Analyzing Polycentricity.

Conceptual Issues and Methodological Challenges.

Dissertation

zur Erlangung des Doctor rerum politicarum (Dr. rer. pol.)
an der Fakultät Raumplanung der Technischen Universität Dortmund

vorgelegt von
Angelika Krehl

Dortmund
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Executive summary

Spatial restructuring processes have been observed in many places worldwide. Drawing the attention to economically advanced countries reveals that most of them have experienced substantial changes of both their urban spatial structure and their economic base. These changes are reflected in the development of larger-scale regional entities caused by spatially separated cities merging with their corresponding hinterlands. Consequently, urbanized areas are gaining importance in the context of a large-scale agglomeration process. At the same time, however, intra-regional dispersion processes dilute the core city's traditional primacy. These opposing forces have led to the emergence of core-city competitive urban subcenters and thus to polycentric urban configurations.

Against that backdrop, it is not surprising to find many studies discussing numerous means of subcenter identification. A review of these contributions leads to the insight that theory-based, exploratory and qualitative research methods are used to analyze urban spatial structure. Yet, these diverging approaches have not added to a commonly agreed understanding and measurement of urban spatial structure in general and polycentricity in particular. They have rather contributed to conceptual confusion and a 'fuzzy' use of the term polycentricity. Thus, answering the question how to consistently analyze morphological, that is, place-based polycentricity is a research desiderate.

It is discussed to what extent the conceptual fuzziness of polycentricity can be narrowed down to derive a working definition for a quantitative study. Furthermore, it is evaluated how to translate this definition into an empirical approach that considers several facets of polycentricity. Therefore, one contribution is a more encompassing understanding of morphological polycentricity by not only addressing employees but also their resemblance in urban form. Another contribution aims at a clarification of morphological polycentricity in analytical respect. To achieve this, it is suggested to combine conceptually different means of analysis and to carefully and comparatively evaluate their results. These issues are addressed under the hood of two leading research questions: Where are spatial densifications of activity in German city regions, that is, where are urban centers and subcenters? Is there, and if so, what is the appropriate way to identify these densifications? These questions are underpinned by different theoretical rationales of urban centers and subcenters that are implicit in the method of analysis. To ensure a high analytical depth, all empirical analyses are conducted on the spatial level of 1 km² grid cells thus permitting intra-municipality considerations.

First, the prospects and limitations of jointly considering employees and built-up volume are evaluated. These analyses not only discuss the possibility and value-added of combining these variables, they also cast light on the intra-municipality distribution of employees and their resemblance in urban form. Second, numerous studies exist discussing subcenter identification procedures, but a systematic comparison of these procedures is missing. This research gap is addressed by applying several methods with different, at times incompatible theoretical rationales to the same data and the same set of study regions. These methods are threshold based density maps; the local Moran's I, which is a

means of exploratory spatial data analysis; and a set of semi-parametric regressions, that is, specifications of a locally weighted regression, which have a gravitational nature.

Referring to the first research question regarding the location of urban centers and subcenters in four German city regions, my answer is that these densifications are mainly located in the core cities and to a smaller extent in legally designated medium sized centers' downtowns. Thus, urban history and spatial planning decisions seem to manifest in both employee and built density, even on a 1 km² grid level. I second asked if there was one appropriate way to identify urban densifications and my answer is no. This answer is disenchanting at first but it does not mean that the choice of methods is irrelevant. In contrast, this answer calls for special attention to the methodology chosen, maybe even implying that it is inevitable to apply more than one method to analyze the complexity of urban spatial structure.

With regard to the polycentricity of German city regions I conclude that spatial disparities exist in all study regions, but they differ in their spatial extent and intensity. Collecting all empirical results reveals that urban subcentering is present, but an agreement regarding the number, size and precise location of the identified centers and subcenters cannot be reached. This conclusion is mainly based on the contradictory notion of subcenters between the local Moran's I on the one hand and the locally weighted regression on the other hand. Nonetheless, a spatial configuration of core city dominance can be established, implying that all study regions are far from being polycentric in the sense of having several equally relevant centers. This finding holds for both employees and built-up volumes, although their spatial patterns differ in details. Referring to a distinction between poly- and multicentricity, this finding speaks in favor of multicentricity.

As an overall methodological result, I suggest applying a 'double-funnel' concept to cope with the conceptual and analytical fuzziness of polycentricity. This concept's characteristic is to successively increase the level of detail of both the spatial scale and the applied set of methods. It recommends starting with a large-grained spatial scale and ending with a fine-grained one and, similarly, starting with global measures and ending with site-specific analyses. Finally, all results of all levels should be synoptically compared regarding their quantitative and qualitative similarity. This procedure does not essentially solve the problem of analytical fuzziness, but it permits in-depth analyses and a multi-dimensional understanding of the phenomena under consideration.

From a theoretical point of view, the consequential step is to revisit each result by reconsidering the particular method's assumptions. It is to be investigated to what extent a priori conjectures or hypotheses prove to be true for each measure and each spatial scale. After that it is to be evaluated whether the methods have contradictory suppositions of why diverging results might occur and how to ponder them in a joint evaluation. Thus, my contribution to the state of knowledge with regard to explaining urban spatial structure is that it is necessary to consider not only one urban or regional economic model but to incorporate several conceptually different models to understand the variegated nature of urban spatial structure.

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Writing a Ph.D. dissertation in a research project funded by the German Research Foundation (DFG) has been a privilege. This setting permitted an intensive and in-depth discussion of my topic without having the burden of writing interim reports. Thus, I had the great opportunity to pursue my own research with a maximum degree of individual freedom – project work and dissertation could go hand in hand therefore enabling many synergies. Thanks to both a committed project team and interested colleagues at the ILS, I always had the chance to exchange ideas and to critically reflect my work.

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List of Abbreviations

ATKIS ... Amtliches Topographisch-Kartographisches Informationssystem
... (Authoritative Topographic-Cartographic Information System)
CBD ... Central Business District
CP ... Core-Periphery
DFG ... Deutsche Forschungsgemeinschaft (German Research Foundation)
ESDP ... European Spatial Development Perspective
FAR ... Floor Area Ratio
FDR ... False Discovery Rate
FIRE ... Finance, Insurance, Real Estate
IEB ... Integrated Employment Biographies
INSPIRE ... Infrastructure for Spatial Information in the European Community
KIBS ... Knowledge Intensive Business Services
LISA ... Local Indicators of Spatial Association
LWR ... Locally Weighted Regression
MAUP ... Modifiable Areal Unit Problem
MSSD ... Most Similar Systems Design
NEG ... New Economic Geography
RDC ... Research Data Centre
TAZ ... Transport Analysis Zone

I INTRODUCTION

I.1 Motivation

"If we academics wonder about why cities exist and grow (or shrink) and why sizable and persistent gaps between and within countries occur, what people and policy-makers care about is where these things happen" (Thisse, 2010: 295). Though a few years old, this assessment is still valid and has been unresolved yet: not so much as a matter of fact but regarding the operationalization of 'where'. Thus, a crucial issue to detect "where things happen" is to find and apply reliable means of identifying urban and suburban densifications of economic activity. To understand this issue's topicality, particularly from an academic point of view, a closer look at spatial (re-) configuration processes is helpful.

Considering economically advanced countries reveals that most of them have been undergoing substantial changes of both their urban spatial structure and their economic base within the last 40-50 years. Formerly spatially separated cities and their corresponding hinterlands have merged into larger-scale regional entities which are characterized by opposing forces: agglomerating forces on the regional scale pull more and more economic activity into urban cores and dispersing forces on the intra-regional scale push activity away from traditional Central Business Districts (CBD) and into rather suburban locations in close proximity to the core city (see Anas et al., 1998; Duranton and Puga, 2015; Hall and Pain, 2006; Kloosterman and Lambregts, 2007, each with further references). Thus, urbanized areas are continuously gaining importance on a regional scale, while intra-regional dispersion processes dilute the core city's traditional primacy. The core city's attenuation manifests in a change in urban spatial structure and urban form: new urban centers of employment have been emerging in close proximity to the core cities thus concurring with traditional inner-city CBDs. Therefore, once monocentric city regions have successively transformed themselves into polycentric or even dispersed urban spatial entities. Core cities are now accompanied by a number of subcenters which are characterized by high densities of employment and correspondingly high masses of built-up volume and urban infrastructure.

Especially a deconcentration of higher-order service sector jobs (also called FIRE – finance, insurance, real estate, or KIBS – knowledge intensive business services) has occurred since the 1970s thus attenuating the core cities' primacy in favor of suburban densifications (see Carlino and Chatterjee, 2002; Garcia-López and Muñiz, 2010; Romero et al., 2014). This subcentering process has triggered a polycentric or even dispersed urban spatial structure, which is characterized by a reconfiguration in the sense that emerging suburban densifications, so-called subcenters, attract employees, jobs and built-up volume that have formerly been located in the core cities and their CBDs (Giuliano and Small, 1991; Gordon and Richardson, 1996; Lang and LeFurgy, 2003; Riguelle et al., 2007). These new employment centers, often called 'edge city' in the US-American context (see Garreau, 1992), are located outside the core city but in rather close proximity to it (Anas et al., 1998; Kasarda and Lindsay, 2011; Lang and LeFurgy, 2007).

However, not only deconcentrating processes but also spatial restructuring processes can be observed. Yet, these restructuring processes seem to be dependent on the economic branches considered – some branches still cluster in the CBD, whereas others tend to have relocated from the CBD. Some studies find that manufacturing firms tend to relocate, whereas (higher-order) service sector firms seem to prefer locations in established CBDs (see Coffey and Shearmur, 2002; Guillain et al., 2006; or Riguelle et al., 2007: 194f. with a wealth of further references).

Against that background, what specific spatial configuration of economic activity and built environment can be expected? Angel and Blei (2016: 27f.) connect the first of these questions to the relevance of urban agglomeration economies: “Do businesses seeking to enjoy the agglomeration economies associated with proximity need to locate in a few employment centers – be they CBDs or sub-centers scattered throughout metropolitan areas – or do they simply need to locate in the same metropolitan area? If the former is true, then we should see significant clustering of workplaces in employment centers. If the latter is true, then we should see significant de-clustering of businesses and their dispersal throughout metropolitan areas outside employment centers.” For these reasons, changes in urban spatial structure, and therefore polycentricity as a new urban spatial configuration, are important research desiderata in urban and economic geography as well as in spatial planning research – thus in regional science.

But why consider polycentricity and the identification of urban centers and subcenters? The overarching issue in the scientific debate about polycentricity is to provide a solid knowledge base for thoughtfully refining the urban system with respect to economic performance, societal sustainability and/or future viability and livability. Thus, there is not only the analytical (academic) side of polycentricity but also a normatively loaded perspective. Deliberations whether polycentricity is something desirable have been an issue in spatial research and planning and are particularly reflected in many contributions regarding the European Spatial Development Perspective (ESDP), which has been approved by the Informal Council of Ministers of Spatial Planning of European Commission in May 1999. The ESDP claims progress “Towards balanced and sustainable development of the territory of the European Union” (European Commission, 1999). But who is essentially in charge of this? According to Isard[1] and his understanding of regional science “economists, geographers, sociologists, and city planners [should] cross disciplinary boundaries, construct theories of urban and regional phenomena, and apply methods of analysis to the emerging urban, regional and environmental policy issues” (Boyce and Miller, 2011: 1). This dissertation is scientifically located at the heart of regional science as it covers aspects from quantitative economic research, economic geography and spatial

[1] Although Walter Isard did not consider the ESDP when he explained his understanding of regional science, his reflections fit well into this issue.

planning. It aims to combine these disciplines' different approaches to urban spatial structure in general and polycentricity in particular.

With regard to the overarching issue of thoughtfully refining the urban system, I contribute to the analytical perspective by providing a solid knowledge base for subsequent (normative) interpretations and evaluations. Precisely, my research objective in this work is to discuss the conceptual and methodological challenges of polycentricity: what is actually seen, that is, where are spatial densifications of economic activity and how is their resemblance in urban form?

I.2 Research gap, objectives and expected contributions

There has been awareness among scientists of the changes and challenges introduced above for decades. As the depicted spatial restructuring processes are, moreover, observed in many places worldwide, it is not surprising to find an enormous amount of literature discussing means of subcenter identification (for overviews and further references, see e.g., Krehl, 2016 or Siedentop et al., 2016b). Comparing and reflecting these studies leads to the insight that further consideration is necessary regarding the question how to consistently measure polycentricity.

Reasons for this need are due to parallel existence of theory-based, exploratory and qualitative research approaches all of them addressing issues of urban spatial structure, subcentering and polycentricity (see Arribas-Bel and Sanz-Gracia, 2014; Garreau, 1992; Kasarda and Lindsay, 2011; McMillen, 2001; Riguelle et al., 2007; Roca Cladera et al., 2009). Consequently, many conceptually different means of analysis are applied in empirical work (see Agarwal et al., 2012; Giuliano and Small, 1991; McMillen, 2001; Redfearn, 2007; Riguelle et al., 2007; Roca Cladera et al., 2009; Siedentop et al., 2003; Siedentop et al., 2016b). These diverging approaches and conceptualizations have certainly not added to a commonly agreed understanding, measurement and evaluation of urban spatial structure in general and polycentricity in particular. Rather, these points have contributed to conceptual confusion and thus a 'fuzzy' use of the term polycentricity (see Meijers, 2008a; van Meeteren et al., 2016). By the same token, lacking analytical and conceptual clarity has led to both an unspecific use and several not necessarily scientifically sustained connotations of the same.

But why is that a concern? An exemplary meta-analysis of Agarwal et al. (2012) has vividly shown that within one and the same region several, at times mutually exclusive, densifications can be identified. These authors have considered studies of the Los Angeles metro area identifying between 13 and 120 subcenters (Agarwal et al., 2012: 441). One explanation for these substantially diverging results is the application of thresholds for subcenter identification. However, thresholds are normative values and thus have often shown to be subject to researchers' interests (Craig and Ng, 2001; McMillen, 2001; Redfearn, 2007; Krehl, 2016 for a discussion of this issue). Of course, threshold approaches can be modified and systematically tested to avoid this kind of criticism. Referring back to the study of Agarwal et al. (2012) it is consequent to find Duranton and Puga (2015: 545) saying that "subcenter formation and diffuse employment decentralization should not be seen as a binary dichotomy. Reality is about a continuum ranging from small isolated facilities, to groups of several offices in a strip-mall, to small industrial parks with a couple hundred workers, to full-fledged business sub-centers with tens of thousands of employees". In other words, due to a lacking analytical and conceptual precision it is not clear what urban densifications actually are, where they are located and how to consistently identify them. This is especially a problem if inter-regional or international comparisons shall be made.

Thus, one objective of this dissertation is to detect what is actually seen, that is, where in a city region are clusters of economic activity? Yet, this question is difficult to answer impartially if neither conceptual matters of polycentricity nor its methods of analysis have been settled. These ambiguities are, accordingly, this dissertation's starting point and its motivation: it is discussed to what extent the conceptual fuzziness of polycentricity can be narrowed down to derive a working definition and a useful empirical approach. Based on this definition, it is evaluated how to identify urban densifications: which variables to choose, which methods to apply? These aspects are underpinned by different notions of urban densifications that are implicit in both the method and the variables under consideration. Likewise, these methods' theoretical foundations are revisited and in the case of exploratory approaches potential explanatory patterns of the obtained results are discussed. The leading research questions thus are:

(i) Where are spatial densifications of activity in German city regions, that is, where are urban centers and subcenters?

(ii) Is there, and if so, what is the appropriate way to identify these densifications?

Knowing the answers to these two questions is important because any kind of policy recommendation or development advice should be based on solid information regarding the current state. Precisely, it is to be analyzed how polycentric four selected German city regions actually are. The polycentricity issue can be directly derived from the questions stated above: its main characteristic is that a number of howsoever defined spatial densifications exist within a study region. These densifications are often called centers and subcenters in the literature and generally refer to 'buzz areas'.

This dissertation's contribution is a survey of theory-based, exploratory and qualitative research approaches used in other studies. Additionally, selected means of these approaches are empirically tested and critically discussed for four German city regions. The work furthermore aims at a clarification of morphological polycentricity in analytical respect. To achieve this, it suggests a combination of different means of subcenter identification and analysis as well as these means' careful and comparative evaluation. Thus, the methodological innovation is to apply a series of conceptually different means of analysis, to juxtapose the obtained results and to determine the number, size and location of urban centers and subcenters based on that juxtaposition.

Another contribution of this dissertation is its focus on the morphological dimension of polycentricity by not only considering employees but also their resemblance in urban form. Whereas numerous studies exist that discuss either the socioeconomic or the physical dimension of polycentricity (see Sec. II.1), a stringent integration of these dimensions has not been achieved so far. Against this backdrop, a multivariate approach will be applied that is based on both socioeconomic data and data regarding urban form. This approach is expected to contribute to a more comprehensive view on urban spatial structure in general and thus to a multi-dimensional analysis of polycentricity in particular.

To ensure the research's feasibility in the sense of reasonable length and clear scope some limitations seem necessary: I analyze urban spatial structure in its morphological dimension thus disregarding any kind of flows (people, commuters, goods, services, that is, a functional dimension of polycentricity). My focus, furthermore, is on explanatory patterns from regional economics and economic geography because these essentially are the subcentering debate's origin. Conversely, explanatory patterns and theories from a solely human and social sciences' perspective are not considered. It should also be noted that the work does not aim to clarify whether polycentricity is a desirable urban spatial structure. These issues will be briefly touched upon in the conceptual framework (see Sec. II.2.2 and II.3.1), but the empirical work's focus is analytical.

Due to limitations in the data availability, all explanatory patterns are largely hypothetical. This means that explanations are not derived in a quantitative-analytical way from own empirical analyses but from interpreting these empirical analyses' results. Thus, ideas and explanations are rather borrowed from theory. One might argue here that borrowing limits this dissertation's scope and, therefore, is a deficiency. However, this argument can be invalidated referring to the research objectives stated above.

The empirical findings and their potential explanations open the stage for further research because they provide an informed understanding of the urban spatial structure. With this informed understanding it becomes feasible to test established theories rooting in primarily US-American urban development patterns – one of this dissertation's academic contributions.[2] Thus, the consequential next step would be to modify, refine and/or complement these theories to establish or improve their suitability for German and probably also European urban spatial structures, their growth and structural development. Based on my empirical results and conclusions, I will outline some ideas in this respect in the concluding section (Sec. VII). This informed understanding makes this dissertation not only valuable for science but also for society: policy makers and other stakeholders can draw on this knowledge and interpret it. Based on their interpretation they can continue with further steps towards a purposeful development of the urban system.

[2] Side note: A discussion of the general transferability of theories from one context to another is, for example, addressed in Scott and Storper (2015) and Storper and Scott (2016) whose line of argument is rejected by Cusinato (2016) and Mould (2016). Bourne (2008: 184) concludes based on a study of Canada, Mexico and the US that "models or explanations cannot be easily and uncritically transferred from one national or cultural setting to another".

I.3 Outline

This cumulative dissertation is organized as follows: Section II introduces into the topic of polycentricity. It, first, presents some stylized fact about the urban spatial structure both in Germany and beyond: How has it emerged and why is it the way it is today? (Sec. II.1). After that, a conceptual framework and an overview of theories regarding polycentricity and spatial planning are provided (Sec. II.2). This framework is not encompassing, but focuses on those theoretical strands and considerations that are referred to in my separate journal papers and book sections. Thus, Section II rather has an umbrella function for these papers. Based on this foundation, I address the conceptual issues of urban spatial structure and polycentricity (Sec. II.3). A main topic is how to distinguish polycentricity from other urban spatial configurations, that is, how to measure it.

Section III is a linking section between the superordinate, theoretical considerations on the one hand and the empirical work on the other hand. It comprises the working definitions used in the papers as well as the choice of study regions and the data basis. Thus, this section frames the journal papers which form this dissertation's core.

Section IV presents detailed summaries of all empirical results relevant to this dissertation. These results are entirely based on own published journal papers and book sections. For that, the subsections' titles are the respective journal papers' or book sections' titles. Originally German titles have been translated for the headings but are naturally provided, too. From a conceptual point of view, this section is two-folded: first, I discuss general thoughts of the variegated nature of urban spatial structure, the concept of urban density and the potentials of integrating employee and built density data (Sec. IV.1). Second, these analyses and considerations are utilized in the analysis of the polycentricity of German city regions (Sec. IV.2). I develop, apply and discuss three methodologically different concepts of quantitatively analyzing polycentricity. Based on these analyses, I provide a joint, synoptic summary of the results and answer my research questions (Sec. V).

The conceptually next step made in Section VI relates these results to the theoretical framework. Its main contribution is a critical reflection of the research objectives, key results and limitations of the obtained findings. Accordingly, this section also illustrates why combining these publications in a cumulative dissertation provides additional insights as compared to considering them individually. Finally, conclusions are drawn and an outlook of future research opportunities is given (Sec. VII).

Figure 1 visualizes the general structure of the dissertation revealing an outline similar to standard outlines of journal papers: Sections I and VII are the general framework of this dissertation containing the motivation and the research gap (Sec. I) and overall conclusions and prospects of future research (Sec. VII). Section II establishes and Section VI later revisits the joint conceptual and theoretical background of the dissertation. Thus, these sections frame the journal papers and book sections, which contain the empirical analyses.

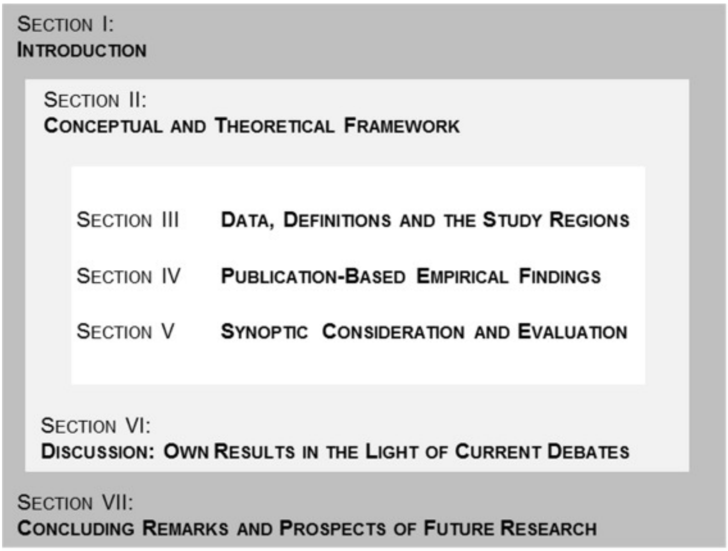

Figure 1: Outline of the dissertation

Due to this dissertation's cumulative nature, there is no essentially pure empirical section. All empirical analyses have been published in separate contributions. These papers and book sections are independent implying that each includes a research gap, a theoretical section, data and methodology descriptions as well as a critical discussion of its scopes and limitations. Nevertheless, these papers and their results can be combined thus offering more in-depth analyses and insights. Figure 2 displays their interlinkages and highlights why their combination in a cumulative dissertation is more than the sum of its parts.

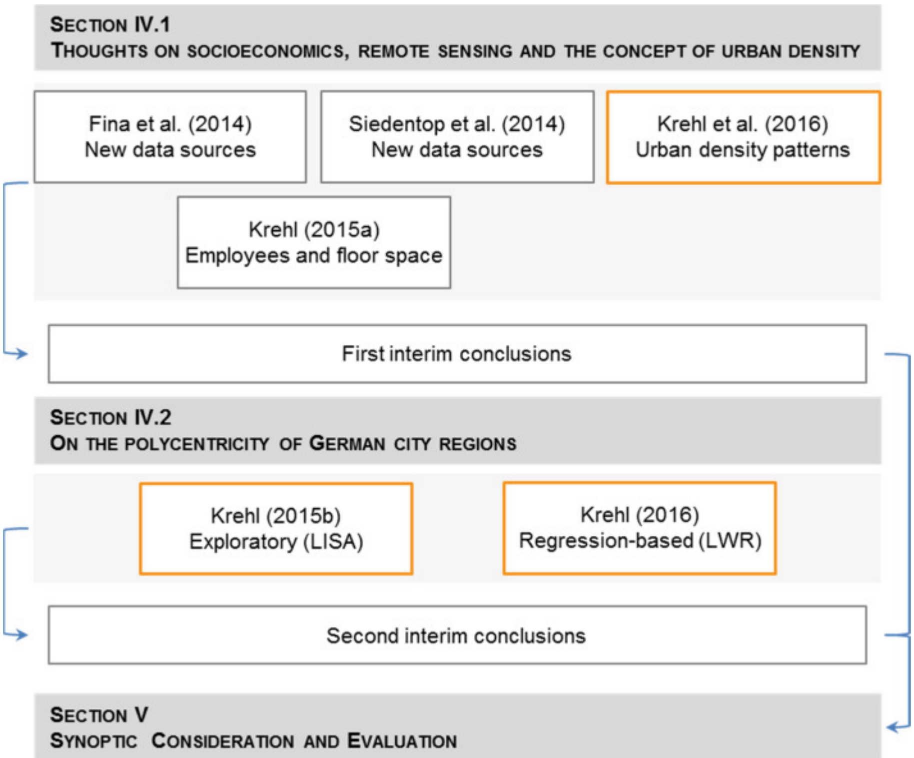

Figure 2: Organization of the journal paper-based empirical part

A first empirical part (Sec. IV.1) discusses general aspects regarding the data base and conceptual issues of urban densities. It is evaluated to what extent socioeconomic and remote sensing data can be fruitfully combined to analyze urban spatial structure. First interim conclusions going beyond each single paper's results close this subsection. Based on these results, the polycentricity of four German city regions is analyzed in the second empirical part (Section IV.2). It is analyzed how polycentric each of the study regions actually is if a certain methodological approach is used. Just as with the first empirical part, this second empirical part is also closed with an interim conclusion which contrasts the polycentricity findings obtained so far. A summary and comparison of the results from all contributions mentioned in Figure 2 is provided in Section V, where also the research questions formulated in Section I.2 are reconsidered and answered (Sec. V.1 and V.2).

Finally, a technical note to Figure 2 refers to the orange frames: These frames indicate publications that meet the formal requirements of a cumulative dissertation as defined by the Technical University of Dortmund (see Appendix A.1 for details). Nevertheless, all publications named in Figure 2 are relevant to my research objective. As not all of them meet the formal requirements, I will additionally mark those contributions that fulfil the criteria by bold font and I will provide their length, that is, the number of characters and words of the accepted manuscript's version, before summarizing them in Section IV. The publications' full bibliographies and, in the case of multiple authorship, my contributions are given there as well.[3]

II CONCEPTUAL AND THEORETICAL FRAMEWORK

II.1 The background of polycentricity

II.1.1 A spatial pattern-oriented point of view

Urban spatial structure has been substantially changing during the last decades, especially in economically advanced countries in the so-called Global North. These countries have in common a change in their spatial configuration, which is caused by several global and local drivers such as metropolization and regionalization, changes in metro areas' economic base and improvements in information and communication technology or advances in infrastructure facilities enabling longer daily commutes within the same amount of time (e.g., Anas et al., 1998; Cairncross, 1997; Castells, 2010; Cavailhès et al., 2007; de Groot et al., 2007; Hall, 2009; Ioannides et al., 2008; Kopecky and Suen, 2010; Lee, 2007; Münter and Volgmann, 2014; Shearmur and Coffey, 2002; Storper and Venables, 2004).

[3] It should be noted that this dissertation originates from the project "The polycentricity of German metropolitan areas – development of a remote sensing-based approach for measuring morphological polycentricity" funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under grant SI 932/4-1 and TA 800/1-1. See Appendix A.1 for further details regarding both the project and this dissertation's relation to the same.

Globalization has produced yet unprecedented mobility of financial capital and labor and thus increased competition among city regions. Especially specialized knowledge labor force is mobile clustering in the particularly most beneficial environments. These environments are usually those in which positive externalities can be utilized most efficiently, that is, regions where highest gains from density, that is, proximity, and knowledge spillovers are expected. Highly dense regions, in turn, are metropolitan regions. Therefore, these metropolization processes and corresponding agglomerating forces have induced capital and specialized labor force to cluster in large urban areas (see Hall and Pain, 2006; Taylor, 2000; also Morin and Hanley, 2004: 370f. for an overview). The result of these forces is a spatial restructuring causing substantial shifts in the urban spatial structure and urban form. These shifts manifest increased spatial concentration and thus growing spatial disparities between metropolitan areas and their hinterlands (see Castells, 2010).

Likewise, the smaller spatial scale of several nearby urbanized areas is subject to restructuring processes and affected by agglomeration forces, too. It can be observed that once spatially separated cities and their corresponding hinterlands have merged into larger-scale regional entities as agglomerating forces on the regional scale pull more and more economic activity away from peripheral, less agglomerated areas and into urban(-ized) cores (see Romero et al., 2014: 891–893 with an extensive overview of studies). Thus, urbanized areas have been continuously gaining importance on the regional scale yielding inter-urban polycentric spatial patterns (for details regarding different kinds of polycentricity, see Sec. II.3.1).

A closer look at these processes within urbanized areas reveals that regionalization has been going on, too. Thus, concentration and deconcentration take place simultaneously, yet on a more fine-grained spatial scale. Whereas concentration took place on the inter-regional level, deconcentrating forces act on the intra-regional scale pushing activity away from the traditional CBD and into rather suburban centers in close proximity to the core city (see Anas et al., 1998; Duranton and Puga, 2015; Hall and Pain, 2006; also Shearmur and Coffey, 2002 with mixed results). Consequently, "[p]olycentric urban structure is a combined outcome of metro-wide decentralization and local level clustering" (Lee and Gordon, 2007: 5, see also Anas et al., 1998: 1431).[4] Put it differently: although urbanized areas are gaining importance on a regional scale, intra-regional dispersion processes dilute the actual core city's traditional primacy.

In terms of spatial hierarchies these restructuring processes lead once dominating core cities to 'merge' into their surrounding area. 'Merge' means a city region that has been transformed from a core city dominated ('spiky') urban configuration into a less clear-cut ('bumpy') spatial entity in which the core city is just one densification amongst others and surrounded by a rather dense urban fabric (see Gordon and Richardson, 1996: 291). However, the core cities still kept some of their re-

[4] Their term 'metro' is similar to the term 'region', which is mostly used here and 'local level' refers to a spatial scale below the entire region (see Davoudi, 2003 and Sec. II.3.3).

gional primacy as Greene (2008), Guillain et al. (2006); Krehl (2016) or Siedentop et al. (2016b) show.[5] This point, nonetheless, should not hide the fact that substantial amounts of economic activity have been shifted away from CBDs into both urban subcenters (see Coffey and Shearmur, 2002; Einig and Guth, 2005; Romero et al., 2014) and further distant places with moderate densities (see Gordon and Richardson, 1996; Lang et al., 2009; Lee, 2007).

As a result of these interfering forces, the spatial outcomes are complex and multi-layered, and show – depending on both the spatial scale and the variable under consideration – polycentric or dispersed patterns of activity (for modeling issues regarding this finding, see e.g., Roca Cladera et al., 2009). Examples addressing the spatial distributions of employees are amongst others provided by Adolphson (2009), Anas et al. (1998), Angel and Blei (2016); Coffey and Shearmur (2002), Duranton and Puga (2015), Garcia-López and Muñiz (2010), Kim et al. (2014), Kneebone (2009), McMillen (2001), McMillen and McDonald (1998), Pfister et al. (2000) or Siedentop et al. (2003). Similarly, studies have been conducted with respect to residents' location (see Duranton and Puga, 2015; Garcia-López, 2010; Kneebone and Holmes, 2015; Siedentop et al., 2003; Yang et al., 2012) or the development of built area and built-up volume (see Carruthers et al., 2010; Duranton and Puga, 2015; Ji et al., 2006; Lang et al., 2009; Salvati et al., 2016; Siedentop et al., 2003). All of these studies essentially support the complexity of urban spatial structure.[6]

An issue related to polycentricity and subcentering is the discussion of so-called edge cities, which can be both sub- or full-fledged centers in polycentric urban configurations. To what extent edge city formation (Garreau, 1992) actually occurred varies among regions and nations and a divide can be found between land-rich and land-scarce countries. Whereas the latter are despite ongoing suburbanization processes characterized by fairly high urban densities and an economically and residentially strong urban core (see Bontje and Burdack, 2005), the aforementioned have established fairly large-scale edge cities in commuting distance to the core city. Examples are Tysons Corner, which is geographically located in Fairfax County, VA but functionally tied to the greater Washington D.C. area or Century City located west of Los Angeles downtown (Phelps, 2012; Garreau, 1992 with further examples). Similar cases can be found for Canada or Australia (Freestone and Murphy, 1998; Shearmur and Coffey, 2002). A European example would be La Défense, a Parisian suburb in the Île-de France region, hosting substantial amounts of employees and built-up volume on a rather small area of land, or Canary Wharf in London, England (Garreau, 1992: 235f.). These cases are in some contrast with edge cities such as Eschborn, Frankfurt-Niederrad[7] or City Nord in Hamburg (all located

[5] The references Krehl (2016) and Siedentop et al. (2016b) are part of this dissertation.

[6] As these articles have by and large been the starting point of my empirical work, I have not included own papers here. Yet, all of them fit into the category 'employees' and/or 'built area and built-up volume'.

[7] Assessment of an edge city adopted from http://www.stadtplanungsamt-frankfurt.de/Buerostadt_Niederrad_5490.html?psid=2 (12/11/16) for Frankfurt-Niederrad and from www.eschborn.de/fileadmin/eschborn/Bilder/Wirtschaft/sprachen/2016_01_Standortexposé_Englisch___FINAL-gb.pdf (12/11/16) for Eschborn.

in Germany). The contrast is in both size and location: the North American and European examples are on a regional scale, whereas the German examples are smaller in size and typically located within regional cores. Both their spatial extent and inner-municipality location lead to discussions whether these sites were true edge cities as compared to the US (Bontje and Burdack, 2005: 317, also with further references).

II.1.2 A school-oriented point of view: Chicago or L.A.?

What is a school? It can either be an agreement regarding methodological steps, empirical procedures and the like or a common understanding of theoretical conceptualizations that are applied in empirical work (Dear et al., 2008; Sampson, 2008; Shearmur, 2008). According to Shearmur (2008: 167) and Nicholls (2011: 190) both Chicago and L.A. are schools as their respective scholars share – to some extent – theoretical and normative positions, institutional (local) cohesion as well as mechanisms for testing and disseminating theories. However, it is currently under debate whether schools are contemporary and several scholars suggest going beyond schools as a structuring element of theoretical currents (see Sampson, 2008).

My main reason to include this school-debate here is to provide a different view on the background of urban spatial structure and its change over time. I have provided a description of urban spatial structure but my discussion has been organized according to different spatial patterns and developments (Sec. I.1, I.2 and especially II.1). Therefore, this section complements that collection by sorting the discussion according to different schools. With a view to my empirical work it is insightful to understand these schools' approaches to and limitations of explaining changes of urban spatial structure in general and polycentricity in particular. As a result, going beyond school-dependency may be reasonable, too.

