reconfigured toward 'shared responsibilities for what mobility does to societies and communities' (Nikolaeva et al., 2019).

The commoning approach could help inspire a paradigm shift at the policy level. At the same time, it remains to be defined what commoning actually means for planning practice. In this context, Rammert (2021) posits that mobility governance in Germany has a persistent institutional bias toward transport planning for economic growth. He strongly argues for integrated measurement methods able to assess a mobility system in a way similar to the human development index or other socioeconomic indicators. In order to conceptualize this approach, Rammert (2021) deconstructs individual mobility as the sum of structural framework conditions, individual preconditions for mobility preferences, and subjective perceptions.

This logic resembles the so-called *person-environment fit* that first emerged in developmental psychology in the towards the end of the twentieth century. When interpreted for behavioral change in mobility, the theory acknowledges the role of lifestyles on the mobility preferences of different groups of people: 'person-environment fit theory focuses on the interaction between characteristics of the individual and the environment, whereby the individual not only influences his or her environment, but the environment also affects the individual [...]. The adequacy of this fit between a person and the environment can affect the person´s motivation, behavior, and overall mental and physical health' (Holmbeck et al., 2007). In this sense, Rammert (2021) structural framework conditions stand for the environment, whereas his dimensions of the individual preconditions for mobility preferences and subjective perceptions characterize the person.

The added value of the developmental psychology perspective lies in an understanding of people's capacities to adapt to their transport environment and—conversely—the need to reconfigure the transport system in line with people's needs and preferences. A prominent example is the *15-minute city* that has recently emerged as a model for urban development. This concept attaches greatest value to pedestrian accessibility to resources at a neighborhood level. It has also been labeled as a 'planning eutopia' (Pozoukidou and Chatziyiannaki, 2021) and is strongly contested by urban development theorists, such as Edward Glaeser: 'I am very worried that a focus on enabling upper-middle income people to walk around in their nice little 15-minute neighborhood precludes the far larger issue, which is how do we make sure our cities once again become places of opportunity for everyone? I am only interested in urban planning concepts that fundamentally solve that and I cannot see how the 15-minute city does' (London School of Economics and Political Science, 2021).

At the same time, Glaeser suggests adopting the most valuable features of the 15-minute city concept - high levels of accessibility and less driving, supported by congestion pricing and tightened on-street parking regulations (London School of Economics and Political Science, 2021). Pozoukidou and Chatziyiannaki (2021) express their reservations from a methodological point of view, looking at the assumptions of researchers when measuring the pedestrian friendliness of urban structures. Deconstructing different measurement algorithms, they reapply them in Vancouver, Canada. The results show that such walkability tools are inconclusive in areas outside the most prominent walkable neighborhoods. The authors attribute this shortcoming to the lack of empirical evidence that assumed dimensions of walkability actually exert on people's travel behavior (e.g., street connectivity, land use mix).

This finding is in line with the research conducted by one of this paper's authors in Stuttgart, Germany. Standard walkability tools do not explain mobility behavior, with people living in walkable neighborhoods not necessarily walking more (Reyer et al., 2014). This observation inspired additional research funded by the German Research Foundation and aimed at collecting empirical evidence on the mobility preferences of social groups in cooperation with psychologists[1]. The objective of this project is to provide input for the development of an assessment tool for the person-environment fit at neighborhood level.

For the purpose of this paper, a provisional version of this tool has been modified to incorporate assessments of areas accessible with high-quality public transport and areas that are car-dependent. The following sections explain the methodological approach and show results for prominent examples of the 15-minute city in three cities on three continents: Paris, Portland, and Melbourne. The research design provides an initial assessment for the status quo.

3 Research design: Concepts, data, and methods

The empirical section of this paper unfolds this assessment based on the work of Newman and Kenworthy (1999) and Wiersma (2020), who describe car dependency as the dominance of automobiles regarding land use, infrastructure, and transportation. Drawing on other work, we conceptualize this definition with a measurement of car dependency. This includes comparative assessments of accessibility and quality of public transport as well as pedestrian accessibility to important infrastructures (Fina, 2015; Siedentop et al., 2013).

[1] https://gepris.dfg.de/gepris/projekt/421868672?language=en, last accessed July 26, 2021.

The research design aims to reapply these methods for a classification of three different inner-city types, in line with the debates outlined in the previous section: the walking city, the transit city, and the automobile city. Newman et al. (2016) describe the main characteristics of these types (see Table 1).

	The walking city	The transit city	The automobile city
Block scale and density	High density (min. 100 inh./ha) in short blocks	Medium density (ca. 35 inh./ha) in medium blocks	Low density (<35 inh./ha) in large blocks
Streets	Narrow and easily accessible	Wide and permeable, allowing pedestrian access to transit stops	Wide and high permeability for cars
Public spaces	Frequent small private open spaces	Less frequent but more private open spaces	Infrequent but much larger private open spaces
Land use	High functional mix	Medium functional mix	Low functional mix
Transport qualities	Low car ownership High pedestrian activity	Medium car ownership High transit activity	High car ownership High car activity

Table 1: Categories of dominant mobility regimes used in the measurement (adopted from Newman et al., 2016)

In order to classify a neighborhood's prevailing mobility structure, the method requires data sets suited to our analysis methods. We make use of OS-WALK-EU, an open-source tool initially designed to measure walkability at neighborhood level in the person-environment fit project described in the previous section. The current version of this tool[2] rearranges indicators for walkability to combine aspects of pedestrian accessibility (e.g., facilities and services) with information on the built environment (e.g., slopes, density, recreational areas).

In a first adaptation step for the case study cities, we set accessibility thresholds in the tool to a 15-minute walking radius around the geometric centroids of equally spaced grid cells of 500x500 meters, a size that stands as a proxy for local neighborhood accessibilities. All data sources and analysis components are open source and available at no cost. For the processing and network calculations we make use of QGIS and the OpenRouteService. The source data was extracted from user generated data in the OpenStreetMap (OSM) data repository. All following indicators are calculated based on the resulting isochrones. The tool was further enhanced to incorporate public transport timetable information available from online local transport authority repositories complying with the general transit feed specification (Google, 2020). All used indicators and components are listed in Table 2 and explained in the following subsections in more detail.[3]

3.1 Proximity to facilities and services

The local provision of facilities and services is an essential feature of neighborhood walkability and a key requirement of the 15-minute city (Moreno et al., 2021; Reyer et al., 2014). Many day-to-day trips can be categorized under the 'visit-live-work triangle' (Dovey and Pafka, 2017). Whereas places of residence and work are highly individual, *visit* destinations are frequently

[2]Available at https://gitlab.com/ils-research/os-walk-eu, last accessed July 26, 2021.

[3]Additional information is available in an online documentation for the tool at https://gitlab.com/ils-research/dominant-mobility-classifier

	Indicator	Source
Walkability	Proximity of facilities and services Functional land use mix Green spaces Pedestrian network	OpenStreetMaps (OSM) OSM OSM OSM / OpenRouteService (ORS)
Public transport	Access to public transport with high frequencies	General Transit Feed Specification of the local transport authorities

Table 2: Walkability and public transport indicators used in the tool

public and subject to planning decisions. Some measurement approaches use shop floor space as a proxy for *visit* activities, focusing on the trip purpose of shopping (Dovey and Pafka, 2017; Frank et al., 2006). In our approach, pedestrian accessibility means proximity to a variety of facilities and services (see Table 3). The data source for the locations is OSM. Their importance for residents can differ with distance and type of facility or service. For this reason, some methods make use of distance calculations and distance decay functions to weight the accessibility of nearby facilities and services (Walk Score, 2011; Otsuka et al., 2021). Our measurement concept simplifies this logic by a count and weighting of facilities and services by type within a 15-minute walking radius.

Table 3 shows the categories, their importance, moderation by variety, and maximum scores of facilities and services. The service quality of supermarkets, for instance, is very important (highest value of 5 in the importance column), with one facility (variety column) being sufficient to reach this maximum score. In contrast, single entertainment facilities are less important (lowest value of 0.5 in the importance column), but they can add up to a maximum score of 2, provided that there are at least four entertainment facilities (see the value of four in the variety column) within the search radius. This assessment logic has been adopted from empirical evidence on the relevance of facilities and services for residents' (daily) activities (see, e.g., Ahlmeyer and Wittowsky, 2018; Regionalverband Ruhr, 2017; Walk Score, 2011).

Category	Importance weighting type	Variety	Maximum score
Supermarket	5	1	5
Education	2	2	4
Health	2	2	4
Retail	1	3	3
Food and Drinks	1	3	3
Sport and Recreation	1	2	2
Entertainment	0.5	4	2
Civic and Institutional	1	1	1
Total	-	18	24

Table 3: Categories, importance, and variety parameters for facilities and services

3.2 Functional land use mix

Proximity to facilities and services relates to daily errands in the neighborhood. The mix of land uses is a complementary indicator. A high mix frequently reduces the need to travel longer distances for all trip purposes in the *visit-live-work triangle*: 'an effective mix shortens the distances between where we are and where we need to be' (Dovey and Pafka, 2017). To rate the land use mix (source: OSM), we decided to use Shannon's Diversity Index (SHDI). Originating in ecology to assess biodiversity, this indicator has seen a multitude of adaptations for other purposes in spatial analysis (Cegielska et al., 2019; McGarigal, 2015; Nagendra, 2002). It includes two diversity components: richness and evenness (Spellerberg and Fedor, 2003). Richness refers to the number of species (here: land use types) in a given area or community, while evenness concerns the population in a land use class and its distribution over all classes (here: land use configuration). To calculate the SHDI, we use equation (1):

$$H' = -\sum p_i * ln(p_i),\ with\ p_i = \frac{n_i}{N} \tag{1}$$

where N equals the number of blocks and ni the number of blocks belonging to land use type i. When all individuals are equally distributed over all blocks, the result is the maximum value of H', which ranges from zero to five. To better interpret the results, we use the true diversity. Here, H' is the power for the base e (Eulerian number), which changes the value range from one to the number of land uses. As we make use of seven land use categories, the SHDI varies between one and seven. One stands for a perfect monofunctional and seven for the most diverse land use mix (see Table 4).

SHDI	Score
More than 5	6
4 up to 5	5
3 up to 4	4
2 up to 4	3
1 up to 2	2
1	1

Table 4: Ratings for land use mix

3.3 Green spaces

Previous research confirmed that, in addition to the indicators shown so far, a neighborhood's design and attractiveness, together with the streetscape, influence walkability (Adkins et al., 2012; Frank et al., 2009; Vale, 2015). We proxy this aspect with an assessment of green spaces as a fundamental building block of neighborhood attractivity. Green spaces and their function as a recreational resource for residents are also positively associated with physical and mental health and motivate social interaction (Picavet et al., 2016; Ward Thompson et al., 2012). The calculation procedure for this indicator computes the share of green areas and woods within a 15-minute walking radius. Table 5 shows how these shares contribute to the overall score in the assessment.

Share of green spaces (%)	Score
More than 20	5
15 up to 20	4
10 up to 15	3
5 up to 10	1
Less than 10	1

Table 5: Ratings for shares of green spaces

3.4 Pedestrian network

The directness and connectivity of the pedestrian network have also frequently been described as an influential dimension for walkable neighborhoods. Gori et al. (2014) consider this '[...] a key component in the development of a more sustainable mobility system [...]'. We make use of the pedestrian radius (Pr) as a proxy for street connectivity and the directness of pedestrian routes. Pr sets the area of the 15-minute walking radius in relation to the area of the highest possible connectivity, which is a perfect circle around the starting point (here: centroid of 500 x 500 meter grid cells).

For the computation, we use equation (2):

$$Pr = \frac{A}{\pi * (v * \frac{15}{60})^2} \tag{2}$$

where A represents the area of the 15-minute walking polygon and v the walking speed in km per hour. The calculation is based on an average speed of 5 km per hour, an average value for walking speeds of pedestrians in cities. Table 6 shows the value range for this indicator.

Pedestrian shed(%)	Score
More than 80	5
65 up to 80	4
40 up to 60	3
20 up to 40	1
Less than 20	1

Table 6: Ratings for the pedestrian network

3.5 Access to high-frequency public transport

Besides the dimensions of walkability presented with the indicators above, we also aim to integrate dimensions of public transport attractivity for the transit neighborhood mobility type. This is done with data derived from the transit feeds of local transport authorities published under the general transit feed specification, a standard that Google originally designed to inform people in online routing applications. The standard provides for georeferenced data sets with information on the mode of transport and its frequency (Google, 2020). We adopt a concept developed by the Regionalverband Ruhr (2017) and Eichhorn et al. (2020) to evaluate the quality of public transport services based on two indicators shown in Table 7. The type and frequency values are multiplied and add up to the total score, which ranges from 1 to 18.