The Chicago School is characterized by rigid modelling and a theoretical foundation, which is oriented towards functional differentiation. It, thus, follows the traditions of Durkheim and Spencer. Based on their theoretical foundation (for details see e.g., Nicholls, 2011: 191[8]) Ernest Burgess and Robert Park – proponents of the Old Chicago School – developed their city model of concentric zones in the 1920s based on empirical observations in and of the city of Chicago. According to this model and later refinements such as the zonal model of Homer Hoyt[9] and the multi-core city model of Chauncy Harris und Edward Ullman, "a city primarily [is] a congeries of socially differentiated neighborhoods caught up in a dynamic of ecological advance and succession together with associated mentalities and behaviors" (Scott and Storper, 2015: 2). In the spirit of the Durkheim-Spencer-tradition, the Chicago School's constituting element is its reliance on theoretical concepts when de-

[8] Walter Nicholls is a L.A. School researcher of the second generation, who also consider politics as a driver of change. Yet, he provides a compact overview of the Old Chicago School and its sociological background.
[9] He was a student of Ernest Burgess.

signing, implementing and explaining urban phenomena. Moreover, the approach to knowledge is characterized by “gathering of information in a systematic, transparent, and reproducible way, and in the explicit description of analytical techniques, theories, observations and previous research that enables knowledge to be derived from it” (Shearmur, 2008: 173). Therefore, a main contribution of the Chicago School is an evidence-based research approach, that is, “scientific method”.

The L.A. School, in contrast, is less a characterized by a homogeneous theoretical foundation than by a number of researchers trying to understand and explain the urban spatial structure of the Los Angeles metro area and its changes since the 1980s. Its origin as well as its researchers’ commonalities is dissatisfaction with the Old Chicago School established by Park and Burgess in the 1920s and refined by Hoyt in the 1930s, its evidence-based research approach, its strict theoretical model foundation and (alleged?) unfeasibility to explain postmodern urban spatial structures that do not reflect a ‘traditional’ industrial city such as Chicago of the late 1920s (see Dear et al., 2008: 102; Nicholls, 2011: 189). It should also be noted that this school emerged from a rather neo-Marxist theoretical background of the 1970s and 1980s, but is complemented by several post-structural influences (Nicholls, 2011: 192). Yet, if there is some agreement about a common background, one could summarize it as follows. The L.A. School is oriented towards a poststructural, post-Fordist, postmodern urban development, which implies no linearity or path dependency in the changes of urban spatial structure. In other words, change occurs due to the interplay of variegated structural, cultural and economic drivers (Nicholls, 2011: 190, 203). Thus, assorting proponents to these strands of the L.A. School is not without risk. However, one might deduce from the literature that Mike Davis tends to follow a neo-Marxist way of thought disagreeing with postmodernism, whereas Michael Dear and Edward Soja on the contrary propose postmodernism (e.g., Soja, 2015), and again others such as Allen J. Scott and Michael Storper rather work with post-Fordist lines of argumentation (e.g., in Storper and Scott, 2009) applying concept of agglomeration and specialization.

Relating these schools one can conclude that the L.A. School criticizes the Old Chicago School for its orientation towards concentric zones and the implicit assumption that the center organizes the periphery (see also Dear et al., 2008: 102; Sampson, 2008: 128). From a conceptual point of view, the L.A. School contrasts especially the Burgess model of an industrial city organized in concentric zones by a model of Keno Capitalism, which essentially describes urban spatial structure consisting of a random set of neighborhoods. A characteristic that is, in turn, criticized by (New) Chicago School proponents, who argue that empirical investigations have shown yet unaltered relevance of location theory (Shearmur, 2008: 172) and consequently a pivotal role of space. Finally, Table 1 contrasts these schools.

Table 1: Comparing essentials of the Chicago and the L.A. School

Chicago School	**L.A. School**
Theoretical currents: • Evidence-based research approaches (“scientific method”) • Encompassing data collection with a focus on the data being related to individuals in the end • Application of a wide range of methodologies to both collect and analyze these data	**Theoretical currents**: • Marxist, • Poststructural, • Postmodern and • Post-Fordist approaches
Relationship between theory and empiricism: • Theory needs empirical foundation • Empirical research is necessary to constructing and refining theories	**Relationship between theory and empiricism:** • Analyses start from theory, which is to be (in-) validated by case study research
On the issue of generalization: • Generalization is an empirical question, that is, it is generally possible, permitted and desired • Middle-range theory • Knowledge can be both objectively acquired and shared	**On the issue of generalization:** • Everything is unique, every opinion is weighted similarly and every observation is valid by the same amount as the next one • Knowledge cannot be shared
Main research objective: • “study of urban social mechanisms and processes, and how (or whether) they vary across time and space” (Sampson, 2008: 129)	**Main research objective:** • “explanations for the social, spatial and symbolic fragmentation found in late-capitalist cities” (Nicholls, 2011: 194)
Conception of change: • Processes and mechanisms interact with space • “social mechanisms provide accounts of the processes and actions that bring about change in a given phenomenon.” (Shearmur, 2008: 128f.)	**Conception of change:** • Urban processes are essentially random resulting in a (new) urban sociospatial disorder (Conzen and Greene, 2008: 98).
Conception of difference: • Differences are the natural consequence in all ecological systems which need to be mitigated by institutions • “two-pronged process of fragmentation and integration” (Nicholls, 2011: 191)	**Conception of difference:** • Structural and cultural forces produce sociospatial differences
The role of space: • Strong focus on the spatial context, especially the site • Spatial dependence of various urban phenomena and processes exists	**The role of space:** • Essentially no spatial dependence to urban phenomena and processes.

(Source: own compilation, mainly based on Conzen and Greene, 2008; Nicholls, 2011; Sampson, 2008; Shearmur, 2008)

The main reason for a New Chicago School to emerge was the Old Chicago School’s unfeasibility to explain current urban spatial structures and dynamics. The main distinction between Old and New Chicago School is that the latter also considers culture and politics as explanatory variables for urban phenomena (Clark, 2008: 155; Conzen and Greene, 2008: 99). The New Schools’ core elements are outlined by Clark (2008: 161–164) who identifies eight pillars: three *methodological pillars* are that no city can represent the entire nation it is located in or even the world (which is in contrast with L.A. School proponents claiming Los Angeles being the city of the future); multiple research methods need to be applied to understand the object of analyses; the objective of analysis is not only the city itself but the city's entire metro area has to be considered. Five *content-oriented pillars* are that cities are pluralistic, diverse and filled with competing subcultures; key concepts in redefining cities are consumption issues often related to topics such as tourism, quality of life and amenities[10]; functional segregation between places of work and places of residence is still ongoing (which is in contrast with many German and European cities); race, ethnicity and subcultural conflicts tend to decline giving rise to tolerance, new forms of political agreement and intergovernmental arrangements among subcenters (which is opposed to the L.A. School); globalization is a source of change thus demanding consideration[11]. Both Clark (2006: 1) and Dear et al. (2008: 106) provided lists of proponents of the New Chicago School. Scholars that are named in both contributions are Andrew Abbott, Harvey Molotch, Robert Sampson and Saskia Sassen. Further names that can be read with the New Chicago School are Terry Clark, Peter Gordon and Harry Richardson or Richard Shearmur, to list the most frequent ones.

Similar to the New Chicago School a 'new' L.A. School seems to emerge, too. Nicholls (2011: 200) characterizes the second generation of L.A. School scientists as being strongly informed by the theoretical insights of the older generation. However, this second generation is less focused on theoretical debates than oriented towards "exploring these insights [from the theoretical debates, author's note] through the lens of politics". One might argue that the new schools tend to approach each other. However, both new schools are still rooted in their predecessors especially with regard to their theoretical currents.

With regard to the issue of polycentricity it can be concluded that both the Chicago and the L.A. School permit changes in the urban form and related restructuring processes. Thus, none opposes the emergence of subcenters and, hence, polycentric spatial patterns. Yet, both the triggers of change and the related spatial reconfiguration processes' explanations differ substantially (see Table 1 for conceptualizations of change, difference and the role of space). Whereas Chicago School-type analyses assume that there is a common 'generalizable' pattern behind all cities and their reconfigurations, the L.A. School has a postmodern understanding of urbanism and focuses on explaining the peculiarities each city region is subject to. Another fundamental difference is the 'benchmark' situation from which empirical analyses depart: A L.A. School oriented analysis would, according to Nicholls (2011), start with the assumption of an essentially empty city center accompanied by a dispersed urban spatial structure. Thus, the causality is that "hinterlands organize what is left of the center" (Nicholls, 2011: 196). Based on that it is analyzed which individual processes have caused a polycen-

[10] that is, ideas pursued amongst other by Glaeser (2011), who discusses quality of life inter alia, or Florida (2002), who addresses amenity issues.

[11] for example, Sassen (1991) and Sassen (2008)

tric or even dispersed[12] urban spatial structure. The Chicago School rather starts from an industrial city model, which has essentially been core city oriented.

According to the quantitative-analytical nature of this dissertation, the "scientific method" is applied to analyze urban spatial structure. However, as some of my results are exploratory, one could also think of explanatory patterns from a L.A. School's perspective. For that, the causes of urban densifications described in the following section are not distinguished between these schools, that is, Scott-Storper post-Fordist strands are captured as well as causalities rooting is models such as the monocentric city model according to Alonso-Mills-Muth.

Finally, a remarkable point is that despite very early German influences (see Jazbinsek et al., 2001) neither the Chicago nor the L.A. School – nor a competing one – have been discussed in a European context, an issue that is criticized by Bourne (2008: 184) who at the same time questions comparisons due to a number of individual influences.[13]

II.2 Urban spatial structure and (sub-) center formation

Driving forces that led and shaped the spatial reconfigurations described above can roughly be grouped into spatial and non-spatial agglomeration economies, path dependencies, matters of accessibility and topography as well as planning laws and decisions. In the spirit of Isard and many others, this dissertation covers both regional economics and spatial planning. Thus, explanatory patterns are oriented towards urban and regional economics and complemented with geographic matters and planning policies.

The starting point is that if spatial agglomeration economies are present, densely populated entities will be clustered in space. In other words, the very nature of urban densifications relies on positive agglomeration economies, amongst others proximity advantages (Agarwal et al., 2012; Arribas-Bel et al., 2015: 24; Duranton and Puga, 2004; Scott and Storper, 2015: 4f.). However, according to Walker (2016: 165)[14], this cannot be all to explaining the very existence of cities and this conjecture neither is fully neglected by regional economists (e.g., Boyce and Miller, 2011: 1). Krugman (1991: 9f.) puts this aspect nicely saying "[t]he long shadow cast by history and accident over the location of production is apparent at all scales […] And this clear dependence on history is the most convincing evidence available that we live in […] a dynamic world driven by cumulative processes". Likewise, Hohenberg (2004: abstract, 3024) explains that much of the city emergence and growth is due to path dependencies and implicitly location issues are based on geography, such as harbors or intersections of trade routes. Additionally, Thisse (2010: 282) points to the fact that urban spatial structure is not only economy-driven due to global forces, but also the result of many individual – also

[12] 'fragmented' is a term often used by L.A. School proponents (see Nicholls, 2011)

[13] Bourne does not oppose comparisons but claims their thorough construction as well as considerations of national and cultural settings when transferring models and explanations.

[14] He rather is a L.A. School proponent than following the currents of the Chicago School.

economically motivated – decisions whose sum might have unintended consequences, a finding similar to the Alonso-Model's outcome (see Sec. II.2.1.1). Last but not least, Anas et al. (1998: 1428) discuss the relationship between market forces and planning regulation and their interplay actually shaping urban spatial structure. Hence, it is not surprising to find Agarwal et al. (2012: 440) concluding that theory is not fully consistent with respect to the causalities that cause certain places to become employment densifications.

For that, economic contributions and explanatory patterns are complemented with insights from spatial planning laws and planning practice. Additionally, both topography and the macro-scale infrastructure system of the study regions are taken into account when interpreting the obtained spatial patterns (see Sec. IV). Again, most explanations are not analytically derived from the empirical results but rely on a thorough and informed interpretation. The interpretation, in turn, originates from theoretical contributions that explain certain relationships and causality chains. Although each paper is self-sustained, a synoptic consideration of all papers delivers valuable insights into the spatial organization of mainly employees and built-up volume within four German city regions (see Sec. V). To make the synoptic comparison more 'accessible', both the theories explained in the papers and those expected to offer explanations regarding an overall consideration of the empirical results are outlined in the subsequent sections.

II.2.1 Economic foundations

As this dissertation is about morphological polycentricity, I focus on contributions explaining monocentricity. Two main reasons support this seemingly contradictory statement: first, "polycentricity is fully consistent with monocentricity applied locally" (Agarwal et al., 2012: 440). Thus, it is reasonable to use monocentric city models as a starting point and to analyze to what extent these models can be used to also explain polycentric urban spatial configurations (see Sec. II.3.3 regarding the spatial scale of polycentricity). Second, my results in Section IV suggest core city dominated (i.e., multicentric, see Sec. III.1) spatial patterns in the study regions. These patterns need to be explained and urban land use theories and their 'translation' into monocentric city models appear as a natural starting point.

To give a brief overview of the basic models, I mainly rely on Waldorf's paper "Path-breaking books in regional science", where she asked scholars to name and review influential books (Waldorf, 2004: 60). Most of the contributions mentioned there proved relevant to my area of study and have been referred to in my journal papers, too. Additionally, I cover further discussions such as the New Economic Geography (NEG) and issues regarding spatial planning and polycentricity (see Sec. II.2.2 for the latter). If necessary or reasonable, I have touched upon further debates in the journal papers. However, these debates are minor issues in the papers' context and thus not outlined here.

II.2.1.1 Early models and theories

First considerations of urban spatial structure were those of Weber (1909) who considers transportation aspects[15] and their relevance to industry location; von Thünen (1826) who analyzed agricultural land use and derived agricultural rent gradients; or Lösch (1940) who discussed the location of economic activity within an economy. For that, Lösch is sometimes considered the founder of regional economics. Based on these scholars' contributions, Isard (1956) compiled his exceptional work on location theory which is also compatible with standard production theory. Particularly, Isard has introduced "centripetal and centrifugal forces, scale economies, and monopolistic competition (of the Chamberlin variety) […] in explaining the transformation of locational structures" (Waldorf, 2004: 66).

Isard's analyses, in turn, set the stage for Alonso to develop his monocentric city model.[16] Core elements of the Alonso-Model are the distance to the CBD, the need for land and the consumption of a composite good consisting of everything but land. Referring to the work of von Thünen, Alonso (1964) developed the bid-rent model which is based on individuals' utility maximizing behavior. The result is a monocentric city model with the highest rents obtained in the (central) CBD. This work of Alonso and later the contributions from Muth (1969) and a few year later Mills (1972) are called New Urban Economics. All of them – particularly Muth and Mills – specify a monocentric city model '(Alonso-)Mills-Muth-Model' and aim to explain different land uses in urbanized areas. This model still is one of the core models and referred to in many other studies. A quick glance into GoogleScholar reveals that Alonso's "Location and Land Use" has been cited more than 6 700 times until December 2016.

Based on Muth's (1969) contribution Mills not only asks "'why do cities exist?'" but also provides the answer: "economies in production, and 'regional differences in natural conditions that affect production, people's utilities, and the cost of interregional trade'" (Waldorf, 2004: 70). Mills furthermore outlines thoughts regarding polycentricity by considering model extensions that permit the existence of subcenters, with subcenters being sites that are located outside the CBD and characterized by higher land rents than surrounding areas. These models' essences are, in a nutshell, bid-rent functions, density gradients and agglomeration economies. I refer to the latter two when searching for explanations of the spatial patterns I obtain in the empirical part of this dissertation (Sec. IV). Bid-rent functions have not been taken into account here as data on rents have not been available. Still, it is a rewarding field for future research to empirically test these functions with fine-grained spatial data.

The New Economic Geography (NEG), often said to be a successor of the previously described models, combines these location theories with urban, regional and international trade theory

[15] Amongst others regarding the distance between places of production and consumption of goods, regarding the wage level, regarding (natural) resources and firm competition effects (positive and negative) at the place of production.

[16] Side note: Walter Isard was one of William Alonso's Ph.D. supervisors.

(for details see Fujita et al., 1999 or Krugman, 1991). It conceptually differs from the Alonso-Mills-Muth model as it is not oriented towards land use but towards the distribution of industry between two dimensionless spaces. Its spatial component is operationalized by Samuelson iceberg transportation costs (i.e., a fraction of the shipped goods 'melts' away just as an iceberg would do if it was shipped around) instead of areas and metric distances as in the Alonso-Mills-Muth inspired models. The core of the NEG is the distinction of an industrialized area and a periphery, also called rural hinterland – without specifying this CP-pattern's spatial outcome. NEG-inspired CP structures are not automatically concentric but a yes/no-style. Critics argue that this notion is, though analytically elegant, not necessarily the prevalent urban form. However, the rationales behind are interesting: agglomeration occurs due to industrial organization, market size and – depending on the particular model specification – footloose capital and/or entrepreneurs (for an overview of most specifications, see Baldwin et al., 2003).

Both New Urban Economics and New Economic Geography were milestones for urban and spatial research since they linked economic trade theories with space and geography (Waldorf, 2004: 70, also Button, 1998: 2; McCann, 2014: 528). Thus, they provide the basis to analyzing urban spatial structure offering explanations of the clustering of activity in space. It should, however, be noted that all contributions outlined in this section interpret space as a featureless, plain area. This is a simplifying assumption which is not unusual in theoretical modeling (see Krugman, 1991: x for some self-criticism). However, as the empirical results obtained in Section IV are not derived from a featureless plain, further strands of explanations such as spatial planning and first-nature geography are used to complement the analyses.[17]

II.2.1.2 Agglomeration economies

Causalities, issues or aspects termed 'agglomeration economies' in the literature roughly refer to externalities due to densifications (see Anas et al., 1998: 1426; Arribas-Bel and Sanz-Gracia, 2014 or Parr, 2002b: 151). In most spatial research papers, agglomeration economies refer to effects such as *(i)* sharing, matching and learning (see Duranton and Puga, 2004; Puga, 2010) or *(ii)* knowledge spillovers (see Eriksson, 2011; Storper and Venables, 2004; also Romero et al., 2014 with further references). Both of these effects occur among people and firms. Moreover, they are prone to distance decay effects. Furthermore, agglomeration economies address *(iii)* internal and external economies of scale and scope, which refer to the firm level (see Parr, 2002b), *(iv)* home market effects or *(v)* developmental issues resulting in lock-in situations as introduced in the NEG (see Fujita et al., 1999; Krugman, 1991). McMillen and McDonald (1998: 159) offer a compact but vivid description of such

[17] As I analyze polycentricity on the regional scale regarding densifications of employees and built-up volume, I do not cover functional modelling approaches on the city level such as the contributions of Burgess (ring model, 1925), Hoyt (zonal model, 1939) or Harris and Ullman (multi-core city model, 1945). Yet, these have been captured in Section II.1.2 as they are amongst others the basis of the Old Chicago School.

different agglomeration economies and their diverging relevance to spatial clustering of firms and thus to urban subcenter formation. Therefore, it is neither surprising to conclude that 'agglomeration economies' is a term far from analytical clarity nor to find Parr (2002b: 152) saying that it is used "impressionistically".

Consequently, the literature is encompassing regarding agglomeration economies' existence and efficiency and it would be beyond this dissertation's scope to summarize and categorize all of these effects. As the data I used in my empirical analyses do not permit to derive causalities referring to agglomeration economies, I rather suspect these economies to cause the phenomena I observed in my empirical work. For that, I will focus on those (notions of) agglomeration economies that are feasible to explain why higher-order service sectors are more concentrated than all employees. A good overview of these KIBS-related matters has been provided by Romero et al. (2014: 894f.) whose research objective is to understand the settlement patterns of KIBS regarding both historic inner city sites and new suburban densifications.

Yet, it should be noted that the precise channels differ through which agglomeration economies work. This is reflected in the different tomahawk diagrams[18] in NEG models but is also evident in the distinction between economies of localization and economies of urbanization. Whereas the latter are, for example, referred to by Berliant and Fujita (2008) or Storper and Venables (2004) who address knowledge creation and the distribution of knowledge between different industries located at a common place, economies of localization rather refer to agglomeration economies in the sense of Marshall, Arrow, Romer and Porter.[19] These scholars discuss amongst others specialization and competition effects and the spread of knowledge between firms in similar industrial branches. Agglomeration economies there are, roughly speaking, due to industrial organization (see Parr, 2002b: 154).

Any spatial agglomeration effect is essentially gravitational in nature implying that it decays with distance. This is especially true for so-called face-to-face interactions (see Storper and Venables, 2004). However, these physical proximity advantages reduce with a diminishing role of distance and thus have attenuated the monocentric gravitation model's explanatory power regarding urban spatial structure (see Partridge et al., 2008; Thisse, 2010; for some empirical results see also Krehl, 2016). Complementary analyses addressing the relationship between knowledge spillovers and localization on the one hand and the role of distance (decay) on the other hand have been done by Figueiredo et al. (2015). Finally, Parr (2002b: 164f.) highlights that economies of urbanization and localization are difficult to distinguish analytically and are likely to exist in parallel, both for the single firm and for the place the firm and others are located at.

[18] See Baldwin et al. (2003) for several examples.

[19] These are Alfred Marshall (1890), Kenneth Arrow (1962), Paul Romer (1986) and Michael Porter (1990). The year in parentheses indicates the year when each of these scholars has published his main contribution regarding agglomeration economies. For an overview of conceptualizations and operationalization see Glaeser et al. (1992), for example.

II.2.1.3 Bringing geography back in: topography and accessibility

Since my empirical analyses are not conducted on a featureless plain, accessibility and topography are relevant drivers to shaping urban spatial structure and urban form. Topography and 'first-nature geography' have often shown to trigger certain developments and particularly the initial location of villages, later turning into cities (see e.g., Ketterer and Rodríguez-Pose, 2016 for a discussion of first-nature geography vs. institutions and the relation to economic growth). Selected, by far not representative examples of first-nature triggered developments are New York (deep and protected natural harbor), Stuttgart (location in a natural valley) or the Ruhr area (easily exploitable coal seams). Examples for accessibility-driven developments are Cologne (intersection of trade routes and location at a river including a bridge) or Chicago (intersection of both main railroads and waterways). Also, monasteries or fortresses have been the trigger for the formation of cities, at least in Europe as Hohenberg (2004: 3029) explains.

Referring to the four city regions that are analyzed here (details follow in Sec. III.2), density maps show that topography matters not only for initial location but also for further development. The lower mountainous areas in the Cologne and Frankfurt region are fairly scarcely populated thus structuring the regions, whereas no such structuring can be observed in the comparatively flat Munich region (see Figures 4 or 7). With respect to accessibilities, it can be seen that the urban spatial structure of the Stuttgart region tends to follow an axial system established by railroad corridors and the river Neckar. Similar patterns are detected in the other regions, too. Therefore, endowment with natural resources is rather the cause of a location, whereas further accessibility aspects – especially man-made ones ('second-nature geography') such as highways or railroads – are drivers of further development of densifications.

Accessibility is one expression of distance and distance has been shown to be a main explanatory factor in the monocentric city model. Due to distance decay effects in agglomeration economies, accessibility and density are linked. High densities imply a shorter distance between individuals and thus proximity advantages can be taken. Likewise, good accessibility in the sense of short(er) travel times can mitigate geographical distances and thus generate proximity, too (see e.g., Melo et al., 2017).[20] Last but not least, economies of localization are also a result of second-nature geography since they occur due to industrial organization and the co-location of similar or related industries.

II.2.2 Spatial planning

Spatial planning policy cannot be disconnected from urban economic theories. Rather, planning concepts and related decisions made with regard to the spatial organization of a territory are inspired by

[20] Complementary distance-related contributions refer to cognitive distance or different types of knowledge that require different levels of proximity. For further references and overviews see, for instance, Audretsch and Feldman (2004) or Kujath and Zillmer (2010).

improving the present situation. These expectations are in turn rooted in causality chains identified and explained from several (economic) theories. Examples are central places, NEG and agglomeration shadows.

It has been under debate for a while that cities, especially core cities, might not emerge or grow too close to each other because of spatial price competition. According to Partridge et al. (2009: 447f.) these growth or agglomeration shadows mean that "population growth in areas nearby similar–sized or larger urban areas may be inversely related to distance from the city rather than positively related (i.e., growth shadows) as predicted by standard NEG/CPT models".[21] The rationale is that denser places are subject to higher land prices and thus proximity advantages are offset by congestion costs – a shadow arises: whereas distance to the CBD would predict that density should be higher, fierce price competition works as a centrifugal force pushing development and density away from the core.

However, this agglomeration shadow can be countered by the concept of borrowed size, originally introduced by Alonso (1973) and revisited by Meijers and Burger (2017) in the context of polycentricity as a political goal. Borrowed size means that small and medium sized cities located in a metro area are economically more successful than they would be if only their own size had been considered, that is, if they had been located in isolation (Meijers and Burger, 2017: 271). Referring to spatial planning and European policies oriented towards territorial cohesion and balanced growth, the concept of borrowed size is an appealing. It offers some theoretical justification of striving for polycentric developments. If borrowing size from neighboring cities worked (Camagni et al., 2015 provide some empirical evidence for this), this would mean that striving for a polycentric urban spatial structure was economically reasonable. Cities could gain from other cities being located in their neighborhood as their inhabitants "can use the shopping and entertainment facilities of other cities to complement their own, their businessmen can share such facilities as warehousing and business services, and their labor markets enjoy a wider and more flexible range of demand and supply" (Alonso, 1973: 200). In other words, cities in a polycentric urban region can benefit from agglomeration economies without suffering from agglomeration diseconomies that would occur in a similar-sized monocentric urban region.

II.2.2.1 National and supra-national policies

In most political or strategic documents it is assumed that polycentricity is something desirable. Examples are European policies regarding territorial cohesion and balanced development, especially the ESDP (e.g., European Commission, 1999; Nordregio, 2007; also Davoudi, 2003: 988f. for an overview). According to EU policies polycentricity is a feasible urban spatial structure to establish both

[21] CPT – Central Place Theory.

territorial cohesion and competitiveness in Europe. These policies' goals are not only argued with sustainable development "by strengthening economic and social cohesion" (European Commission, 1999: 10), but it is also expected that a "balanced urban system" (European Commission, 1999: 19) in the sense of a polycentric urban spatial structure is the means of choice to overcome the urban-rural divide. Evidence for this positive assessment of polycentricity is presented in Arribas-Bel and Sanz-Gracia (2014) who consider US metro areas over a time span of 20 years. Cavailhès et al. (2007: 402) conclude their contribution on trade and city structure saying that it pays off to promote the development of smaller cities within a city region (secondary business districts as they call it) in terms of pushing/pulling KIBS to these places to ultimately attract both employees and residents to these places. Counter-evidence is, however, provided by Brezzi and Veneri (2015) who show that a polycentric urban configuration is not necessarily associated with higher economic success. Moreover, they identify cases in which multi-core urban spatial structure even worsens economic development. Burger et al. (2015) and Meijers (2008b) find similar evidence. Consequently, political goals and economic sense can but not necessarily do coincide.

As a result of these documents, polycentricity is politically fostered and manifests spatially, probably after some time. However, this spatial manifestation is not a direct effect from European policies but essentially the physical consequence of national and regional planning policies. With regard to zoning, for example, issues are that urban development is not permitted everywhere for any kind of intended land use at any desired intensity. In turn, certain sites can be designated to take pressure (e.g., overcrowding, excessive rents) from the core cities, thus called relief sites or sometimes edge cities – urban subcenters (see Sec. II.1.1)

Empirical evidence of planned polycentricity has been presented by Sorensen (2001) who analyzed the Tokyo metro area. He concludes that it "is not clear that this outcome is a result of planning policy, however, as a significant number of other centres are growing at the same rate as the most successful designated subcentres, and many of the designated subcentres show only moderate growth" (Sorensen, 2001: 29). Carruthers (2002: 393) provides a rather conceptual paper in which he remarks that planning policies are not necessarily efficient if there is rather competition among jurisdictions than cooperation. Moreover, unintended 'leap-frogging' effects due to urban containment policies, however, might trigger inter-urban or intra-regional polycentric developments.

Other planning documents referring to both regional and local levels address urban growth management. One example are greenbelts as a means to avoid neighboring city or metro regions to merge into each other (see Siedentop et al., 2016a with further references). With regard to the polycentricity issue one could think of inter-urban polycentricity (see Sec. II.3.3 for the definition) as one outcome of greenbelt designations as these prevent cities from merging into each other and thus into a large-scale dense urban fabric. Referring to the Ruhr area, which was one of the first areas implementing greenbelt designations, this conclusion seems reasonable: the area is one renowned example of inter-urban polycentricity (Münter et al., 2016: 22).

Further development schemes exist that are, at times, beyond the spatial planning departments but that have spatial impact. One example for such schemes are structural policies such as the European Regional Development Fund or the joint scheme for improving regional economic structures (“Gemeinschaftsaufgabe ‘Verbesserung der regionalen Wirtschaftsstruktur’”) (Mackrodt and Lerch, 2017). These schemes can be used for infrastructure investments thus enhancing a region’s accessibility, which – according to distance as a main explanatory variable or urban densities – should have positive effects (e.g., creating or re-allocating jobs), provided that density does not get too high and diseconomies prevail.

Yet, the outcome of planning policies and spatially effective funding schemes is controversial regarding both actively fostering polycentricity at certain scales or trying to preserve open spaces and compact cities by urban intensification. Likewise, it has not been resolved yet whether polycentricity is desirable from a social, economic or environmental point of view. Similarly, it is not clear whether a polycentric urban spatial structure is more energy efficient due to its potentials of reducing traffic demand. Both the conceptual fuzziness especially of polycentricity and the disagreement regarding its analytical identification and evaluation do not contribute to an objectification of the drafted ‘desirability-debate’ outlined above.

II.2.2.2 The assignment of central places

The assignment of central places has a long tradition in both spatial planning and regional science. The theory was formalized by Christaller in 1933, refined by Lösch in 1940 and later adopted in the NEG. The idea of Christaller (1933) is to have a set of different goods that are supplied over a certain geographical area with each good having its particular market size. The more ‘standard’ a good is the smaller is its market area (e.g., daily groceries) and the more specialized a good is (e.g., tertiary education) the larger is that good’s catchment area. Places offering specialized goods, however, also offer the goods of all hierarchy levels below. Thus, hierarchies emerge in the sense that the lower-ranked a place is the fewer goods it supplies (see e.g., Mulligan et al., 2012 or Partridge et al., 2009 for descriptions). In the Christallerian scheme, hexagonal market areas of different hierarchy levels emerge with similar level market areas not overlapping each other. Lösch (1940) relaxes these assumptions by introducing a continuum of goods thus permitting market areas of any size. The NEG adopted the rationales of population sizes and geographic market sizes but remained largely a-spatial.

From the planning perspective, the assignment of central places is still in practice: due to the German Spatial Planning Act (particularly § 2 Abs. 2 Nr. 2 ROG), each federal state has to consider a system of central places which are further clarified in both the statewide development plan (“Landesentwicklungsplan”) and in the corresponding regional development plans (“Regionalpläne”). Thus, a multicentric urban spatial configuration is legally mandatory. Referring to regional development plans, most federal states have established at least the distinction between regional centers

("Oberzentren"), medium sized centers ("Mittelzentren"), small centers ("Klein- or Unterzentren") and places not assigned any central function.[22] Based on these designations some inter-urban polycentricity is established by legal means. However, these 'centers' are assigned at the level of municipalities, whereas subcenter formation is analyzed on the grid level here. The issue regarding polycentricity thus is to understand to what extent legally binding central place designations are actually reflected by employee and built-up volume densifications. Moreover, former medium sized centers might grow into the role of regional center's competitors thus transforming a once core city dominated region into an intra-regional polycentric spatial entity. The line of arguments behind this process could be the following: the regional centers suffer from congestion effects such as high rents and overcrowding. Thus, relief sites, which may be both established, less congested medium sized centers and newly developed sites ('edge cities'), gain attraction and pull employees from the core. As a result, new densifications of KIBS employees emerge or grow – after some time probably into core city competitors.[23]

II.2.2.3 Density as a central measure in spatial planning[24]

The concept of density is an established means in spatial planning and amongst others referred to in the Federal Land Use Ordinance. Density generally describes the number of objects per reference area. Although the concept thus seems easy to understand and ready to use, it is quite complex and analytically challenging. We draft these difficulties both in Fina et al. (2014) and in Siedentop et al. (2014) and we systematically analyze the concept of urban density in Krehl et al. (2016). Core issues are that density is not uniquely defined: there are gross versus net conceptualizations, there are economic (activity) densities, residential and built densities, there are densities referring to use intensities, there is no agreement on the appropriate spatial scale or reference area.

As we outline it in Krehl et al. (2016: 3) density is thus not only challenging from an analytical point of view but also from a normative perspective. One example for the normative side of urban density is an ongoing debate about appropriate densities. The advantages of high urban densities go with aspects of lower energy consumption in higher densified areas; higher economic prosperity; or higher cost efficiency of infrastructure. The disadvantages, in contrast, are associated with several congestion costs, such as traffic congestion or higher rents; heat vulnerability, which refers to higher morbidity and mortality among certain groups of residents, for example; or further health risks due to unfavorable microclimatic conditions. It is furthermore notable that especially high residential densi-

[22] These center types may differ among the federal states as some states additionally permit to mix different types.

[23] It is under some debate whether people follow jobs as this line of argumentation suggests or if the causality is reversed, that is, jobs follow people. Addressing this question, however, is beyond this dissertation's scope.

[24] This section paraphrases the conceptual part of Krehl et al. (2016). Thus, I only provide references if the information is not taken from Krehl et al. (2016).

ties are socially rather unwanted in Germany, despite planners' efforts towards urban intensifications to reduce land consumption (and/or to utilize brownfield sites) and indications of – not unambiguously – positive sides of higher densities.

Referring to the German Federal Land Use Ordinance, maximum densities vary greatly: Whereas the floor area ratio (FAR) may be up to 3.0 in core areas, areas for residential use are only permitted FARs of 1.2. Combining these maximum densities with the corresponding maximum site coverages, ranging between 0.4 for residential areas and 1.0 for core areas permits a rough understanding of the diverging legally permitted densities within a city. We have evaluated the extent of over- and underuse of these figures for the city of Cologne in Fina et al. (2014: 191f.) finding a massive underuse of all types of use for the entire city except for core and mixed use areas in downtown Cologne. One might consider this finding empirical evidence of socially undesired high urban densities. However, these figures also show that exceptions from the Federal Land Use Ordinance are possible – an issue that might explain some of the empirical results shown in Section IV.

From an analytical point of view, densities can be distinguished by the type of activity that is addressed, such as employees, residents, built area or built-up volume to name the most common types of interest. What is more ambiguous, however, is the distinction between gross and net densities. Whereas there is no ambiguity regarding the concept itself (i.e., objects per area), it is often not clear what kind of density is addressed. Gross densities are individuals per area of land, no matter whether the land is developed or not. Net densities, in contrast, relate the number of individuals to the actually relevant area, such as the number of employees per area of developed land excluding streets, local community services and public open spaces (see Krehl et al., 2016: 4). Thus, net densities are more precise regarding the actual intensity of use of an area[25]. Likewise, they are less prone to MAUP-related (MAUP – Modifiable Areal Unit Problem) issues as we have highlighted in Fina et al. (2014: 182f.).

Another, yet less precise, way to mitigate the MAUP is using gross densities based on a regular grid such as INSPIRE (Infrastructure for Spatial Information in the European Community). In contrast to standard municipality data all INSPIRE grid cells are of similar shape and size – rectangular 1 km² grid cells here. Thus, all reference areas are identical and the corresponding gross densities more comparable among each other and among different city regions than gross densities based on municipalities as reference areas. I have analyzed this issue in Krehl (2015a) showing that MAUP still is an issue in itself. As the main part of my work, however, is conducted on the spatial level of grid cells, the MAUP does not play a substantial role in the cross-regional interpretations. Referring to the analyses for the city of Cologne, the differences between gross and net densities should be higher the further away a grid cell is located from the regional center.

[25] A discussion of gross versus net densities and their suitability for different kind of analyses is provided in Section IV.1.2 as this is one of the main results obtained in Krehl et al. (2016).

As a result, it can be concluded that density is a highly complex measure, which desires thorough definitions to provide reliable and interregional or international comparative results. If that is granted, it can fruitfully be implemented in urban and regional research.

II.3 Conceptualizations of urban spatial structure

The term *urban spatial structure* generally refers to the organization of activity within a given territory (Garcia-López, 2010: 119). Within this territory, activity can be either place-based such as the distribution of employees, firms, residents, built-up volume and so on, or it can be flow-based such as origin-destination relations of commuters, goods, services or information. The relation between the morphological notions of urban spatial structure and polycentricity is amongst others stated by Garcia-López and Muñiz (2013: 515) saying that "urban spatial structure is the degree of spatial concentration of the population and employment and their spatial distribution in the metropolitan space". Thus, urban spatial structure is the morphological form and polycentricity is one key term to describe it. Polycentricity as well as monocentricity and dispersion are those terms that characterize the most prominent configurations of urban spatial structure.

The term *monocentricity* is used to describe urban spatial configurations which show a clear hierarchy between centers and subcenters. This hierarchical organization implies that a distinct urban center – typically located in the regional core city's CBD – is surrounded by a clearly subordinate hinterland. However, it is not trivial to distinguish monocentricity from polycentricity as the one might easily look like the other one if a different spatial scale is considered. Moreover, it is not clear to which account the core city primacy must exist or how to measure it.

Dispersion refers to a situation of balanced distribution of economic activity in the NEG. Economists often take a normative perspective towards dispersion, whereas planners rather use the term descriptively (see Anas, 2012: 124). Thus, dispersion refers to a region's spatial configuration that is characterized by an urban fabric that is equally spread across the region.[26] However, to what extent activity (i.e., employees, residents, firms etc.) must be spread within a region to call it dispersed is not defined. Similarly, no agreement has been reached regarding upper or lower bounds of average densities that a region must score to be considered dispersed. Although the urban fabric's density is not agreed upon, economists tend to argue that it is below its optimal level thus inducing excessive land use (Anas, 2012: 124).

Polycentricity is used both as an analytical and a political-normative concept. Though originating from an analytical background, the term has been adopted in planning documents and strategies, particularly in EU policies on territorial cohesion and competitiveness as well as balanced development (Davoudi, 2003; Faludi, 2006; Waterhout et al., 2005, also European Commission, 1999).

[26] Dispersion is not similar to poly- or multicentricity as its main characteristic is the lack of one or more explicit (sub-) centers. Still, sprawl is sometimes used in the literature to describe polycentric spatial patterns.

Thus, analytical understandings are complemented by normative assessments leading to a situation in which “the concept is not supported by clear definition, a robust theoretical framework and rigorous empirical analysis” (Davoudi, 2003: 979). One example regarding the analytical aspect can be found in Sarzynski et al. (2005: 5), who explain that a “metropolitan area is polycentric to the extent that two or more separate and distinct centers of employment contain a significant amount of the area’s total employment, and the ratio of employment in the core center to employment in all other centers is low”. This is an appealing, easy to understand description but does not reveal anything of how to consistently analyze a region and when to ‘label’ it polycentric (for the definition of polycentricity in this dissertation, see Sec. III.1).

Thus, the challenge is not only to explain these urban configurations at least in relation to each other but also to quantitatively operationalize their qualitative descriptions. Referring to Duranton and Puga’s (2015: 545) statement that spatial patterns are more complex than a binary dichotomy, the latter issue is not solved easily. However, this dissertation will show that the combination of different means of analysis and a subsequent synoptic comparison contributes to a quantitative, fairly objective and interregional comparative assessment of several study regions’ urban spatial structure.

II.3.1 Facets of polycentricity

Due to a variegated or even fuzzy conceptualization of polycentricity in the literature (see Veneri and Burgalassi, 2012), it is worthwhile to have a closer look at polycentricity and its facets. The most essential distinction is between the analytical conceptualization of polycentricity and its normative connotation, especially in European politics.[27] Although the latter it is not considered in this dissertation, it will be briefly outlined to clarify the conceptual fuzziness of polycentricity.

The analytical notions of polycentricity can be divided into a morphological, a functional and an integrated perspective. The morphological perspective of urban spatial structure refers to a place- or location-based notion: it is considered where in a region socioeconomic activity actually culminates. In that sense, the morphological perspective is static but it can easily be extended to be quasi-dynamic if time-series are analyzed instead of cross-sectional data. Issues that fall into the morphological notion of polycentricity are amongst others the number, size and location of urban centers and subcenters.

Further analytical notions of polycentricity are a functional and an integrated understanding. For the sake of completeness, these notions will be briefly outlined although they are not considered empirically in this dissertation. The functional perspective refers to flows of people, goods, or ser-

[27] Münter et al. (2016) furthermore suggest distinguishing five dimensions: morphological, functional, symbolic, spatial development, and political/normative. The first, second and in part also the fourth dimension can be summarized as essentially analytic, whereas the third and fifth dimension are rather normative in the sense of infeasible to be analyzed quantitatively.

vices (see Green, 2007; Vasanen, 2013).[28] Proxies to tangibly measure these flows are, for example, infrastructure networks (see Giffinger and Suitner, 2015) and commuter matrices, standard input-output tables as well as further trade data (see Burger et al., 2011; Cats et al., 2015; Hanssens et al., 2014; Vasanen, 2013; Zhong et al., 2017).

An integrated perspective aims to jointly analyzing morphological and functional polycentricity. Its origin is the criticism that urban form and functional connections between settlement areas cannot be considered separately. Burger et al. (2011) and Burger and Meijers (2012: 1128) suggest conflating these mostly separately considered facets of polycentricity. They furthermore argue that urban form is a result of functional relations such as commuter flows between centers (Burger and Meijers, 2012: 1133f.). For that morphological and functional polycentricity are not mutually exclusive but two sides of a coin. Giffinger and Suitner (2015: 1175) agree saying that "polycentric structures in terms of morphology are the material outcome of functionally intense, longterm relations, and that these functional ties are often dependent enough on earlier strategic polycentric endeavors regulating or facilitating these functional ties". Some suggestions how to operationalize a rather integrated perspective have also been made by Burgalassi (2010: 19f.).

The strategic perspective introduced by Giffinger and Suitner refers to the political dimension of polycentricity. It particularly is about different planning actions regarding strategic developments of an urbanized area. These actions do not only cover planning documents but also the process of networking among stakeholders and the exchange of ideas among municipalities (Giffinger and Suitner, 2015: 1174). Last but not least, polycentricity also has an implicitly normative connotation as especially highlighted by the ESDP. As explained in the beginning of Section II.2.2, a polycentric urban spatial structure is often referred to as 'good' suggesting that it is desirable and should be supported to realize its putative welfare gains. As a result, the political facet of polycentricity is tightly linked to a normative assessment of the same.

II.3.2 On the means of identification

According to the research questions stated in the Section I.2, this dissertation only considers analytical aspects of morphological polycentricity. Thus, I only cover means of identification feasible to cover these issues. An initial conceptual and methodological overview is provided in Siedentop et al. (2016b)[29]. First, we discuss studies of urban spatial structure regarding the distribution of employees

[28] In the European context the phrase *relational polycentricity* is also used to address flows between cores (see ESPON, 2012: executive summary)

[29] A technical note: We wrote this book section in spring 2013. Thus, it served as a stock-taking regarding both the current state of urban spatial structure in Germany and the compilation and classification of means of analysis. Due to external delays in the book publication, we updated the book section in summer 2015 to cover more recent literature. By that point in time, subsequent contributions such as Krehl (2015a) and Krehl (2015b) had already been published.

and its change over time. Second, we highlight the intra-municipality distribution of employees in the Stuttgart region. Third, we introduce the most commonly used means of analysis regarding polycentricity.

Our main finding in Siedentop et al. (2016b) is a distinction between global and local measures. Global measures reveal information about a region's degree of (spatial) concentration. There is one global measure per study region, in other words: a global measure yields one value per study region. Examples are the global Moran's I or a Gini coefficient. If each entity that is part of the region is assigned a separate value, the measure is called local. Thus, local measures are feasible to reveal the locations of spatial densification. This global/local-distinction is revisited in Krehl (2015b) where I calculate global and corresponding local measures to assess a region's polycentricity degree.

I complement the methodological overview in Siedentop et al. (2016b) with a conceptually different one outlined in Krehl (2016). The idea in that paper was to elaborate several methods' peculiarities and to discuss their strengths and weaknesses. So, I distinguish between three basic types: first, I discuss normative or threshold based methods such as the definition of minimum densities. These means' strengths is a comparatively easy implementation but their weakness is the arbitrariness any threshold incorporates (Krehl, 2016: 4). The second type of methods is exploratory. These methods' objective is to visualize patterns without delivering any causal explanation for the obtained result. Examples are box plots as well as all measures belonging to the family of exploratory spatial data analysis such as the global and local Moran's I (Krehl, 2016: 5). Regression-based methods are the third type that I have identified. As opposed to the means introduced before, this type is based on theoretical considerations thus permitting hypothesis testing. A (sub-) type are semi-parametric analyses such as the geographically or the locally weighted regression. These are essentially regression- and thus theory-based but still contain non-parametric, exploratory elements (Krehl, 2016: 5). An example for each methodology type has been applied in at least one of my publications (Sec. IV), which jointly establish this dissertation's empirical core.

II.3.3 On the spatial scale

It is agreed that polycentricity implies that a region has more than one core or center. The notion of a core and how to define it, however, is far from being decided. Thus, it is straightforward to find that, "the term 'polycentric' is used as a shorthand means of describing a region that is not 'monocentric', that is, not excessively dominated by a particular centre" (Parr, 2014: 1928 (1936)). Similarly, a region might be dispersed on a very large spatial scale, polycentric on a smaller one and monocentric on a very fine spatial scale. Against that background, it is not surprising to find statements such as "poly-

My contributions to Siedentop et al. (2016b) were *(i)* the literature review of the state-of-the-art regarding polycentricity, *(ii)* the methodological design and calculation of all Local Indicators of Spatial Association (LISA) as well as the interpretation of the results, and *(iii)* the calculation and interpretation of all values referring to the spatial level of grid cells.

centricity is fully consistent with monocentricity applied locally" (Agarwal et al., 2012: 440), an issue which has been described and analyzed in Siedentop et al. (2016b: 68f.) for both the region and the municipality of Stuttgart.

So, what is the appropriate spatial scale if there is one after all? A fairly common distinction is provided by Davoudi (2003) who separates the *intra-urban* from the *inter-urban* and the *inter-regional* spatial scale. The first one, *intra-urban*, seeks to identify densifications, that is, centers and subcenters, within a city or municipality; the second one, *inter-urban*, refers to a region which is characterized by once separate and spatially distinct cities; the third one, *inter-regional*, considers regions that have started to merge into each other forming large-size urbanized areas such as the 'BosWash' area described by Gottmann (1957) covering the entire strip from Boston, MA in the north to Washington, D.C. in the south. Similar but geographically much smaller European examples are the Dutch Randstad or the Ruhr Area in western Germany (see Hall, 2009: 806 for a conceptualization, a few US-American, Asian and European examples as well as further references).

Additionally, my work covers the *intra-regional* scale. This spatial scale addresses a city region, that is, a city plus its functionally related hinterland. The intra-regional scale is distinguished from the inter-urban scale by the trajectories the respective city region follows. If a region is considered intra-regional polycentric, it has once been monocentric but successively transformed into a polycentric region by the growth of formerly small cities into core city-competitive subcenters.

Brezzi and Veneri (2015: 1131) furthermore suggest covering a national scale to consider several city regions. The issue on this spatial scale is to see whether a country is organized in a centralistic manner such as Norway or France or whether it rather has a 'balanced' distribution of urbanized areas. The national scale in European countries, however, can be similar to the inter-regional scale in land-rich countries such as the US.[30] Referring to the potential geographical sizes, the following ranking from small to large could be established, with overlaps between the second and third as well as between the fourth and fifth 'category': intra-urban → intra-regional → inter-urban → inter-regional → (supra-) national. The spatial scales reslevant to this dissertation are the intra-urban, the intra-regional and the inter-urban scale.

III DATA, DEFINITIONS AND THE STUDY REGIONS

As outlined above, I address urban spatial structure in its *morphological* dimension, that is, I look at spatial densifications at certain locations within functional regions (see Sec. III.2 for details regarding functional regions). Furthermore, I use a *quantitative-analytical* approach, but I neither judge the identified morphological patterns nor will I discuss the advantages and disadvantages of concentrated versus dispersed urban spatial structure (see Sec. I.2). Of course, these aspects are not irrelevant but

[30] The 'BosWash' area for example covers about 40% of the area of entire Germany and stretches about 750 km in North-South direction.

the data available do not permit such analyses and the focus of this dissertation is oriented to identifying and understanding the spatial patterns.

III.1 Definitions

Except for the distinction of polycentricity from multicentricity, the following definitions are applied in all publications included in this dissertation. Slight distractions, however, could not be avoided due to the dissertation's cumulative nature. Some notions and definitions have been clarified in the process of working on the separate papers and thus vary between earlier and later contributions.

The first central term in this work is *urban spatial structure***.** It is defined as "the way in which a metropolitan city is organized in a territory" (Garcia-López, 2010: 119), especially with regard to "the degree of spatial concentration of […] employment and their spatial distribution in the metropolitan space" (Garcia-López and Muñiz, 2013: 515).

Polycentricity – actually the most important technical term here – is one potential manifestation of urban spatial structure. Technically, polycentricity is "about the balance in the size distribution" (Meijers and Burger, 2010: 1387; see also Parr, 2014: 1927; Veneri and Burgalassi, 2012: 1020). Thus, my definition of polycentricity is oriented towards these statements. Precisely: a region is considered polycentric if and only if it has more than one densification and if all densifications additionally are of roughly equal size and relevance. Since 'roughly equal' is not analytically clear, I furthermore use multicentricity and core city dominance to specify more accurately what 'roughly equal' does not mean.

Multicentricity is conceptually similar to polycentricity and often used synonymously. In this work, multicentricity describes a region that has more than one spatial densification but these densifications are not equal in size and/or relevance, that is, the spatial pattern is not polycentric according to the definition above. A multicentric region is characterized by a dominating core which is complemented by a number of smaller and therefore less important (sub-) urban densifications. This spatial configuration has been referred to as *core city dominance* in some publications. However, as a monocentric region is also dominated by the core city, the term multicentricity addresses configurations with substantial densifications outside the core city.

For that, *monocentricity* and core city dominance are not the same. A monocentric city region is characterized by one outstanding spatial densification usually located in the core city and urban densities monotonically decline from the regional core to the periphery – a pattern similar to the standard gradient model by Alonso.

If poly- or multicentricity is addressed, it is almost inevitable to use the terms center and subcenter. The *center* describes the (historic) core or downtown area of the core city. It is mostly characterized by the highest densities within the entire region. A *subcenter*, in contrast, is an urban spatial densification less relevant than a center. This relevance may be in terms of size (area), density or both.

It is, furthermore, located outside the traditional CBD of the predefined core city. Thus, subcenters are usually younger, that is, emerged later than centers. Whereas the understanding of a center is comparatively clear being the most important area in its region, the notion of a subcenter is dependent on the methodology to analyze urban spatial structure as Section IV will show. Moreover, the discussion of edge cities in Section II.1.1 has revealed that subcenters also differ between Europe and the US.

III.2 Choice and delineation of the study regions

The choice of the study regions is based on a most similar systems design (MSSD). A MSSD implies that within a corridor of similarities, such regions are chosen that differ in the outcome of interest (de Vaus, 2008; Pierre, 2005; Yin, 2009). In this dissertation's case the regions should be as similar as possible in all contextual issues but differ in their respective polycentricity degree. The polycentricity degree has a priori been operationalized by the number of core cities within each region. A core city is defined in accordance with the definition of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR, 2012b) saying that "[c]ore cities have more than 100 000 inhabitants and an incommuter-outcommuter relation greater than 1" (Krehl, 2016: 11). Mostly for economic (i.e., DFG funding-based) reasons the number of study regions was set to four. The sample should include a monocentric and a polycentric region as well as two regions with ex ante less clear-cut patterns. Thus, the regions of choice were Frankfurt, Cologne, Munich and Stuttgart having the following a priori assumed characteristics:

- Frankfurt: four core cities, inter-urban polycentric by definition (see Sec. II.3.3)
- Cologne: two core cities, bipolar structure, if polycentric then inter-urban
- Munich: one core city, monocentric, if polycentric then intra-regional as defined in Section II.3.3
- Stuttgart: one core city but several medium sized cities in the region, polycentric or according to local knowledge probably dispersed, if polycentric then intra-urban (see Sec. II.3.3)

These study regions have been delineated based on regional labor markets ("Arbeitsmarktregionen") and metropolitan areas ("Großstadtregionen"), which are defined by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR, 2012a; BBSR, 2012b). These area types are spatially overlaid (see Figure 3). Considering only labor market areas was discarded as they were too large[31] in geographical size and capturing too many sparsely populated areas. So, combining them with the metropolitan areas was consequential. The rationale to combine regional labor

[31] With regard to the financial constraints in the DFG project.

markets and metropolitan areas was to still maintain a daily urban system and to best possibly ensure that the regions under consideration are actually functional regions.[32]

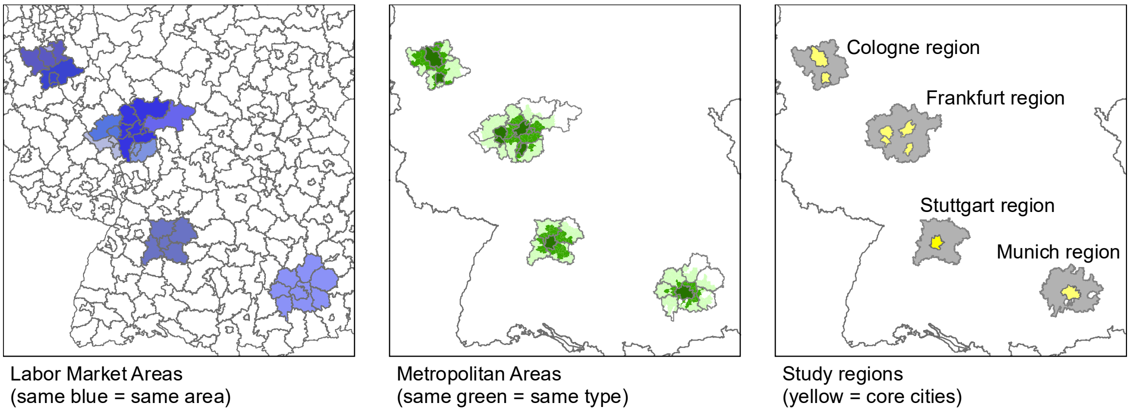

Figure 3: Regions' delineations based on regional labor markets and metropolitan areas

We finally included those municipalities into the sample that are covered by both area types and furthermore located in the metropolitan area's core ("Zentrum einer Großstadtregion"), its supplementary area ("Ergänzungsgebiet") or its closer commuting area ("engerer Pendlerverflechtungsraum"). These spatial limitations were made for economic reasons only: In the DFG project's beginning it seemed necessary to buy expensive high-resolution data to obtain the built-up volumes from. Thus, the study areas had to be as small as reasonably possible for which the wider commuting area ("weiterer Pendlerverflechtungsraum") has been cut off. The wider commuting area is quite rural, so we plausibly assume that substantial urban spatial densifications are not located there. Thus, we consider the omission of the wider commuting area as unproblematic regarding the validity of our expected results regarding the polycentricity of the study regions. Table 2 provides an overview of the final study regions' main characteristics.

Within these city regions all analyses are conducted on the spatial scale of 1 km² grid cells located in accordance with the European grid INSPIRE. Using the spatial level of grid cells has several advantages: *(i)* political considerations and administrative trajectories resulting in varying municipality sizes in different federal states are mitigated. *(ii)* The notion of absolute numbers (i.e., employees per spatial entity) and densities (i.e., employees per km²) is identical thus allowing comparisons of the results among all study regions. *(iii)* The analyses could easily be expanded to entire Germany or Eu-

[32] Debates about the issue how to delineate a region have been ongoing since decades. The regions used here are functional regions roughly reflecting a daily urban system. However, there are several, also conceptually contradictory ways of delineating a region, apart from discussions of what is a region. Examples for other approaches to regions' delineations than functional regions are *(i)* administrative entities, such as municipalities; *(ii)* planning regions and 'Raumordnungsregionen'; *(iii)* regions based on internal homogeneity and external heterogeneity, that is, statistically-based results (e.g. Krehl and Rusche, 2014). Another, less analytical means of delineation is to consider living environments in the widest sense (e.g., "Designerregionen", Weichhart, 2000). Regions, thus, can also be essentially delineated based on certain attributions by different stakeholders and, similarly, region building can also take place on a discursive level (see amongst others, Balke and Reimer, 2016).

rope if the data were available because overlaps or holes are avoided due to the coordinated European grid. A minor issue, finally, is that a decision on the grid's location, which might have altered the empirical results, became obsolete.

Table 2: Overview of the study regions' main characteristics

	Frankfurt region	Cologne region	Munich region	Stuttgart region
Area (km²)	4 843	2 812	3 277	2 842
Number of core cities	4	2	1	1
Employees (million, 2009)	1.06	0.80	0.79	0.77
Residents (million, 2011)	3.51	2.77	2.41	2.35
Grid cells containing employees	2 914	2 293	2 462	2 029
Number of censored grid cells	774	481	923	596
Share of censored grid cells (%)	26.6	21.0	37.5	28.0
Share of employees 'lost' due to censoring (%)[i]	0.7	0.5	1.0	0.7
Censoring for dominance reasons[i]				
Number of grid cells[ii]	0	1	6	3
Number of employees 'lost'[ii]	0	64	7 411	5 184
Average employee density	363	351	320	378
Median employee density	142.5	117	41	147
Average employee density, censored grid cells excluded	494	444	512	535
Median employee density, censored grid cells excluded	288	214	151	337
Average distance to … in km				
(main) CBD	32.80	26.44	26.76	25.78
Next highway entrance ramp	7.78	5.73	7.97	11.94
Next main station	15.69	15.18	21.50	14.81
Next international airport	31.88	27.01	39.20	30.67
Built-up volume (million m³)	1 028.53	1 158.90	942.26	658.96
Built area in 1970 (km²)	570.95	449.50	351.73	338.21
Built area in 2010 (km²)	655.95	488.78	395.44	405.23

[i] Numbers provided by the RDC.
[ii] Information on these grid cells' location unavailable.

(Source: own compilation based on Krehl, 2016: 10 and further unpublished material)

III.3 Data basis

According to the cumulative nature of this dissertation each paper contains its own section discussing the data applied as well as its advantages and limitations. Nevertheless, I introduce all data used in the entire dissertation in a joint section to provide an overview and to discuss the data's strengths and weaknesses right from the beginning. Some repetitions thus might occur in later sections when summarizing the separate papers.

III.3.1 Employees subject to social insurance[33]

Centers and subcenters in the sense of (sub-) urban densifications of employees have been considered using a unique data set obtained from the Research Data Centre of the Federal Employment Agency at the Institute for Employment Research (RDC). The data set is called georeferenced Integrated Employment Biographies (georeferenced IEB) and has been compiled at the RDC[34]. These data are as of 30 June 2009 and have originally been individual point data. For that and due to German privacy laws, neither the entire data set was accessible nor could the raw data be obtained. Thus, RDC members aggregated the point data into the INSPIRE grid cells. Thus, instead of point data I had to work with data on a regular grid. As the grid cell size is 1 km² all employee data are simultaneously employee densities.

Due to German privacy laws, all grid cells had to be censored that met one of the following requirements: less than three employees belonging to less than three firms (‘minimum case’) or one firm accounting for more than 50% or – depending on the number of firms in the respective grid cell – 85% of all employees (‘dominance case’) (see Bundesagentur für Arbeit, 2014: 5–9 for details). To avoid losing these censored grid cells I set each of them to one, that is, I assigned it one employee knowing that this procedure might induce a severe downward bias in the cases of censoring for dominance reasons. A downward bias in minimum case-censorship has not been considered a problem here because the objective is to identify urban centers and subcenters. Grid cells censored due to too few observations will hardly be a center. Still, I conducted some quantitative analyses to understand the problem: the censored cells only contain 0.5-1.0% of all employees in each study region (Krehl, 2015b: 294). Table 2 furthermore clarifies the magnitude of the dominance case censoring, which in fact hardly occurs and thus is neglected here. It might be argued that these ‘subsets’ of all employees (e.g., self-employed persons are not captured) and the censoring spoil the validity of the analyses. An imputation of employees not subject to social insurance and rescaling them into grid cells would theoretically validate the comprehensive database but would not necessarily increase the quality of the analyses. One example is that it would not be clear anymore whether over- or underestimation of employees per grid cell was present.

A further subset of all employees subject to social insurance is used here covers employees in higher-order service sector only. These are registered in sections J-N or S according to the Classification of Economic Activities, issue 2008 (WZ 2008). Regarding the censoring, these employees are more severely affected than all employees because they are fewer and thus censoring occurs more

[33] This section is a paraphrased, partially supplemented version of the descriptions originally published in Krehl (2015b: 293f.).

[34] For details regarding the RDC and the project, which we were not involved in, see http://fdz.iab.de/292/section.aspx/Projektdetails/k110803304 (12/14/16). See Scholz et al. (2012) for details regarding the georeferenced IEB.

frequently. However, the number and shares lost are still low: 2.0-3.0% of employees in higher-order service sectors are missing in the used data file.

III.3.2 Built-up volume and floor space

According to the multidimensional notion of urban spatial structure (see Sec. I.2), I do not only consider employee density but also built densities, such as built-up volume density and floor area ratio. Data on built environment has been obtained from The German Remote Sensing Data Center, where they have been processed in the course of the DFG project. The data mostly applied in the journal papers originate from satellite-borne data, precisely: stereo images (see Wurm et al., 2014 for technical details regarding data generation). A brief description of the data generation is also provided in Krehl et al. (2016: 6) stating that the building model is the result of combining height data obtained from Cartosat-1 with building footprints and normalizing these data with a digital terrain model. The normalization means to correct the surface model obtained from Cartosat-1 data for ground level elevation. After several performance analyses to ensure sufficient data quality, building footprints and building height could be derived. Combining these two measures permits the analysis of built density measures.

An additional estimation of the number of floors per building furthermore allows the analysis for FARs on the level of individual buildings. However, we do not exploit this very fine-grained building specific level but aggregate these numbers into 1 km² grid cells (INSPIRE grid) to harmonize the spatial entities between built density and activity density measures.[35] It should be noted that the FAR represents a net density, implying that the reference area, that is, each grid cell, is reduced to its built area by excluding vegetation areas and land used for transportation.

Finally, these building models have been aggregated into the 1 km² grid cells to obtain values for built-up volume per grid cell (m³ per m²) and floor area ratio (FAR, measured in m² per m²). If a building crossed the border of two neighboring grid cells, only the built-up volume of the respective part of the building is considered (Krehl et al., 2016: 9).

IV PUBLICATION-BASED EMPIRICAL FINDINGS

IV.1 Thoughts on socioeconomics, remote sensing and the concept of urban density

To start the analysis of urban spatial structure and polycentricity in the four study regions the data integration potentials are investigated and first density considerations are made. Data integration potential refers to the opportunities and limitations of a joint consideration of employees on the one hand

[35] Aggregation was also due to the DFG project setting as most analyses have been carried out on this spatial scale. Thus, comparisons between the findings in all papers are meaningful, too.

and built-up volume and floor space on the other hand. Density considerations primarily refer to 'getting to know the data' and obtaining a first idea of fine-grained spatial patterns in each study region. According to the DFG project's initial objective, built-up volumes are considered a valid proxy for economic activity and, hence, the identification of (sub-) urban densifications in a city region. The validity assumption is – as far as the data permit it – set on trial in two publications (Krehl, 2015a; Krehl, 2015b).

Combining these data sources is innovative not only in the German context but also from a more international point of view as the subsequently presented papers will amongst others show. The following papers, thus, cast light on intra-municipality distributions of employees and their resemblance in urban form.

IV.1.1 Getting Closer! New Ways of Integrating Geodata, Statistics and Remote Sensing to Analyze and Visualize Urban Structures Using Density Surfaces and -Profiles

This paper discusses the seeming objectivity and comparability of 'density' as a measure of choice in urban and regional research. Against a backdrop of conceptual issues, this discussion is held and clarified by integrating geo and socioeconomic data for the city of Cologne. The city of Cologne is analyzed here because reference data necessary for the first steps in processing the remote sensing data have been available for this city only.[36]

Fina et al. (2014)

Fina S, Krehl A, Siedentop S, Taubenböck H and Wurm M (2014) Dichter dran! Neue Möglichkeiten der Vernetzung von Geobasis-, Statistik- und Erdbeobachtungsdaten zur räumlichen Analyse und Visualisierung von Stadtstrukturen mit Dichteoberflächen und -profilen. [Getting Closer! New Ways of Integrating Geodata, Statistics and Remote Sensing to Analyze and Visualize Urban Structures Using Density Surfaces and – Profiles] *Raumforschung und Raumordnung* 72(3): 179–194. doi:10.1007/s13147-014-0279-6

Contribution of Angelika Krehl:

- Section 4.3 ("Analyse von städtischen Zentrenstrukturen", that is, analysis of spatial patterns of urban centers): Design, calculation and interpretation of the Local Indicators of Spatial Association (LISA).
- Comments and feedback on the other sections.

Publication date: 28 March 2014

We discuss the normative and descriptive nature of 'density' in the introductory section explaining both the positive and the negative effects of high urban densities (see Sec. II.2.2.3). Based on a literature review in Section 2, we identify the following research gap: there is a lack of both data to

[36] This paper also had an exploratory nature for us as all data sources have been novel and not yet tested. 'We' refers to both the paper's authors and to the DFG project members: Stefan Siedentop (head of the team, project applicant), Hannes Taubenböck (co-applicant), Michael Wurm and Angelika Krehl. Stefan Fina contributed to this paper but not to the project itself.

measure urban density and a clear definition of density itself, especially with respect to gross versus net densities. This paper's contribution therefore is to calculate and apply fine-grained built densities for an urban environment. Moreover, we show similarities and differences of built and activity density patterns for the city of Cologne.

The scientific background (Sec. 2) of these in the end exploratory analyses is the finding that density is a highly controversial concept. First, density is not only applied interdisciplinary but also driven by social and cultural norms and attitudes, especially when it comes to its evaluation. Second, data availability issues, privacy laws in Germany and the application of density in the planning practice have not been tackled yet. Third, density is subject to the well-known MAUP. Though we cannot fully solve the latter, our analyses show how to fruitfully apply urban net densities in spatial research and planning.

Before analyzing the data, a thorough description of the new built-up volume data generation is provided (Sec. 3). This description is followed by a discussion of the results regarding both the urban spatial structure of Cologne and the potentials of integrating geodata, statistics and remote sensing. The data generation is based on airborne laser scanning methods: a scanner sends laser impulses to the ground and the height of the reflecting object can be detected based on the time needed for reflection. At first, the result is a cloud of point data which is further processed to obtain a digital surface model (DSM) in grey scales. The subsequent steps are similar to those explained in Section III.3 for the satellite-based building models. As a final point, three net density values can be calculated: built density ("Grundflächenzahl"), volume density and floor area ratio ("Geschossflächenzahl", FAR). Built density is the share of all buildings' footprints per block of housing (i.e., "Baublock") that these building are located in. Volume density, accordingly, is the 'share' of built-up volume per block of housing. Lastly, FARs are calculated as the share of the sum of all floor area per block of housing (see Fina et al., 2014: 185f.). We chose the block of housing as reference area because individual buildings are too small thus resulting in massive censoring problems due to German privacy laws (see Sec. III.3).

Having established the physical density parameters we start our analysis of density patterns in the city of Cologne (Sec. 4). We introduce employee and residential density to complement the built density calculations. Both employee and residential density are computed using the number of individuals per block of housing and are measured in individuals per hectare. To distinguish between gross and net densities we additionally use employees, residents and built-up volume per 'area of similar use' to calculate gross density values. These 'areas of similar use' have been provided by the Authoritative Topographic-Cartographic Information System ("Amtliches Topographisch-Kartographisches Informationssystem", ATKIS). Heat mapping techniques are then used to visualize the spatial pattern of urban net densifications and inspecting them reveals that all densities are highest in the downtown areas and decline towards the municipality's fringe. Nonetheless, subcenters in the sense of non-downtown densifications are evident as well. When comparing employee and residential densities, we find fairly similar spatial patterns. However, similarities are less clear if employee or residential density is compared to the spatial pattern of built density.

As visual inspection is just one part of the story, we complete these analyses by adding a statistical measure to identify spatial clusters and outliers. Precisely, we apply a Local Indicator of Spatial Association (LISA), which provides us with statistically significant spatial clusters and outliers.[37] Mapping the LISA mainly confirms the results obtained by the heat maps: there is significant similarity of both high clusters and positive outliers (i.e., 'peaks') between residents and employees. Furthermore, and as expected, we find that employee density is more concentrated in the downtown area than residential density. The built density pattern again differs but does not contradict the socioeconomic density patterns. This finding is interesting and thus reviewed in Krehl (2015a).

The last part of our analysis is to understand to which extent the identified densities actually meet, over- or underutilize the maximum densities permitted by the national planning law. Thus, we have collected information on maximally permitted FARs and built densities from the Federal Land Utilization Ordinance and compared these values with our values calculated for Cologne. The results show a strong core-periphery pattern with over-utilization in the core and massive under-utilization in the fringes for all types of use. Mixed land use areas disrupt this pattern as there is a strong peak in about 11 km distance from the center due to a large housing estate.

We close with a brief summary (Sec. 5): according to our research objectives we have shown that obtaining fine-grained spatial density data with remote sensing techniques is possible. Yet, it is an issue to further improve the spatial and technical 'fit' of the data developed and used in this paper. Nonetheless our empirical analyses in Section 4 have revealed obtaining and using remote sensing data is possible and provides valuable information for spatial research and planning.

After having generated these new built-up volume data from remote sensing further though in the DFG project context still preliminary analyses were carried out in Siedentop et al. (2014).