Type of public transport	Value	Frequency (minutes)	Value
Rail (intercity/long distance)	3	Less than 5	6
Tram, streetcar, light rail, subway, metro	2	5 up to 10	5
Bus	1	10 up to 15	4
		15 up to 30	3
		30 up to 60	2
		More than 60	1

Table 7: Ratings of public transport stops

3.6 Classifying the neighborhoods

The five indicators described above allow for a typification of mobility structures into three categories: the walking neighborhood, the transit neighborhood, and the car (-dependent) neighborhood. This is done by summing up all walkability indicator scores with resulting value ranges from 1 to 40. For the classification we set threshold values:

- The *walking neighborhood* is defined by high walkability values. We set a minimum value of 32, which corresponds to 80% of the maximum.
- The *transit neighborhood* is characterized by accessibility to high-frequency public transport. This requires at least one stop with a minimum value of 8 in the 15-minute walking radius. This is equivalent to a subway station with a minimum frequency of 15 minutes or a rail station with a minimum frequency of 30 minutes.
- The *walking/transit neighborhood* fulfills the criteria of both types.
- The *car (-dependent) neighborhood* is defined by a lack of alternative transport options. As we focus on the three main transport modes (walking, transit, and car), a (populated) neighborhood is car dependent when neither of the abovementioned criteria are met.

Besides mapping these types, we add population numbers and newly developed built-up areas to the analysis. This helps to understand how many people reside within each neighborhood type and where population and settlement growth has occurred. The data is sourced from the Global Human Settlement Layer, which provides harmonized information on population and built-up area worldwide. In this context, the term *built-up* refers to all sealed areas (including residential, commercial, industrial, and transport infrastructure). Based on census and remote sensing data, this information is available in a 250 x 250 meter grid (European Comission, 2018). Values for population and built-up area are aggregated and transposed into the 500 x 500 meter grid used in our study. In order to assess population and settlement trends in each neighborhood type, we calculate growth rates between 2000 and 2015.

4 Application for the three case studies

We applied the methodological approach described above in three cities strongly advocating the 15-minute city (in the case of Melbourne and Portland: 20 minutes) in their transport policies: Paris, Portland, and Melbourne. The final results of our spatial analysis are shown in Figure

4. Besides mapping the neighborhood types on the 500 m grid, we also calculated the distribution of inhabitants living in walking neighborhoods, transit neighborhoods, or car-dependent neighborhoods in two variations. First, we calculated the population share within city boundaries to verify whether we could classify the inner city as a walking, transit, or a car-dependent city (see Figure 2). In a second analysis, we calculated travel time polygons from the city center (by car) to classify the outskirts based on neighborhood type changes from the city center (max. 5 minutes driving time from the city center) to the suburban fringe (max. 20 minutes driving time from the city center) (Figures 5–7). The use of static buffers would also have been possible. However, we think that the travel time polygon can better represent the urban structures and the spatial connection to the suburban fringe. In addition, we plot the distribution of new population and built-up area in each neighborhood type in Figure 3. Due to the high overlap of walking neighborhoods and walking/transit neighborhoods, we make no distinctions between these types in the graphs. For simplicity, both are classified as walking neighborhoods. The results are interpreted in the following section for each city.

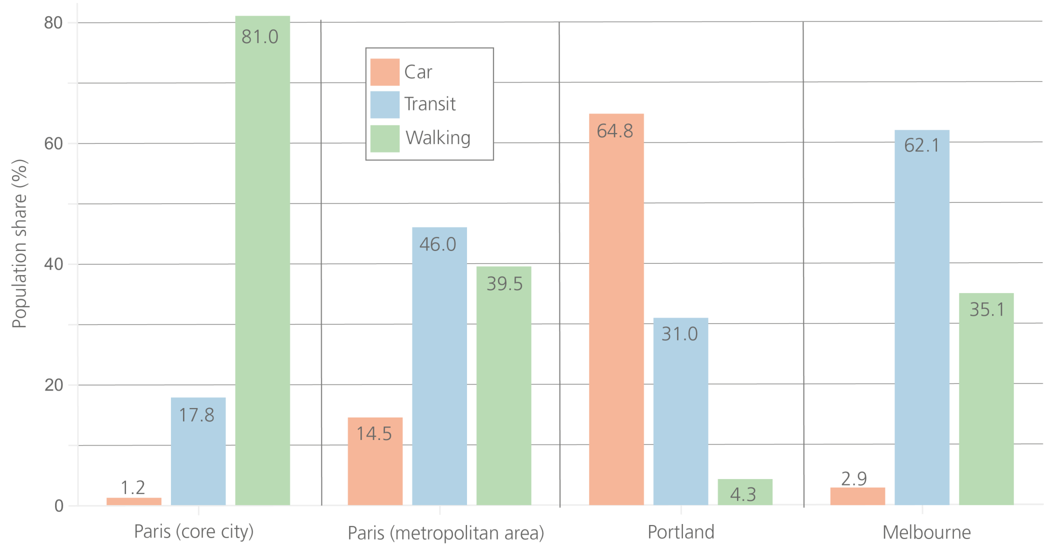

Figure 2: Population shares in the dominant neighborhood type of Paris, Portland, and Melbourne

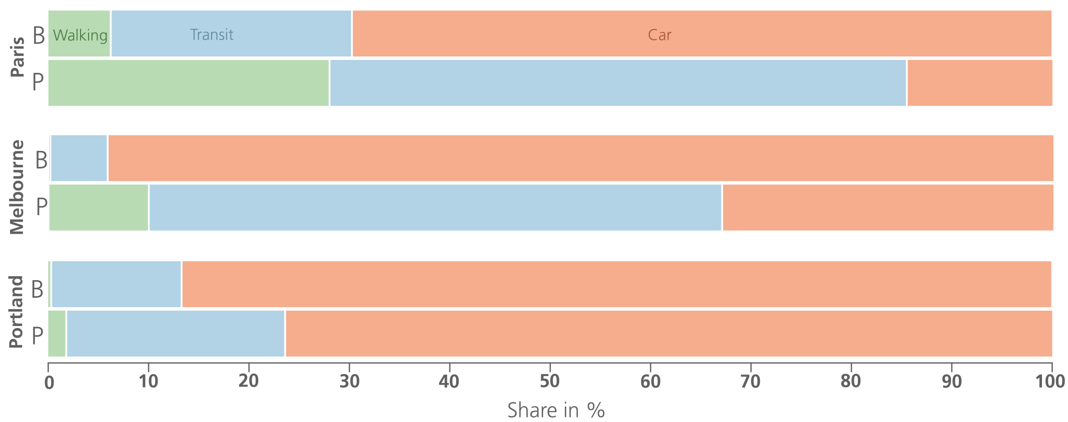

Figure 3: Share of new built-up area (B) and new population (P) for each neighborhood type

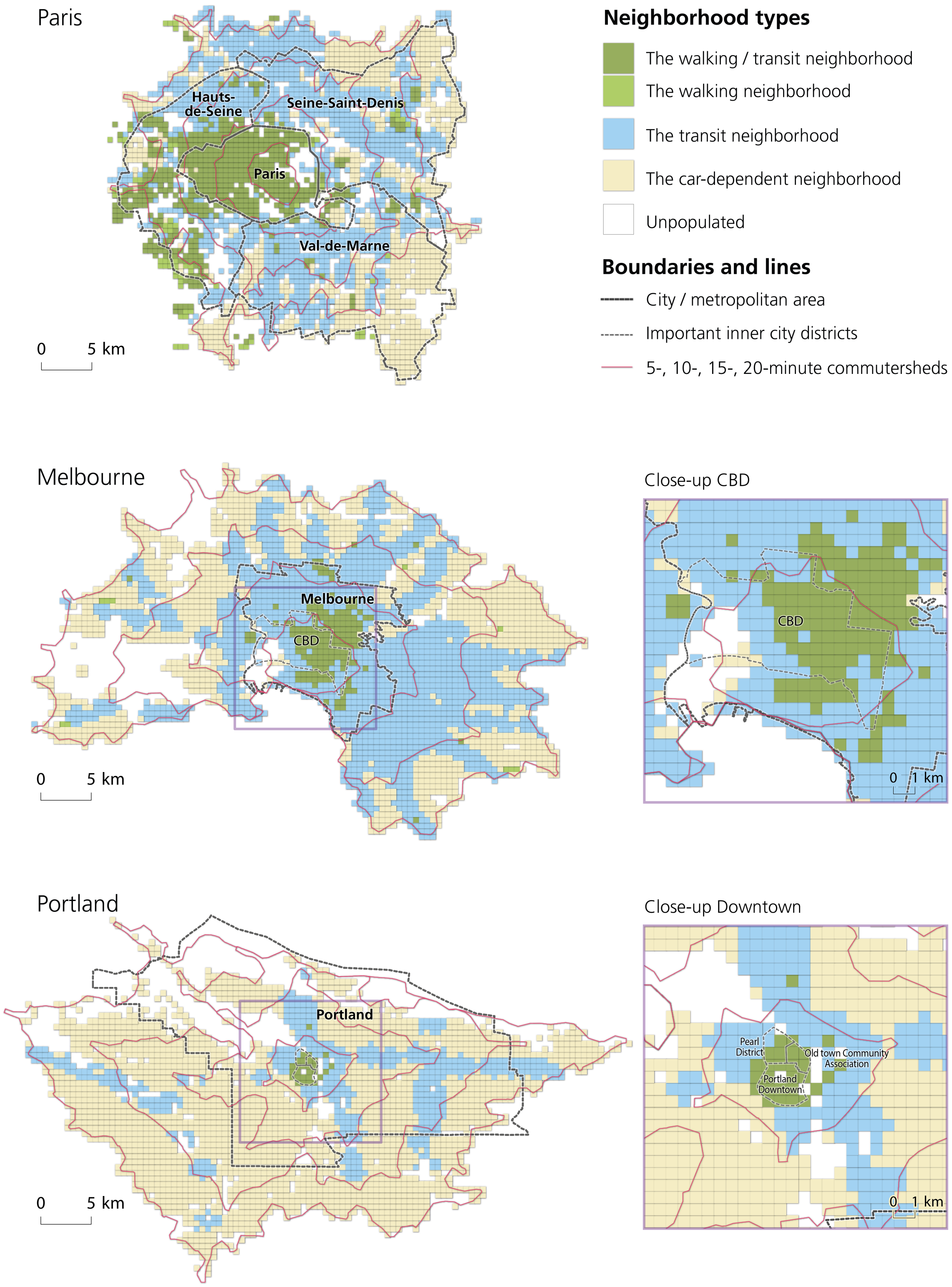

Figure 4: The dominant neighborhood types in Paris, Portland, and Melbourne

4.1 Paris

Paris has recently received considerable attention in the media and in academia for its ambitious goals of retrofitting urban structures under the 15-minute city concept to make it a 'city of proximities' (O'Sullivan and Bliss, 2020). Our analysis shows that the city center already has a remarkably high number of cells with a high walkability score (Figures 2 and 4). More than 80% of residents in the core city live in highly walkable neighborhoods. These areas are also well endowed with high-frequency public transport. Neighborhoods that are not walkable but have good access to public transport account for about 17.8% of the total population, while just 1.2% live in car-dependent neighborhoods. These areas show concentrations on the south-eastern and western part of the city. The three bordering départements differ. In Hauts-de-Seine, the predominant neighborhood type is walking, while there are many car-dependent neighborhoods in Seine-Saint-Denis and Val-de-Marne. From 2000 to 2015, only about 30% of new developed land has been in walking (6.2%) or transit (24.0%) neighborhoods (see Figure 3). However, the analysis also shows that the population growth in car-dependent areas (14.5%) is significantly lower than in walking (28%) and transit (57.5%) neighborhoods. This result hints at a decoupling of new land take from population growth.

The assessment of urban structures is also reproduced when looking at the distribution of residents by dominant mobility type in the commuter sheds of Paris. Figure 4 illustrates the travel time by car from the city center in minutes on the x-axis and the total share of population in percent on the y-axis. The colors represent the dominant mobility types: walking in green, transit in blue, and car in red. We observe that the walking neighborhood is the dominant type in the 5- and 10-minute commuter shed areas. This proportion gives way to higher transit neighborhood shares, up to almost 70% in the 15-minute catchment area. One ring further out, the number of residents in car-dependent neighborhoods increases, although the transit neighborhood remains dominant.

Figure 5: Travel-time based calculation of population share in the dominant mobility structures of greater Paris

4.2 Melbourne

Melbourne integrated the concept of a *20-minute neighborhood* and *living locally* in its long-term planning strategy Plan Melbourne 2017–2050 (Victoria State Government, 2019). The plan is to create more inclusive, vibrant, sustainable, and healthy neighborhoods by enhancing walkability and reducing the length of daily trips. In contrast to other concepts, the city stresses the importance of public transport as an efficient connection for work and higher-order services. Implementation in the city has already started with a pilot program, including several case studies.

Our analysis of Melbourne reveals a high share of very walkable areas and neighborhoods with access to high-frequency public transport within the city boundary. Around 35% of inhabitants live in a walking neighborhood and 62% in a transit neighborhood (see Figure 2). Thus, only about 3% of the city population is dependent on cars. The spatial distribution of the dominant mobility types is highly clustered: highly walkable areas are located in the inner city and subcenters in suburban areas. This spatial cluster is entirely surrounded by transit neighborhoods. Car-dependent areas are concentrated in locations on the city outskirts. The visual dominance of the transit neighborhoods is also reflected in the distribution of new population from 2000 to 2015. About 57% of the increase occurred in transit areas, while just 10% of the new population lives in walking neighborhoods. However, the situation is different in the newly developed urban areas. The share of built-up areas in car-dependent neighborhoods is 95%.