Siedentop et al. (2014)

Siedentop S, Krehl A, Taubenböck H and Wurm M (2014) Die bauliche Dichte der Stadtregion – Erzeugung kleinräumiger Dichtedaten mit fernerkundlichen Mitteln. [Built density of city regions – developing spatially fine-grained density data using remote sensing techniques] In: Meinel G, Schumacher U and Behnisch M (eds) *Flächennutzungsmonitoring VI: Innenentwicklung - Prognose - Datenschutz*. Berlin: Rhombos, 179–188.

[37] This is described in detail in Krehl (2015b) because I started working on Krehl (2015b) before Fina et al. (2014) has been published. During the work on Krehl (2015b) I found that it is necessary to use a false discovery rate (FDR) to assess the statistical significance of the LISA measure. Thus, I changed the standard 5% significance level originally applied in Fina et al. (2014) to the FDR when addressing the revisions from the review process. Details on both LISA and FDR have been presented in Krehl (2015b: 297).

Contribution of Angelika Krehl:

- Section 3 (“Ergebnisse”): Visualization, statistical analyses and interpretation of the obtained results.
- Comments and feedback on the other sections.

Publication date: September 2014

This book section addresses further ways of using built density in regional research. The contribution’s focus is on built densities and, in contrast to Fina et al. (2014), this book section comparatively analyzes the four city regions mentioned in Section III.2, but in a different delineation.[38] We explain how to generate these built densities and present a first application example. After a thorough description of the steps necessary to generate a Level-of-Detail-1 model of built-up structures (for details, see Siedentop et al., 2014: 181–183), we plot the obtained net densities on the INSPIRE grid level in each study region. Our results show that floor areas are highest in the region of Cologne, not only in the municipality of Cologne itself but also in the municipalities around. One explanation might be early, extensive industrialization and thus a denser urban fabric as compared to the other regions considered here. Another result is the axial system in the Stuttgart region: densities follow main transportation lines and the river Neckar.

IV.1.2 A Comprehensive View on Urban Spatial Structure – Urban Density Patterns of German City Regions

This paper revisits the concept of urban density in spatial research and practice with respect to its conceptual fuzziness and its complex nature. Exploiting the global availability of remote sensing data, we address this complexity issue discussing the “analytical opportunities that [these] data offer in regard to an objective and transparent measurement of built density patterns of city regions” (Krehl et al., 2016: 1). Thus, our research objective is to highlight “the analytical capacity of spatially-refined density indicators for the purposes of comparative urban research at a regional scale” (Krehl et al., 2016: 1).

Krehl et al. (2016)

Krehl A, Siedentop S, Taubenböck H and Wurm M (2016) A Comprehensive View on Urban Spatial Structure: Urban Density Patterns of German City Regions. *ISPRS International Journal of Geo-Information* 5(6): n° 76. doi:10.3390/ijgi5060076

Contribution of Angelika Krehl:

- All empirical analyses except for the remote sensing data generation and processing.
- Conceptualization and realization of Sections 4 (“Patterns of Built Densities and Their Relation to

[38] We have written this book section in an early stage of the DFG project in which we did not have data for the study regions’ final delineation. Thus, the regions are different as compared to those introduced in Section III.2.

Activity Densities"), 5 ("Discussion") and 6 ("Conclusions and Outlook").
- Section 1 ("Introduction") has been written jointly with Stefan Siedentop.[39]

Length of the accepted manuscript:
- Ca. 59,000 characters (without blanks)
  - Ca. 38,500 characters (without blanks and excluding sections 2, 3 and 50% of Section 1)
- Ca. 10,400 words
  - Ca. 6,600 words (excluding sections 2, 3 and 50% of Section 1)

Publication date: 25 May 2016

This paper's first section motivates the research efforts by stating two main issues: *(i)* density is a key factor to both describing urban structure and *(ii)* built and activity densities show a strong positive correlation. Against this backdrop, we first argue the pros and cons of high urban densities (see Sec. II.3.2.3). Based on this argumentation, we conclude that density is agreed to be a key concept but at the same time its empirical and analytical conceptualization are far from being agreed upon. Moreover, density measures on fine-grained spatial scales are fairly challenging because the necessary data are both limited in their availability and often restricted in their use. However, newly available remote sensing data can – and have in recent years – substantially mitigate(d) these limitations. Thus, we contribute a multifaceted notion of density, especially including the third dimension in the analysis of urban morphology.

Section 2 introduces our conceptualization of built densities and the empirical challenges associated. Against the introduction's backdrop and based on the results from previous papers (Fina et al., 2014; Siedentop et al., 2014) it is not striking to find that an objective evaluation of 'appropriate density' does not exist. To get an overview of this whole issue, we summarize the most commonly used density measures and outline the empirical problems with computing them (see Sec. II.2.2.3). The main challenge, so far, has been the non-coverage of small-scale spatial entities in official statistics resulting in built density measures being rare in research and practice. Utilizing remote sensing data, we have raised the challenges of FAR calculation regarding data availability. To measure built density (Sec. 3) we use stereo images specifically designed for large-scale and large-area stereo mapping and explain how these images are processed to obtain the desired built density measures (for the exact procedure and further references, see Sec. III.3.2).

With this data set we are ready to analyze built density patterns and their relation to activity densities (Sec. 4). At first, a brief overview of the study regions insights into very different density values in the regions despite similar sizes in residents and employees. To gain a deeper understanding of our data and the (spatial) patterns they establish, we additionally calculated use intensities, that is, floor area per resident, per employee and per built-up volume (see Table 2 in Sec. III.2). An evalua-

[39] The paper declares that Angelika Krehl has also contributed to Section 2 (see Krehl et al., 2016: 17). This is correct but Stefan Siedentop wrote this section's first draft. Thus, my contribution cannot be separate from his as required by the Technical University of Dortmund. Consequently, I did not count the whole section.

tion of these density measures reveals that the regions of Cologne and Munich score the highest densities, whereas the regions of Frankfurt and Stuttgart acquire the highest use intensity values. Since we suspect that the density values have an upward bias due to extraordinary high values in very few grid cells, we additionally provide box plots of the density values to better understand their spread (Krehl et al., 2016: 11). The box plots visualize the conjectured disparities and suggest a log-distribution of the data. However, log-linearization eliminated most of the disparities in the data. Thus, we refrained to use this transformation (Figure 4; see Krehl, 2016: 12 for level vs. log).

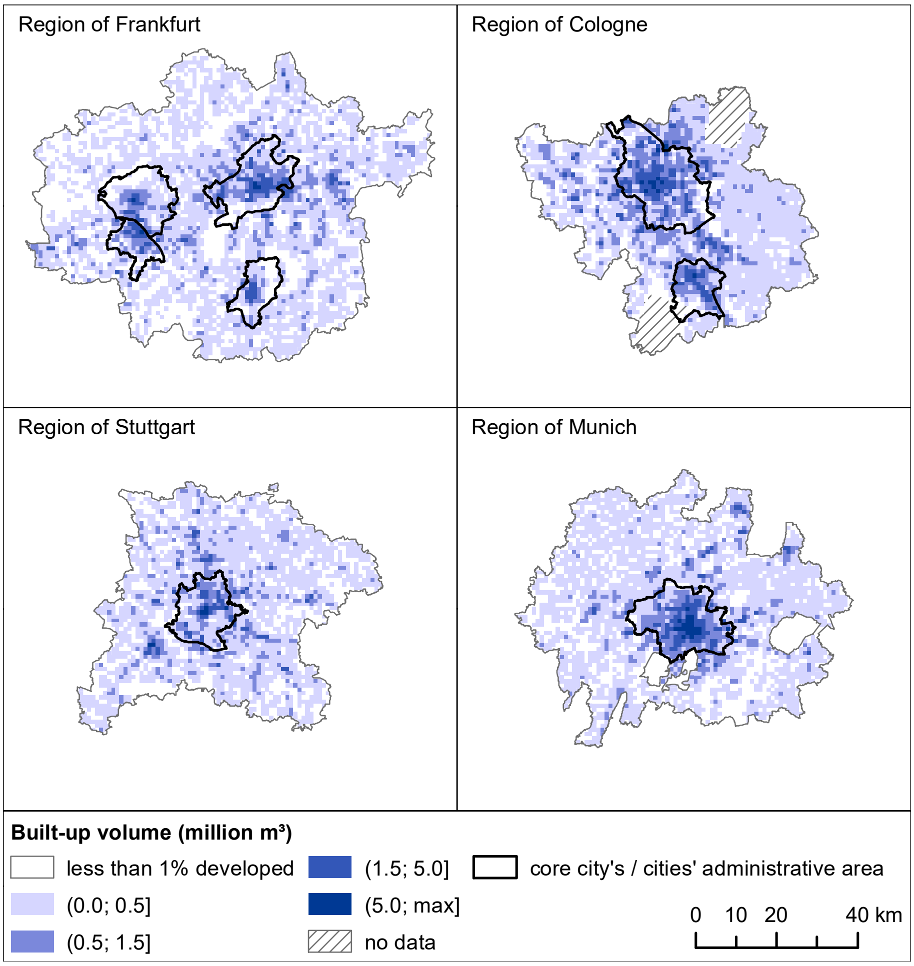

Figure 4: Patterns of built densities
(Source: Krehl et al., 2016: 13, modified)

Analyzing Figure 4 shows an axial structure in the Stuttgart region which sharply contrasts the monocentric patterns in the Munich region. Still, dominating sites are located in the core cities' downtowns in all regions but especially culminate in Frankfurt city. These visual inspections in line with the results obtained in Krehl (2015b) where local spatial associations have been analyzed. Both there and in this paper CP-patterns are observable in all study regions but differ in their spatial extent. In "Munich and Cologne, a larger, more compact urban core is visible, while the dense inner cities of

Frankfurt and especially Stuttgart give way to lower-density construction within a few kilometers" (Krehl et al., 2016: 12).

This result is particularly highlighted if an east-west cut through the regions is made and the densities on this 'cutting line', that is, a band stretching from the western to the eastern fringe of each region, are visualized (Figure 5).[40] We observe substantial differences between rather monocentric and rather polycentric regions: The latter show a densified core extending 7-8 km (Frankfurt region) and 2-3 km (Stuttgart region) and (sub-) urban densification in 5-10 km distance from the CBD, which is defined by the location of the respective town hall. Conversely, the width of the highly densified core is about 10 km in both the Munich and the Cologne region.

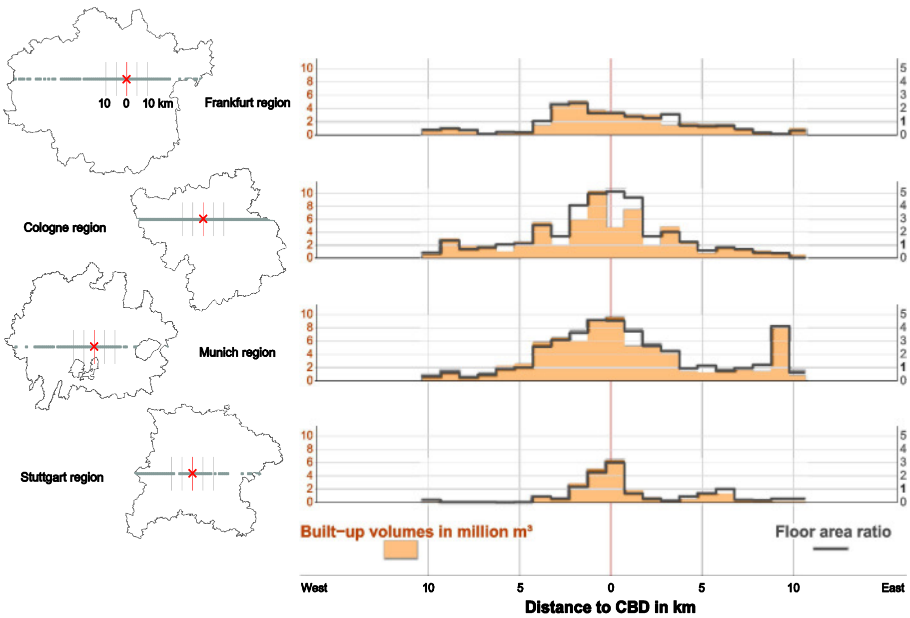

Figure 5: Selected density profiles of the study regions
(Source: Krehl et al., 2016: 14)

Studying the relationship between urban morphology and socioeconomic activity shows high and strongly positive correlations between all variables considered. Moreover, there is much evidence of both positive relationships among the built density indicators and positive but less apparent relationships between built and activity densities. A possible explanation for this finding could be that "people work and live in buildings, but that this fact is not necessarily associated with a linear/proportional amount of land or floor area demand" (Krehl et al., 2016: 15).

As a result, what do these findings imply regarding our multifaceted notion of density? The analyses have shown improved empirical possibilities to study complex, multifaceted urban density patterns. Thus, we open our discussion section (Sec. 5) with the main finding that built density and

[40] In fact, this 'cutting line' rather is a band of 1 km width in North-South direction, which covers the respective region's CBD (see left part of Figure 5). The values of built-up volume and FAR thus refer to complete 1 km² grid cells.

activity density measures need to be considered jointly, although we found striking similarities of built and activity density patterns. Yet, these are not perfect. Explanations for this 'resemblance but difference'-finding could be topographical situations and transportation infrastructure; historical path dependencies, settlement history, and urbanization processes; or regional economic structure and its change over time. Another aspect of our findings is fairly low population-job densities, which we suspect to be due to small subsequent densification of suburban residential areas originating from the 1950s-70s. We expect especially two forces to be responsible for this this result: planning regulations limiting higher densities on the one hand and fairly low social acceptance of high urban densities on the other hand.

Finally, we conclude from a technical point of view that satellite-based density models covering large areas can be produced also covering the third dimension which is especially useful to study urban density patterns. However, these data also offer a wide range of applicability in future research such as studies on urban climatology and ecology; planning of urban revitalization and the evaluation of densification projects; an expansion of conventional spatial monitoring systems; or interregional comparative analyses of urban density patterns.

IV.1.3 Polycentric spatial patterns in German city regions – an integrated perspective

Having introduced and discussed the meaning and empirical usefulness of density the next step is to understand how these densities manifest in city regions and to analyze the patterns and hierarchies they produce. Thus, the following book section does not only establish relations between built-up volume and socioeconomic activity but it also asks whether spatial and non-spatial hierarchies exist in the study regions. The hypothesis is that hierarchies are present in monocentric city regions – the core is more 'important' than the periphery – but should also be present in multicentric city regions.[41]

Krehl (2015a)

Krehl A (2015) Polyzentralität in deutschen Stadtregionen – eine integrierte Bestandsaufnahme [Polycentric spatial patterns in German city regions – an integrated perspective]. In: Taubenböck H, Wurm M, Esch T and Dech S (eds) *Globale Urbanisierung – Perspektive aus dem All*. Berlin Heidelberg: Springer Spektrum, 159–170.

Publication date: 23 April 2015 (available online via http://dx.doi.org/10.1007/978-3-662-44841-0_17)

Starting from a seemingly persistent core city decline, I analyze how far these processes have developed in the study regions triggering a polycentric or even dispersed urban spatial structure. My

[41] I have not used the distinction between polycentric and multicentric in this book section, but started using it later. For that, the term polycentric/polycentricity is applied throughout this (book) section although it is not fully consistent with the terms applied in this dissertation.

research objective thus is to analyze hierarchies in four city regions according to Section III.2. Thus, my research hypothesis in the end of Section 1 is that there is a marked hierarchy between centers and subcenters in all study regions, implying that subcenters are centers of secondary (or lower) relevance.

Section 2 then introduces the object of study. Referring to data and spatial scale I present the four city regions, suggest a means of tackling the MAUP and introduce the data. Referring to the MAUP I suggest to consider patterns on both the municipality and the grid level (see Sec. II.3.2.3). However, both of these spatial scales show substantial densifications around the regional cores. A consideration of the grid level instead of the municipality level does not alter the overall picture but the patterns become much more distinct and more detailed: the highest density values, employees as well as FARs, are located in the core cities suggesting a spatial hierarchy in the regions with a dominating core and subordinate fringe and periphery.

According to the research objective stated in the introduction I outline measures of concentration in Section 3. First, Lorenz curves and corresponding Gini coefficients are used to assess inequality in the study regions. Inequality is seen as a form of concentration implying that stronger concentrations denote higher inequality. This relationship is exploited here with regard to urban hierarchies. If a region shows higher concentration measures, it is more hierarchically organized than a region where inequality is comparatively low. Applying Lorenz curve and Gini coefficient leads to the conclusion that the Munich region is most unequal among the four regions considered. This results holds with respect to both FAR and employees. Several versions of the Gini coefficient are calculated to test the results' qualitative stability, which can be established: Munich is most concentrated, Stuttgart is least. However, comparisons of the four study regions are not permitted as their Lorenz curves intersect and spatial concentration cannot be directly addressed as locating the grid cells is not possible with Lorenz curve and Gini coefficient. An interesting finding of these analyses finally is to see a more equal distribution of the FAR as compared to employees (Table 3). An explanation could be that the FAR inequality is restricted by the Federal Land Use Ordinance which sets maximum density values.

After having established marked inequalities in all study regions, I evaluate whether and if so to what extent these inequalities actually indicate urban hierarchies (Sec. 4). An established method to analyze urban hierarchies is the application of Zipf's law and the corresponding rank-size rule. Whereas it is usually applied to population data on the municipality level, I apply the method to employee and FAR data on both the municipality and the grid level. Applying the rank-size rule assumes that absolute numbers and a solely morphological consideration are appropriate to analyze hierarchies in urban systems.

Table 3: Gini coefficients

	Frankfurt region	**Cologne region**	**Munich region**	**Stuttgart region**
	Municipality level Employees subject to social insurance			
Gini coefficient, no weighting scheme	0.822	0.748	0.854	0.775
Gini coefficient, weighted by area size	0.872	0.848	0.955	0.881
	INSPIRE grid level, 1 km² Employees subject to social insurance			
Gini coefficient, all grid cells[i]	0.815	0.763	0.870	0.785
Gini coefficient, non-empty grid cells[ii]	0.674	0.685	0.809	0.673
	INSPIRE grid level, 1 km² FAR			
Gini coefficient, all grid cells	0.789	0.686	0.787	0.763
Gini coefficient, non-empty grid cells	0.713	0.643	0.743	0.710

[i] Censored grid cells were manually set to one (i.e., one employee), grid cells without employees were set to zero and considered in the Gini calculation.
[ii] Censored grid cells were manually set to one (i.e., one employee), grid cells without employees have not been considered in the Gini calculation.

(Source: Krehl, 2015a: 165, translated)

Considering the municipality level reveals that no linear relationship exists between the municipality's rank and its number of employees if the full data set is considered. The rank-size rule neither applies to the employee data on the grid level, even if only the upper tail of the data (i.e., all grid cells scoring an employee number above the regional median) is considered. Analyses of the FAR show that gross FARs neither follow Zipf's law. Interestingly, there is an almost perfect linear relationship on a log-log scale if the data set is reduced to those grid cells that score gross FARs above 0.4. Based on these results I conclude that hierarchies exist, but these are flatter than 'demanded' by Zipf's law. Moreover, spatial (de-)concentration is yet unclear as these measures are a-spatial. To mitigate these measures' a-spatiality, I have selected and mapped those 20 grid cells in each study region that score the highest density values (Figure 6). A look at the resulting maps reveals distinct spatial concentration in all regions but Stuttgart.

Quantifying these spatial concentrations lead to the following insights: *(i)* across all regions, the mean value of employees in these 20 grid cells exceeds the mean value of each entire region by 9-20 times, *(ii)* regarding FARs the results are qualitatively similar but concentration is less pronounced than that of employees, *(iii)* the shares of employees and FAR within these 20 grid cells each largely exceed the share area they cover, and *(iv)* spatial employee densifications find their resemblance in FARs in all regions although the correlations are not perfect and discrepancies occur (Krehl, 2015a: 167f.).

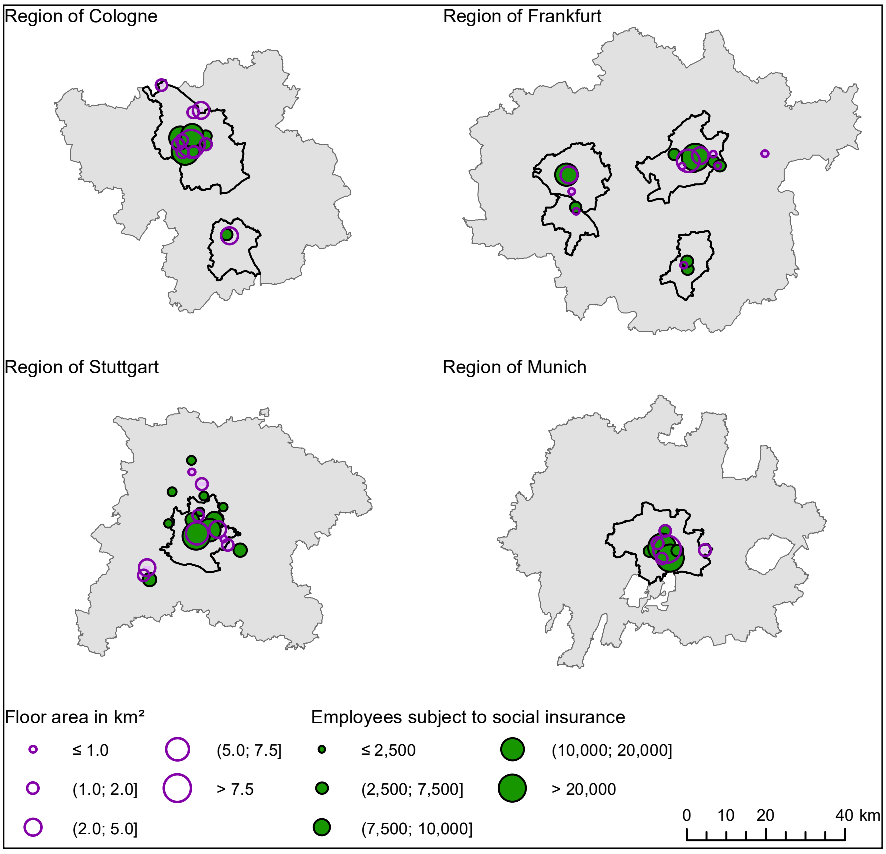

Figure 6: Location of the 20 densest grid cells in each study region
(Source: Krehl, 2015a: 168, translated)

The resulting question is how to interpret these results (Sec. 5). Concentration measures and rank-sizes revealed obvious core city dominance in all study regions. However, substantial densifications outside the core city's administrative area are especially sensed in the Stuttgart region thus partially confining the core city dominance result. Still, the Stuttgart region should not be considered truly polycentric but rather be understood as a region with extended core city dominance because the core city's size still dominates the subcenters. Yet the expected similarity of employee density and FARs is proven, cause and effect are, however, beyond this paper's scope.

Finally, the research hypothesis is revisited (Sec. 6). The hypothesis is paraphrased asking whether there was a 'primus inter pares' in each city region and the response is yes, there is a 'primus' as the defined core city dominates each study region. However, the response also is no, there is no 'inter pares' as the identified suburban densifications are less important and smaller than the core cities. Thus, spatial hierarchies exist speaking in favor of persistent core city dominance. Actual persistency, however, implies analyzing processes. Due to limited data availability, this aspect had to remain for future research efforts.

IV.1.4 First interim conclusions

The papers in Section IV.1 have shown that newly available data provide good prospects of analyzing the morphology of urban spatial structure in a more encompassing way than before. On the one hand, the new data sources provide additional information thus separately permitting more in-depth analyses. On the other hand, their joint consideration substantially contributed to the more encompassing picture. Furthermore, analyses on the fine-grained spatial scale of 1 km² grid cells are novel as they have not been possible for Germany so far and therefore shed light on hitherto unconsidered intra-urban spatial configurations.

The contributions to this section have revealed that employee and built density match spatially, that is, many employees are registered in grid cells with a lot of floor space and vice versa (see Krehl, 2015a; Krehl, 2015b). However, due to both data manipulation issues and the fact that data referring to the built environment are estimates these similarities are disturbed at times. One cause for these disturbances is that vacancies could not be detected by the data and methods currently available. Another issue is that it has not been possible to automatically distinguish between buildings of different type of use so far. Some experiments have been made by manually combining these data with information from ATKIS which provides information amongst others on the type of use (see Krehl, 2015b). This combination permits to eliminate built-up volume and floor space for residential use only. Subsequent correlation analyses have shown that this procedure improved the results as solely residential areas have been excluded thus leading to more realistic values of floor area and built-up volume 'left' for employees (see Krehl, 2015b: 300).[42]

There are some non-technical explanations of the sometimes diverging patterns of built-up volume or floor space and employees, too. Whereas there are legally binding restrictions regarding FAR, there is hardly any legal restriction of a maximum employee density at a certain place (there are physical restrictions, but that should not play an important role in these analyses). Moreover, planning regulations permit or reject the location of certain industries in certain places. Depending on the industry structure in a place, the correlation of employees and built-up volume or floor area varies: ware houses and trade fairs need a lot of space but there are not many employees in these building. Conversely, office towers are packed with employees on a comparative small amount of floor space per person.

From a conceptual point of view both the strengths and weaknesses and the seeming simplicity of density as a measure of urban spatial structure have been considered (Krehl et al., 2016). The conclusion is that density is a good measure of comparative urban research – provided that it is calculated *(i)* transparently regarding gross versus net conceptualization and *(ii)* similarly with respect to

[42] However, it needs to be considered that ATKIS, airborne laser scanning and satellite data do not perfectly match. In particular, ATKIS does not attribute any type of use to about 0.03% of a region's entire built area (Krehl, 2015b: 295).

both the objects (employees or floor space, for example) and the reference area (e.g., regularly shaped grid cells). Furthermore, we have addressed the distinction between gross and net density and found it to be essential. Knowing whether the density considered is gross or net density clarifies the interpretation and thus the understanding of the identified spatial patterns (Krehl et al., 2016: 4). Net densities provide valuable information regarding the actual intensity of use of a reference area whereas gross densities rather contribute to a more general picture (see also Fina et al., 2014: 182). Therefore, one could discuss to what extent net densities are more appropriate if a micro level in the sense of site specific analyses is focused, whereas gross densities are more appropriate to describe a macro level in the sense of broader 'spatial trends' in a study region.

Referring to the analysis of urban spatial structure, this section has also provided insights into spatial hierarchies in German city regions. Thus, the question to be solved is how polycentric is a region if spatial hierarchies are present? Do hierarchies imply polycentricity? Where are spatial densifications, called urban (sub-) centers, and how can they be identified?

IV.2 On the polycentricity of German city regions

The previous section indicated a fruitful combination of socioeconomic and remote sensing data. However, these analyses have also shown that things are not as simple as they might seem: measurement issues and spatial scales influence the results, and so does the choice of variables. Thus, to gain a deeper understanding of the urban spatial structure, a broad set of methods is applied to identify and classify urban centers and subcenters. Whereas numerous studies have been conducted discussing urban subcenter identification procedures, a systematic comparison of these procedures is still missing. This research gap will be narrowed here: several methods with different and sometimes incompatible theoretical backgrounds are applied to the same data and the same set of study regions.

IV.2.1 Urban spatial structure: an interaction between employment and built-up volumes

The first paper in this part of the work explicitly deals with analyzing polycentricity and subcenter identification. Precisely, I synoptically consider employees', employees' in higher-order service sectors and built-up volumes' spatial distribution in Krehl (2015b). Thus, the morphological dimension of polycentricity is addressed from a multidimensional perspective.

Krehl (2015b)

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Similar to this dissertation's introduction, this paper's introduction (Sec. 1) opens with the ongoing suburbanization processes in most city regions in economically advanced ('western') countries (see Sec. I.1 and II.1). From an empirical perspective, the starting point is that different types of employees require different amounts of space. Knowledge workers, for example, only need an office to work in, whereas employees in manufacturing sectors work in large production halls or in offices which are located in buildings that also contain production sites. Nevertheless, all employees in Germany are registered at addresses referring to a building. The spatial patterns of employees and built-up volume should thus be similar though not perfectly matching in detail. To what extent this starting point is justified will be examined throughout the paper. Therefore, the paper's novelty is that it is the "first study to analyse the implications of polycentricity in terms of physical urban form" (Krehl, 2015b: 291).

To contextualize the empirical analyses, a literature survey of the current debates is provided (Sec. 2). This survey captures discussions regarding urban spatial structure, polycentricity and means of their analytical investigation (see Sec. II for details). Additional insights from the literature review provided in this paper are that discussions of urban spatial structure and polycentricity seem US-focused, although research efforts have been made for European and German city regions, too. Common objectives in these studies are *(i)* general issues of urban spatial structure and polycentricity, *(ii)* subcenter identification, *(iii)* spatial scales to be analyzed, and *(iv)* means of analysis for urban spatial structure or subcenter identification in particular. Finally, a brief summary is outlined which refers to theoretical underpinnings and explanatory patterns for empirical results derived from distinct methodological procedures. This section's conclusion is that much research has been done, but several issues remain unresolved. Therefore, this paper adds to the knowledge by using intra-municipality data sources and by considering a combination of physical and socioeconomic data. Moreover, these analyses have not been conducted for Germany so far.

Section 3 then presents the research design. The study regions are delineated according to the explanations in Section III.2 and the data applied are a combination of employee data from the georeferenced IEB and data on built-up volume in each study region (see Sec. III.3). Following these technical details, the methodology used to analyze urban spatial structure and to evaluate the study regions' polycentricity is presented.

The empirical procedure is organized in two consecutive steps to first address the issue of general spatial disparities and to second identify subcenters. Step 1 is operationalized by applying Spearman's rank correlation coefficient and the global Moran's I. Whereas the rank correlation coefficient sheds light on the general relationship between employees and built-up volumes, the global Moran's I – a measure of spatial association – clarifies the spatial dependencies of each variable. It thus offers first insights into the overall spatial structure of the study regions. Actual subcenter identification is done in step 2 by applying a LISA. The method of choice is the local Moran's I, which permits the detection of spatial clusters of high and low values as well as spatial outliers, that is, a low value surrounded by high ones and vice versa. This measure belongs to the family of exploratory spatial data analysis, which has especially one advantage for the kind of research question asked in this paper: the local Moran's I does not require an a priori definition of a CBD. Thus, it does not assume a monocentric urban spatial structure as many other means of analysis do. Although there have been some hints that the core cities dominate (see Krehl, 2015a), it seems reasonable to enter the analysis of subcenters in German city regions without that monocentricity assumption. Moreover, the local Moran's I detects spatial clusters which can be explained by theories referring to agglomeration economies, spatial spillovers and so on. Its calibration is that the spatial weights are based on second-order queen contiguity and statistical significance is evaluated by a permutation approach and the application of a false discovery rate (see Krehl, 2015b: 297).

Spearman's rank correlation coefficient and the local Moran's I are calculated and interpreted in Section 4. First, the maps based on z-scored values of both employees and built-up volume provide an interregional comparable, visual impression of the study regions and a rough idea of the clustering in these regions (Figure 7). Inspecting Figure 7 reveals clustering tendencies within the core cities. Additionally, spatial concentration seems to be higher for higher-order service sector employees than for all employees, which appears reasonable. Built-up volumes furthermore seem to be more concentrated than employees. These inspections are supported by statistically significant positive global Moran's I values. Thus, significant spatial clustering occurs in all regions and across all variables.

Spearman's rank correlation coefficient scores statistically significant medium values of 0.63-0.71 (Krehl, 2015b: 300). A general finding is that the correlation coefficient is higher for all employees and built-up volume than for employees in higher-order service sectors and built-up volume. This surprising finding might amongst others result from incomplete residential use elimination as buildings with mixed use tend to be occupied by employees in higher-order service sectors rather than by employees belonging to another, truly industrial branch. Thus, if built-up volume for residential use is not completely eliminated, each employee is assigned too much built-up volume which causes the correlations to be lower than in reality.

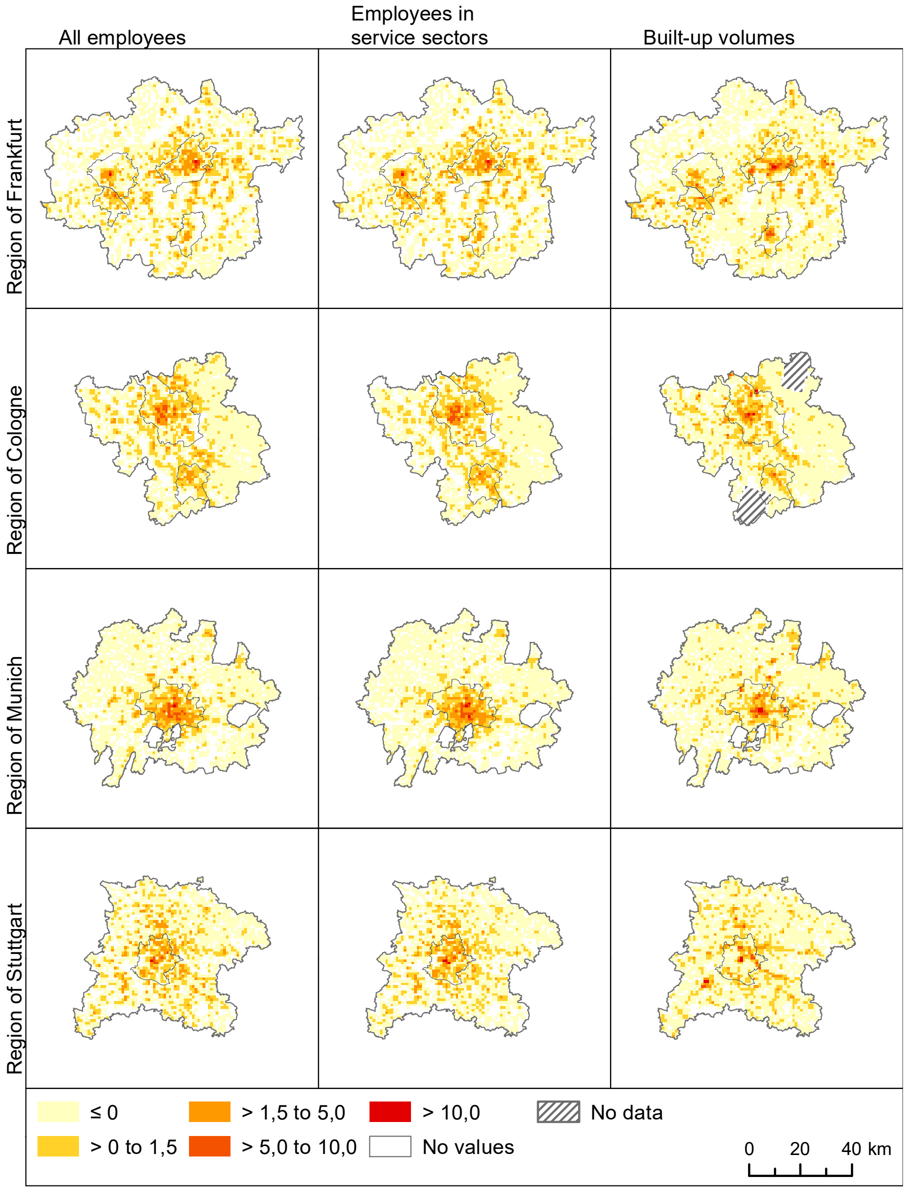

Figure 7: z-scored densities in the study regions
(Source: Krehl, 2015b: 298)

These results are the starting point for an exploratory approach. So far, similarities have been analyzed but nothing about the spatial outcome of these similarities has been derived. Thus, LISA cluster maps (Figure 8), which are based on the local Moran's I, are presented and explained. Regarding their interpretation it is essential to note that 'high' means substantially above the local mean, but it does not necessarily imply a high density value in absolute region-wide terms. I find significant spatial clustering of similar values in all regions, whereas spatial outliers just occasionally occur. The spatial clusters of high values are predominantly located in the core cities. Another finding is that high-high clusters (red areas in Figure 8) are more frequent for all employees than for employees registered in higher-order service sectors. Thus, the latter seem more concentrated than the first, which has been expected due to positive spillovers resulting from face-to-face interactions (see Sec. II.2.1.2).