This pattern is also visible when considering the population share for each neighborhood type in the travel-time-based commuter sheds. The share of inhabitants living in walking neighborhoods in the 5-minute commuter shed is very high (70%) but goes down rapidly as distance to the city center increases. In the 5–10-minute ring, the proportion is 18%, but it goes down to a negligibly low share in the 10–20-minute ring. In this context, Figure 4 shows the cells along radial rail-bound transport axes from the city center to the outskirts. This pattern explains the shares in the second and third ring, with a dominance of transit neighborhoods of around 75%. This value drops to approximately 40% further out. The proportion of car-dependent residents increases steadily with distance from the center. In the 20-minute catchment area, car-dependent neighborhoods are home to nearly 60% of residents belonging to this mobility type.

4.3 Portland

Portland, Oregon, has a long history of promoting walkable and cyclable neighborhoods. In the United States, it is one of the pioneers of urban sustainability policies in general and of the 15-minute city in particular (O'Sullivan and Bliss, 2020), with the city presenting an analysis of walking accessibility to commercial services and amenities as early as 2010 (City of Portland, 2010). The plans were published under the *20-minute neighborhood* label back then and have since been integrated into the Portland plan for Future Possibilities and Choices.

For the case study on Portland, we had to cope with the limitation that the domestic border of the Portland commuter shed extends from Oregon into Washington State. This caused

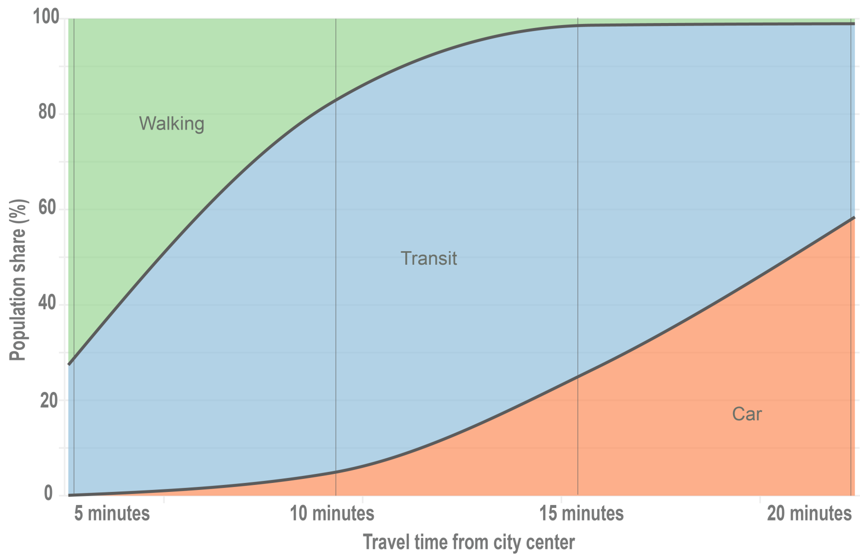

Figure 6: Travel-time based calculation of population share in the dominant mobility structures for Melbourne

inconsistencies in the availability of public transport timetable data. For this reason, cells with implausible results in the north were excluded from the commuter shed classification.

Figure 4 shows that, compared to Paris, there is a geographically smaller cluster in the Portland city center with highly walkable areas. This includes Downtown, Old Town, and Pearl District and some smaller areas on the southern side of the Oregon River. Starting from the cluster in the western part of the city, the public transport network radiates in all directions except the southwest with neighboring car-dependent cells. The classification procedure identified some elongated transit neighborhoods in the rest of the city region. Besides some smaller subcenters and isolated structures with high walkability and transit accessibility, the rest of the city's neighborhoods are classified as car dependent. This is also shown when looking at the population distribution: almost 65% of residents live in car-dependent neighborhoods but just 4.3% in walking neighborhoods. This observation is substantiated by the results shown in of Figure 3. Less than 1% of new built-up areas was developed in walkable neighborhoods and only 13% in transit neighborhoods. For new population, we can observe slightly higher shares in walkable (1.8%) and transit (21.8%) areas. Overall, recent development in Portland concentrates in car-dependent areas.

The results of the commuter shed analysis come as no surprise. In the 5-minute catchment area, the share of highly walkable neighborhoods is about 25%, while transit neighborhoods have the dominant share, covering 70% of residents. Patterns change with increasing distance from the city center. The share of inhabitants living in car-dependent neighborhoods exceeds 60% of the total population in the 10-minute commuter shed, going up further to 80% in the maximum travel time ring. An analysis of the individual components of our assessment shows that a lack of facilities and services leads to classifications other than the walking neighborhood in the outer rings. The average walkability value per cell in the first ring is about 26. In the commuter sheds further out, this value drops to 16 (10-minute commuter shed), 13 (15-minute commuter shed), and 11 (20-minute commuter shed).

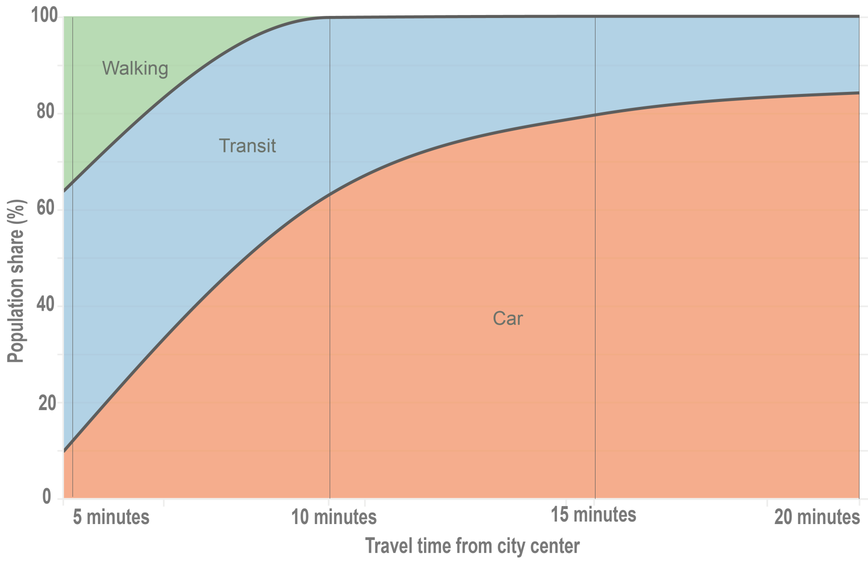

Figure 7: Travel-time based calculation of population share in the dominant mobility structures for Portland

5 Discussion

Our study provides a new method for classifying neighborhoods according to their dominant mobility types: high walkability, high-frequency public transport, or car dependency. For the three cities of Paris, Portland, and Melbourne, we were able to identify similarities but also significant differences.

Our main findings can be summarized as follows:

- **All cities** have highly walkable areas in the city center. However, outside the city center, results differ greatly.
- **Paris**, one of the most densely populated and oldest cities in Europe, is very walkable within the metropolitan area. Just 1.2% of the population in the core city and 14.5% in the metropolitan region live in car-dependent neighborhoods. Paris is therefore very close to its goal of being a 15-minute city.
- **Melbourne**, one the largest cities in Australia, has a lower share of inhabitants living in walkable neighborhoods and a slightly higher share living in car-dependent neighborhoods than Paris; 2.9% of the Melbourne population lives in car-dependent areas. Therefore, it is also very close to its goal of being a walkable city.
- In **Portland**, one of the role models of walkability in the United States, major shares of the population living outside the city center live in car-dependent neighborhoods, which

affects about 65% of the population. Portland is by far the most car-dependent city region in this comparison.

Overall, our results are consistent with the findings of other studies, despite some differences in methodology. The high results for walkable neighborhoods in **Paris** are confirmed in studies that rank it as one of the most walkable cities (Carrington, 2020; Institute for Transportation & Development Policy, 2020). Due to its historic development as a high-density metropolis, Paris has a more mature urban fabric than Melbourne or Portland. Car-dependent areas are primarily located in suburbs outside the metropolitan region, as visible In the 20-minute catchment area (Motte-Baumvol et al., 2010). Due to a well-developed regional public transport network, transit neighborhoods dominate outside the core city. It is noticeably here where the highest population growth between 2000 and 2015 occurred (see Figure 3), giving effect to the planning paradigm to strengthen public transport and to focus on transit-oriented development (TOD). This paradigm has been pursued for decades and is also part of the strategic plan for greater Paris (Debrincat, 2015; Desjardins, 2018). Turning to **Melbourne**, Giles-Corti et al. (2014)developed and applied a walkability index. Although the set of indicators and assessment methods differ greatly, the authors come to similar conclusions, confirming the city's high degree of walkability. Dodson and Sipe (2008) and Jeffrey et al. (2019) identified areas with a high car dependency in the outer suburbs and around the metropolitan fringe. To some extent, these findings are also reflected in Figure 2. The main difference is that we find larger areas with public transport options, meaning that not that many neighborhoods in the outer areas are car dependent. This also represents the city's approach to sustainable planning. In its vision for 2030, Melbourne focused on restructuring and strengthening public transport, which also contains the promotion of TOD (State of Victoria, 2002). Our results in Figure 2 show that these planning efforts are already visible from 2000 to 2015. However, the outcome is limited to population growth in existing areas of sustainable transport options. In newly built-up areas, car dependency dominates. The success of the *20-minute neighborhood* goals in the Melbourne strategic plan must therefore be monitored over the long term.

Portland presented its own findings on the 20-minute neighborhood a decade ago (City of Portland, 2010). Based on its methodology, a high share of inner-city areas is walkable due to the high proximity to facilities and services, particularly in Downtown, Old Town, and Pearl District. Despite Portland's international reputation for pioneering urban sustainability practices, our results reveal shortcomings in the mobility structures outside the inner core when compared to Paris and Melbourne. We posit that this finding can be explained by the observation that car use and car dependency in U.S. cities are generally higher than in European and Australian cities (Dodson and Sipe, 2008; Newman and Kenworthy, 1999). Our comparison of three global cities therefore provides a somewhat different picture for the status quo in Portland when compared to the self-picture painted by the city's sustainable transport concepts such as the *20-minute neighborhood* or TOD (City of Portland, 2010; Oregon Metro, 2020). Figure 2 reveals that most of the population and built-up growth between 2000 and 2015 concentrates in car-dependent areas.

At this point, we would like to remind readers that our results reflect on the structural preconditions for mobility and not on individual mobility preferences. It is important to note this focus when we talk about deficits in the urban fabric. Overall, the results seem to be robust and consistent with other research findings. Nevertheless, we have some limitations to discuss. The simplified measurement methods - compared to other studies we are currently conducting in European city regions - generalize at the expense of more refined weightings of individual indicator components. High-frequency public transport is a case in point. It can theoretically be assessed by such quality criteria as good connectivity, opportunities for changing train/bus/etc., and design elements. Such characteristics can certainly vary across international cities. At this point, we have not yet integrated all of these criteria. This indicator is therefore significantly simplified compared to our walkability assessment, which analyzes routes to infrastructures and sets different weightings. We are aware that there is some potential for optimization, opening up opportunities for further research. For further methodological development, additional components from other methodological approaches could be integrated, such as elements of the Public Transport Access Level of London's transport authorities (Transport for London, 2015).

In addition, other transport modes, such as cycling, need to be included in the future. This could possibly affect the results in Portland, with its high share of bike commuting, at least in comparison to other major U.S. cities (O'Sullivan and Bliss, 2020). Furthermore, alternative transport modes, such as car-sharing and e-mobility options, are becoming increasingly important (WBGU, 2016). It should also be stated that our results are only as valid as the data sets used. This applies especially to the quality of OSM data. While it can vary locally, it is generally good in world cities such as Paris, Portland, and Melbourne, which feature large numbers of contributors. On the upside, the simplification we offer in this approach provides possibilities for a fast and potentially worldwide classification of mobility structures. Ease of use and simplicity are useful for an intuitive understanding of the structural predicament influencing the mobility transition.

Referring back to the theoretical sections of this paper, we would like to recap the criticism of the concept of the 15-minute city (London School of Economics and Political Science, 2021; Pozoukidou and Chatziyiannaki, 2021). The idea is that reducing trips could also reduce the amount of business opportunities and social interaction in the city region and lead to further segregation between privileged and disadvantaged households. Whether and to what extent inequalities exist should be examined and monitored using valid socio-economic data. In this way, it is also possible to check in the long term whether such concepts have negative social effects. In addition, locally improved accessibility can lead to higher property values and downstream effects, such as gentrification and social inequalities (Pozoukidou and Chatziyiannaki, 2021). Our methodological approach is designed to provide planners and policymakers with assessments identifying shortages in the supply of mobility options, which in turn serve urban structures characterized by the supply of facilities and services as well as public transport.

In summary, we present our results as an explorative component for a more comprehensive system for measuring the mobility transition as proclaimed by Rammert (2021). Our analysis is an option to initially measure the structural conditions he calls for, although we are currently unable to cover his additional dimensions of 'individual preconditions for mobility preferences' and 'subjective perceptions'. Our analysis is currently limited to an assessment of the status quo. Future monitoring applications, however, can use this as the baseline to monitor if the 'cycle of structural land use changes with increasing car ownership' and its resulting car dependency (as shown in Figure 2) can be redeemed for sustainable transport modes.