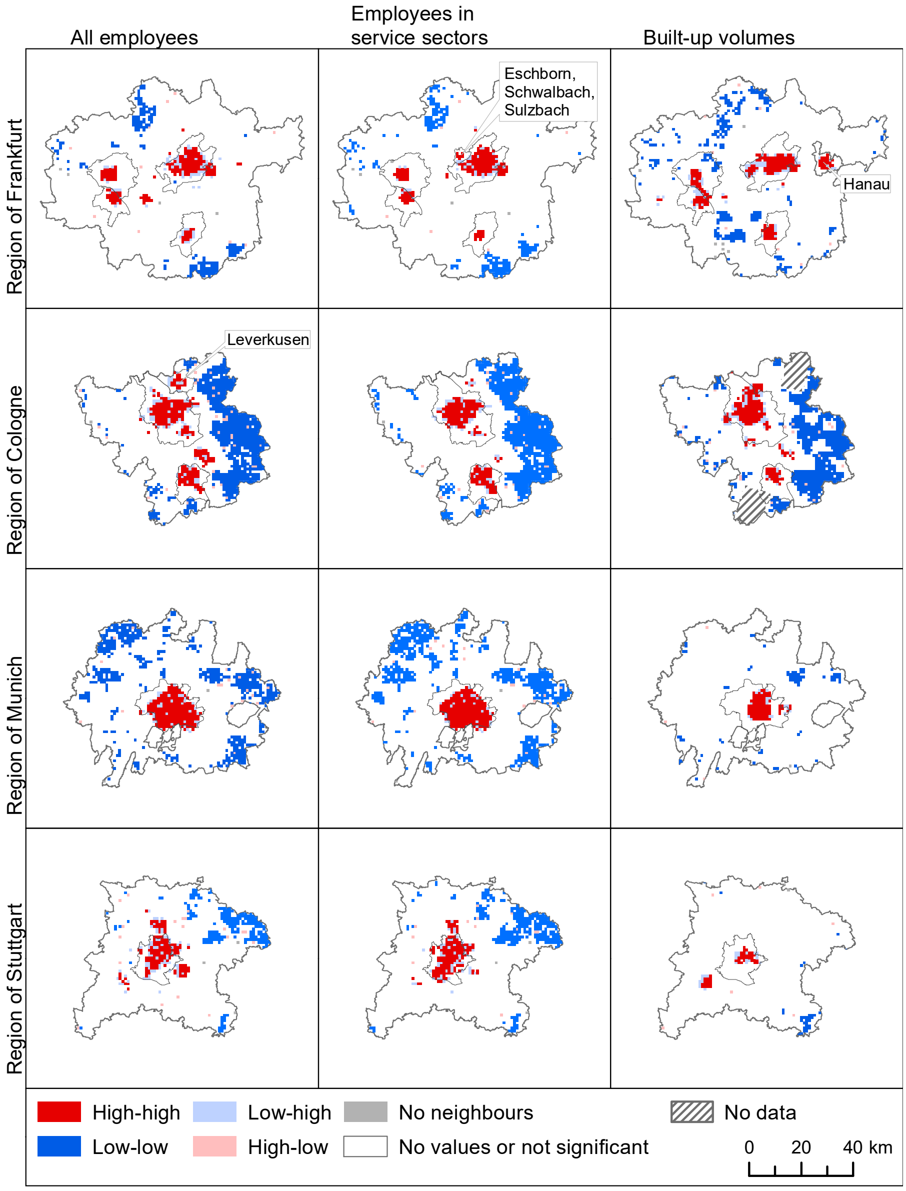

Figure 8: LISA cluster maps
(Source: Krehl, 2015b: 302, modified)

Figure 8 can be summarized as follows: The region of Frankfurt is polycentric due to its four core cities, in each of which a high-high cluster is located. However, this cluster type is also identified outside of core cities and their CBDs if all employees are considered. The pictures slightly changes if only employees in higher-order service sectors are considered. There are fewer high-high clusters, which might be a hint that this subgroup of all employees profits more from agglomeration economies than all employees do. The Cologne region's high-high clusters cover a geographically larger area than those in the Frankfurt region. Cologne's patterns regarding employees in higher-order service sectors are, still, similar to those in Frankfurt, although less in numbers and more concentrated to the largest core city. The spatial patterns of employees and built-up volumes patterns coincide well, too.

In contrast to these quite polycentric regions, the region of Munich is characterized by monocentricity for both employee considerations. Built-up volumes, however, show a slightly different but still core city dominated spatial pattern. An explanation might be that planning regulations are strict in the city of Munich and vacant lots are scarce. Thus, substantial differences are scarce, too, and hence the local Moran's I does not identify significantly positive deviations from the mean. The region of Stuttgart, finally, shows significant spatial clustering at several places in- and outside core city thus revealing a polycentric pattern for employees. Built-up volumes, in contrast, show a rather bipolar urban spatial structure which might be the result of a fairly equally distribution of built area with just occasional deviations. The density maps in Figure 7 support this conjecture.

A closing synthesis and interpretation of the results based on the LISA cluster maps is that the region of Stuttgart is intra-urban polycentric, the region of Munich is monocentric or very slight intra-urban polycentric, and the regions of Frankfurt and Cologne are characterized by their respective multiple core cities. Thus, these regions' urban spatial structure is inter-urban polycentric as only the core cities establish the polycentric structure. These characterizations' base is the definition of a subcenter: spatially separated high-high clusters located either outside the core city or outside the core city's CBD. Another point to revisit is the synoptic analysis of employees, employees in higher-order service sectors and built-up volumes. Jointly considering these three variables has proven to be useful as the patterns are not identical. Thus, a more encompassing analysis of urban spatial structure was reached than it would have been possible if just one variable had been considered.

Finally, a conclusion is drawn and some prospects of future research are outlined (Sec. 5). Significant core city dominance has been proven in all regions except for Stuttgart although subcenters could be identified which are mostly located close to the core cities. Thus, American-style rather isolated edge cities do not exist in these city regions. Regarding the empirical procedure it could be highlighted that the suggested integrated approach turned out to be informative: employees and built-up volumes are complements instead of substitutes and they jointly shape a city region's urban spatial structure. Last but not least, several prospects of future research are drafted.

IV.2.2 Urban subcentres in German city regions. Identification, understanding, comparison.

Based on the findings of Krehl (2015b), it can be concluded that the regions are neither fully monocentric nor largely dispersed. Yet, fairly strong core city dominance seems to prevail in all study regions. This finding speaks in favor of *(i)* an intra-urban polycentric configuration as there is a (once?) dominating core city that nowadays tends to be mitigated by emerging (sub-) urban subcenters. It *(ii)* speaks in favor of further analyzing the polycentricity of the selected four German city regions by choosing a method that is based on a monocentric urban configuration. Thus, the methodologically consequent step is to choose an identification procedure that is based on a monocentric city model but also permits the identification of urban subcenters. The so-called locally weighted regression (LWR) according to McMillen (2001)[43] fulfils these prerequisites and is used and evaluated in Krehl (2016).

Krehl (2016)

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Publication date: 27 May 2016

This paper's starting point is similar to the one used in Krehl (2015b) and also based on the observation that a spatial reconfiguration process has been taking place and "deconcentration processes (e.g., dispersion, sprawling) are overlapping with (re-) concentration processes (e.g., subcentre formation, reurbanization)" (Krehl, 2016: 2). What is particularly innovative in this paper is that it *(i)* applies methods developed and calibrated for US-American city regions to German city regions and *(ii)* introduces a cross-regional and qualitative cross-national comparative perspective. Thus, the research objectives are to evaluate whether one selected method (LWR) that has been originally designed for US city regions can be directly applied to German city regions or if adjustments in the parametrization are necessary. Moreover, a deeper understanding of the urban spatial structure in four German city regions will be provided and juxtaposed with findings for US-American city regions.

The empirical procedure is to first apply the LWR according to McMillen (2001) to the study regions, to evaluate the method's sensitivity with respect to some framing parameters, and to derive the set of parameters that yields best results for the city regions under consideration. Second, a discussion regarding the identified centers' and subcenters' characteristics and the appropriateness of the term 'subcenter' is held. It is asked to what extent a spatial densification can be considered a subcenter or whether the word fragment 'center' might be misleading. Third, comparisons are drawn with regions this LWR-method was originally designed for and a discussion of possible explanations of the diverging results is held.

Section 2 contains an encompassing of the state of the research addressing aspects of why considering subcenters (Sec. 2.1), means of subcenter identification (Sec. 2.2) and a comparison of German and US city regions as well as the usefulness and feasibility of such a comparison (Sec. 2.3). In this paper, I distinguish density threshold and cut-off value methods, (regression-based) exploratory methods including approaches such as the geographically weighted regression or kernel density

[43] McMillen was the first scholar to applying this methodology to issues of subcenter identification. The techniques have been developed much earlier amongst others by Stone (1977), Cleveland (1979) and Cleveland and Devlin (1988) as McMillen (2001: 452) outlines himself.

estimations, and regression-based methods which are rooted in theoretical considerations referring mostly to gravity and monocentric city models. Each of these families of methods has been widely used in the literature and is – with respect to this paper's objective – more or less feasible for international comparisons. Although the same methods are applied in studies of city regions on both sides of the Atlantic Ocean and qualitatively similar results can (but do not have to) be derived, cross-national comparisons are still limited. Reasons are not only different path dependencies and development trajectories in these two countries but also land-richness and land-scarcity and corresponding higher and lower urban densities.[44]

However, before these comparisons are made here, the method of choice is thoroughly introduced (Sec. 3). The reasons to choose a locally weighted regression (LWR) approach are that I wanted a method that *(i)* does not require much local knowledge about the region under consideration; *(ii)* is based on a theoretical model or concept; *(iii)* identifies (sub-) centers based on statistical significance; and *(iv)* captures the influence a subcenter exerts on the entire region. Previous analyses have shown that the regions under consideration tend to be core city dominated (see Krehl, 2015a; Krehl, 2015b). Thus, a CBD-oriented method is reasonable. Additionally, the LWR is more flexible than other commonly used regression lines such as the negative exponential model. From a technical point of view, the LWR applied here is based on the McMillen (2001)-formulation. It is a two-step procedure with iterative elimination of subcenter candidates that do not reach statistical significance.

Step one is to obtain a smoothed density surface from nonparametrically estimating an employment density function based on the distances north and east of the CBD. A subcenter candidate is then defined by statistically significant, positive residuals from the estimated density function, that is, the smoothed density surface. These candidate grid cells' distances to the CBD are included into a new regression line. To avoid multicollinearity only those grid cells with the highest significantly positive residuals in a 3 mi-radius[45] are considered subcenter candidates and included into the new regression line. Thus, the new regression line explains employee density by the nonparametric estimation of the distance east and west to the CBD and all distances to all subcenter candidates (full details and equations in Krehl, 2016: 7). In order to distinguish between global and local subcenters, these candidates' distances are included both in levels (for a global subcenter) and in inverse form (for a local subcenter). Step two is then to estimate this new regression line using ordinary least squares and those subcenter candidates are iteratively eliminated whose coefficients are either negative or fail to reach statistical significance. Steps one and two establish the paper's baseline model.

After having established the baseline model, I introduce modifications to analyze the results' robustness and to evaluate whether a method calibrated for one region can be directly transferred to

[44] Discussing issues of Chicago versus L.A. School would be informative here but I have not done this in Krehl (2016). For that, I refrain from including this discussion in the summary here because it would suggest that I have held this discussion in the paper – which is not the case.

[45] This radius has been suggested by McMillen (2001: 453).

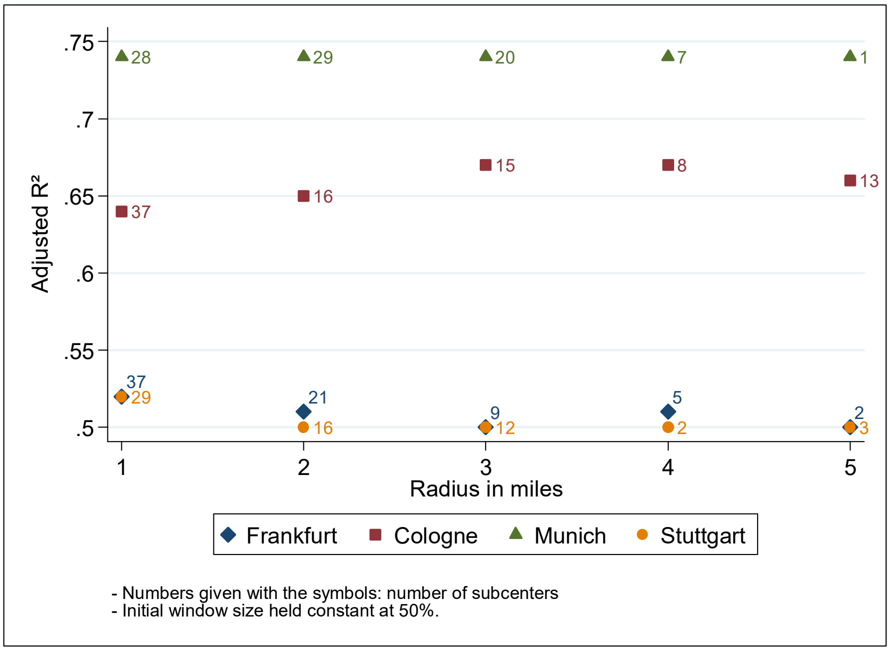
another. Thus, I vary the distances that any two subcenter candidates must be apart from each other between 1-5 mi. Similarly, I estimate another set of regression lines where I alter the window size which is essential in obtaining the density surface in step 1. The window size describes the share of observations that are included in the nonparametric regression. According to the baseline model the initial window size is 50%, that is, the closest 50% of all grid cells in a region are considered to estimate the employee density of the one grid cell under consideration. I vary the window size between 25% and 75%. Finally, previous analyses have revealed that the regions of Frankfurt and Cologne seem to be polycentric. Thus, instead of constructing the regression lines focused on the largest CBD (Frankfurt and Cologne downtown, respectively), I assume that according to my polycentricity definition (see Sec. III.1) any CBD is adequate. Therefore, I insert the distance to the closest CBD into the regression lines in steps 1 and 2. The expectation is that if the regions are polycentric, these modified models should yield a better fit than the baseline model. To provide additional robustness checks for all study regions I furthermore estimate two benchmark models often used in similar studies: a linear model which explains employee density solely by its distance to the CBD and a linearized version of the negative exponential model which is sometimes called the standard model in the literature regarding urban density estimations.

Section 4 introduces the data and study regions for which I conduct all analyses (see Sec. III). To permit distance calculations all grid data are aggregated into their respective centroids and the distances to the CBD are calculated by the great circle formula. The CBD is defined by each core city’s town hall’s longitude and latitude. Thorough analyses of the employee data in the four study regions reveal from a technical point of view that a log-transformation is not feasible for the research objective. If the data are transformed, the disparities disappear and hence any kind of subcenter cannot be identified. Thus, “[t]his finding gives rise to the first hypothesis that employment densities are more dispersed in German than in US metro regions” (Krehl, 2016: 13).

Section 5 is dedicated to the conduction of all regression analyses and the synoptic comparison and interpretation of the results. Applying the baseline model reveals that all regions are massively core city dominated. Furthermore, the regions of Cologne and Frankfurt prove to be not truly polycentric as the specifications considering the closest instead of the largest CBD have markedly lower explanatory power in all specifications. Finally, all identified subcenters are local ones, which is in line with the seeming core city dominance. To assure these findings, I made several modifications of both the window size and the minimum distances (Figure 9 provides an overview).

The most striking finding of Figure 9a is a nearly unchanged explanatory power of the regression lines but dramatically changing numbers of subcenters. The latter vary in numbers by as much as 35 in the Frankfurt region and by 27 in the regions of Munich and Stuttgart, whereas the explanatory power measured by the adjusted R^2 remains close to 0.75 for the Munich region and about 0.5 for the Frankfurt and Stuttgart regions. Thus, I discover a non-pivotal role of distances between any two subcenters suggesting that the LWR requires a minimum level of disparities in a study region to identify subcenters. By the same token, I find the initial window size to be even less crucial than the minimum distances: the adjusted R^2 varies by as little as 0.005 and the number of subcenters is comparatively stable (Krehl, 2016: 17, also Figure 9b).

a) varying radius



b) varying window size

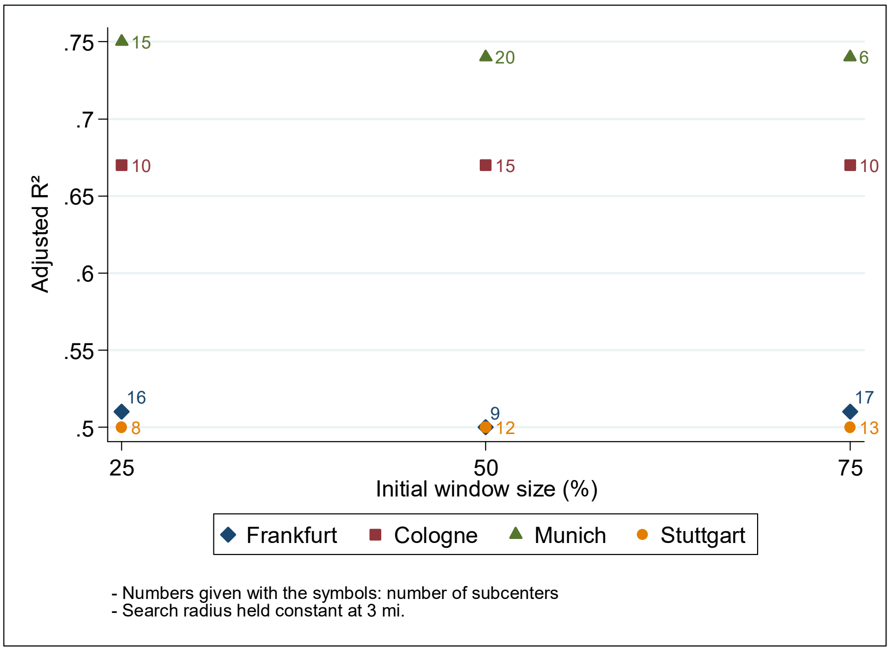


Figure 9: Number of subcenters and goodness-of-fit depending on the search radius and the initial window size (Source: Krehl, 2016: 16f.)

Mapping the results that score the highest explanatory power on average of all study regions provides a picture with overarching core city dominance and rather surprising subcenter locations in each region's periphery (Figure 10). Whereas the results are comparatively robust for the Munich region, they are rather volatile for the conjectured polycentric to dispersed regions of Stuttgart and Cologne. Before interpreting and hypothetically explaining the results, I conducted a number of descriptive analyses of the LWR results. These analyses prove that the shares of employees captured by the subcenters and their spheres of influence[46] remains between 7-11%, whereas the areas covered change with the size of the 'spheres of influence' as defined by the distances (Krehl, 2016: 17).

Additionally, the finding that all subcenters are 'local', that is, significance of the inverse distance's coefficient, fits well into the location of the subcenters according to Figure 10. The subcenters are small in absolute densities and, thus, do not exert an influence on the entire region but on the local neighborhood. Conversely, the CBD dominance is marked in all regions. Nonetheless, it can be proven that considering the subcenters in the density regression lines adds explanatory power. Therefore, a purely monocentric specification would be misleading (Krehl, 2016: 19).

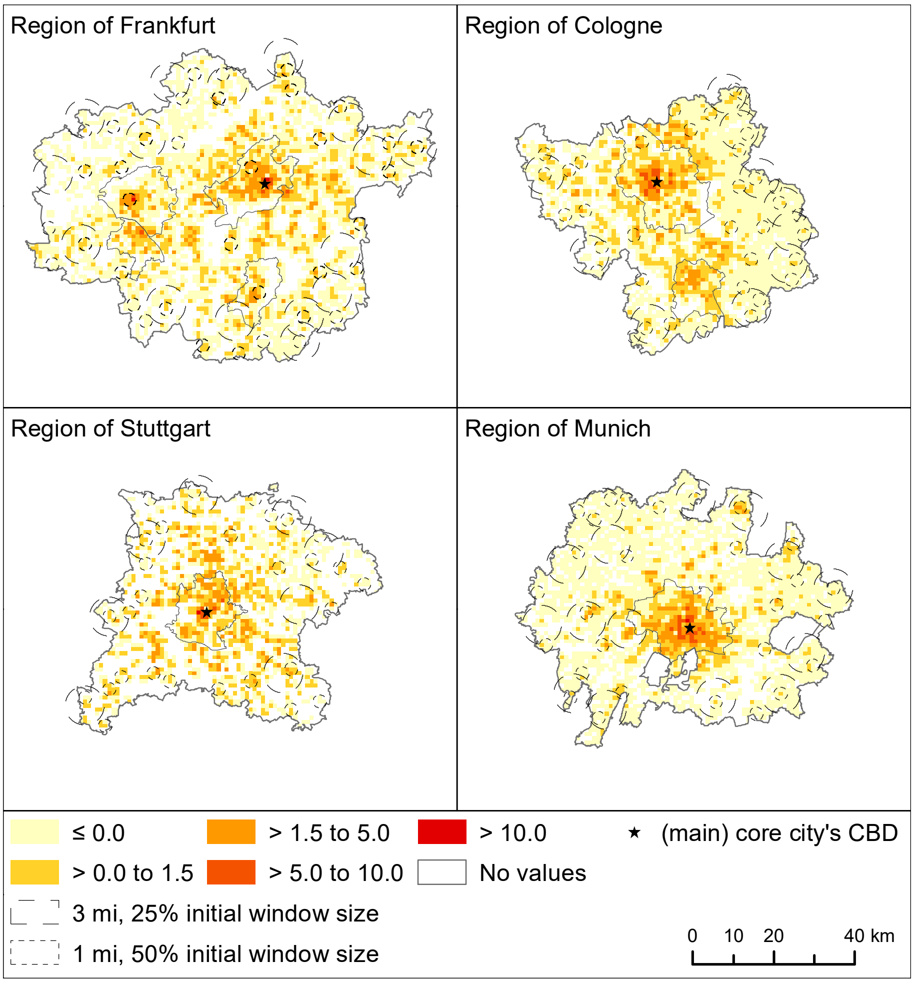


Figure 10: Subcenters in German city regions according to the LWR
(Source: Krehl, 2016: 18)

[46] The 'sphere of influence' is the area covered by a circle whose radius equals the distance any two subcenters must be apart from each other. The circle's center is the subcenter under consideration.

One comment on these results before interpreting them is that analyses on the spatial level of grid cells preclude descriptive terms such as ‘satellite city’. Densifications occur on a fine-grained spatial scale of just 1 km² both within core cities and in other places within the study region. So, the term subcenter might be misleading here as well because the area covered by a subcenter is small as compared to transport analysis zones (TAZ, used a lot in US studies). Thus, characteristics of single grid cells might differ substantially from TAZ characteristics and hence the US-American-based term subcenter might indeed be misleading here.

The discussion section (Sec. 6) contains lines of arguments that support the empirical results from several perspectives: data quality, transferability and objectivity of methods, similarity and complementarity with previous results, as well as planning laws, land availability and other drivers of urban spatial structure. My core conclusion is that methods can be transferred if they are adjusted thoroughly and validated by robustness checks. The empirical results here and elsewhere (e.g., Krehl, 2015a; Krehl, 2015b) support this conclusion, although I could not identify densifications of similar geographical size and regional relevance as identified by this LWR but applied to US-American regions. Reasons for identifying comparatively small subcenters are conjectured to be planning law driven. Additionally, the present analyses show that employee-to-resident ratios are hardly above 1.0 and mostly even below 0.5 (Krehl, 2016: 21). This finding speaks in favor of a mixed land use pattern in the four study regions, which is likely to explain the diverging results for German and US-American city regions and the (non-) existence of suburban subcenters in German city regions in terms of employee densifications.

The final section (Sec. 7) concludes with a brief summary: A method cannot be transferred 1:1 between the study regions even if it is a regression-based one. However, after thoughtful and theoretically well-based modifications a transfer is feasible. Both the method and the sensitivity analyses provide valuable information on the urban spatial structure of the study regions considered. The analyses prove a significant core city dominance that masks most of the subcenters and causes a rather dispersed and functionally mixed urban spatial structure without characterizing subcenters, a finding that cannot be seen for US-American regions. Referring to theoretical work that expects a subcenter to emerge at about 2.7 million residents (see McMillen and Smith, 2003: 333) the result of Frankfurt suggests that this region is polycentric. However, the CBD is Frankfurt and the other three core cities are the subcenters. Finally, this paper closes with some suggestions of future research that could include ‘anti-centers’ in the regression line to explain urban density, that could focus on truly comparative analyses, or that could imply panel data analyses with LWR instead of a cross-sectional approach.

IV.2.3 Second interim conclusions

The papers summarized in Sections IV.2.1 and IV.2.2 have shown that spatial disparities exist in all study regions. These disparities are different in their spatial extent across the regions and they also differ in their intensity. Thus, subcentering is present but the study regions are yet far from being explicitly polycentric in the sense of having several equally relevant centers.

Density maps based on z-scores (Figure 7) offered a purely visual therefore also subjective impression of spatial trends. Additionally, they are not based on statistical significance but on a threshold approach, which can easily be adjusted to show the desired picture. Thus, if a certain density value is defined as a threshold above which a spatial entity is considered a subcenter, the identified subcenters should be supported with further analyses. For that, density maps are restricted in their use as actual means of subcenter identification. Of course, similar adjustments can also be done for statistical procedures. However, this needs more justification as there is some agreement of standard significance levels, for example.

Subcenters as identified by LISA are understood as spatially contingent densifications or hot spots (high-high clusters, see Figure 8) in a predefined neighborhood. As the method is exploratory, there is formally no theory to substantiate the results. However, regional economic theory provides many contributions that offer fruitful and reliable strands of explanations for spatial densifications (see Sec. II.2.1). According to this dissertation's analytical orientation, Chicago School inspired explanations for the obtained result seem obvious. Yet the LISA is exploratory, that is, it only visualizes a pattern, which is why it does not necessarily exclude L.A. School based ways to explain the observed patterns. Agglomeration economies can be related to both schools as Storper and Scott (2009) have shown for the L.A. oriented way of argumentation, for example.

Subcenters identified by a LWR, on the contrary, are spatial entities whose employment density works in a gravitational manner: the closer a spatial entity, grid cell here, is to a center or subcenter, the more it is influenced by this (sub-) center. The assumption is that distances are the driving factor of agglomerations, which is why the spatial patterns obtained after applying the LWR are explained by theoretical considerations and models based on the monocentric city model inspired by Alonso (1964) (see Sec. II.2.1.1). Due to the modelling background, this method is deeply rooted in a Chicago School way of thinking.

Collecting the results from Krehl (2015b) and Krehl (2016) reveals that subcentering is an issue in the study regions. However, agreement regarding the number, size or location of the identified centers and subcenters cannot be reached. This conclusion is based on the contradictory notion of subcenters between LISA and LWR. Nonetheless, a spatial configuration of core city dominance can be concluded from all empirical analyses.[47]

[47] Some further work has been done with respect to characterizing subcenters as multidimensional entities based on a cluster analysis and a subsequent combined threshold approach. According to this approach hierarchies in the urban densifications can be identified, too. Although this combined cluster analysis and threshold based approach is spatially unconstrained from a technical point of view, the subcenters are predominantly identified within the administrative boundaries of the core cities (the region of Stuttgart is an exception in this respect).

Referring to the definitions of poly- and multicentricity in Section III.1, the results of Section IV.2 speak in favor of multicentricity in all city regions. The spatial configuration is multicentricity because the LWR-subcenters add some explanatory power to the model and the LISA cluster maps have shown that high-high clusters are mostly though not necessarily located within the core city's municipality. Polycentric spatial patterns cannot be observed as not one global subcenter is detected that is CBD-competitive. Rather, one could discuss whether the CBDs overwhelming influence (for a quantification, see Krehl, 2016: 16f., 19) suggests that all city regions are even monocentric.

V SYNOPTIC CONSIDERATION AND EVALUATION

Studying not only built but also employee density has permitted a more encompassing picture of urban spatial structure due to both more information and a value-added of jointly considering these variables. Krehl (2015a) has revealed that high density grid cells of employees and floor area often coincide and that both of them are subject to massive disparities, that is, few high density and many low density grid cells. However, it could also be shown that high built densities do not necessarily reflect in high numbers of employees (Figure 6). A quantification of these spatial (dis-) similarities has been given in Krehl (2015b: 300) revealing that correlations score between 0.63 and 0.71.[48] The LISA cluster maps shown in Figure 8 are another example of the value added by a joint consideration. Applying the local Moran's I separately to employees, employees in higher-order service sectors and built-up volume and comparing the corresponding LISA cluster maps points to a 'similarity in general but difference in details'-picture. Whereas one variable, say all employees, indicates several clusters of high densities in the Stuttgart region, this finding is complemented by a bi-polar structure if built-up volume is considered (Krehl, 2015b: 302, Figure 8 here).

Another benefit of considering both the socioeconomic and the built dimension of urban spatial structure is the possibility to elucidate interrelations between built and activity densities. Their joint consideration helps explaining the multifaceted nature of urban spatial structure (Krehl et al., 2016: 3). Considering intensities of use such as employees per m² floor area does not only permit a higher analytical depth but also reveals a region-wide positive relationship between employees, residents and built environment. Positive relationships have been expected a priori (see Sec. IV.2.1) but the analyses show that they are not necessarily clear cut and neither linear – and they vary substantially among the four study regions (Krehl et al., 2016: 15).

From a technical point of view, employees have been used in their gross density form, that is, employees per 1 km² grid cell, thus ensuring full comparability among all study regions due to identical reference areas (see Sec. II.2.2.3). Gross densities can be interpreted as an average density per grid cell. This point implies that a high gross density indicates a very highly densified grid cell, in which

[48] These numbers reflect rank correlations between employees, higher-order service sector employees and built-up volumes without residential use.

certain locations, such as business parks comprising of a few hundred hectares, might be even denser than the grid's displayed average density. For that, the gross density approach is reasonable to analyze polycentricity within a city region – it is much more detailed than the municipality level but sufficiently aggregate to produce interpretable patterns (see also Fina et al., 2014: 187 regarding heat mapping techniques due to too fragmented pictures at the block level).

V.1 Where are spatial densifications of activity in German city regions, that is, where are urban centers and subcenters?

My first research question was "Where are spatial densifications of activity in German city regions, that is, where are urban centers and subcenters?". My answer is that these densifications are mainly located in the core cities and to a lesser extent in the downtowns of close-by cities. These cities' downtowns mostly are the CBDs of legally designated medium sized centers ("Mittelzentren"). Thus, urban history and spatial planning decisions seem to spatially manifest in both employee and built densities on a grid level consideration. This finding is notable as spatial planning policies usually do not refer to spatial grids but to administrative units or entities defined by zoning regulations. In other words, centers and subcenters seem to be fairly path dependent meaning that history and historical settlement structures still matter today – a conjecture that is similar to the finding from Appold (2015: 426) and in line with the descriptions of Hohenberg (2004: 3029).

Initially, I have used both standardized and non-standardized density maps to illustrate the spatial distribution of employees and built-up volume (e.g., Krehl, 2015b; Krehl, 2016; Krehl et al., 2016). Especially non-standardized density maps are subjective in their interpretation and the spatial patterns they depict massively depend on the chosen thresholds. The latter issue could be mitigated by using the same thresholds for all city regions (Figure 4; for further maps, see also Siedentop et al., 2016b: 68f.). Thus, the patterns are interregional comparable and each of them less arbitrary than in a separate consideration. Standardized density maps have been shown in Krehl (2015b) and Krehl (2016). These maps are subject to the same problems and limitations as non-standardized density maps. However, their advantage is that high and low are not derived in relation to other study regions but in relation to the underlying data in each region. Combining all these density maps' results provides the following picture: core city dominance is complemented by substantial suburban densifications of smaller size (both geographically and in terms of employees, m² floor area or m³ built-up volume). Additionally, the density patterns follow rivers, high- and especially railways in traditionally industrialized regions. Thus, the conclusion is that subcentering is present but polycentricity in the sense of equally relevant densifications does not exist.

The LISA cluster maps' rationale is to visualize statistically significant spatial clusters of high and low activity as well as peaks (positive spatial outliers) and valleys (negative ones). Thus, the notion of centers and subcenters is an entity's 'distinctness' within a predefined neighborhood instead of a 'striking' value in absolute terms. The LISA cluster maps generated in Krehl (2015b) as well as in Fina et al. (2014) and Siedentop et al. (2016b) have revealed significant spatial densifications in all study regions and for employees, employees in higher-order service sectors and built-up volumes. According to the most encompassing and interregional comparative depiction in Krehl (2015b) the regions of Frankfurt and Cologne are inter-urban polycentric as almost all high-high clusters are located in the (traditional) CBDs of the separate core cities. Both the region of Stuttgart and the region of Munich are core city dominated as they are characterized by their respective core city. Yet, the analyses have shown that the Stuttgart region is multicentric identifying a large high-high cluster in downtown Stuttgart and several geographically smaller ones in neighboring cities, whereas the Munich region shows a quite monocentric spatial configuration. There is one dominating high-high cluster that covers nearly the whole city of Munich (Figure 8).

The third methodology to identify urban centers and subcenters has been the application of a LWR (Krehl, 2016). Starting from a monocentric city model, it is evaluated to what extent subcenters play a role in explaining the urban density surface. The results show that all subcenters are local, which means that their distance-decay effect is strong and that they only have an influence on their closer neighborhood but not on the entire region's employee density surface. Conversely, the distance to the predefined CBD is overwhelming (Krehl, 2016: 13, 19). Thus, the LWR indicates core city dominance in all city regions which masks much of the spatial variation in its neighborhood (see also Appold, 2015: 421 who finds similar results for some US metro areas[49]). A novel insight from the LWR analyses is that the multi-core cities of Frankfurt and Cologne turn out to be not polycentric in the sense of several core cities with similar relevance. Rather, these regions are, according to Section III.1, multicentric "with their subcentres being the 'non-largest' core cities" (Krehl, 2016: 23).