6 Conclusion

In this paper, we presented a methodological approach contributing to the current discussion on implementing a mobility transition aimed at achieving carbon reductions and greater equity in transport. The methodology classifies urban structures and their mobility options into walking neighborhoods, transit neighborhoods, and car-dependent neighborhoods. In this way, strategic approaches as requested by, for example, Newman et al. (2016) can be localized at a small-scale level. The underlying spatial assessment logic is derived from an enhancement of walkability and transit indicators from the literature. This approach enables evaluations of transport policies and remaining challenges in urban mobility structures. The results show to what degree three case-study cities already have high-walkability urban structures, as advocated in the concept of the 15-minute city or, in contrast, the car-independent city. Our assessment shows that despite similar policy objectives, mobility structures especially outside inner core cities differ greatly. However, the methodological approach unfolds its greatest potential when long-term developments are monitored in addition to the status quo. In this way, the success of sustainable mobility planning can be evaluated and counterproductive path dependencies and related negative outcomes can possibly be identified at an early stage.

The literature research presented in this paper emphasizes that an effective mobility transition is hindered by many path dependencies deeply ingrained in transport planning procedures. Academia and transport policymakers are calling for new or modified concepts to accelerate the transition. Measurement methods and monitoring systems such as the one presented here are of fundamental importance in this process. In future research projects, we plan to enlarge and validate the sample with empirical data, to integrate mobility preferences and individual perceptions, and to combine our results with socioeconomic indicators on transport equity.

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A.3.3 How to Identify and Typify Arrival Spaces in European Cities- A Methodological Approach

How to Identify and Typify Arrival Spaces in European Cities - A Methodological Approach

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Abstract: In the context of increasing mobility in recent decades, numerous studies have analysed the impact of migration on urban spaces. International immigration is mainly concentrated in certain urban areas, with these so-called arrival spaces offering important opportunities for migrants to gain a foothold in their new surroundings. However, the current state of research provides just limited ways of identifying and typifying these spaces. On the one hand, there are no transferable, quantitative concepts. On the other hand, current discussions tend to focus on socio-economically deprived spaces, neglecting more affluent areas. To identify a city's different (and partly newly emerging) arrival neighbourhoods and to adapt local policies to the specific needs of their residents, we have developed a methodological approach to identifying and typifying arrival spaces on a small-scale level. Using the case study of Dortmund in Germany, this paper presents this approach and its transferability to other European cities.

Keywords: arrival spaces, diversity, infrastructures, integration, migration, monitoring, neighbourhoods

Contents

1 Introduction

The global increase in mobility and migration experienced in recent decades is accelerating urbanisation, in turn leading to greater social and ethnic diversity (Heider et al., 2020; Vertovec, 2007). Against this background, cities and urban communities are facing an increase in socio-economic inequality, together with integration[1] and social cohesion issues (Hickman and Mai, 2015; WBGU, 2016).

Despite a wide variety of migration forms, it is noticeable that many immigrants first settle in specific urban areas characterised by affordable and accessible housing, giving them a chance to gain a foothold in their new country. Several studies in recent decades (Ostendorf and Musterd, 2011; Zwiers et al., 2018) have dealt with ethnically segregated and in many cases socially deprived urban neighbourhoods, provoking academic and political discussions on the consequences of living there.

With reference to Doug Saunders' (2011) book 'Arrival Cities', the more recent literature on arrival spaces[2] focuses on local factors contributing to immigrants' social mobility, taking the ambivalent character of these neighbourhoods into account (Hanhörster and Wessendorf, 2020; Hans et al., 2019; Meeus et al., 2019). While often characterised by poverty and deprivation, these neighbourhoods often enable access to infrastructures facilitating the arrival process of newcomers. Summarising this new body of literature, arrival spaces can generally be described as urban areas characterised by international migration and high population fluctuations. However, they differ with regard to the socio-economic status and diversity of their populations as well as their building structure and infrastructures. Despite the fact that these characteristics are shaped at micro-level, neighbourhood-level approaches are often unable to fully explain them.

The aim of this paper is thus to address two shortcomings in current research into arrival spaces: (i) there are no transferable, quantitative concepts for identifying and typifying such spaces; and (ii) current discussions tend to focus on socio-economically deprived spaces, neglecting more affluent areas. With regard to the first shortcoming, we propose a new methodological approach to identify and typify arrival spaces in European cities[3], using a city-block-level perspective to analyse small-scale characteristics resulting from international migration flows to gain a clearer picture of the dynamics shaping arrival spaces in cities. For this purpose, we have developed an approach designed to be transferable to cities in other European regions. In so doing, we contribute to small-scale urban monitoring, linking different data sources and thereby advancing the discussion on arrival spaces. This brings us to the second important shortcoming in current research: with current discussions on arrival neighbourhoods mainly focused on areas characterised by socio-economic deprivation, this paper's intention is to expand these discussions to capture and illustrate the existing varieties of arrival spaces. By focusing

[1]We understand the term 'integration' as an analytical concept capturing different forms of access to functional, social and symbolic resources (Ager and Strang, 2008)

[2]Also referred to in the literature as 'arrival neighbourhoods' or 'arrival areas'.

[3]While the debate on arrival spaces is worldwide, our analysis refers to the global North and in particular the European context

on migration data without taking socio-economic data (poverty indicators) into account, different types of urban arrival spaces become visible. Further qualitative characterisation of these spaces provides a basis for further in-depth studies and political debates on how to deal with the different challenges facing different types of arrival spaces.

We start by providing an overview of the state of research and existing methodological concepts, before going on to present in detail which data and methods are used in our analytical approach. The application of this approach to the city of Dortmund as our case study city is subsequently explained. We end by discussing the potential and limitations of our analytical concept.

2 Background and research focus

Over the last decade and especially in the last few years, an intensive debate has developed around arrival spaces and their city-wide role in integrating migrants and facilitating their access to resources and social mobility.

The debate over ethnically segregated urban areas has been raging for at least a century. Back in the 1920s, the Chicago School (e.g. Park and Burgess, 1925) described these areas as 'urban transition zones' where new immigrants arrive and where social (and spatial) mobility begins. A number of studies have subsequently been published on ethnically segregated urban areas. Depending on the group studied, the chosen scale, and so on, scholars come to different conclusions about the role of these neighbourhoods for integration processes: some emphasise the disintegrative effect of living in ethnic communities (Ezcurra and Rodríguez-Pose, 2017; Heitmeyer, 1999), while others highlight the advantages of 'ethnic enclaves' (Wilson and Martin, 1982), 'immigrant enclaves' (Portes and Manning, 1986) or 'urban enclaves' (Zhou and Portes, 1992).

The Canadian journalist author Saunders (2011) took up these discussions in his 'Arrival City', a book describing different arrival spaces worldwide. In it, he analyses how local factors in these very dynamic urban areas can contribute to migrants' social mobility. Looking at such recent developments as the influx of refugees and the related further diversification of the population, recent literature focuses on local factors enabling access to resources and facilitating the arrival process of newcomers (Hanhörster and Wessendorf, 2020; Hans et al., 2019; Meeus et al., 2019).

Arrival spaces are described as 'platforms of arrival' (Meeus et al., 2019), where many immigrants find their first home in their new city. Key characteristics of arrival spaces are thus international immigration and a high foreign population. As arrival spaces are also home to earlier immigrants, newcomers can often rely on existing social (ethnic) networks (Hans and Hanhörster, 2020; Kurtenbach et al., 2019; Wessendorf and Phillimore, 2019). Similarly, as such spaces are not only 'platforms of arrival' but also 'platforms of take-off' (Meeus et al., 2019), these neighbourhoods are characterised by high fluctuation rates.

In addition to these key characteristics, the literature points to other features describing these arrival spaces. With their size varying from a few blocks to entire districts, there is currently no clear spatial delineation. However, most studies describe highly diversified neighbourhoods that are home to a wide variety of immigrant groups whose composition is constantly changing (e.g., Biehl, 2014). Several studies investigate neighbourhoods affected by social deprivation and poverty (e.g., Schillebeeckx et al., 2019). Another feature of arrival spaces often mentioned by scholars is their high spatial concentration of arrival-related opportunity structures. These include retail or service offers (e.g., money transfers, medical care in different languages), places of worship (e.g., mosques) or social infrastructures (e.g., counselling and social support services). These structures help people maintain their transnational lifestyles while at the same time providing guidance and support for their arrival process. They are furthermore places enabling encounters between 'old' and 'new' immigrants and permitting an easily accessible resource transfer (Hall et al., 2017; Hans and Hanhörster, 2020; Schillebeeckx et al., 2019). As Saunders (2011) argues, a neighbourhood's building structure can have a significant impact on the development of infrastructures in arrival spaces. For example, in neighbourhoods where it allows small ground-floor shops and businesses to be opened, it is easier for migrants to become self-employed entrepreneurs.

There are several quantitative studies monitoring (inter-)national migration flows within arrival spaces based on census and registration data (see, e.g., Bailey and Livingston, 2008; Etzo, 2011), while other papers focus on alternative and innovative data sets, such as mobile phone data, to model migration processes (Deville et al., 2014; Sîrbu et al., 2021). However, there are few studies analysing such phenomena on a small scale: López-Gay et al. (2020) and Costa and de Valk (2018), for instance, look at migration movements in neighbourhoods based on ethnic and socio-economic characteristics on a small-scale level in Spanish and Belgian cities. Yet no analytical classification and shared understanding of arrival spaces' spatial characteristics exist. In recent years, however, scholars have tried to develop analytical approaches to distinguish types of arrival spaces, with some attempting to identify such characteristics on a small-scale level (Hanslmaier and Kaiser, 2017; Heidbrink and Kurtenbach, 2019), or on a larger scale (Dunkl et al., 2019; Kurtenbach, 2015). Using nationality and immigration from abroad as key indicators, most studies rely on classification methods and cluster analysis to identify arrival spaces. Some studies have also contributed to an internal differentiation of arrival spaces. Taubenböck et al. (2018) provide a first categorisation of different arrival spaces based on their morphology. The above-mentioned characteristics as well as the studies referred to above form the starting point for this paper's contribution to developing a more systematic and transferable methodological approach to capturing different types of arrival neighbourhoods.

3 Data and methodology

3.1 Demographic data and analysis level

To identify and typify arrival spaces, various demographic variables are required. The data used in our analysis is sourced from local government statistical offices, the recipients of citizen registration information and a guarantee of data reliability. In contrast to existing approaches, our analysis and all indicators are based on averaged data from a 5-year period (2013–2017). The aim was to cover a longer period encompassing not only the peak of the refugee influx to Europe in 2015/2016. Any statistical outliers can be harmonised by averaging the values. The individual indicators generated from this data are described in the respective processing steps.

It is important to choose spatially appropriate units. On the one hand, such units should have sufficient residents to eliminate statistical outliers. On the other, the level of analysis should be small enough to get accurate results. We opted for the city block level, the smallest local unit in German and other European population statistics. Delimited by structural features such as buildings or roads (IT NRW, 2009), a city block in Germany has a maximum population of 2000.

3.2 Processing and analysis

As a preprocessing step, we excluded all city blocks with fewer than 50 inhabitants. Spatial units with low population values are prone to be statistical outliers due to specific local features such as new development areas or the demolition of buildings, or on account of data quality and privacy issues. The remaining city blocks were analysed in three steps (Figure 1). In the first step, potential arrival spaces were identified in a cluster analysis. The identified city blocks were then classified according to their diversity and socio-economic status. Finally, we characterised them using a more descriptive process based on additional quantitative indicators and qualitative analyses.

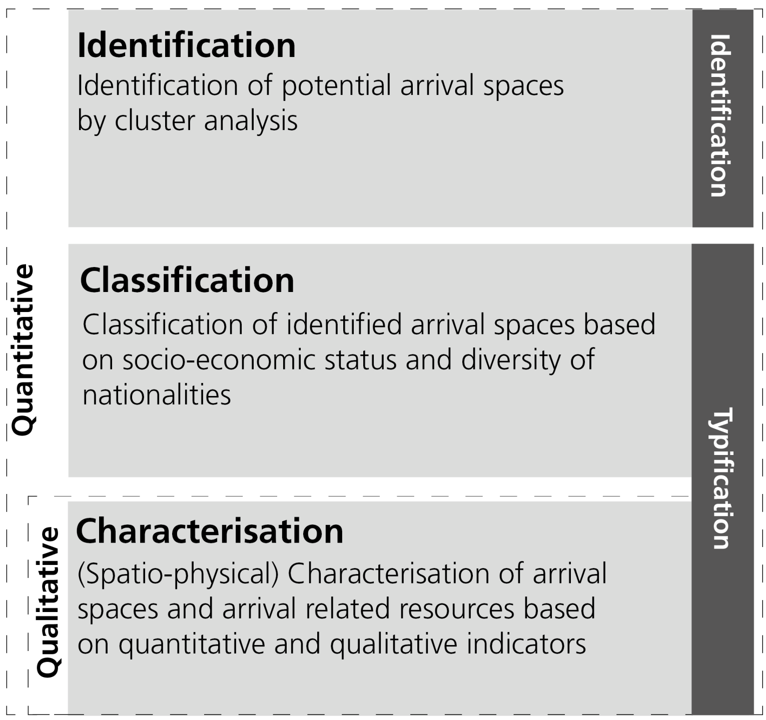


Figure 1: Steps of analysis

3.2.1 Identification

The process of identifying potential arrival spaces begins with a hierarchical cluster analysis initiating an explorative filtering. This is an important step: as European cities feature many different demographic compositions and conditions, filtering helps avoid defining static thresholds. The analysis is based on three key indicators characterising arrival spaces derived from the literature: (i) the share of foreigners living in the area; (ii) population exchange; and (iii) arrivals from abroad (see Table 1). In contrast to other methodological approaches, we refrain from using economic indicators to identify arrival spaces, enabling arrival spaces to be identified regardless of their socio-economic status.

Indicator	Formula	Value range
(1) Share of foreigners	$\frac{\text{Number of foreigners}}{\text{Resident population}} * 100$	0 - 100
(2) Population exchange	$\frac{\text{Migration volume}}{\text{Resident population}} * 100$	0 - 100
(3) Arrivals from abroad	$\frac{\text{Arrivals from abroad}}{\text{Resident population}} * 100$	0 - 100

Table 1: Indicators for analysis

Referring to a neighbourhood's migration history, the first indicator is the share of foreigners. While other studies make use of the migration background, our approach focuses on registered nationalities. As there is no uniform procedure in Europe for determining a person's migration background, its use would lead to noncomparable results. The second indicator illustrates population exchange, as this occurs at a significant rate in an arrival space (El-Kayed et al., 2020; Kurtenbach, 2015). For many people, the first place of residence is only a 'stop-over' before moving to other districts or cities (Meeus et al., 2019). In line with Kurtenbach (2015), this indicator is defined as the sum of immigration and emigration in a city block divided by the resident population. It includes people moving in (from abroad and from other cities), moving out (to abroad and to other cities) and moving within the city (to other city blocks). The higher the value, the higher population exchange is. To shed light on the important function of arrival spaces in international migration, the indicator 'Arrivals from abroad' only includes movements (absolute numbers) into the city from abroad within the last 12 months. The following applies to all indicators: the higher the value, the higher the probability that the respective city block is an arrival space.

These population-based indicators serve as input for the hierarchical cluster analysis. Their values are z-standardised and clustered based on Ward's linkage method (Ward, 1963). We are aware that the input variables might correlate as they are all based on the same demographic data sets. Nevertheless, all indicators represent different key characteristics of arrival spaces and need to be reflected in the analysis: population exchange and the important fact that newcomers from abroad strongly influence the composition of a neighbourhood's population. Therefore, we consider this as the best option for our approach, with the analysis allowing us to identify clusters of potential arrival spaces. The next two steps analyse the identified city blocks in greater depth.

3.2.2 Classification: Socio-economic status and diversity

The second analytical step is the classification of the identified blocks as potential arrival spaces on the basis of the diversity of inhabitants' nationality and socio-economic status. The latter should be represented by appropriate indicators, such as income, social welfare ratio, employment rate or poverty risk. Even though they appear different, all indicators provide information on a neighbourhood's socio-economic structure. For our case study, we used the official social welfare ratio, defined as the share of social welfare recipients in relation to the working-age population (Schaumberg, 2020). Though we are aware that this indicator does not fully capture the variety of socio-economic status, it serves as a good proxy for identifying areas with higher shares of households reliant on social transfers. To capture ethnic diversity, we decided to use a person's registered nationality, as this is the most reliable and consistent variable. To overcome potential data privacy issues, we decided to group countries into clusters (see Table 2). Commonly used in statistical offices in German cities, the clustering reflects major regions of origin. Other compositions of nationalities could have been used for this analysis, with the selection determined individually to reflect a city's ethnic composition.

	Nationality groups
1	Germany
2	Turkey
3	Syria, Iran, Iraq
4	Bulgaria, Romania, Macedonia
5	Algeria, Morocco, Tunisia
6	Poland, Czech Republic, Slovakia, Hungary, Ukraine, Belarus, Lithuania, Latvia, Estonia, Russia
7	Greece, Italy, Croatia, Portugal, Spain, Slovenia
8	Albania, Bosnia and Herzegovina, Serbia, Montenegro
9	Remaining countries

Table 2: Nationality groups

To quantify ethnic diversity, we decided to use Shannon's Diversity Index (SHDI). Compared to other indicators (e.g. Herfindahl-Index), this indicator, originally used in ecology to assess biodiversity in habitat analysis, includes two important components of diversity: richness and evenness (Shannon and Weaver, 1964). While richness refers to the number of groups in a given area or community, evenness concerns a specific group's population and distribution, that is, whether a group is more common or rare. In our context, the groups refer to nationality groups. However, a high proportion of foreigners does not necessarily result in high diversity, as a city block with a high share of foreigners could be dominated by a single nationality. We use Equation (1) to calculate the SHDI:

$$H' = -\sum p_i * ln(p_i),\ with\ p_i = \frac{n_i}{N} \quad (1)$$

N represents the number of individuals and n_i the number of individuals belonging to nationality group i. The maximum of H' is reached when all individuals are equally distributed over the species. The value range for H' is between 0 and 5. To better evaluate the results, we make use of True diversity. Here H' is the power for the base e (Eulerian number). This changes the value range to 0 - no. of groups. Although this equation is widely used in ecology, there are already some studies applying it in a socio-economic context (Eagle et al., 2010; Kurtenbach et al., 2019; Wu et al., 2014).

For both indicators, the social welfare ratio and the diversity index, we assign the values to four quartiles, distinguishing between 'below average' (first quartile), 'average' (second and third quartile) and 'above-average' (fourth quartile). This is then used to create an evaluation matrix classifying blocks as low/medium/high diversity and low/medium/high social status.

3.2.3 (Spatio-physical) Characterisation

The final analysis step involves characterising potential arrival spaces to draw conclusions on their (arrival-related) resources. The characterisation is intended to describe the blocks in greater detail with regard to their urban structure, rent levels, location, and their accessibility to important arrival infrastructures. We start by analysing the urban structure based on the construction volume, the proportion of residential buildings and population density. When typifying arrival spaces, the urban structure can play a significant explanatory role. Saunders (2011), for example, describes arrival spaces as highly dense and crowded areas, characterised by ground-floor shops. Such functionally diverse areas offer opportunities and further services to new immigrants. As yet, only few studies have considered these factors (see, e.g., El-Kayed et al., 2020). Specific infrastructures offer important resources to newcomers, helping them in their individual arrival process. Beyond their primary functions, arrival-related infrastructures like shops offering money transfer services or call shops provide opportunities for social interaction with other customers (Kurtenbach, 2015). Under certain conditions, these interactions can lead to resource transfers, for example, information about a vacant flat, and thus contribute significantly to the individual arrival process (Hans and Hanhörster, 2020). For our analysis, we selected a variety of types, ranging from retail and service facilities to organised social, educational and cultural infrastructures (see Table 3). Furthermore, the density, spatial distribution and diversity of arrival infrastructures are decisive parameters in determining whether a neighbourhood's arrival character is well-established or quite new. While, for example, shops offering money transfer services emerge relatively quickly in reaction to needs in such neighbourhoods, cultural and religious associations are generally found in a later development stage, often by already established migrants. Data on migrant associations, money transfer services and translation services originate from Google Places (Google, 2020). To assess the accessibility of the identified arrival infrastructures, we measured the walking distance between the city blocks and the nearest facility. To merge the different distances and make them comparable within a city, we normalised the values with the min-max-function (Equation 2).

$$Ai = \sum_{i=1}^{n} \frac{(x_i - min_x)}{(max_x - min_x)} \tag{2}$$

X represents the distance to the individual infrastructure. It uses a value range from 0 to 1 per infrastructure, where the value 0 represents the shortest and 1 the longest distance. These normalised values are added together to form the accessibility indicator (Ai), represented in a range from 0 to 4 (Table 3).

Infrastructure	**Relevance**	**Measure**
Money transfer services	Remittances to family and friends in the country of origin	Distance in m
Translation services	Translating forms needed on arrival	Distance in m
Migrant associations	Socialise and worship	Distance in m
Integration courses	Language courses and support structure, for example, for registration issues	Distance in m

Table 3: Arrival infrastructures

Quantitative analyses reach their limits when typifying arrival spaces, yet a detailed qualitative analysis for all identified arrival spaces is often not feasible with restricted resources. Therefore, we select areas composed of individual city blocks that share specific characteristics regarding their socio-demographic composition, urban structure and arrival-related resources. For the selected areas, in-depth qualitative analyses including on-site visits are then performed, including the recording of the building structure and visible foreign languages in the (semi-) public space.

As part of the qualitative characterisation, the urban structure is analysed in greater detail. For the selected areas, we consider georeferenced building data and use photos to document the built environment, thereby classifying the building structure by quantitative and qualitative aspects derived from the literature (Bürklin and Peterek, 2008; Lehner and Blaschke, 2019). Going one step further, we also used photos to document the identified potential arrival spaces, depicting public spaces, buildings and existing businesses, and including foreign languages visible in public spaces. The analysis of linguistic landscapes gives an impression of spatial use, power relations, language diversity and intercultural networks (Kurtenbach et al., 2019; Landry and Bourhis, 1997). Furthermore, the visible occurrence of languages can also be an indication of an area's spoken languages. We use this method primarily as an indicator for language and ethnic diversity for residents with only little knowledge of the local language. In our analysis, we documented all foreign languages visible in public space. In general, this included billboards, shop offers and advertising, informal notices in windows or announcements posted in cultural or religious facilities (Figure 2).

Similar to the arrival-related infrastructures, the frequency and distribution of foreign languages can provide an indication of whether an arrival space is well-established or new. We

Figure 2: Example of identifying foreign languages with the Google Vision engine

analysed the photos using the Google Vision engine, a software identifying and translating foreign languages. These results can be combined with official demographic data to refine the analysis. Furthermore, photo documentation allows us to monitor changes. A repeat exercise revealing the disappearance or appearance of specific languages could give indications of small-scale urban processes.

3.3 Case study

Europe has had a highly positive migration balance since the middle of the 20th century, though migration flows vary in intensity and origins across the different Member States (Portal, 2022). Germany is one of the countries with a significant intake. For example, many so-called Gastarbeiter (guest workers) settled in German industrialised regions in the middle of the 20th century. During the European 'refugee crisis' of 2015/2016, Germany was the destination of almost half (49%) of all asylum seekers coming to the EU. Similarly, in recent years, the number of refugees applying for asylum in Germany was very high compared to other EU states (28% of all refugees; Eurostat, 2022a). In Germany, urban areas and metropolitan regions in particular function as arrival 'hubs' (Heider et al., 2020; WBGU, 2016). Within them, neighbourhoods characterised by income poverty and low rents are primary arrival places where social and ethnic segregation overlap, as in other European countries. Yet German cities have relatively low levels of ethnic segregation compared to other European countries (Musterd, 2005), as confirmed by recent studies by Benassi et al. (2020). Nevertheless, while ethnic segregation has slightly decreased in German cities over the past 10 years, social segregation has increased significantly (Helbig and Jähnen, 2018).

We chose the German city of Dortmund as a case study for the first application of our methodological approach. Located in the polycentric Ruhr area, Dortmund has a longstanding history of migration due to its former coal and steel industry. In waves of immigration, various nationalities flocked to the Ruhr area, such as Poles in the late 19th century or Turks in the 1960s. With a population nearing 600,000, of whom 17% are foreigners, Dortmund is among the 50 largest cities in the EU and 1 of the 10 largest cities in Germany (Eurostat, 2022b). Increased immigration in recent years has led to significant growth in the city's population (+19,000 since 2015; Stadt Dortmund, 2019).

As evidenced by a nationwide comparison of German cities, Dortmund is one of the most ethnically segregated cities (Helbig and Jähnen, 2018). The city, and Innenstadt-Nord in particular, are often referred to as a traditional arrival space (see, e.g., Cindark, I. & Ziegler, E., 2016; Gottschalk and Tepeli, 2019; Hans and Hanhörster, 2020; Kurtenbach, 2015). About 75% of the population of Innenstadt-Nord have a migration background, among whom more than half (52%) have a foreign nationality (Stadt Dortmund, 2019). Dortmund is thus a good case study city for analysing various layers of arrival.