As a result, the following can be concluded based on density as a measure of polycentricity and a set of three conceptually different means to analyze the location of centers and subcenters: Due to an essentially fuzzy concept of polycentricity (see Sec. II.3.1) all study regions can be considered polycentric. However, if the definition of polycentricity of Section III.1 is applied, none of the regions is polycentric as urban densifications of similar size and relevance could not be detected by any of the methods used here. What I find is a core city dominated spatial pattern in all regions. These patterns are multicentric in the regions of Frankfurt, Cologne and Stuttgart and monocentric in the Munich region.

[49] This does not contradict my conclusions from Krehl (2016: 5f.) where I said that German and US-American regions are different. The conjectures regarding amongst others planning policies still hold. Moreover, the comparisons there were made between four German city regions (see Sec. III.2) and the Los Angeles region. Appold (2015: 421), however, refers his results to smaller city regions in the US.

V.2 Is there, and if so, what is the appropriate way to identify these densifications?

This multicentricity finding leads me to my second research question. I asked whether there was one appropriate way to identify urban densifications – and thus to implicitly characterize the urban spatial structure of a study region – and my answer is no. This answer is disenchanting at first but it does not mean that the choice of methods is irrelevant. Quite the contrary, this answer calls for special attention to the methodology chosen. One might even go so far as to say that it is inevitable to apply more than one method to analyze the complex and variegated nature of urban spatial structure.

I have shown in my papers summarized in Section IV that the method to identify urban centers and subcenters imposes distinct notions and conjectures about the spatial densification's nature. Against that background, *one* correct method conceptually cannot exist. This finding is well reflected in a large amount of studies dealing with urban spatial structure and (methods of) subcenter identification (see Sec. II.1; Sec. II.3.2 as well as Krehl, 2016; Siedentop et al., 2016b for further details). Yet the empirical analyses collected in this dissertation have, first, systematically analyzed this issue by applying several methods to the same study regions considering the same set of variables at the same spatial scale. The analyses here have, second, evaluated several methods' validity either with respect to the results' robustness by applying each method (e.g., density maps, Gini coefficients, global and local Moran's I) to several variables or with respect to the methods' transferability among nations and stability issues within the methods' parametrization (several LWR specifications).

The conclusion from all separate analyses is that spatial disparities exist in all study regions but hierarchies of both employees and floor space are not as pronounced as Zipf's law and the rank size rule suggest (Krehl, 2015a: 166; see Anderson and Bogart, 2001 or Meijers, 2008a: 1320 for similar results but in other study regions). Going one step further addressing spatial clustering reveals that clustering occurs and that it is – congruent with expectations from theory regarding KIBS (see Sec. II.2.1.2) – more explicit for higher-order service sector employees than for all employees (Figure 8). These LISA results are furthermore in line with the visual inspections from Krehl (2015a). A LWR approach has been applied to understand if gravitational forces are present and to analyze to which extent a monocentric city model applies to the study regions. It turns out that core city dominance is substantial in all study regions, but subcenters also add explanatory power to the model (Krehl, 2016: 19). This LWR result does not contradict the others but is complementary and helps to understand the complex and variegated nature of urban spatial structure. Addressing the functional profiles of urban densifications in another, so far unpublished, work also indicates that subcenters exist but most of them are located within the administrative area of the core city.[50]

[50] This paper, written by Stefan Siedentop and me, is oriented towards understanding urban centers and subcenters. Precisely, a typology of different urban centers and subcenters is aimed to. Thus, the idea is to complement the papers discussing how to find urban densification with another contribution that asks for the characteristics and functional profile of different centers and subcenters.

A synoptic consideration of these different methods contributes to addressing the analytical fuzziness of polycentricity. As a result, one appropriate measure does not exist, but it is appropriate to apply several measures and to both compare and combine the obtained findings. Therefore, the take-away for future research of analytically unclear issues is to choose a variegated approach and to thoroughly test and synoptically compare the results. If possible, a 'double-funnel' concept should be used, which permits to successively increase the level of detail. This means to start with a large-grained spatial scale and to end with a fine-grained one as well as to start with global measures and to end with site-specific analyses. Both local and global measures should furthermore be applied to all spatial scales (thus the name 'double-funnel'). Finally, the obtained results should be synoptically compared regarding their quantitative and qualitative similarity. This procedure does not solve the problem of analytical fuzziness, but it permits in-depth analyses and a multi-dimensional understanding of the phenomena under consideration.

From a theoretical point of view, the consequential step is to revisit each of the obtained results, to reconsider their underlying theoretical assumptions and to separately investigate to which extent these a priori conjectures (or hypotheses) prove to be correct for each measure and each spatial scale. After that it is to be evaluated whether the methods have contradictory suppositions of why – especially with regard to different spatial scales – diverging results might occur and how to ponder them in a synoptic interpretation and a joint evaluation of all results. This procedure does not solve the MAUP, but it helps to understand its effects on the results obtained and misleading interpretations thus might be avoided (see also Franklin and van Leeuwen, 2016: 9).

With regard to a measure's 'appropriateness' it should be noted that this is not least dependent on the research objective and the theoretical currents. According to the Chicago School a method or procedure is appropriate as long as it has a strong theoretical and modelling background (see Table 1). Thus, and quite in line with the suggested double-funnel concept suggested here, it is necessary to thoroughly analyze and systematically set on trial all methods, data and assumptions to determine whether they are appropriate. The L.A. School would not consider a purely quantitative measure appropriate as it is essentially oriented towards generalization, which is rejected in this school.

VI DISCUSSION: OWN RESULTS IN THE LIGHT OF CURRENT DEBATES

VI.1 Methodological implications

One research objective was to identify urban centers and subcenters in four selected German city regions. Thus, means of analysis were not only collected from the literature but also applied to different variables in four comparable study regions and thoroughly tested thereafter. It could be shown that a number of subsequent means of analysis (particularly global and local measures as well as all results' comparison) permits the analysis of urban spatial structure in general and polycentricity in particular, despite analytical and conceptual fuzziness. By collecting these analyses and discussing them in this dissertation, it could furthermore be clarified that the suggested double-funnel concept is necessary to understand “where […] things happen” as I have put it in the beginning (Sec. I.1, citing Thisse, 2010: 295).

In particular, the proposed double-funnel concept permits the following insights: different spatial scales have initially been used to address the MAUP from a descriptive point of view (see Krehl, 2015a; Siedentop et al., 2016b) and different measures have been applied to approach the analytical fuzziness of polycentricity (Krehl, 2015b; Krehl, 2016; Siedentop et al., 2016b for an overview). At the same time, it has been disclosed in each paper that the analyses are quantitative, but descriptive and mostly exploratory (LWR is the exception). For that, the methods were applied and discussed regarding their respective scopes and limitations in each of the contributions. As an overall result of all contributions summarized in Section IV, it can be concluded that the suggested double-funnel concept is useful to studying both analytically and conceptually unclear issues. Thus, this dissertation’s empirical contribution is informed evidence that a comparative, quantitative and consistent analysis of urban spatial structure is possible (see Sec. V).

The consideration of employee density and its resemblance in urban form has furthermore added another facet not only to the polycentricity and subcentering debates, but also to the discussion about urban densities in itself. Most density considerations in spatial planning refer to the built dimension (e.g., FARs and site coverages, see Sec. II.2.2.3) and residents (see Westphal, 2009 for several issues in this respect). What I could additionally provide in this work is a quantitative link between built densities and employee densities showing that they have a positive though not perfect (statistical) relationship (Krehl, 2015a; Krehl, 2015b). For that, the contribution is a more informed understanding of employee densifications and their resemblance in urban form. First comparisons of employee-to-resident ratios in the study regions have shown that employee densities are often reflected in a substantial number of residents thus indicating a mixed land use on the spatial level of 1 km² grid cells (see Krehl, 2016: 21). Thus, discussions in spatial planning regarding built and residential densities can be complemented by employee densities – all available at the spatial scale of 1 km² grid cells. As a result, this work might also establish a first link between comparatively abstract discussions about urban reconfigurations and polycentricity on the one hand and rather site-specific built density considerations in spatial planning on the other hand.

Yet, there is another aspect related to a methodological point: the papers dedicated to analyzing the polycentricity of German city regions in Section IV.2 are not only conceptually different to understand both if and if so to what extent the patterns change with a change in the methodology. Their conceptual difference also implies that the object of interest, the subcenters, has different notions (see Sec. IV.2.3). Thus, all papers’ results’ joint interpretation is that the identified differences regarding the number and size of urban centers and subcenters are not only due to the conceptually different methods, but also imply that there is not *the one* subcenter. In fact, the analyses put forward that 'subcenter' might be an umbrella term under which several types of different urban spatial densifications arise. The term 'subcenter' is primarily used in the literature to address urban densifications in general, that is, without specifying their functional profile, their particular location or their development history – a definition that has widely been used here, too (see Sec. III.1). Nevertheless, it should be discussed whether the connotation of a 'subcenter' in a US-American metro area denotes a quantitatively and qualitatively similar spatial phenomenon in a German city region. Based on all analyses conducted for this dissertation, I expect that an American-style subcenter connotation is too 'exaggerated' for the kind of densifications that I have identified here. One reason for that result certainly is that a 1 km² grid cell is hardly comparable to a full-fledged business 'gravity' center as described by Duranton and Puga (2015: 545) or as discussed in McMillen and Smith (2003). Still, the results from Krehl (2016) revealing that only local subcenters exist in the study regions speak in favor of a different term than subcenter for the identified densifications – maybe (sub-) urban densification is reasonable.

A further point to discuss here is the conceptualization and trajectory of urban spatial structure itself. It has been highlighted in Section II.3.2 and it is well reflected in a vast amount of studies dealing with urban spatial structure (see Sec. II.1) that the urban form of any city region is not solely determined by a number of preconditions or variables. I have discussed the variable issue above but there are some notable points to the trajectory/precondition issue, too, as identical preconditions may lead to opposing results as Cavailhès et al. (2007: 402) have stressed saying that "[D]ifferent types of spatial patterns may coexist under identical technological and economic conditions. It should be no surprise, therefore, to observe a variety of urban systems in the real world". Notably, these scholars derive their conclusion from a model-driven approach, which has proven that multiple stable equilibria exist. The debates about a (New) Chicago School versus L.A. School oriented approach to analyzing city regions go in a similar direction arguing that spatial contexts need to be considered as well. On the one hand, one might conclude from the citation above that any region is too special to be analyzed in a (comparative-) quantitative manner. This would be fairly in line with the L.A. School inspired way of investigation. On the other hand, this citation may be equally interpreted as a call for both more and more systematic comparative urban research. This claim is amongst others due to the fact that similar patterns may have different trajectories or have emerged out of different spatial and/or political contexts. From a (New) Chicago School's point of view, it is thus necessary to collect more data to identify the underlying patterns and causalities as well as to consider the political and spatial context of the region under consideration.

VI.2 Theoretical contextualization

How can the spatial patterns discussed in Section IV and V be explained and what do my analyses contribute in this respect? Referring to Angel and Blei (2016: 27f.) and their question whether firms that take benefit from agglomeration economies associated with proximity need to locate in a few employment centers or whether these firms simply need to locate in the same metropolitan area (see Sec. I.1), my analyses permit the following conclusion: substantial clustering of employees has been observed, but the majority of all employees are located outside the high-high clusters as identified by the LISA. Analyzing the high-high clusters for higher-order service sector employees, however, reveals that between 32% (Frankfurt region) and 61% (Munich region) are located in these clusters, although they cover only 4-7% of the entire study regions' area (Siedentop et al., 2015: 15). Complementary results have been obtained in Krehl (2016: 17): the local subcenters and their 'spheres of influence' cover between 7-27% of an entire region's area, whereas only 7-11% of all employees are located in these subcenters.[51] Thus, firms, implicitly captured by the number of employees per grid cell, tend to utilize agglomeration benefits from proximity especially in the Munich region, whereas firms in the Frankfurt and Stuttgart regions rather profit from being in the same metro area.

Drawing on the theoretical contributions from the monocentric Alonso-Mills-Muth model (see Sec. II.2.1.1), the LWR approach applied in Krehl (2016) has shown that distance to the CBD is the main explanatory variable of employee density. Nevertheless, suburban densifications have proven to be weakly relevant to explaining spatial employee density patterns. This result has been interpreted as persistent though not uncontested core city dominance (Krehl, 2016: 18f.). For that, it is similarly expected that agglomeration shadows are present.[52] Though essentially hypothetical in this dissertation, the rationale of agglomeration shadows would be in line with other research. One example is Partridge et al. (2009: 445) who find for US-county population growth that "there is some evidence [that] the largest urban areas cast growth shadows on proximate medium–sized metropolitan areas".

Despite prominent core city dominance, it has also been revealed in Section IV that spatial clustering occurs both in the core cities and in places close by (see Figure 8). It has been highlighted that employees in higher-order service sectors tend to be more spatially clustered than all employees. This finding has been expected and can be well explained with the whole bundle of agglomeration economies referring to proximity and density advantages. Drawing on the classifications provided in Section II.2.1.2, I suspect the following two types of agglomeration economies to be relevant to the spatial clustering observed for both all employees and employees in higher-order service sectors: *(i)* sharing, matching and learning (see Duranton and Puga, 2004; Puga, 2010), *(ii)* knowledge spillovers (see Storper and Venables, 2004; also Romero et al., 2014). The reason to suspect these two types is that they are essentially based on physical proximity and distance decay effects as well as on urban density. Additionally, these effects occur among people, whereas larger scale effects such as those described in the NEG (e.g., home market effects) refer to a larger or less detailed spatial scale.

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[51] Note that the CBD and the number of employees located there are not considered in these percentages.
[52] New and yet unpublished analyses where I omit the core cities strongly support this finding.

Finally, the aspect of planning policies and their spatial manifestation as well as the (economic) rationales behind has been touched upon in Section II.2.2 and thoroughly discussed in Krehl et al. (2016: 16). We have highlighted that spatial planning is especially relevant to urban density in terms of built-up volume as legal provisions set a maximum limits for the FAR for areas of certain types of use, such as residential, mixed or commercial use. These limits might explain the comparatively divergent LISA patterns of built-up volume as compared to those of employees (see Figure 8). Moreover, the assignment of central places can also be shown to spatially manifest in employee and built-up volume densifications in the city regions (see Sec. V.1 for a discussion).

Edge cities, which are often found in US-American city regions, are hardly detected in the analyses here. If one is familiar with the region of Frankfurt, it is possible to see two of them: the edge city of Eschborn (highlighted in Figure 8) and the relief location of Frankfurt-Niederrad (Figure 7: a single dark red square in the map of built-up volumes, which is located in the municipality of Frankfurt, southwest of the CBD). Due to these scarcities, it can be concluded that a 1 km² grid level is not sufficiently fine-grained to identify planned locations on an urban scale (see also the discussion of edge cities in Sec. II.1.1). Thus, the 1 km² grid level is more appropriate to analyze regional spatial patterns, such as polycentricity. The relevance of medium sized centers' CBDs can be assumed according to the LISA cluster maps in Figure 8 which shows significant clustering of employees in these cities. In combination with both the LWR results (Figure 10) and the hierarchies analyzed in Krehl (2015a), however, these centers prove that they are not full-fledged core city competitors but secondary centers – as spatial planning has designated it.

As an overall result, my contribution to the state of knowledge of theories explaining urban spatial structure is that it is necessary to consider not only one – probably highly abstract – urban or regional economic model. My analyses have rather shown that several conceptually different approaches are necessary to understand the variegated nature of urban spatial structure and thus several theoretical approaches are necessary as well. For that, the theoretical contribution is that the empirical 'double-funnel' concept needs complementation by a qualitative or quantitative consideration of political, cultural and historical contexts. With the informed quantitative understanding of urban spatial structure, which I have provided above, it becomes feasible to formulate, test and refine such theoretical considerations.

Similar to the claims outlined by Bourne (2008) it is furthermore necessary to thoroughly test and refine established theories primarily rooted in US-American urban development patterns. The contributions of both Old and New Chicago School and L.A. School are based on certain developments observed in US-American metro regions. However, it is yet not clear, to what extent these can be – if at all – transferred to German or European city regions. My LWR results have shown that the urban spatial structures differ substantially, not least due to the regions' different geographical sizes. However, it is not granted that similar spatial patterns are driven by the same causalities, and similarly, that identical causalities might result in different spatial outcomes due to political or other contextual and cultural contexts, for example. Based on the empirical procedure suggested and applied in this dissertation, it would be possible to address these issues thus deriving middle-range theories for cross-national comparative urban research. Therefore, my contribution to further developments in urban theory is a solid quantitative-analytical base regarding urban spatial structure which can serve as a platform to test and refine schools such as New Chicago, that is, to also go beyond them.

VI.3 Limitations of the work

Nevertheless, there are some limitations to my work that should not remain unaddressed. I have considered one point in time (cross-sectional analysis). Thus, any kind of performance or growth analysis has been precluded. Additionally, information on the spatial scale of 1 km² grid cells could not be obtained for variables measuring, for example, economic success and performance, such as gross domestic product per capita or capital-to-labor ratios, as suggested by Meijers and Burger (2010: 1391f.) or the share of residents below the poverty line as suggested by Arribas-Bel and Sanz-Gracia (2014: 992f.). It would have been instructive to analyze the efficacy of agglomeration economies and diseconomies on the spatial level of grid cells but with respect to the entire study regions. Other studies have addressed similar issues concluding that agglomeration economies have different geographical scopes (e.g., Gordon and Richardson, 1996; Melo et al., 2017; Parr, 2002a).

Built-up volumes or FARs have not been considered for the LWR approach because its essentially gravitational nature does not seem reasonable for built-up volumes. Although it has been proven that built-up volumes, floor area, employees and employees in higher-order service sectors show significantly positive correlations (Krehl, 2015b: 300; Krehl et al., 2016: 14), built areas are conjectured to be restricted by planning law rather than to be driven by economic agglomeration forces. Although the data do not permit a causal interpretation, the LISA measures (Krehl, 2015b) and the findings from Fina et al. (2014) and Krehl et al. (2016) provide evidence of this conjecture. This does not mean, however, that economic development can be decoupled from the development of built structures and urban form. It rather calls for a thorough analysis and consideration of contextual aspects, such as specific spatial planning regulations and special permissions for, for example, higher inner city densities than a FAR of 3.0.

Regarding agglomeration economies it should be noted that the term is used rather “impressionistically” (Parr, 2002b: 152) here, too. Due to the exploratory approaches towards spatial clustering in this dissertation (particularly Krehl, 2015a and Krehl, 2015b), an explanation to what extent agglomeration (dis-) economies are actually responsible for these spatial outcomes has to remain for future research. The same is true for a consideration regarding the channels through which these economies operate as different economic reasons are possible (see Sec. II.2.1.2).

VII CONCLUDING REMARKS AND PROSPECTS OF FUTURE RESEARCH

This dissertation has contributed to a more comprehensive analysis of polycentricity by systematically analyzing four German city regions regarding their polycentricity of both the socioeconomic and the built dimension (i.e., employees, employees in higher-order service sectors, built-up volume and floor area). Additionally, combining the separate publications this cumulative dissertation is based upon, relating them conceptually and making a synoptic comparison of their results has particularly added to an informed understanding of polycentricity. Insights were gained by visualizing the spatial manifestation of agglomeration economies (i.e., spatial densifications of employees and their resemblance in urban form), the degree of polycentricity (i.e., number, size and location of subcenters as well as considerations regarding concentration and spatial association), and the interplay between built environment and socioeconomic activity (i.e., intensities of use). Similarly, explanations for the identified patterns of (sub-) urban densifications have been taken from both urban economic theory and from spatial planning. Thus, empirical contributions have been made to especially two issues: *(i)* a new, comprehensive data set has been applied to four selected German city regions permitting both spatially and content-wise more detailed analyses than before, and *(ii)* a procedure has been suggested to quantitatively analyze morphological polycentricity, despite its conceptual and analytical fuzziness.

It has been shown that secondary cities in each region are comparatively densely populated and appear as high-high clusters in some of the LISA cluster maps (see Krehl, 2015b). These cities are, especially in the Stuttgart and partly also in the Frankfurt region, medium sized centers thus having to fulfil certain functions defined by legally binding planning provisions. Thus, there are hints that spatial planning has an effect on the location and development of (sub-) urban densifications – at the spatial scale of 1 km². Yet unpublished work by Stefan Siedentop and me, for example, suggests that land consumption is among the characterizing features of different subcenter types. However, to what extent these designations caused the spatial densifications or whether it has rather been history and/or economic forces that caused spatial clustering could not be entangled here.

From a modelling point of view, the cross-sectional and mostly exploratory analyses conducted here contribute little to directly refining existing models or combining separate stands into new models. However, contributions were made regarding the refinement of theories, which can be 'translated' into models and test procedures in a second step. It has been this dissertation's objective to analyze the conceptual and methodological challenges associated with polycentricity. As a result, I have provided an informed quantitative understanding of the urban spatial structure in four study regions. Additionally, I have qualitatively compared the obtained spatial patterns to similar analyses conducted in US-American regions finding that the spatial patterns differ substantially (see Sec. IV.2.2). Thus, my work has revealed some limitations of economic theory: although urban and regional economic theory assumes the same forces to be effective, it fails to explain the divergent patterns in the US and Germany. Consequently, these standard theories have to be complemented by contextual aspects such as geography, history, planning policy and political or institutional frameworks (see Sec. VI.2).

Another, less purely academic prospect of future research is to further analyze the polycentricity issue itself. It would be informative to have a deeper understanding of the efficiency both of polycentricity in general and different center and subcenter types in particular. A fundamental issue in this respect could be: which subcenter types are most successful? Depending on the definition of success, aspects worth consideration could be *(i)* economic performance of different subcenter types, *(ii)* a subcenter's ability of borrowing size from another subcenter or from the center thus realizing efficiency gains, or *(iii)* different subcenter types' resilience capacities. From a planner's perspective it might additionally be relevant to know if – and if so to what extent – differences exist between rather supply-driven and rather demand-driven centers and subcenters.

Understanding these aspects and the inherent mechanisms in more detail would be valuable for both science and society. If scientists understood the mechanisms at work in more detail, they could provide more thorough analyses, make more precise forecasts, and offer more solid information bases to decision makers. Society would therefore gain from better informed decisions made by stakeholders resulting in more beneficial outcomes – in economic, social and/or ecological respect. Further aspects society might benefit from in the long run could be more livable urban densities. The density concept regarding, for example, health and microclimatic effects has been sketched in Section II.2.2.3. Densities and their relevance to urban agglomeration effects have been outlined in Section II.2.1.2. Bringing these together and understanding whether more or less subcenters of certain densities are more or less favorable would be a valuable contribution more livable cities in a more prosperous and healthy environment.

This dissertation made some contributions to this broader issue: the analysis of urban densifications, these urban (sub-) centers' spatial location and potential explanations of the identified spatial patterns. Revisiting the statement by Thisse (2010: 295)[53] and the leading research questions of this dissertation have highlighted that it is essential to know "where things happen". Thus, knowing how to find statistically significant urban densifications, that is, centers and subcenters, in poly- and multicentric city regions is the first step. Understanding their rationale, number, size and location is a second one. These two steps have been suggested, made and discussed here. Similarly, suggestions have been outlined how to proceed further regarding the rationales of urban centers and subcenters. The consequential third step is to understand these issues over time, implying causalities and trajectories, performance, and normative evaluations. At this point in time, precisions of step three are still up in the air – a broad field for future research and thus another rewarding direction regional science could go.

[53] "If we academics wonder about why cities exist and grow (or shrink) and why sizable and persistent gaps between and within countries occur, what people and policy-makers care about is where these things happen."

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A. Appendix

A.1 Formalities and technical aspects

This dissertation is cumulative, which means that its empirical core is based on a number of peer-reviewed journal papers. According to the PhD Regulations of the Faculty of Spatial Planning of TU Dortmund University each of the journal papers has to meet the following criteria:

- It must have a length of at least 30 000 characters or in the case of joint authorship the PhD student has to have contributed at least 30 000 characters.
- At least two of the articles must have been published and a third article must have been accepted for publication by the time the dissertation is submitted.
- Each paper has to be written either exclusively by the PhD student or the PhD student has to be the corresponding author.
- There should be no substantial overlapping content between the articles submitted.

Additionally, these journal papers have to be framed by a text which documents that papers are thematically associated. Last but not least, in all cases of non-exclusive authorship the PhD student's contributions to the papers have to be highlighted. The exact and legally binding German wording regarding these formalities is given in §10 of the PhD Regulations of the Faculty of Spatial Planning of TU Dortmund University as of September 3rd, 2015. Appendices A.2 and A.3 (here) give a compact overview of both the peer-reviewed papers satisfying the formal requirements (A.2) and further peer-reviewed journal papers and book sections used in this dissertation (A.3). All full texts are attached in Appendix C.

This dissertation originates from the project "The polycentricity of German metropolitan areas – development of a remote sensing-based approach for measuring morphological polycentricity" funded by the German Research Foundation under grant SI 932/4-1 and TA 800/1-1. For that, some basic decisions such as the choice of the study regions have been made in advance and have not been an essential part of this dissertation.

The DFG project's initial objective was to develop, apply and analyze the potentials of remote sensing data to investigate on the polycentricity of four selected German city regions. However, in the course of the proposal being submitted and granted it turned out that not only earth observation data have been available but also fine-grained data regarding employees subject to social insurance. Thus, the project's scope has been widened to capture both data of socioeconomic activity and of urban form to analyze German city regions' polycentricity. The potentials of combining these data are, therefore, one pillar of this dissertation.

A.2 Journal papers meeting the formal requirements of a cumulative dissertation

(1) **Urban spatial structure: an interaction between employment and built-up volumes**
Krehl A (2015) Urban Spatial Structure: An Interaction between Employment and Built-up Volumes. *Regional Studies, Regional Science* 2(1): 290–308. doi:10.1080/21681376.2015.1034293

(2) **Urban subcentres in German city regions. Identification, understanding, comparison.**
Krehl A (2016) Urban subcentres in German city regions: identification, understanding, comparison. *Papers in Regional Science*: n/a. doi:10.1111/pirs.12235

(3) **A Comprehensive View on Urban Spatial Structure: Urban Density Patterns of German City Regions**
Krehl A, Siedentop S, Taubenböck H and Wurm M (2016) A Comprehensive View on Urban Spatial Structure: Urban Density Patterns of German City Regions. *ISPRS International Journal of Geo-Information* 5(6): n° 76. doi:10.3390/ijgi5060076

A.3 Additional publications supporting this dissertation's content and idea

(4) **Getting Closer! New Ways of Integrating Geodata, Statistics and Remote Sensing to Analyze and Visualize Urban Structures Using Density Surfaces and –Profiles.**
Fina S, Krehl A, Siedentop S, Taubenböck H and Wurm M (2014) Dichter dran! Neue Möglichkeiten der Vernetzung von Geobasis-, Statistik- und Erdbeobachtungsdaten zur räumlichen Analyse und Visualisierung von Stadtstrukturen mit Dichteoberflächen und -profilen. [Getting Closer! New Ways of Integrating Geodata, Statistics and Remote Sensing to Analyze and Visualize Urban Structures Using Density Surfaces and –Profiles] *Raumforschung und Raumordnung* 72(3): 179–194. doi:10.1007/s13147-014-0279-6

(5) **Polyzentralität in deutschen Stadtregionen – eine integrierte Bestandsaufnahme**
Krehl A (2015) Polyzentralität in deutschen Stadtregionen – eine integrierte Bestandsaufnahme [Polycentric spatial patterns in German city regions – an integrated perspective]. In: Taubenböck H, Wurm M, Esch T and Dech S (eds) *Globale Urbanisierung – Perspektive aus dem All*. Berlin Heidelberg: Springer Spektrum, 159–170. doi:10.1007/978-3-662-44841-0_17

(6) **Morphologische Polyzentralität der Beschäftigung in deutschen Metropolregionen – Aktuelle Befunde und Veränderungen seit 1970**
Siedentop S, Krehl A, Guth D and Holz-Rau C (2016) Morphologische Polyzentralität der Beschäftigung in deutschen Metropolregionen – Aktuelle Befunde und Veränderungen seit 1970 [Morphological polycentricity in German metropolitan areas – current state and changes since the 1970s]. In: Danielzyk R, Münter A and Wiechmann T (eds) *Polyzentrale Metropolregionen*. Lemgo: Verlag Dorothea Rohn, 45–75.

(7) **Die bauliche Dichte der Stadtregion – Erzeugung kleinräumiger Dichtedaten mit fernerkundlichen Mitteln**
Siedentop S, Krehl A, Taubenböck H and Wurm M (2014) Die bauliche Dichte der Stadtregion – Erzeugung kleinräumiger Dichtedaten mit fernerkundlichen Mitteln [Built density of city regions – developing spatially fine-grained density data using remote sensing techniques]. In: Meinel G, Schumacher U and Behnisch M (eds) *Flächennutzungsmonitoring VI: Innenentwicklung - Prognose - Datenschutz*. Berlin: Rhombos, 179–188.

B. Erklärungen und Eidesstattliche Versicherung

Die Dissertation ist nicht in der gegenwärtigen oder in einer anderen Fassung oder in Teilen an der Technischen Universität Dortmund oder an einer anderen Hochschule im Zusammenhang mit einer staatlichen oder akademischen Prüfung bereits vorgelegt worden.

Hiermit erkläre ich an Eides statt, dass ich meine Dissertation mit dem Titel „Analyzing Polycentricity. Conceptual Issues and Methodological Challenges“ selbstständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe und dass ich alle Stellen, die ich wörtlich oder sinngemäß aus anderen Veröffentlichungen übernommen habe, als solche kenntlich gemacht habe.

Dortmund, 14.12.2016

(Angelika Krehl)

C. Full-texts of own publications in alphabetical order

Accepted manuscript version
The final publication is available at Springer via http://dx.doi.org/10.1007/s13147-014-0279-6.

Fina, S., Krehl, A., Siedentop, S., Taubenböck, H., & Wurm, M. (2014). Dichter dran! Neue Möglichkeiten der Vernetzung von Geobasis-, Statistik- und Erdbeobachtungsdaten zur räumlichen Analyse und Visualisierung von Stadtstrukturen mit Dichteoberflächen und -profilen. Raumforschung und Raumordnung, 72(3), 179–194. doi:10.1007/s13147-014-0279-6

Dichter dran! Neue Möglichkeiten der Vernetzung von Geobasis-, Statistik- und Erdbeobachtungsdaten zur räumlichen Analyse und Visualisierung von Stadtstrukturen mit Dichteoberflächen und -profilen

Stefan Fina, Angelika Krehl, Stefan Siedentop, Hannes Taubenböck, Michael Wurm

Zusammenfassung

In der Stadtforschung und Stadtplanung fungiert die „Dichte“ als eines der wichtigsten Maße für die Beschreibung der baulichen Physis einer Stadt. Im Vergleich zu anderen Maßen – genannt seien beispielhaft die „Nutzungsmischung“, die „Polyzentralität“ oder die „Kompaktheit“ – erscheint die „Dichte“ auf den ersten Blick als objektiv ermittelbar und gut verständlich. Bei näherer Betrachtung handelt es sich jedoch um ein Konzept, das sich einer einfachen empirischen Ermittlung weitgehend entzieht. Bis heute gibt es kein international anerkanntes Dichtemaß und Dichteangaben für verschiedene Länder, Regionen und Städte sind in der Regel nicht oder nur eingeschränkt vergleichbar. In diesem Beitrag werden die analytischen Möglichkeiten neuer Geodatenanwendungen für eine objektive und transparente Ermittlung der baulichen und nutzungsbezogenen Dichte städtischer Siedlungsgebiete aufgezeigt. Eine Fallstudie für das Gebiet der Stadt Köln demonstriert an ausgewählten Themen die Einsatzmöglichkeiten kleinräumiger Dichtedaten.

Schlüsselwörter

Dichte | Bauliche Dichte | Nutzungsdichte | Monitoring | Fernerkundung | Köln

Getting Closer! New Ways of Integrating Geodata, Statistics and Remote Sensing to Analyze and Visualize Urban Structures Using Density Surfaces and -Profiles

Abstract

In urban research and planning, “density” is one of the most important measures to analyze a city’s structural morphology. Compared to other measures such as “neighborhood mix of uses”, “polycentricity” or “compactness”, density seems to be a rather objective and comprehensible choice. However, when having a closer look at it, it is a rather complex concept with different measurement options. There is no internationally accepted standard for the implementation of density or density measures that would allow for a robust comparison of different countries, regions or cities. This article deals with the analytical opportunities that new geodata options offer with regards to an objective and transparent measurement of cities' structural and use-related densities. A case study for the city of Cologne demonstrates possible applications based on high-resolution and disaggregated density data.

Keywords

Density | Built-up density | Urban density | Monitoring | Remote sensing | Cologne

1 Einführung

In der Stadtforschung und Stadtplanung fungiert die „Dichte" als eines der wichtigsten Maße für die Beschreibung der baulichen Physis einer Stadt, ihrer Form und ihrer Struktur (vgl. Acioly Jr./Davidson 1996; Churchman 1999; Roberts 2007; OECD 2012). Dichteindikatoren kommt sowohl als deskriptive als auch als normative Größe Bedeutung zu. Die physische Dichte anthropogener Aktivität wie des Wohnens und Arbeitens gilt als Schlüsselfaktor bei der Erklärung von standörtlichen Unterschieden des Verkehrsverhaltens (Newman/Kenworthy 1989; Forsyth/Oates/Schmitz et al. 2007; Ewing/Bartholomew/Winkelman et al. 2007; Ewing/Cervero 2010), der Gesundheit der Bevölkerung (Kelly-Schwartz/Stockard/Doyle et al. 2004; Hinde/Dixon 2005), der Kosten für die Bereitstellung infrastruktureller Leistungen (Doubek/Zanetti 1999; Burchell/Mukherji 2003; Siedentop/Schiller/Gutsche et al. 2006), der ökonomischen Prosperität und Innovationsfähigkeit (Bettencourt/West 2010; OECD 2012) und der mikroklimatischen Bedingungen einer Stadt (Watkins/Palmer/Kolokotroni 2007; Kropp/Holsten/Lissner et al. 2009).

Die empirische Forschung konnte zeigen, dass mit zunehmender baulicher Verdichtung einer Stadt der Anteil der zu Fuß, mit dem Fahrrad oder mit öffentlichen Verkehrsmitteln zurückgelegten Wege steigt, da Wegelängen geringer ausfallen und die Bedienungsqualität des öffentlichen Verkehrs immer besser wird (OECD 2010 mit zahlreichen weiteren Nachweisen; OECD 2012). Das höhere Maß an nicht-motorisierter Mobilität in verdichteten Stadtgebieten verringert die Emissionen von Luftschadstoffen und Klimagasen und hat nachweislich positive Auswirkungen auf gesundheitliche Parameter der Bevölkerung (Frank/Engelke 2001). Höhere Dichten steigern ferner die Effizienz technischer Infrastrukturen, weil die Kapitalaufwendungen für die Vorhaltung von Ver- und Entsorgungsleistungen auf eine höhere Zahl von Nutzern umgelegt werden können (vgl. z. B. Siedentop/Schiller/Gutsche et al. 2006: 6 ff. mit weiteren Nachweisen). Neuere Forschungsergebnisse zeigen darüber hinaus, dass der Grad der Verdichtung auch positive ökonomische Effekte nach sich zieht. So konnten Bettencourt und West (2010) zeigen, dass die Größe und Dichte von Städten eine exzellente Schätzgröße für die ökonomische Produktivität (Bruttoinlandsprodukt je Einwohner), das Einkommensniveau oder die Anzahl der Patente je Einwohner darstellt.