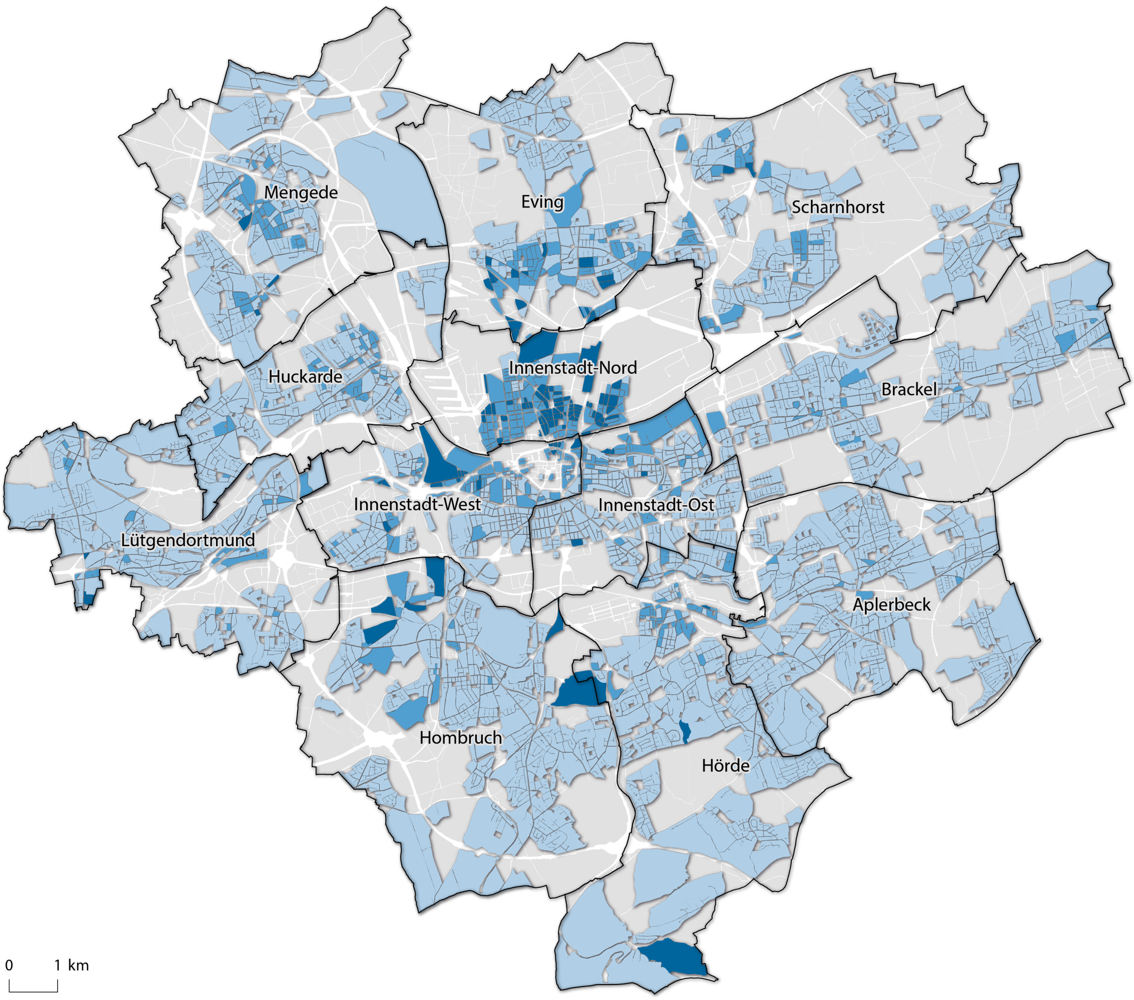
4 Application and results

4.1 Identification of potential arrival spaces in Dortmund

Figure 3 shows the result of the first analysis step, the hierarchical cluster analysis. It divides the 3,174 city blocks into three clusters. The optimal number of clusters was determined using the elbow method (see graph and dendrogram in the Supporting Information: Appendix Figures 1 and 2). The first cluster covers all city blocks with (i) a significantly higher percentage of foreigners (with a value of 54.6% in the cluster centre) than the city as a whole; (ii) higher population exchange (71.2%); and (iii) a higher value with respect to arrivals from abroad (15.5%). Totalling 120 city blocks, we define this cluster as high-potential arrival spaces. Similar characteristics are found, yet to a lower extent, in the second cluster: the percentage of foreigners (31.7), population exchange (36.5) and the arrivals from abroad (3.1). As the values of this cluster are still very high compared to the city-wide average, we categorise the 446 city blocks in this cluster as potential arrival spaces. In the third cluster, the values are significantly lower than the city-wide average, meaning that its 2608 city blocks have, in line with our definition, no potential to be an arrival space and are therefore not relevant for further analysis.

Looking from a spatial perspective, the first cluster is concentrated in the northern part of the city core (Innenstadt-Nord), with 66 of the 120 blocks located there. The remaining blocks are scattered over the city. By contrast, cluster 2 blocks are dispersed over the whole urban area, with several accumulations of spatially connected blocks, for example in the northern district of Eving, in the (north-) western districts of Mengede and Huckarde as well as in the northern part of Hörde.

For the following steps, the city blocks belonging to the first two clusters are merged as potential arrival spaces. These are the focus of our further analysis. One striking feature is the



Cluster No.	Cluster Name	Share of foreigners (in %)	Population exchange (in %)	Arrivals from abroad (in %)	No. of city blocks
1	High Potential	++ (54.6)	++ (71.2)	++ (15.5)	120 (3.8 %)
2	Potential	+ (31.7)	+ (36.5)	+ (3.1)	446 (14.1 %)
3	No Potential	- (7.6)	- (18.7)	- (0.5)	2,608 (82.1 %)
Average values		(16.0)	(25.8)	(2.1)	3,174 (100 %)

source: City of Dortmund

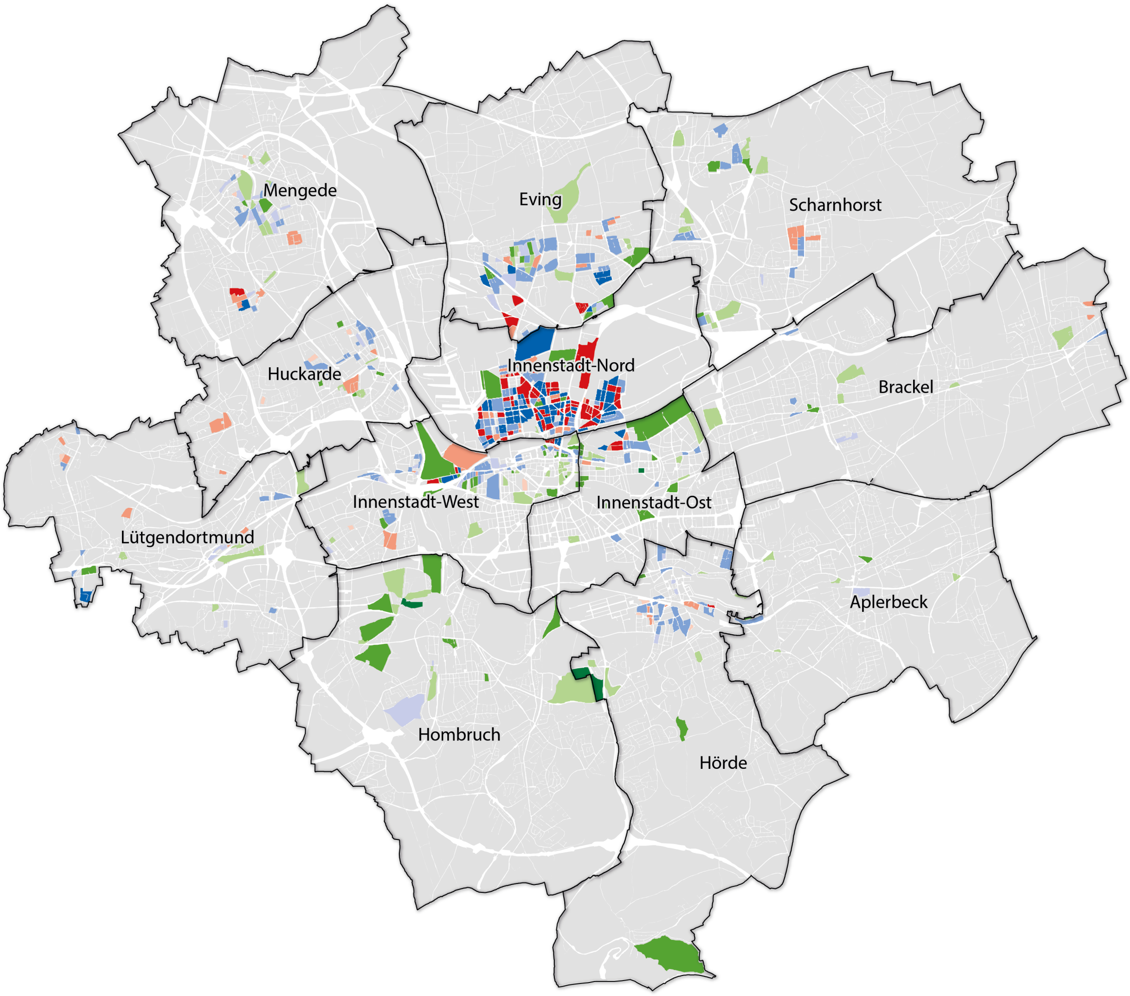
Figure 3: Results of the cluster analysis—Potential arrival spaces in Dortmund

extremely high share of potential blocks in the Innenstadt-Nord, where 95% of all blocks are assigned to cluster 1 or 2. The share is considerably lower in the districts of Innenstadt-West and Eving (slightly higher than 30%). In the remaining districts, the value is between 5% and 18%. The lowest value is in Aplerbeck, where only 2.3% of blocks are classified as potential arrival spaces. Overall, potential arrival spaces are to be found mainly in the densely populated areas in the inner centre of Dortmund and in the subcentres of some districts.

4.2 Socio-economic status and diversity

The city blocks identified as potential arrival spaces are classified in the following step based on their ethnic diversity and their socio-economic status. As mentioned in the methodological section (see Section 3.2.2), the values for Shannon's Diversity Index and the social welfare ratio are each assigned to one of four quartiles, with the result shown in Figure 4. The attached tables present the rating and distribution of the city blocks (left side) and the value ranges of the individual quartiles (right side). The individual blocks can be classified according to the ethnic diversity and socio-economic status of their inhabitants. The characterisation of the indicators (low ($-$)), medium (o) and high ($+$)) results in a 3 x 3 evaluation matrix. For example, when a city block has a low ethnic diversity and a low socio-economic status, it is in the upper left of the matrix. While the city block distribution shows a predominance of medium-value ranges (since two quartiles were combined here), the low-low and high-high fields also contain significant numbers. We were able to identify 65 city blocks with a higher socio-economic status and a low ethnic diversity, equal to 11.5% of all identified arrival spaces. Low-diversity blocks are usually dominated by a single immigrant group. By contrast, 9.7% of city blocks are highly diverse and show a low socio-economic status.

The spatial distribution of the different types of arrival spaces is shown in Figure 4, where socio-economic status is indicated in different colours, diversity by the colour intensity. Patterns emerge in the distribution of the types. A high number of city blocks with a medium or high social welfare ratio and high ethnic diversity are located in the northern part of the city core, the Innenstadt-Nord: 145 blocks feature a low socio-economic status, of which 55 also feature high ethnic diversity. Overall, this district can be classified as both ethnically highly diversified and socio-economically deprived. Other areas of the city show different compositions of social status and diversity. One example is the northern sub-districts of Eving, where we were able to identify some directly connected blocks with a high socio-economic status and different levels of diversity, but also other areas with medium socio-economic status and medium diversity. Similar patterns can be seen in smaller areas near the city centre. By contrast, the identified arrival spaces in Hombruch are characterised by a high socio-economic status and low diversity. In general, inner-urban areas are much more diverse and socio-economically more disadvantaged. With a few exceptions, diversity decreases and socio-economic status increases as the distance away from the centre of Dortmund increases.



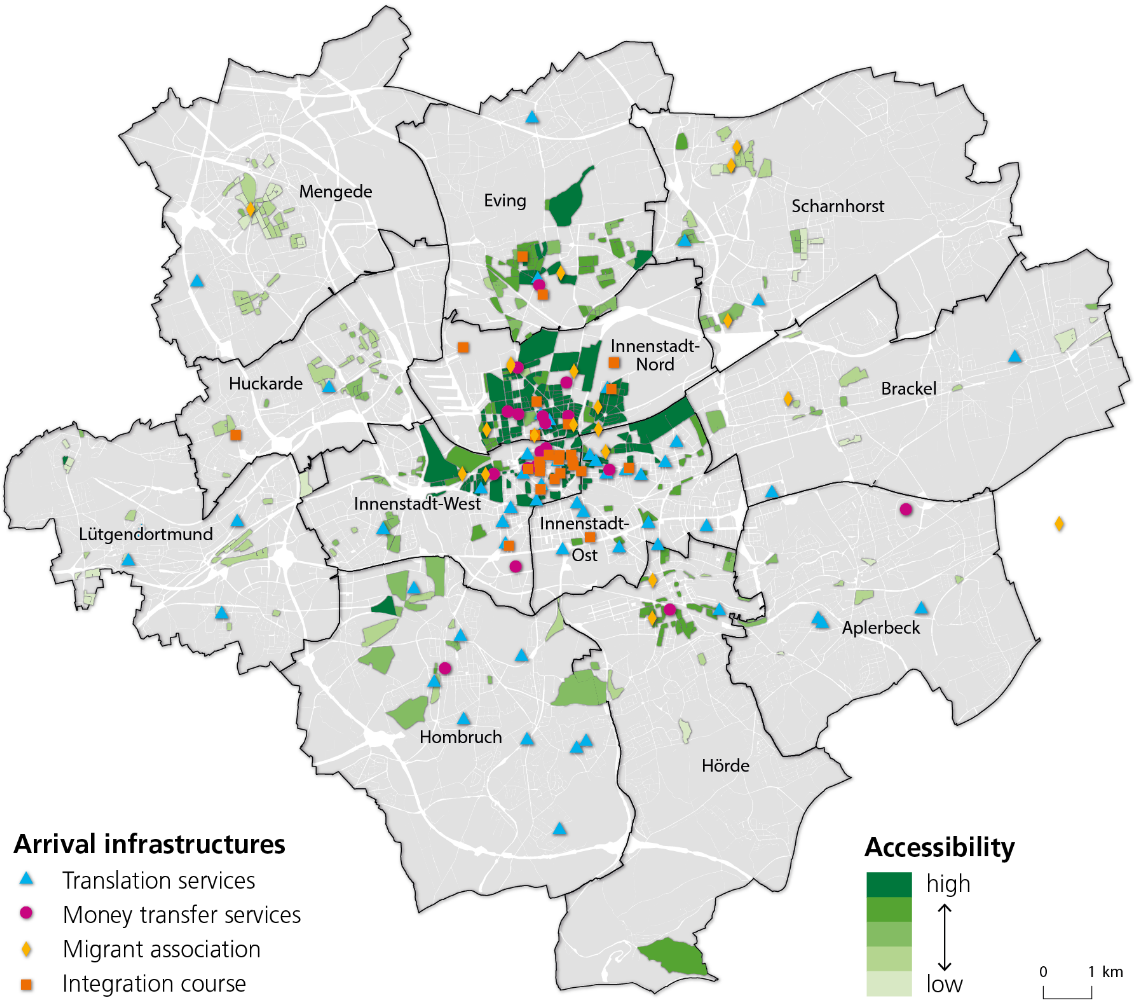
Potential Arrival Spaces			Diversity:		Shannon Index low ← medium → high		
					1.0 - 3.0	3.0 - 4.2	> 4.2
Social status:			Rating		-	o	+
				Quantil	1	2 3	4
Social welfare quota	high	0 - 15 %	-	1	**83** (14.7 %)	**64** (11.3 %)	**3** (0.5 %)
	medium	15 - 28 %	o	2 3	**46** (8.1 %)	**157** (27.8 %)	**68** (12.0 %)
	low	> 28 %	+	4	**13** (2.3 %)	**61** (10.8 %)	**71** (12.5 %)

sources: City of Dortmund

Figure 4: Socio-economic status and diversity of the identified arrival spaces

4.3 Supply of arrival infrastructures

To interpret the results in greater detail, we first take a closer look at the spatial distribution and supply of arrival infrastructures. As previously mentioned (see Section 3.2.3), we selected four different arrival-related infrastructures: Money transfer services, translation services, migrant associations and integration courses. The identified locations are shown in Figure 5. The largest share is to be found in the area close to the city centre, especially in the northern and western centre. More isolated facilities can be found in outer districts like Hörde, Eving or Mengede.



sources: City of Dortmund, Google Places

Figure 5: Socio-economic status and diversity of the identified arrival spaces

Money transfer services are mostly offered in kiosks, travel agencies or call shops. Similar to cultural associations, there is a prevalence of these services in the city centre but significantly fewer in suburban areas. Integration courses are offered by the city administration, mostly using existing facilities like (language) schools. Their spatial distribution illustrates that integration courses are mainly offered in the inner city, with only a few locations in other parts of the city. In contrast to integration courses, translation services are distributed more evenly throughout Dortmund. Although not used solely by immigrants, we were able to identify an accumulation in the city centre.

To measure the accessibility of arrival infrastructures, we calculated the foot distance to the nearest facilities. To merge the individual distances into a single indicator, we standardised the values and added them up, arriving at a value range between 0 and 4, where low values indicate short distances. We see that especially the previously identified potential arrival spaces in the inner-city area feature very low values, between 0 and 1 in the city centre north, west and east. The values in the city blocks in Eving and Hörde are in a similar range. People living in suburban areas have to travel furthest to reach arrival infrastructures. This accessibility finding shows that the identified potential arrival spaces differ with regard to the availability of arrival infrastructures.

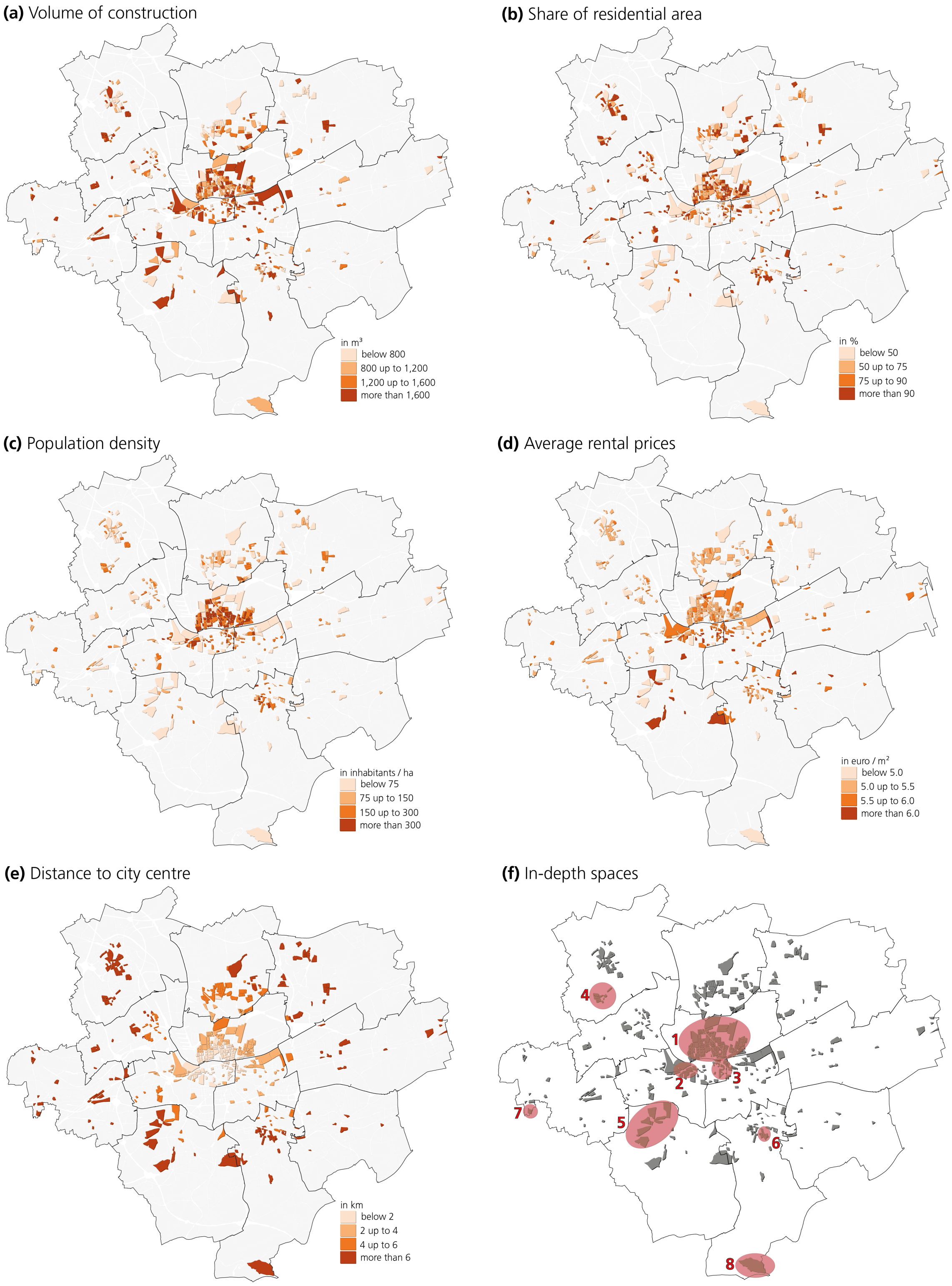
4.4 Types of arrival spaces and their key characteristics

To illustrate the internal differentiation and variety of arrival spaces, we take a closer look at certain areas, that is, the grouping of several city blocks. To select these, we draw on spatial-physical characteristics: (a) volume of construction; (b) share of residential buildings; (c) population density; (d) average rental prices; and (e) distance to city centre (see Figure 6). Using indicators (a–c), we can draw first conclusions about the urban structure in the observed areas. Average rents give us a further indication of economic status, while the distance to the city centre represents information about the location of potential arrival spaces within the city.

On the basis of the analyses conducted so far, we now subject eight areas differing in their location, size, urban design, supply of arrival infrastructures and socio-demographic composition to an in-depth, qualitative analysis (see Figure 6). Close to the city centre, areas (1)–(3) feature a high population density and high prevalence of arrival infrastructures. However, the socio-economic status in (3) is significantly higher. Located in the suburbs, areas (4)–(6) feature high population densities and construction volumes to a certain extent, but limited access to arrival-related infrastructures. Even in these areas, social status varies. Areas (7) and (8) are isolated spaces on the outskirts of the city without direct access to any arrival-related infrastructures and with low population densities.

As outlined in the methodology section (see Section 3.2.3), we go on to conduct qualitative analyses on the selected areas. We were able to record a varying density and diversity of foreign languages visible in public space, with significantly more languages and a greater variety found in the inner-city areas than in the outer districts. Likewise, the building structure in the respective areas featured major differences in height, size, density and arrangement. Different types of arrival spaces were thus identified on the basis of the similarities and differences of these studied areas:

- **Traditional arrival space:** The spaces located in the inner-city Nord (1) and West (2) feature many similarities: their urban location and building structure (block perimeter), high population density and ethnic diversity. Overall, the socio-economic status is quite low, although average rental prices are in line with the citywide average. Moreover, the preva-



sources: City of Dortmund (a-f), Geobase NRW (a), Infas360 (d), OSM (e)

Figure 6: Spatial-physical characteristics and selection of in-depth spaces

lence of arrival-related infrastructures and visual occurrences of foreign languages is very high.

- **Suburban arrival space in high-rise buildings:** The two suburban areas (4) and (6), located in the districts of Hörde and Mengede, constitute a second type of arrival space. While their population density, social welfare ratio and ethnic diversity are comparable to the inner-city locations, their morphological structure featuring several high-rise buildings is completely different. Especially in location (4), access to arrival infrastructures is limited.

- **Arrival space for highly qualified immigrants:** An arrival space with significantly different characteristics is located in Hombruch (5), near to the University of Dortmund. In contrast to the previously analysed areas, the average social welfare ratio in this area is very low and rents comparably higher. Besides the higher socio-economic status, diversity is also much lower and the area less densely populated. English is the only visible foreign language in this area, appearing on signs outside student residences. We assume that the influx relates primarily to highly qualified immigrants studying or working at the university. The location (3) is somewhat different. We observed a high socio-economic status in this inner-city area, as well as very high rents. Presumably, the inner-city location and proximity to high-quality local and long-distance transport are attractive residential location factors for highly qualified migrants.

- **A created arrival space:** We found the last identified type for our case study in two isolated areas in the outskirts of the city (7) (8). The special feature of these areas is the existence of refugee accommodation, where people live in flats rented from the city authority. This distribution policy for refugees could explain the isolated and peripheral location.

5 Discussion

Our study provides a new methodology for identifying arrival spaces in European cities. In contrast to existing approaches, it avoids socio-economic indicators in the first step, thereby not focusing solely on deprived neighbourhoods. This seems important against the background of migrants' increasing diversity and forms of temporal stays (Vertovec, 2007), for example, also covering middle-class circular migration and multi-locality in European metropolitan areas (Barwick & Le Galès, 2021). Based on a cluster analysis for Dortmund, this methodology allowed us to identify different types of arrival spaces at micro- (city block) level using the 'share of foreigners', 'population exchange' and 'arrivals from abroad' as indicators. In contrast to previous studies, we were thus able to identify areas smaller than districts or sub-districts. This small-scale approach helps identify the many newly emerging arrival spaces and clusters of arrival infrastructures in European cities (Meeus et al., 2019). In many European cities with tight housing markets, new arrival spaces are constantly emerging, with new migration being increasingly directed towards the suburban fringe (Boost and Oosterlynck, 2019).

To describe the identified arrival spaces in greater detail, we used various factors: an area's socio-economic status and ethnic diversity as well as its population density, urban structure and arrival-related infrastructures. With regard to our case study city of Dortmund, we observed that city blocks with an ethnically highly diverse and economically comparably poor population occur mainly in inner-city locations. While aware that a local population's socio-economic status and diversity cannot be measured by single indicators, we nevertheless wanted to develop an approach based on (relatively easily) available data sources to facilitate its use in European cities. By using quartiles to define different degrees of diversity and socio-economic status, we created intracity comparability. However, this procedure is not intended to ensure direct intercity comparability due to their different structures.