Hohe Dichten haben indes auch Nachteile, da sie mit höheren lufthygienischen sowie mikroklimatischen Belastungen einhergehen können. So ist die Vulnerabilität verdichteter Stadtbereiche in Bezug auf sommerliche Hitzestressphasen und die mit diesen verbundenen gesundheitlichen Risiken signifikant höher als in vorstädtischen oder ländlichen Siedlungsgebieten (Koppe/Kovats/Jendritzky et al. 2004). Hoch verdichtete Bereiche können ferner von Defiziten der Freiraumversorgung betroffen sein. Schließlich wurde mit der sogenannten „Crowding-Forschung" die Relevanz der Dichte als sozialpsychologischer Stressfaktor intensiv untersucht. Bis heute herrscht über die Wirkungen hoher Dichten auf die menschliche Psyche allerdings kein Konsens (vgl. ausführlich Newman/Hogan 1981; Churchman 1999).

Im Vergleich zu anderen Maßen der baulichen Form von Städten – genannt seien beispielhaft die „Nutzungsmischung", die „Polyzentralität" oder die „Kompaktheit" – erscheint die „Dichte" auf den ersten Blick als eine einfache, objektive, gut verständliche und leicht handhabbare Größe. Bei näherer

Betrachtung handelt es sich jedoch um ein Konzept, das sich einer einfachen empirischen Auseinandersetzung weitgehend entzieht. So wies Churchman Ende der 1990er Jahre (Churchman 1999: 390) darauf hin, dass es bis zum damaligen Zeitpunkt kein international anerkanntes Dichtemaß gab und dass Dichteangaben für verschiedene Länder, Regionen und Städte in der Regel nicht oder nur eingeschränkt vergleichbar sind, wenn sie aus verschiedenartigen Quellen stammen. Diese Feststellung kann nach wie vor Gültigkeit beanspruchen.

Unstrittig ist, dass Dichte ein Verhältnismaß von Objekten (dies können etwa Individuen, Arbeitsplätze oder Wohneinheiten sein) und einer Bezugsfläche darstellt, auf der diese Objekte verortet sind (vgl. ausführlich Westphal 2008: 38). Dichte wird mit einem Bruch aus der Menge der Objekte (im Zähler) und der Größe der Bezugsfläche (im Nenner) ausgedrückt. Eine grundsätzliche Unterscheidung kann zwischen baulichen Dichten und Nutzungsdichten vorgenommen werden. Bauliche Dichten beziehen sich auf die räumliche Verteilung von Baumassen, während Nutzungsdichten die Intensität der menschlichen Nutzung besiedelter bzw. bebauter Flächen ausdrücken. Erstere sind naturgemäß eher statischer Natur, da sich bauliche Strukturen zumindest in einem größeren räumlichen Zusammenhang nur sehr langsam verändern. Demgegenüber unterliegen Nutzungsdichten stetigen Veränderungen, da die ihnen zugrunde liegenden demographischen, ökonomischen und sozialen Prozesse äußerst dynamisch sind.

Im empirischen Umgang mit der Dichte einer Stadt oder eines Stadtraumes treten mannigfaltige Probleme auf, die zum einen konzeptioneller Natur sind, zum anderen mit Restriktionen bei der Verfügbarkeit von Grunddaten erklärt werden können. So leidet die Validität und Interpretierbarkeit von Dichteangaben häufig unter einer fehlenden oder unscharfen Definition des räumlichen Bezugs (Forsyth 2003: 3). Vielfach bleibt unklar, ob eine Dichte als Brutto- oder Nettogröße zu interpretieren ist, da nicht deutlich wird, welche Arten von Flächen (Grundstücksflächen, Erschließungsflächen, sonstige Siedlungsflächen) in die Dichteberechnung eingegangen sind. Zudem entstehen bei der Erhebung von Dichtewerten praktische Probleme, da die erforderlichen Grunddaten nicht immer verfügbar sind. Das betrifft vor allem die Ermittlung von baulichen Dichten auf der Ebene von Parzellen oder größeren Raumeinheiten. Aber auch Einwohner- oder Arbeitsplatzdichten lassen sich nicht immer in der gewünschten räumlichen Körnigkeit ermitteln, da die Verfügbarkeit von Strukturdaten auf der untergemeindlichen Ebene eingeschränkt ist.

Die flächenhafte Verfügbarkeit von Geodaten, mit denen nicht nur die Bodennutzung, sondern auch die Höhe baulicher Anlagen modelliert werden kann, bietet vor diesem Hintergrund vollkommen neue Möglichkeiten, diese Lücke zu schließen. Möglich werden großflächige Massenberechnungen und aus diesen abgeleitete Dichtemaße wie beispielsweise die Geschossflächenzahl. Vorteile ergeben sich durch

- die Objektivierbarkeit der Dichteberechnung, da sich Gebäudehöhen und -volumen eindeutig ermitteln lassen,
- die hohe räumliche Auflösung der Daten und die Möglichkeit ihrer Aggregation in beliebigen Raumbezugssystemen (wie Baublöcke, statistische Bezirke oder Raster),
- die großflächige Verfügbarkeit zu vergleichsweise moderaten Kosten und
- die einfache Verknüpfbarkeit mit demographischen und sozioökonomischen Strukturdaten, sofern diese auf untergemeindlicher Ebene vorliegen.

Hinzu kommt, dass auch demographische und ökonomische Strukturdaten verstärkt kleinräumig verfügbar sind. So hat beispielsweise die jüngst erfolgte Georeferenzierung der Beschäftigungsstatistik durch das Forschungsdatenzentrum der Bundesagentur für Arbeit im Institut für Arbeitsmarkt- und Berufsforschung (IAB) neue Möglichkeiten für die Untersuchung untergemeindlicher Verteilungsmuster der Arbeitsplätze eröffnet (vgl. Scholz/Rauscher/Reiher et al. 2012: 4 ff.). Ähnliches kann für die Bevölkerungsstatistik ausgesagt werden, da auch hier neue Datenangebote existieren. Verwiesen sei auf die Innerstädtische Raumbeobachtung des Bundesinstituts für Bau-, Stadt- und Raumforschung (BBSR) oder den KOSTAT-Datensatz der kommunalen Statistikämter.[1]

In diesem Beitrag sollen die analytischen Möglichkeiten neuer Geodatenanwendungen für die Ermittlung der baulichen und nutzungsbezogenen Dichte städtischer Siedlungsgebiete aufgezeigt werden. Nach einer knappen Darstellung des wissenschaftlichen Hintergrunds (Kap. 2) wird die methodische Vorgehensweise bei der Erzeugung kleinräumig differenzierter Dichtedaten vorgestellt. Ausführlich wird dabei auf die Erhebung von geometrisch detaillierten räumlichen Grundlagendaten mit Methoden der Erdbeobachtung eingegangen (Kap. 3). Anhand einer kommunalen Fallstudie (Stadt Köln) soll in einem weiteren Schritt das analytische Potenzial der auf diese Weise erzeugten Informationen für die Stadtforschung und -planung aufgezeigt werden (Kap. 4). Ziel ist es letztendlich, ein umfassendes Bild der Morphologie einer Stadt zu erzeugen und die methodisch-analytischen Möglichkeiten diesbezüglicher Daten in verschiedenen Anwendungsbereichen der Stadt- und Raumforschung sowie der Planungspraxis aufzuzeigen. Abschließend erfolgt ein knappes Fazit mitsamt einer Diskussion perspektivischer Anwendungsmöglichkeiten des Datenbestands (Kap. 5).

2 Wissenschaftlicher Hintergrund

Die Diskussion um die ‚richtige' oder die ‚angemessene' Dichte einer Stadt und ihrer Teilräume ist vielleicht so alt wie die Disziplin der Stadtplanung selbst und sie kann zweifelsohne als eine der kontroversesten gelten (Gassner 1994; Westphal 2008). „Dichte" ist ein ausgeprägt interdisziplinäres Konzept (vgl. ausführlich Roskamm 2011), dessen Bedeutungsgehalt im Zeitverlauf immer wieder Veränderungen ausgesetzt war. Unstrittig ist, dass die Wahrnehmung und Bewertung von Dichte in hohem Maße kulturellen und sozialen Prägungen unterliegt (Acioly/Davidson 1996: 6). Ein objektiver Maßstab, mit dem bauliche oder nutzungsbezogene Dichten als „hoch", „gering" oder gar als „angemessen" zu bewerten sind, kann vor diesem Hintergrund nicht erwartet werden.

Der Umgang mit dem „Konzept Dichte" ist aber nicht nur aus normativ-planerischer Perspektive problembehaftet. Auch eine objektive Messung der städtischen Dichte ist verschiedenen Restriktionen ausgesetzt, die in der Einleitung bereits angesprochen wurden. Grundsätzlich gilt, dass die Schwierigkeiten der Ermittlung von Dichtewerten positiv mit dem zugrunde gelegten Maßstab korrelieren. Insbesondere auf der Ebene von Parzellen, Blockseiten oder Baublöcken fehlt es häufig an genauen und aktuellen Dichtewerten. Der Grund hierfür ist, dass die amtliche Statistik in Deutschland im Regelfall keine Daten unterhalb der Gemeindeebene bereitstellt (bzw. bereitstellen darf). Studien, die sich auf eigene Erhebungen (z. B. durch Ortsbegehungen) oder auf private Geodatenangebote stützen, sind entweder aus Aufwandsgründen oder aus Gründen der intransparenten Validität der Daten in ihren Möglichkeiten eingeschränkt. Bis heute werden Dichtestudien meist in Form von kommunalen Einzelanalysen durchgeführt (vgl. z. B. Landeshauptstadt Stuttgart 2005), deren Ergebnisse oftmals nur begrenzt mit anderen Kommunen oder Gebietseinheiten vergleichbar sind.

Die Modellierung von urbanen Dichteoberflächen und -profilen leidet daher an einer geringen räumlichen Körnigkeit. Dies wirkt sich nicht nur negativ auf die Planungspraxis aus (z. B. im Rahmen der Modellierung von Lärmbelastungen oder der Durchführung von klimatischen Vulnerabilitätsstudien), sondern behindert auch die Stadt- und Raumforschung. Die Bedeutung der Dichte als Schätzgröße bei der Erklärung der räumlichen Varianz bestimmter Phänomene (wie z. B. der standortspezifischen Verkehrsmittelwahl oder der Infrastrukturkosten) stellt eigentlich hohe Anforderungen an die Qualität

[1] Vgl. http://www.staedtestatistik.de/kostat.html (17.01.2014).

verfügbarer Daten. In vielen Studien müssen jedoch einfache Bevölkerungs- oder Siedlungsdichten verwendet werden, da präzisere Dichteindikatoren nicht verfügbar sind.

Besonders große Schwierigkeiten entstehen bei der Abbildung baulicher Dichten. Meistens bezieht sich dies auf das Verhältnis von Gebäudegeschossfläche oder -volumen zur Grundfläche. Ein Standardindikator ist dabei die Geschossflächenzahl bzw. -dichte (GFZ bzw. GFD, im Englischen als *Floor Area Ratio*, *Floor Space Ratio* oder *Floor Space Index* bezeichnet). Die Ermittlung der Geschossflächendichte ist voraussetzungsvoll, weil in der Regel keine amtlichen Erhebungen zu Gebäudemaßen (z. B. Volumen- oder Höhenangaben) verfügbar sind. Zwar existieren viele Studien, die auf der Ebene von ausgewählten Baugebieten oder Strukturtypen Spannbreiten der baulichen Dichte (z. B. die GFZ) angeben. Häufig sind deren Ergebnisse aber nicht vergleichbar, da unterschiedliche Definitionen von Dichte verwendet werden oder sich die Vorgehensweise bei der Erhebung unterscheidet.

Dies lenkt den Blick auf ein zweites, eher konzeptionelles Problem: Der Umgang mit Dichteindikatoren leidet häufig unter einer nicht präzisen Definition der Bezugsfläche. So ist zum Teil nicht immer deutlich, ob die Gesamtfläche einer Gebietseinheit oder nur die von einer bestimmten Nutzung belegte Fläche (z. B. Wohnbaufläche) in die Berechnung eingeht. In derartigen Fällen bleibt es unklar, ob sich die Angabe als Brutto- oder Nettodichte interpretieren lässt. Bei einer Nettodichte werden die gezählten Objekte auf die relevante Nutzfläche bezogen (z. B. die Anzahl der Einwohner auf Wohnbauflächen). Sonstige Bodenflächen wie Verkehrserschließungsflächen, Grün- und Erholungsflächen, gewerbliche Nutzungen oder gar land- und forstwirtschaftlich genutzte Flächen bleiben unberücksichtigt. Nettodichten informieren in weitaus geeigneterer Form über die „Realität" der Verdichtung, da sie weniger stark vom räumlichen Zuschnitt des Untersuchungsraumes abhängig sind. Das sogenannte *Modifiable Areal Unit Problem (MAUP)*, wonach die Aggregation von Messergebnissen zu räumlichen Phänomenen (z. B. Dichtewerte) mit der Größe des zugrunde gelegten Untersuchungsgebiets variiert, kann durch die Verwendung von Nettodichten begrenzt werden (vgl. Abb. 1; vgl. auch Forsyth 2003). Ein Großteil der in der Literatur anzutreffenden Dichteangaben sind allerdings Bruttodichten (vgl. z. B. Senatsverwaltung für Stadtentwicklung und Umwelt Berlin 2013).

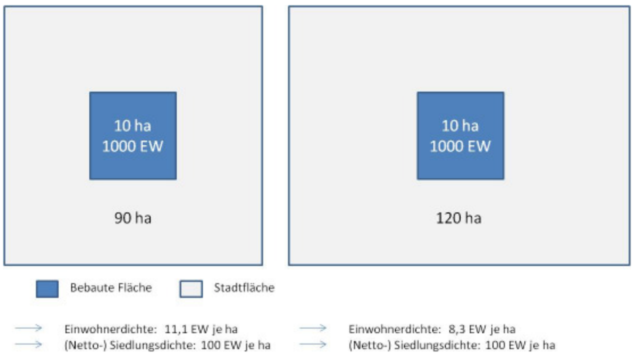

Abb. 1: Modifiable Areal Unit Problem: Die Einwohnerdichte eines Gebiets verringert sich, wenn sich die administrative Bezugsfläche *(grau)* verändert; die Siedlungsdichte bleibt hingegen konstant, da sich die besiedelte Fläche *(blau)* nicht verändert hat

Im weiteren Teil dieses Beitrags werden methodische Möglichkeiten aufgezeigt, um mit neuartigen Daten der Fernerkundung sowie der Bevölkerungs- und Beschäftigungsstatistik Dichteeigenschaften von Städten hochauflösend zu erfassen.

3 Verfahren zur Berechnung der physischen Dichtekennwerte

In diesem Kapitel wird das Verfahren zur Ermittlung baulicher Dichtemaße dargestellt. Eingesetzt werden Daten für das Gebiet der Stadt Köln. Die Ergebnisse werden im nachfolgenden Kap. 4 hinsichtlich ihrer planungs- und forschungspraktischen Relevanz mit Daten zu kleinräumigen Einwohner- und Arbeitsplatzdichten zusammengeführt.

Die Beschreibung und Quantifizierung von baulichen Dichteparametern beruht auf der Aggregation von individuellen Objektparametern zu einer übergeordneten räumlichen Ebene. Im konkreten Anwendungsfall der Bebauungsdichten ist damit die Beziehung zwischen physiognomischen Gebäudemerkmalen und Baublöcken gemeint. Die Erzeugung der individuellen Gebäudemerkmale wird durch neue Technologien in der Geodatenerfassung erheblich erleichtert, da nicht mehr ausschließlich auf Daten der amtlichen Landes- und kommunalen Vermessungsämter zurückgegriffen werden muss oder Vor-Ort-Erhebungen durchzuführen sind. Das Verfahren zur Herstellung der räumlichen Grundlagendaten und Berechnung der physischen Dichtemerkmale wird im Folgenden beschrieben.

3.1 Flugzeuggetragenes Laserscanning

Mit Aufnahme- und Auswertungsverfahren der Erdbeobachtung können flächendeckende, aktuelle Daten der physischen Struktur der Erdoberfläche und, seit dem Aufkommen geometrisch besonders hoch aufgelöster Bilddaten, insbesondere die städtische Struktur erfasst werden. Dabei stellt die Datenaufnahme durch flugzeuggetragenes Laserscanning ein etabliertes Verfahren für die Herstellung von digitalen Oberflächenmodellen dar, das bereits seit vielen Jahren nicht nur im wissenschaftlichen Kontext zur Anwendung kommt (Ackermann 1999). Diese Daten sind die Grundlage für die Ableitung von physiognomischen Merkmalen der Einzelgebäude. Bei dieser digitalen Akquisition von Informationen der Erdoberfläche wird in der Regel ein Flugzeug mit einem Laserscanner über dem Beobachtungsgebiet zum Einsatz gebracht. Der Scanner sendet dabei Laserpulse aus, welche von Objekten auf der Erdoberfläche reflektiert werden und wieder vom Scanner erfasst werden. Über die Messung der Laufzeit der einzelnen Laserpulse und die absolute äußere und innere Orientierung des Scanners mittels Inertialem Navigationssystem (INS)[2] und Globalem Positionierungssystem (GPS) kann die exakte Distanz zum Scanner und daraus folgend die exakte räumliche Position des Objektes auf der Erdoberfläche erfasst werden (vgl. z. B. Albertz 2001; Lillesand/Kiefer/Chipman 2004). Bei den reflektierten Laserpulsen werden dabei *first pulse*, *last pulse* und *full wave form pulse* unterschieden. Die Bezeichnungen richten sich nach der Reihenfolge der Reflexion, wonach zuerst die Pulse von den höchsten (in der Regel gehört die Vegetation bzw. Gebäude auf der Erdoberfläche dazu) Objekten reflektiert werden und dann von den niedrigsten Objekten, zumeist die Geländeoberfläche. Die letzte Form der Datenspeicherung beinhaltet sämtliche Informationen.

Aus der gewonnenen, diskreten Punktwolke der Einzelmessungen werden zu Darstellungs- und Analysezwecken kontinuierliche Oberflächen mittels Interpolationsverfahren berechnet. Diese, die Geländehöhen inklusive der Objekthöhen beinhaltenden Modelle werden als Digitale Oberflächenmodelle (DOM) bezeichnet. Für die Verarbeitung dieser dreidimensionalen Daten im urbanen Anwendungsfeld hat sich die Auswertung von Digitalen Oberflächenmodellen aus *last pulse* Daten etabliert, da diese Daten hauptsächlich physische Bebauungsstrukturen bzw. die Geländeoberflächen enthalten und die Vegetation in diesen Daten weitgehend nicht enthalten ist. Höhenmodelle, welche nur die Höheninformationen des Geländes ohne die darauf befindlichen Objekte beinhalten, werden als Digitale Geländemodelle (DGM) bezeichnet. Sie werden zumeist über Filterungsverfahren direkt aus dem Digitalen Oberflächenmodell oder aus anderen Quellen (z. B. Isohypsen aus topographischen Karten) hergestellt.

Für das Untersuchungsgebiet der Stadt Köln wurde sowohl ein digitales Oberflächenmodell *aus last pulse*-Daten aus einer flugzeuggetragenen Laserscannerbefliegung vom 4. Oktober 2007 verwendet als

[2] Mit dem „Trägheitsnavigationssystem“ (Inertialem Navigationssystem (INS)) werden über Sensoren die Bewegungen von im Raum frei beweglichen Körpern gemessen.

auch ein aus derselben Quelle stammendes Digitales Geländemodell. Die Gitterweite der Daten beträgt 1x1 m.

3.2 Extraktion von Einzelgebäuden aus dem Digitalen Oberflächenmodell

Das Digitale Oberflächenmodell bildet die Grundlage für die Herstellung der räumlichen Basisinformation zur Ableitung der städtischen morphologischen Dichtemassen. Da die darin enthaltenen Höheninformationen neben den Objekthöhen aber auch Geländehöhen beinhalten, ist vor der Auswertung der Höheninformationen eine Normalisierung durchzuführen. Sie stellt die Reduktion der Höhenwerte um die Höhen des Geländes dar. Dafür werden die Höhenwerte des Digitalen Geländemodells von den Höhenwerten des Digitalen Oberflächenmodells subtrahiert. Als Ergebnis liegt nach diesem Verarbeitungsschritt ein normalisiertes digitales Oberflächenmodell (nDOM) vor. Eine Gegenüberstellung der Datensätze für die Normalisierung ist in Abb. 2 dargestellt.

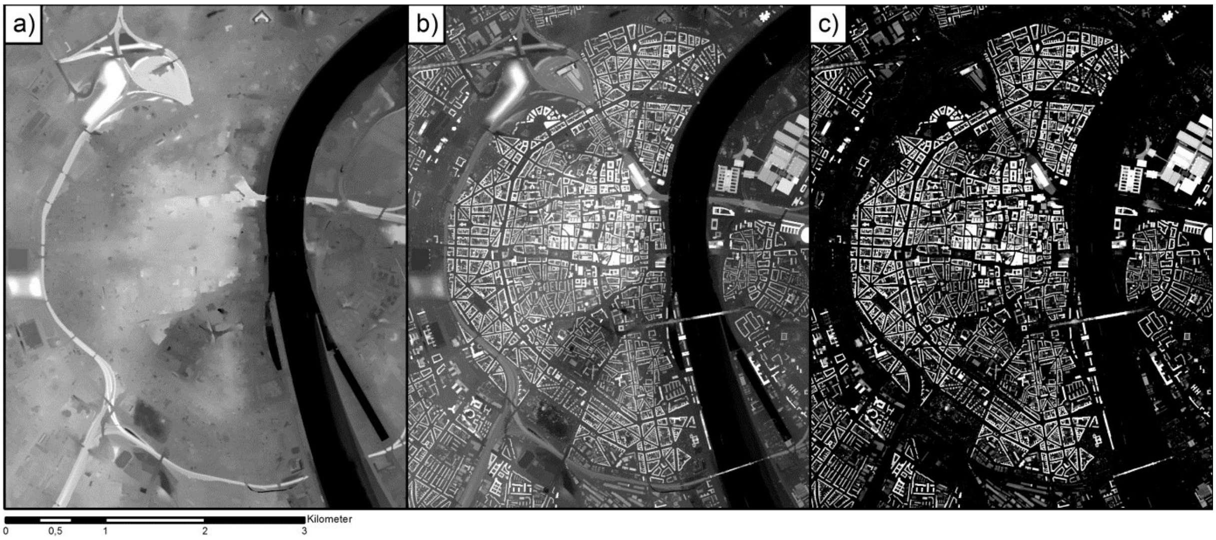

Abb. 2: Gegenüberstellung der unterschiedlichen Höheninformationen. **a** DGM, **b** DOM, und **c** nDOM

Aus dem normalisierten Oberflächenmodell können im folgenden Verarbeitungsschritt Daten auf der räumlichen Ebene der Einzelgebäude gewonnen werden. Dafür müssen zunächst die aneinandergereihten, aber zusammenhanglosen Bildpunkte des normalisierten Oberflächenmodells zu semantischen Bildpunktverbänden zusammengefasst werden. Sie repräsentieren Gebäudegrundflächen, für welche die relative Höhe bekannt ist. Die Ableitung dieser Gebäudegrundflächen geschieht basierend auf der Hypothese, dass Gebäude erhabene Objekte auf der Erdoberfläche darstellen und entsprechend eine größere Höhe als ihre Umgebung aufweisen. Im normalisierten Oberflächenmodell sind diese relativen Höhen als hellere Bildpunkte zu erkennen (vgl. Abb. 2). Dieser Grauwertunterschied im Bild wird für die Abgrenzung der Einzelgebäude in der computergestützten Bildanalyse genutzt. Das Bildanalyseverfahren untersucht den lokalen Grauwertunterschied des Bildes und ermittelt in einem empirischen Verfahren den besten Kontrast. Dafür werden für die einzelnen Baublöcke aus dem Basis-Digitalen Landschaftsmodell (Basis DLM) des amtlichen topographisch-kartographischen Informationssystems (ATKIS) die Kontraste ermittelt. Die Berechnung des höchsten Kontrastes ist ein iteratives Verfahren, welches wiederholt den Kontrast zwischen zwei Testgrauwerten auswertet. Diese Testschwellwerte liegen zwischen dem lokal kleinsten und dem lokal größten Grauwert. Zwischen den Grauwertbereichen, für welche der höchste Kontrast gefunden wurde, wird ein Schwellwert gesetzt, welcher die erhabenen (helleren) Objekte von den niedrigen (dunklen) Objekten trennt. Dieser Schritt wird für jeden Baublock durchgeführt. Für die Berechnung des Kontrastes wurde im verwendeten Verfahren die Kantenratio verwendet. Sie stellt eine Weiterentwicklung der Auswertung des Kontrastes auf Basis der Objektdifferenzen dar. Bei der Kantenratio wird der Kontrast zwischen den Testgrauwerten der potenziellen Kanten, die helle von dunklen Objekten unterscheiden, ausgegeben. Sie wird auf der Basis folgender Gleichung berechnet:

$$k = \frac{a-b}{a+b}, \text{ mit } a \geq b \geq 0 \qquad (1)$$

wobei k der Kontrast ist, a der Mittelwert der Grauwerte der hellen Kantenobjekte und b der Mittelwert der Grauwerte der dunklen Objekte. Die Grauwerte der erhabenen Objekte im normalisierten Oberflächenmodell sind immer größer oder gleich Null, weshalb der Kontrast immer positiv ist. Die Grauwerte innerhalb jedes ATKIS-Baublockes werden nach der Ermittlung des höchsten Kontrastes in helle – also erhabene – und dunkle – also niedrige – Bereiche unterteilt. Die erhabenen Bereiche repräsentieren entsprechend auch die Gebäude, welche aus zusammenhängenden Bildpunktverbänden bestehen. Somit ist jedes Gebäude als eigenständiges Objekt definiert und durch eine Gebäudegrundfläche repräsentiert. Diese individuellen Gebäudegrundflächen, welche zunächst als zweidimensionale, flächenhafte Information vorliegen, werden mit den relativen Höheninformationen aus dem normalisierten Oberflächenmodell kombiniert und resultieren in einem dreidimensionalen Gebäudemodell. In Abb. 3 sind die oben beschriebenen Verfahrensabläufe chronologisch visualisiert. Sie zeigen das normalisierte Oberflächenmodell mit den überlagerten Baublöcken, für das die lokal höchsten Kontraste berechnet wurden, die abgeleiteten Gebäudegrundflächen und eine perspektivische Darstellung des dreidimensionalen Gebäudemodells. Detaillierte Informationen zur Berechnung der Kontraste können bei Wurm (2013: 72 ff.) nachgelesen werden.

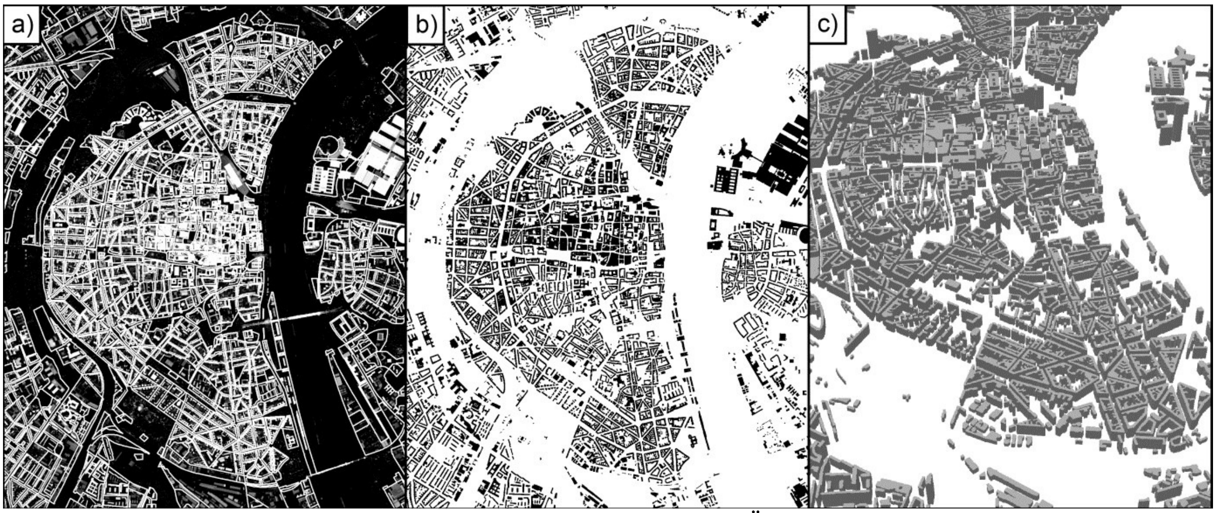

Abb. 3: Ableitung des Gebäudemodells aus der Höheninformation **a** Überlagerung des nDOMs mit den ATKIS-Baublöcken, **b** abgeleitete Einzelgebäude, und **c** 3D-Visualisierung

Neben der Gebäudegrundfläche und der metrischen Höhe der Einzelgebäude ist für die Berechnung von Dichtekennwerten auch die Geschossigkeit der Gebäude von Relevanz. Sie ist nicht bekannt und kann auch nicht direkt aus den Höhendaten ermittelt werden. Allerdings kann über eine einfache Hypothese ein Zusammenhang zwischen der Geschossigkeit und der bekannten metrischen Gebäudehöhe hergestellt werden. Die Hypothese orientiert sich an der Feststellung, wonach in der Regel Gebäude mit einer hohen Geschossigkeit auch eine hohe metrische Höhe aufweisen und je größer die metrische Höhe ist, desto größer ist in der Regel auch die Geschossigkeit. Für die Überprüfung und Quantifizierung dieses Zusammenhangs wird ein empirisches Modell anhand bekannter Geschossigkeiten und Gebäudehöhen erstellt. Dafür werden exakte Gebäudehöheninformationen aus offiziellen Referenzdaten des amtlichen Gebäudekatasters verwendet (vgl. Wurm/Taubenböck/Schardt et al. 2011). Der ermittelte empirische Zusammenhang zwischen der metrischen Gebäudehöhe und der Geschossigkeit ist in Gl. (2) festgehalten.

$$h = 5{,}59 * g^{0{,}73} \quad (2)$$

wobei $\boldsymbol{h}$ die metrische Gebäudehöhe darstellt und $\boldsymbol{g}$ die Geschossigkeit. Aus dieser Gleichung kann für jedes Gebäude, dessen metrische Höhe bekannt ist, die Geschossigkeit abgeschätzt werden. Die ermittelte Beziehung der Geschossigkeit mit der Gebäudehöhe auf Basis der Formel stellt eine nichtlineare Potenzregression dar, welche bereits unterschiedliche Geschosshöhen von Gebäuden unterschiedlicher Epochen zumindest ansatzweise berücksichtigt. Eine einheitliche Höhe für eine lineare Beziehung führt aufgrund der stark unterschiedlichen Geschosshöhen zu Überschätzungen der Geschossigkeiten für typische Altbauten mit Raumhöhen bis zu 4 m und zu Unterschätzungen für Hochhausbauten mit mittleren Geschosshöhen von etwa 2,2 m. Eine Visualisierung des Zusammenhangs findet sich in Abb. 4. Im Vergleich der inneren statistischen Annahme mit den Kalibrierungsdaten zeigt sich, dass für knapp 60% aller Gebäude die exakte Geschossigkeit abgeschätzt werden kann und mit einer Fehlertoleranz von einem Geschoss über 90% Übereinstimmung erreicht werden (Wurm/Taubenböck/Schardt et al. 2011: 140). Die Abweichungen ergeben sich aus der mathematischen Annahme der Hypothese, dass die Geschosshöhe für sämtliche Gebäude gleich groß ist und dass Ausbauten von Dachgeschossen für Wohnnutzungen aus den Höhendaten nicht ableitbar sind. Darüber hinaus wirkt sich auch die Dachform auf die ermittelte Geschossigkeit aus.

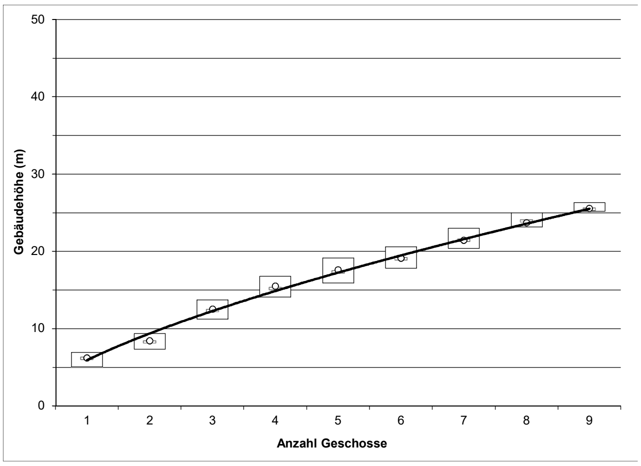

Abb. 4: Empirische Ermittlung der Geschossigkeit der Gebäude

Aus den oben beschriebenen gebäudespezifischen, physiognomischen Merkmalen können weitere quantitative Maßzahlen berechnet werden (vgl. Tab. 1), welche für die Berechnung der blockspezifischen Dichtekennwerte relevant sind. Damit sind allerdings noch keine Nutzungseffizienzwerte gemeint, die einer Verknüpfung dieser Kennwerte mit der Anzahl der Nutzer bedarf (z. B. für den Wohnraum: Anzahl Einwohner pro Wohnung = Wohnraumbelegung).

Tab. 1: Gebäudespezifische Maßzahlen

	Fläche	Höhe	Volumen	Geschossigkeit	Wohnraum
Kürzel	A	h	V	g	W
Einheit	m^2	m	m^3	Anzahl Geschosse	m^2

3.3 Berechnung der blockspezifischen Dichtekennwerte

Aus den im vorigen Abschnitt beschriebenen gebäudespezifischen Maßzahlen werden in der Folge die blockspezifischen Dichtekennwerte berechnet. Dafür wird jeweils die Gesamtheit der gebäudespezifischen Maßzahlen zur räumlich übergeordneten Einheit des Baublocks in Bezug gesetzt.

Bebauungsdichte

Die Bebauungsdichte definiert sich als Anteil der Gebäudefläche pro Baublock. Im Planungs- und Baurecht entspricht sie der Grundflächenzahl (GRZ). Der Baublock stellt dabei die Begrenzung einer Bebauung durch das umgebende Straßengeviert dar. Die räumliche Abgrenzung ist eine gängige Raumeinheit in der Stadtplanung und wird in dieser Form durch das Bundesamt für Kartographie und Geodäsie (BKG) im Basis-DLM von ATKIS als Sachthema ausgegeben. Für die Berechnung der Bebauungsdichte werden sämtliche Gebäudegrundflächen pro Baublock kumuliert und durch die Fläche des ATKIS-Baublocks dividiert. Der proportionale Bezug stellt das Verhältnis der Gebäudefläche zur Baublockfläche dar und kann zwischen 0 und 100% liegen.