In a second step, we took a deeper look at the identified arrival spaces. Through analysing the accessibility of arrival infrastructures, we were able to determine the availability of important resources for newcomers. Though we are aware that not everyone living in the area necessarily takes advantage of these offers, this does provide a first approximation regarding the supply of arrival infrastructures. Our final analytical step allowed us to describe some selected areas in greater detail and identify different types of arrival spaces by taking urban structure into account. We identified established arrival spaces in the inner city, shaped by a very urban building structure and a high supply of arrival infrastructures and characterised by the low socio-economic status of the population and its high ethnic diversity—as reflected in the multitude of foreign languages visible in (semi-)public spaces. Kurtenbach (2015) describes the northern part of Dortmund's city centre as a historically grown and established arrival space which is highly socially and ethnically segregated. But similar studies conducted in Antwerp (Schillebeeckx et al., 2019), Leipzig (Haase et al., 2020) or Düsseldorf (Heidbrink and Kurtenbach, 2019) have identified established arrival spaces featuring the same characteristics. We are aware that this established type can also be found in suburban areas, reflecting local housing markets. A second type of arrival space identified is the suburban and less-established arrival space in (small) high-rise buildings. Primarily characterised by its building structure, spatial location and an overall low supply of arrival infrastructures, this type can be defined as less-established. It is prevalent in some East German cities (El-Kayed et al., 2020) as well as in suburban and even rural areas in Belgium (Boost and Oosterlynck, 2019) and Italy (de Vidovich and Bovo, 2021). In addition, our analysis allowed us to identify an arrival space of highly qualified immigrants. Characterised by the population's high socio-economic status, in Dortmund, this space is located near the university and the inner city, near to the central station. We assume that this type is located primarily in the vicinity of large research and educational institutions or large (globally operating) companies, as Maslova and King (2020) identified 'easy and fast transport connection' and 'proximity to work' as two important factors for high-skilled migrants. The fourth type identified is a created arrival space, where no housing market mechanism or individual preferences dictate choices, but where residents are forced to stay there for a certain time. In our study, such spaces feature (former) refugee housing, are located in the suburbs and lack any arrival-related infrastructures. This type is also described in Thorshaug (2019) ethnographic study of refugee camps in Norway. However, this type could also occur in other forms (e.g., a military base or housing for people in the low-wage sector). Although only a few studies consider this type, from our point of view, it is very important to take these spaces into account, as further arrival spaces may emerge in close proximity to them (e.g., established by former residents). While new arrival spaces may emerge, others can lose their arrival character under certain circumstances. Those with a high potential to become an attractive place to live for socio-economically privileged user groups may even be subject to gentrification processes (Haase et al., 2020).

Even though the chosen method has many strengths, some methodological challenges became apparent during implementation. First, while it was our aim to develop an approach applicable to (all) European cities, there are certain limitations to the replicability of the cluster analysis, as the selection of the optimal cluster constellation varies depending on the study area. Therefore, the determination of the clusters as (non-) potential arrival spaces is also a process that needs to be done individually for each case study. This also applies to the qualitative analysis of potential arrival spaces and the determination of key characteristics.

Furthermore, as already mentioned, some of the indicators used in our approach are based on similar demographic variables, for example, 'arrivals from abroad' and 'population exchange'. We consciously decided to include them, as we perceive them as key variables in the identification and characterisation processes. However, their correlation might overstress the analysis methods, as certain areas are overemphasised (see Supporting Information: Appendix Figure 3). However, as we focus on high values in the interpretation of the cluster analysis, we do not consider this as bias. Another critical issue regarding our cluster analysis was the selection of indicators representing population exchange. We decided against including the indicator 'duration of residence', as our preanalysis revealed that a long period of residence can distort the overall values of a spatial unit. Instead, we used population exchange, as this indicator better characterises an arrival space.

While the quantitative identification and characterisation point to potential arrival spaces, the chosen quantitative approach does not allow for a typification of these spaces. Thus, a mixed-methods approach, including qualitative data, is necessary to describe and define different types of arrival spaces in greater detail. This requires expertise in both quantitative and qualitative analysis, as well as a certain level of local knowledge of the study area. Overall, in our opinion, the presented methods and indicators provide a valid basis for further qualitative research and promote the discussion about different types of arrival spaces within a city.

Finally, it is important to mention that this first systematic approach cannot cover all varieties of arrival spaces. It is instead intended as an approximation to describe and compare them over time, possibly making it easier to predict and control the development of neighbourhoods within a city.

6 Conclusion

The aim of this study was to develop a methodological approach to identifying and typifying arrival spaces. Using the proportion of foreigners, population exchange and arrivals from abroad as key indicators, we were able to identify arrival spaces. Combining these with other indicators such as spatial location, socio-economic status, ethnic diversity and supply of arrival infrastructures, we were able to identify a variety of facilities offering newcomers access to resources to different degrees.

With this analytical focus, we expand the current debate on arrival spaces—a debate mainly focused on urban areas with a low socio-economic status and a host of migrant infrastructures (e.g., Kurtenbach, 2015; Meeus et al., 2019; Schillebeeckx et al., 2019)—, contending that different types of arrival spaces require different support strategies and policy measures.

The results of our analysis also illustrate the importance of small-scale monitoring based on quantitative and qualitative data to identify arrival spaces. This is growing in importance, especially against the background of the war in Ukraine and the resulting influx of refugees into many European cities. The use of block-level data helped us identify arrival spaces at micro-level. Integrating this approach into a continuous city-wide monitoring can also provide essential information on the ongoing development of arrival spaces, covering the expansion or even disappearance of existing arrival spaces and the emergence of new ones. In addition, this approach can be used for long-term observations. For example, the (dis-)appearance of visible foreign languages may be first signs of a change in a population's composition, perhaps as a result of gentrification.

One important question for further research regards the mobility of such residents. Combining the current results of our methodological approach with small-scale migration data would make it possible to identify and visualise relocation processes. The permeability of arrival spaces with regard to relocation processes provides an important hint as to the extent to which they are not only 'platforms of arrival' but also 'platforms of take-off' (Meeus et al., 2019).

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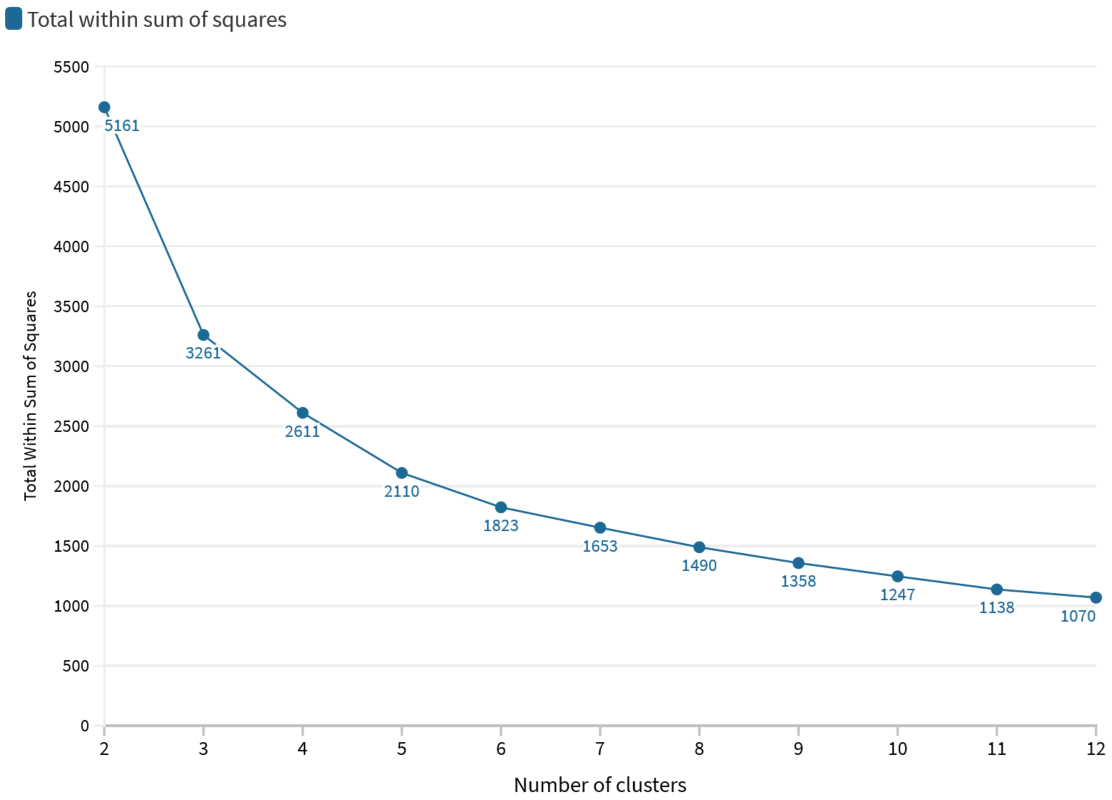
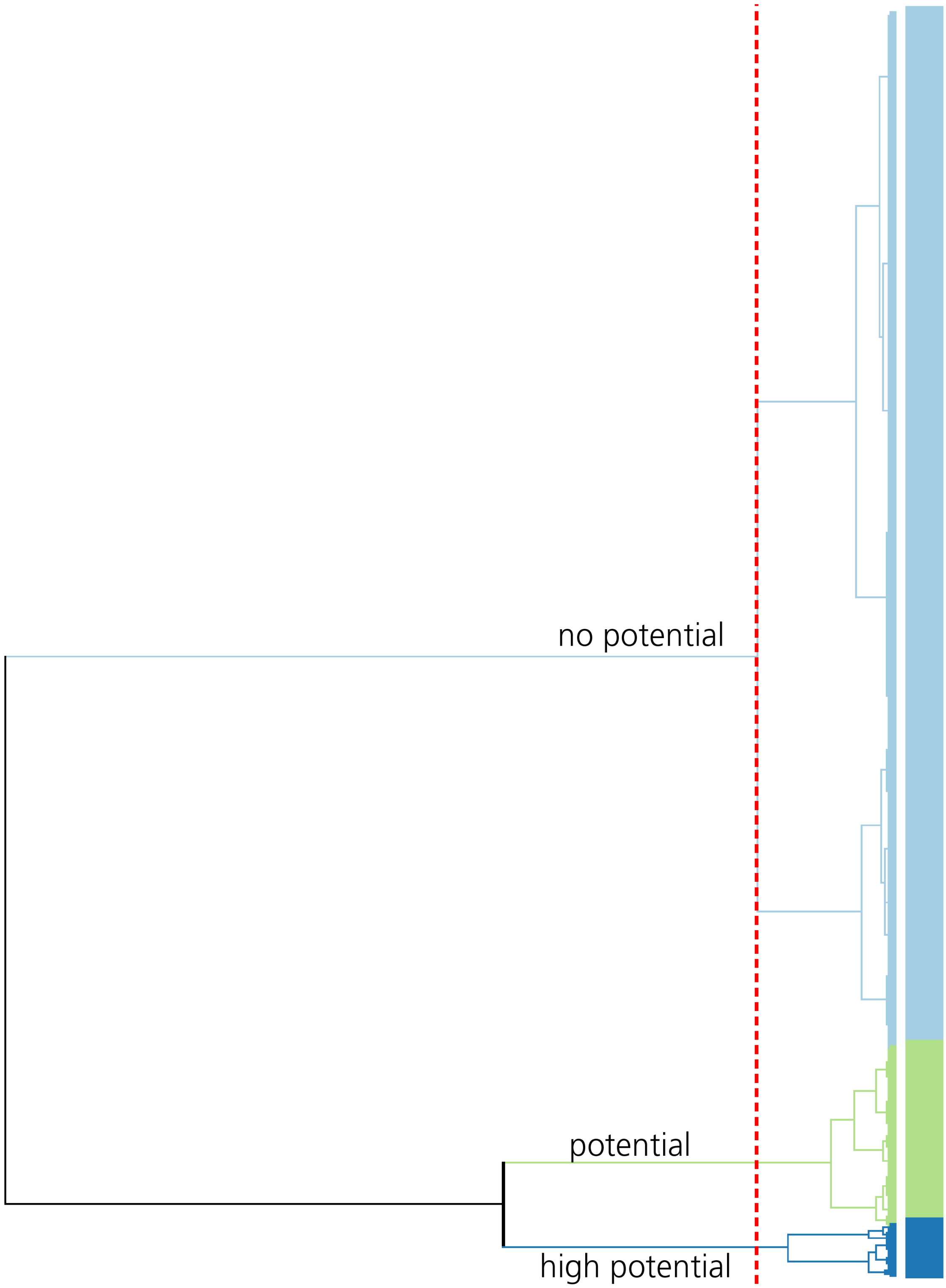
A Supplementary Figures



Supplementary Figure 1: Determining optimal number of clusters (Elbow method).



Supplementary Figure 2: Determining optimal number of clusters (Dendrogram).

	Share of foreigners	Population exchange	Arrivals from abroad	SHDI	Social welfare quota
Share of foreigners	-	0.664*	0.593*	0.969*	0.292*
Population exchange	0.664*	-	0.589*	0.667*	0.338*
Arrivals from abroad	0.593*	0.589*	-	0.623*	0.119*
SHDI	0.969*	0.667*	0.623*	-	0.280*
Social welfare quota	0.292*	0.338*	0.119*	0.280*	-

* $p < .05$

Supplementary Figure 3: Spearman correlation of cluster analysis input variables.