Volumendichte

Die Volumendichte stellt den proportionalen Volumenanteil sämtlicher Gebäude zur Fläche des Baublocks dar und berechnet sich aus der Summe der Volumina der Einzelgebäude im Verhältnis zur Grundfläche des Baublocks.

Geschossflächendichte

Die Geschossflächendichte ist ein Maß der baulichen Dichte, welches vor allem im Städtebau zur Anwendung kommt. Sie berechnet sich analog zur Bebauungsdichte, mit dem Unterschied, dass auch die Geschossigkeiten der Gebäude berücksichtigt werden. Es wird nicht nur die Summe der Gebäudegrundfläche mit der ATKIS-Baublockfläche in Beziehung gesetzt, sondern die Summe der Flächen sämtlicher Geschosse. Die Geschossflächendichte kann daher im Gegensatz zur Bebauungsdichte ein Vielfaches der zur Verfügung stehenden Bezugsfläche des ATKIS-Baublocks sein. Ein Beispiel soll dies verdeutlichen: eine Geschoßflächendichte von 1 kann eine eingeschossige Bebauung der gesamten ATKIS-Baublockfläche bedeuten. Es ist allerdings auch möglich, dass nur die Hälfte der zur Verfügung stehenden ATKIS-Baublockfläche mit einem zweigeschossigen Gebäude bebaut ist. Die Summe der Gebäudeflächen ist in beiden Fällen die gleiche.

Für einen Ausschnitt der Kölner Innenstadt ist die Geschossflächendichte in Abb. 5 dargestellt.

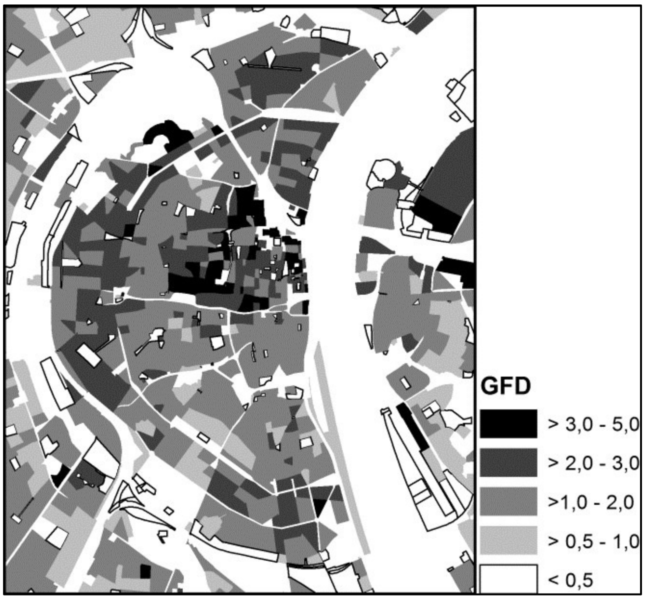

Abb. 5: Geschossflächendichte (GFD) für einen Ausschnitt der Kölner Innenstadt

4 Einsatzmöglichkeiten von Dichtedaten in der Stadtplanung und Stadtforschung

Räumlich hoch auflösende Messwerte zu baulichen Dichten, deren Ermittlung im vorangegangenen Abschnitt beschrieben wurde, lassen sich mit demographischen und ökonomischen Daten verknüpfen, was viele neue Anwendungsmöglichkeiten für die Stadtplanung und Stadtforschung bietet. Möglich wird erstmals ein integriertes, multidimensionales Dichtemonitoring, welches verschiedene Dichteindikatoren zusammenführt. Nachfolgend wird zunächst die Vorgehensweise bei der Errechnung von baublockscharfen Einwohner- und Arbeitsplatzdichten vorgestellt, bevor beispielhafte Anwendungen für die Stadt Köln für den aktuell verfügbaren Zeitschnitt aufgezeigt werden. Ein echtes Monitoring würde darauf aufbauend wiederholte Beobachtungen ermöglichen und Veränderungen von Dichtewerten erfassen.

4.1 Erzeugung kleinräumiger Daten zu Bevölkerungs- und Arbeitsplatzdichten

Für die Stadtforschung und Stadtplanung sind neben baulichen Dichten Nutzungsdichten wie die Einwohner- oder die Arbeitsplatzdichte von zentraler Bedeutung. Hierfür wurden die oben beschriebenen fernerkundlich erhobenen Baumassen mit statistischen Daten der Stadt Köln (Einwohnerzeitreihen auf Baublockebene, digitaler Flächennutzungsplan 2012), amtlichen Geobasisdaten (ATKIS Basis-DLM) und disaggregierten Beschäftigungsdaten des Instituts für Arbeitsmarkt- und Berufsforschung (IAB) (vgl. Scholz/Rauscher/Reiher et al. 2012) kombiniert. Im Ergebnis stehen grafische Auswertungen, die Trends und Zustand von Dichteverteilungen über das Stadtgebiet veranschaulichen.

Bei der Berechnung von Einwohner- und Arbeitsplatzdichten ist zu beachten, dass aus Datenschutzgründen keine adress- oder gebäudescharfen Daten zur Verfügung gestellt werden können. Möglich ist indes die Verknüpfung mit adressscharfen Daten in einer vorgegebenen Gebietsstruktur. Mit der Baublockebene wurde in diesem Zusammenhang eine Raumbezugsebene verwendet, die ausreichend kleinräumig und gleichzeitig nur mit geringen Restriktionen durch Datenschutzbestimmungen konfrontiert ist.

Von Seiten der Stadt Köln wurden Baublöcke mit Einwohnerdaten ohne Verkehrsflächen und Innenhöfe bereitgestellt. Die daraus resultierenden Dichtewerte sind als Nettodichte anzusehen. Um zusätzlich auch Bruttodichten ermitteln zu können, wurden die Baublockdaten auf die Flächennutzungsdaten von ATKIS umgelegt. Dabei kam folgendes Verfahren zum Einsatz: Die Baublöcke der Stadt Köln wurden räumlich mit allen ATKIS-Flächen verschnitten und daraus ein Anteilsfaktor für die Einwohner in der geschnittenen Fläche berechnet. Dieser Faktor basiert auf dem Flächenanteil der geschnittenen Fläche am ursprünglichen Baublock und wird auf die Einwohnerzahlen angewandt.

Die baulich geprägten Flächen aus ATKIS (Objektarten: 2111, 2112, 2113 und 2114) stimmen überwiegend mit den Baublöcken der Stadt Köln, weshalb die dafür berechneten Einwohnerdichten als hoch plausibel anzusehen sind. Aus Gründen der Anwendbarkeit des beschriebenen Verfahrens wurden mögliche Umlegungen von Einwohnern aus Baublöcken auf nicht bewohnte ATKIS-Blöcke nicht weiter analysiert. Dies stellt einen Sonderfall dar und kommt nur vor, wenn durch Digitalisierungsunterschiede kleinere Baublockteile unbewohnte ATKIS-Flächen überlagern. Die flächenproportionale Umlegung stellt hier sicher, dass die Einwohnerdichte für diese Überstände entsprechend niedrig bleibt. In die Weiterverarbeitung der berechneten Daten gehen also nur ATKIS-Flächen mit plausiblen Einwohnerdichten ein.

Parallel zur Berechnung von Einwohnerdichten wurden ebenfalls auf der räumlichen Ebene der Baublöcke die Arbeitsplatzdichten ermittelt. Vom IAB werden lediglich Angaben zu sozialversicherungspflichtig Beschäftigten abgegeben, aus Datenschutzgründen nur für die von den Autoren zur Verfügung gestellten ATKIS-Flächen, die eine rechtlich unbedenkliche Anzahl an Betrieben enthalten. Für alle anderen Baublöcke können keine Informationen zur Verfügung gestellt werden (= Schwärzung, vgl. Bundesagentur für Arbeit 2012). Um auch mit „geschwärzten" Baublöcken arbeiten zu können, wurde hier ein Wert von exakt einem sozialversicherungspflichtig Beschäftigten angenommen. Dieser hypothetische Wert kann nur dann zu einer kritischen Verzerrung führen, wenn ein Baublock von sehr wenigen Betrieben mit hohen Beschäftigtenzahlen dominiert wird. Eine für die Datenschutzanforderungen zu kleine Anzahl an sozialversicherungspflichtig Beschäftigten wird damit adäquat repräsentiert.

Es muss weiterhin darauf hingewiesen werden, dass die vorliegenden Daten zur Beschäftigung die Konzentration tendenziell überschätzen. An mehreren Standorten innerhalb Kölns agierende Unternehmen können alle Mitarbeiter an einer Adresse im Stadtgebiet melden, wenn die Mitarbeiter in demselben Wirtschaftszweig („5-Steller" der Wirtschaftszweigklassifikation der Bundesagentur für Arbeit von 2008) angemeldet sind. Sind die Mitarbeiter in unterschiedlichen Wirtschaftszweigen gemeldet, müssen sie an einer Stelle gemeldet werden, an der sie entweder selbst oder weitere Beschäftigte desselben Wirtschaftszweiges arbeiten.

4.2 Erzeugung von „Heat Maps" zu städtischen Dichteoberflächen

Die erzeugten baublockscharfen Dichtedaten über Bewohner und Beschäftigte lassen im Folgenden differenzierte Analysen und kartographische Anwendungen zu. So können beispielsweise Techniken des *Heat Mappings* angewendet werden. Diese Visualisierungsmethode ermöglicht eine kartographische Herausarbeitung der generellen räumlichen Trends in den Datenpunkten. Eine thematische Karte auf Baublockebene (mit 20.624 Flächen) wäre kaum darstellbar und zu detailliert, um auf den ersten Blick Muster erkennen zu können. Die Einwohnerdichte für die ATKIS-Blöcke wird damit zur Grundgesamtheit für die räumliche Interpolation nach dem Verfahren des *Diffusion Kernel* [3] (Gauß'sche Verteilung mit einer Bandbreite von 500 m), die die Dichtewerte über die Stadt Köln generalisiert (vgl. Abb. 6). Für das *Heat Mapping* wurden bewusst keine Barrieren gesetzt, das heißt, die Interpolation verläuft frei im Raum über Verkehrsflächen und auch topographisch-geographische Barrieren wie den Rhein hinweg. Grund hierfür ist die Annahme, dass in einem hoch verdichteten Raum wie der Stadt Köln derartige Schranken kaum Einfluss auf die Verteilung der Einwohnerdichte haben. Anders formuliert: Die Attraktivität benachbarter Baublöcke ist unabhängig von einer eventuellen räumlichen Trennung durch physische oder natürliche Barrieren gegeben, sondern orientiert sich eher an anderen Aspekten wie der Verkehrserschließung oder dem Bodenpreis.

Zunächst werden die Ergebniskarten für die errechneten Dichtekennwerte (morphologische Dichtekarten der Stadt Köln) vorgestellt. Abbildung 6 zeigt in der oberen Reihe links die Einwohnerdichte, gemessen in Einwohner je Hektar (Stand 2011). Während die gesamte Stadt im arithmetischen Mittel eine Einwohnerdichte von 25,5 Einwohnern pro Hektar hat, liegt der Mittelwert für die Arbeitsplatzdichte bei 7,4 Beschäftigten pro Hektar (oben rechts) bzw. bei 2,5 Dienstleistungsbeschäftigten[4] pro

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[3] Für eine genaue Beschreibung vgl. http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00310000002t000000 (20.01.2014).

[4] Unter Dienstleistungsbereich sind folgende Wirtschaftsabschnitte gemäß der Klassifikation der Wirtschaftszweige (WZ) 2008 zu verstehen: J (Informationen und Kommunikation), K (Erbringung von Finanz- und Versicherungsdienstleistungen), L (Grundstücks- und Wohnungswesen), M (Erbringung von freiberuflichen, wissenschaftlichen und technischen Dienstleistungen), N (Erbringung von sonstigen wirtschaftlichen Dienstleistungen) und S (Erbringung von sonstigen Dienstleistungen). Auch hier werden lediglich die sozialversicherungspflichtig Beschäftigten (SVB) berücksichtigt, zusätzlich die geringfügig Beschäftigten. Diese gehen pauschal mit 20% der Arbeitszeit eines Vollbeschäftigten in Abb. 6 ein, das heißt, die Werte repräsentieren Vollzeit-SVB plus 0,2*geringfügig SVB.

Hektar (unten rechts). Für die Baumassendichte ergibt sich arithmetisch ein Mittel von knapp 8.000 m^3 pro Hektar (unten links).

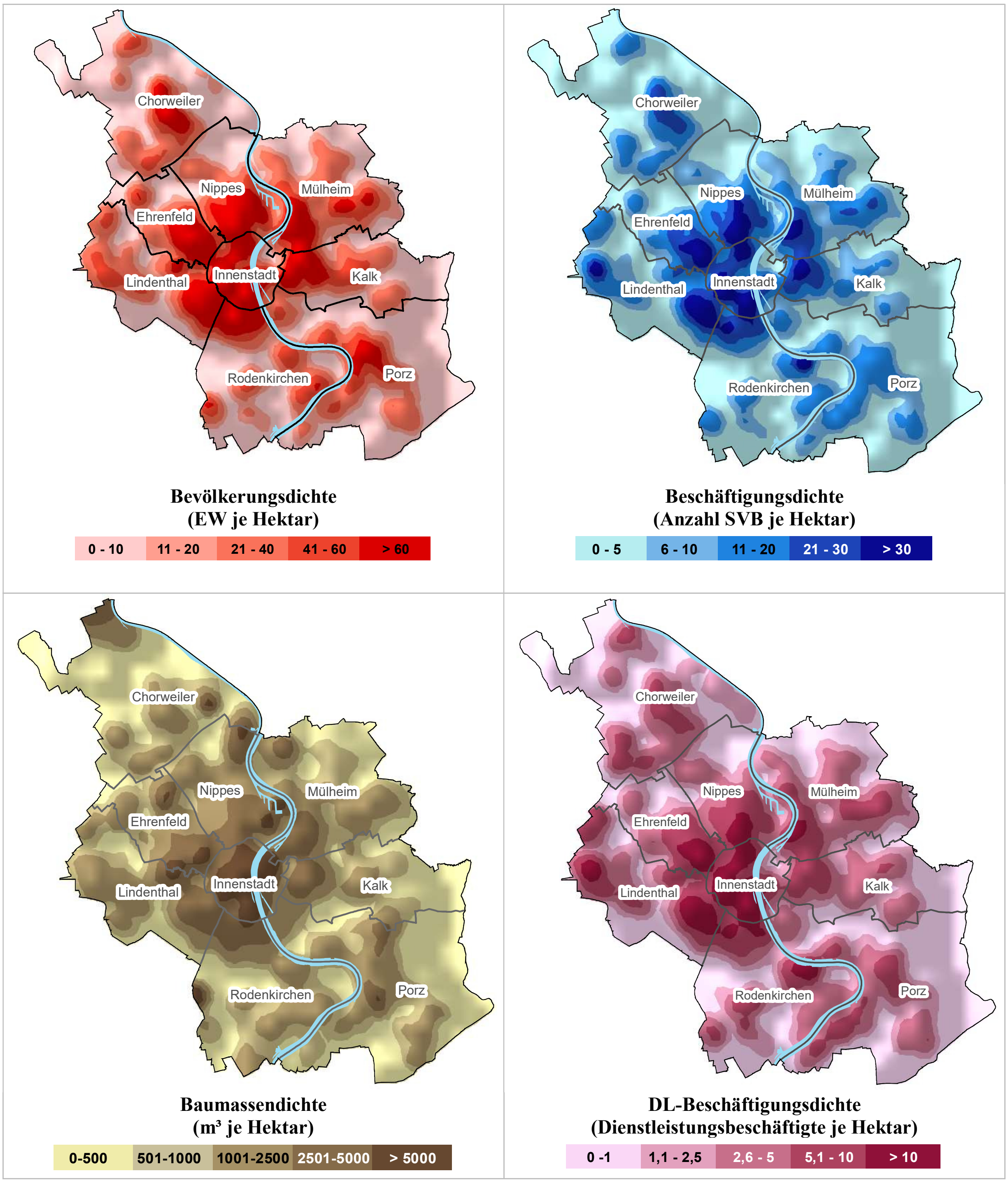


Abb. 6: Morphologische Dichtekarten der Stadt Köln

Erwartungsgemäß sind die Dichten bei allen Indikatoren im (erweiterten) Innenstadtbereich am höchsten und nehmen tendenziell zum Stadtrand hin ab. Die Bevölkerung ist im Zentrum und in zentrumsnahen Wohnschwerpunkten konzentriert. Bemerkenswert ist der hohe Wohnanteil der innerstädtischen Gebiete in Köln, was auf ausgeprägte Mischstrukturen schließen lässt. Trotz einer auch in Köln in den vergangenen Jahrzehnten vollzogenen Tertiärisierung der Innenstadtlagen als Ergebnis eines standörtlichen Verdrängungswettbewerbs existiert dort nach wie vor in erheblichem Umfang Wohnraum.

Darüber hinaus sind in den äußeren Stadtbezirken Subzentren hoher Wohndichte erkennbar, z. B. in Chorweiler, im östlichen Mülheim oder im Süden entlang der Rheinschleife im Grenzbereich Rodenkirchen/Porz. Auffällig ist die hohe Übereinstimmung der räumlichen Ausprägung von Einwohner- und Arbeitsplatzdichte, auch der Dienstleistungs-Arbeitsplatzdichte. Daraus lassen sich erste Hinweise auf eine grundsätzlich gegebene Nutzungsmischung ableiten: Die räumliche Nähe von Einwohnerkonzentrationen und Arbeitsmöglichkeiten scheint gegeben. Bei den Baumassen dagegen zeigt sich ein leicht anderes Bild: Hier sind im Stadtzentrum die höchsten Werte konzentriert, was sich vor allem auf den hohen Anteil von öffentlichen Bauten, die keine oder nur teilweise Wohn- oder Beschäftigungsfunktion haben, zurückführen lässt. Die höchsten Einwohnerdichten hingegen reichen weiter in die unmittelbar anschließenden Stadtteile.

4.3 Analyse von städtischen Zentrenstrukturen

Kleinräumige Dichtedaten können auch für eine Untersuchung der kernstädtischen Zentrenstrukturen verwendet werden. Im Allgemeinen hat in den meisten deutschen Großstädten die Dominanz der ursprünglichen Zentren – vor allem der historischen Innenstadt – im Arbeitsplatzangebot für den gesamten städtischen Raum seit den 1950er Jahren abgenommen. Die heutige Zentrenstruktur von Stadtregionen hat sich stattdessen im Lauf der Jahrzehnte zu einem komplexen, funktional arbeitsteilig organisierten Netzwerk von Zentren und Subzentren entwickelt (vgl. Thierstein/Lüthi/Kruse et al. 2008; Hesse 2010; Knapp/Volgmann 2011). Wie aber solche metropolitanen Zentrensysteme strukturell beschaffen sind, in welchem Verhältnis sich beispielsweise die Arbeitsplätze auf klassische Innenstadtlagen und randstädtische Standorte verteilen, ist bislang empirisch kaum fassbar.

Eine hier angewendete Methode erfolgt durch eine Analyse der räumlichen Autokorrelation der Dichtewerte mithilfe des *Anselin Local Moran's I* (vgl. Anselin 1995). Dabei wurden solche Standorte (Baublöcke) als potenzielle Zentren betrachtet, die sich in ihrer Dichteausprägung in statistisch signifikantem Maße von benachbarten Baublöcken unterscheiden („Spots“) bzw. ihnen ähneln (Clusterbildung). Im Gegensatz zur kartographischen Klassenbildung, die lediglich einen visuellen Eindruck über die Dichteverteilung liefert, erfolgt hier eine auf einer Umgebungsanalyse basierenden Abgrenzung von Zentren.[5] Mithilfe iterativer Zufallsverteilungen der vorkommenden Werte werden die Abweichungen der tatsächlichen Werteverteilung von der Zufallsverteilung gemessen und als Index-Wert inklusive *z-Score* und *p-Value* für jeden Datenpunkt ausgegeben. Als signifikant werden solche Werte bezeichnet, deren *p-Value* gemäß der Anwendung der *False Discovery Rate (FDR)* kleiner als der jeweils zugehörige kritische Wert ist (Caldas de Castro/Singer 2006: 187).[6]

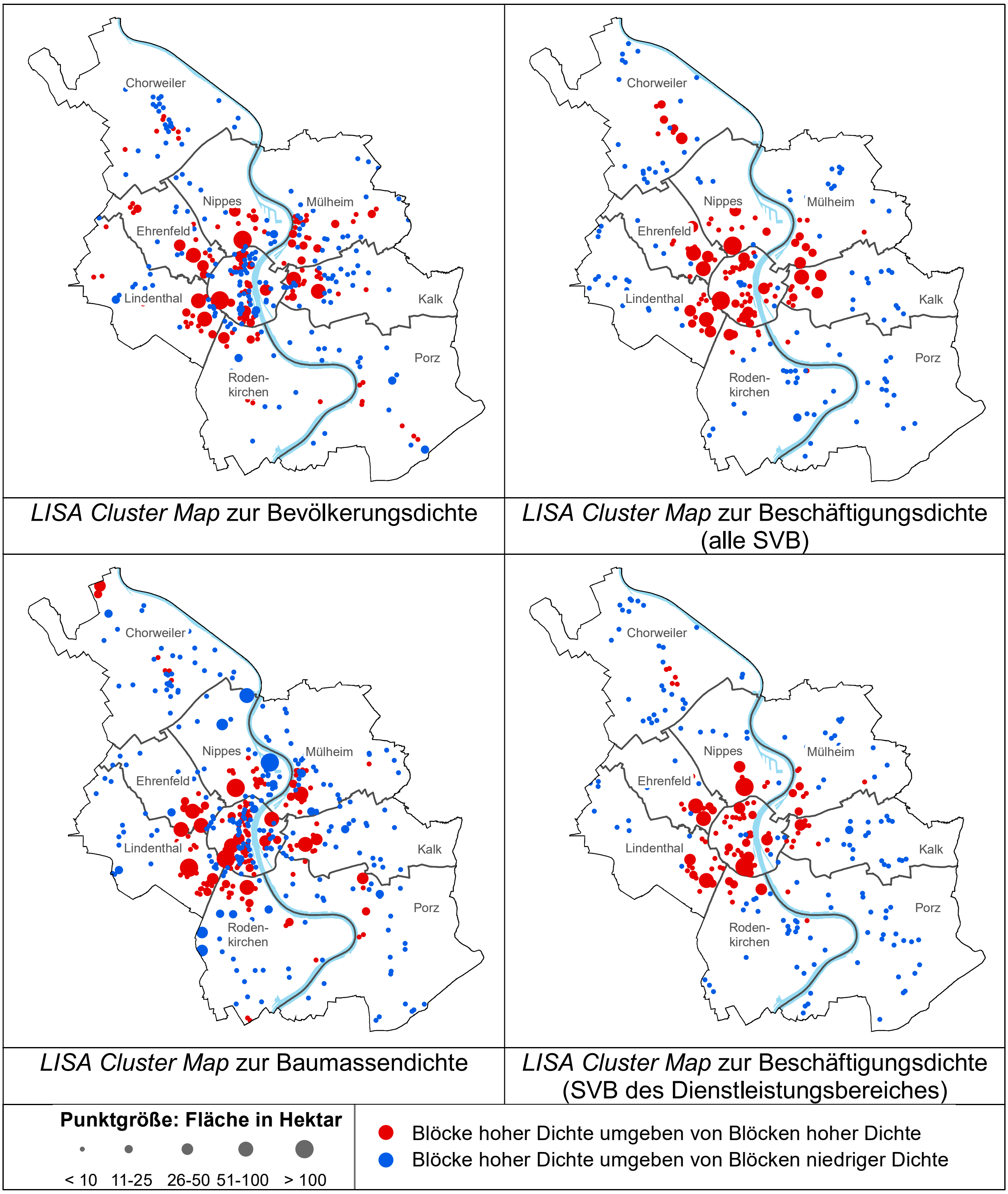
Im Ergebnis stehen vier Klassen räumlicher Autokorrelation: Blöcke hoher Dichte umgeben von Blöcken hoher Dichte (HH), Blöcke hoher Dichte umgeben von Blöcken niedriger Dichte (HL), Blöcke niedriger Dichte umgeben von Blöcken hoher Dichte (LH) sowie Blöcke niedriger Dichte umgeben von Blöcken niedriger Dichte (LL). Von besonderem Interesse sind die ersten beiden Kategorien, da sie typisch für eine Zentrenausbildung sind (vgl. z. B. Riguelle/Thomas/Verhetsel 2007). Mit Hilfe von *LISA Cluster Maps*[7] können statistisch signifikante (Sub-)Zentren der Einwohner-, Arbeitsplatz- und Baumassendichte abgegrenzt und damit räumlich-funktionale Strukturmuster in ein Monitoring eingestellt werden. Bei dem Vergleich der kartographischen Ergebnisse und ihrer Interpretation muss be-

[5] Nachbarschaft wird hier als „queen contiguity of second order“ modelliert, das heißt, auch Nachbarn, die sich nur in einem Punkt berühren, sowie die ersten Nachbarn der Nachbarn werden berücksichtigt.
[6] Die *False Discovery Rate* wurde gewählt, da zum einen eine positive räumliche Autokorrelation in den Daten vorliegt. Nach Anselin (1995: 95 f.) sind zum anderen die ‚klassische‘ Rate von 5 % zu wenig restriktiv und eine *Family Wise Error Rate* nach der von ihm zitierten Bonferroni und Šidák-Methode zu konservativ. Die *False Discovery Rate* ist dabei ein guter Kompromiss und zudem auch unter positiver räumlicher Abhängigkeit gültig (Benjamini/Yekutieli 2001: 1168)
[7] LISA steht für „Local Indicators of Spatial Autocorrelation“.

rücksichtigt werden, dass statistische Signifikanz nicht zwangsläufig eine absolut betrachtete hohe Dichte bedeutet. Vielmehr gibt die Signifikanz an, wie die Dichte eines betrachteten Baublocks im Verhältnis zu seinen Nachbarn ausgeprägt ist. Ist der Wert für den Baublock in diesem Kontext ‚herausragend' (das heißt, der p-Wert des *LISA-Indexes* ist kleiner als der kritische p-Wert gemäß der *False Discovery Rate*), kann von Signifikanz gesprochen werden.

Der Vergleich zwischen der Arbeitsplatzdichte aller sozialversicherungspflichtig Beschäftigter und der Arbeitsplatzdichte im Dienstleistungsbereich (vgl. rechte Karten in Abb. 6) zeigt eine hohe Übereinstimmung: Bereiche, in denen die Beschäftigung sehr hoch ist, haben auch eine hohe Beschäftigung im Dienstleistungsbereich. Die erzeugten *LISA Cluster Maps* (vgl. Abb. 7) erlauben hingegen weitergehende Bewertungen der Zentrenstrukturen. Die roten Punkte in der *LISA Cluster Map* repräsentieren die Flächengrößen zusammenhängender ATKIS-Flächen hoher Dichte, die von anderen Flächen hoher Dichte umgeben sind (HH-Cluster). Die blauen Punkte repräsentieren in ihrer Größe Flächen hoher Dichte, die von Flächen relativ niedriger Dichte umgeben sind (HL, „Hot Spots").

Betrachtet man zunächst die Einwohnerdichte (vgl. Abb. 7, oben links), so lassen sich die Wohnschwerpunkte der Stadt räumlich deutlich herausstellen. Es bestätigt sich das bereits aus der Dichtekarte abgeleitete Ergebnis, wonach in einem Ring um die Innenstadt und punktuell auch in den Verdichtungskernen der Randlagen die höchsten Einwohnerdichten zu finden sind. Darüber hinaus wird für die blauen Konzentrationen aufgezeigt, wo Wohnschwerpunkte isoliert liegen und von anderen Nutzungen umgeben sind. Dies ist außerhalb der Innenstadt vor allem in Chorweiler der Fall, in geringen Ausprägungen auch verstreut in den Randlagen der Stadtregion. Im Bereich der Arbeitsplatzdichte zeigt sich eine deutliche Konzentration von Schwerpunkten im Zentrum und im zentrumsnahen Innenstadtbereich. Diese sind in der Mehrzahl als Cluster hoher Dichte in rot erkennbar, gleichermaßen für Gesamt- (oben rechts) und Dienstleistungsbeschäftigung (unten rechts). Großflächige isolierte Beschäftigungszentren sind nicht erkennbar. Anders stellt sich dies bei der räumlichen Verteilung der Baumassendichten (unten links) dar. Hier sind natürlich ebenfalls im und um das Zentrum statistisch signifikante Cluster ähnlich (hoher) Baumassendichten zu finden. Mit zunehmender Entfernung zum Zentrum werden diese jedoch spärlicher und bilden nur noch in den Kernbereichen der Subzentren Cluster aus. Bemerkenswert ist, dass es hier großflächige isolierte Baublockcluster in blau gibt, die sich deutlich von ihrer Umgebung abgrenzen, z. B. in der größten Ausprägung im Stadtteil Nippes die Hafenanlagen in Niehl und die Fordwerke, aber auch im Westen von Rodenkirchen die Industriegebiete südlich von Hürth.



LISA Cluster Map zur Bevölkerungsdichte; *LISA Cluster Map* zur Beschäftigungsdichte (alle SVB); *LISA Cluster Map* zur Baumassendichte; *LISA Cluster Map* zur Beschäftigungsdichte (SVB des Dienstleistungsbereiches)

Abb. 7: Räumliche Korrelation von Dichtekennwerten in der Stadt Köln

4.4 Ausschöpfung der planungsrechtlich möglichen Dichte

Abschließend wird eine weitere Anwendungsoption kleinräumiger Dichtedaten aufgezeigt. Sie stellt eine Analyse der realen Ausschöpfung der planungsrechtlich möglichen Dichte dar. Aus früheren Studien ist bekannt, dass die realen Baudichten die planungsrechtlich mögliche Verdichtung zum Teil drastisch unterschreiten (Losch 1994: 136). Eine Ausnahme kann für Zentrumslagen angenommen werden, wo punktuell deutliche Überschreitungen als Ergebnis von Befreiungen von den baurechtlichen Vorschriften zu erwarten sind. Genauere Erkenntnisse, in welchem Umfang die realen Dichten die in der Baunutzungsverordnung vorgegebenen Obergrenzen unterschreiten (oder auch punktuell überschreiten), gibt es aber bislang nicht. Der hier vorgenommene Abgleich von Plan- und Solldichten erfolgt allein unter Bezugnahme auf den Flächennutzungsplan der Stadt Köln und die darin erfolgte Darstellung von Nutzungsarten. Bebauungspläne und die in ihnen festgesetzten Dichten konnten im Rahmen dieses Beitrags nicht einbezogen werden, weshalb die Ergebnisse nur einen generalisierten Überblick über die Ausnutzung der möglichen Dichte geben.

Der digitale Flächennutzungsplan der Stadt Köln enthält 2.113 Flächen mit den in Tab. 2 dargestellten Nutzungstypen und ihren Flächen.[8] Für diese Nutzungstypen wurden aus der Baunutzungsverordnung (BauNVO) die Geschossflächenzahl (GFZ) und die Grundflächenzahl (GRZ) recherchiert. Ein Abgleich dieser theoretisch realisierbaren Geschossflächen erfolgte über die Auswertung der oben beschriebenen fernerkundlich erhobenen Baumassen (vgl. Kap. 3). Zunächst wurde für die ATKIS-Flächen die dominante Flächennutzung ermittelt. Das oben beschriebene Umlegungsverfahren ermöglicht im Weiteren eine Zuordnung der Gebäude bzw. Gebäudeteile zu den Grundflächen der baulich geprägten ATKIS-Flächen einschließlich der Angabe der Anzahl der Stockwerke. Die geschätzte, tatsächlich verbaute Geschossflächenzahl ergibt sich letztlich aus den auf Blockebene aggregierten Geschossflächen im Verhältnis zur Grundfläche des Baublocks. Dabei ist zu beachten, dass sich Verzerrungen gegenüber einer städtebaulich korrekt berechneten Geschossflächenzahl aus einer abweichenden Grundfläche der ATKIS-Flächen gegenüber den Grundflächen eines Bebauungsplanes ergeben können, für den die Geschossflächenzahl letztlich Rechtsgültigkeit hat. Zwar wird die Reduktion um Verkehrs- und Grünflächen sowohl im Bebauungsplan als auch im Datenmodell von ATKIS vorgenommen, allerdings nicht nach dem gleichen Regelwerk und in einem anderen Detaillierungsgrad.

Tab. 2: Flächennutzungstypen Stadt Köln mit gesetzlichen Grundflächen- (GRZ) und Geschossflächenzahlen (GFZ)

Nutzungstyp	Fläche (ha)	GRZ	GFZ
Bahn	13	–	–
Besonderes Wohngebiet	822	0,6	1,6
Fläche für die Forstwirtschaft (Erholungswald)	2.846	–	–
Fläche für die Landwirtschaft	2.891	–	–
Fläche für die Ver- und Entsorgung	229	–	–
Fläche für Windenergieanlagen	21	–	–
Gemeinbedarfsfläche	527	–	–
Gewerbefläche	1.968	0,8	2,4
Grünfläche	544	–	–
Grünfläche mit besonderer Nutzung	23	–	–
Grünfläche mit teilweise landwirtschaftlicher Nutzung	11.112	–	–
Industriefläche	1.957	0,8	2,4
Kerngebiet	96	1,0	3,0
Mischbaufläche	783	0,6	1,2
Sonderbaufläche	1.043	0,8	2,4
Verkehrsfläche	37	–	–
Wohnbaufläche	8.446	0,4	1,2

Der letzte Analyseschritt trägt die Ausnutzung der erlaubten baulichen Dichte durch die geschätzte tatsächliche Dichte im Ringzonenmodell um das Stadtzentrum der Stadt Köln auf. Auf der X-Achse in Abb. 8 sind die Distanzen in Kilometer zum Kölner Dom angegeben, auf der Y-Achse die flächengewichtete mittlere Ausnutzung in Prozent pro Nutzungstyp (in Farbe) und im Mittel aller Flächennutzungstypen (schwarz). Die Ergebnisse verdeutlichen ein starkes Zentrum-Stadtrand-Gefälle in der Ausnutzung der theoretisch möglichen baulichen Dichte, vor allem in Bezug auf Flächen mit Wohnfunktion sowie Mischflächen. Für Mischflächen ist aus historischen Gründen im Stadtzentrum eine Übernutzung der nach Baunutzungsverordnung zulässigen Geschossflächenzahl zu erkennen. Es wird aber auch deutlich, dass außerhalb des innerstädtischen Zentrums (etwa ab 2 km) die Nutzungseffizienz stark abnimmt und eine generelle Unterschreitung der möglichen Dichtegrenzwerte zu verzeichnen ist. Des Weiteren zeigt sich bei Kilometer 11 eine Spitze (*peak*) für Mischflächen (80% der er-

[8] Teilweise zusammengefasst bei gleichen Nutzungstypen mit unterschiedlichen Schreibweisen

laubten Geschossflächenzahl werden genutzt). Verantwortlich hierfür sind Flächen im Zentrum der Großwohnsiedlung Chorweiler mit GFZ-Überschreitungen in einzelnen Baublöcken von über 300%.

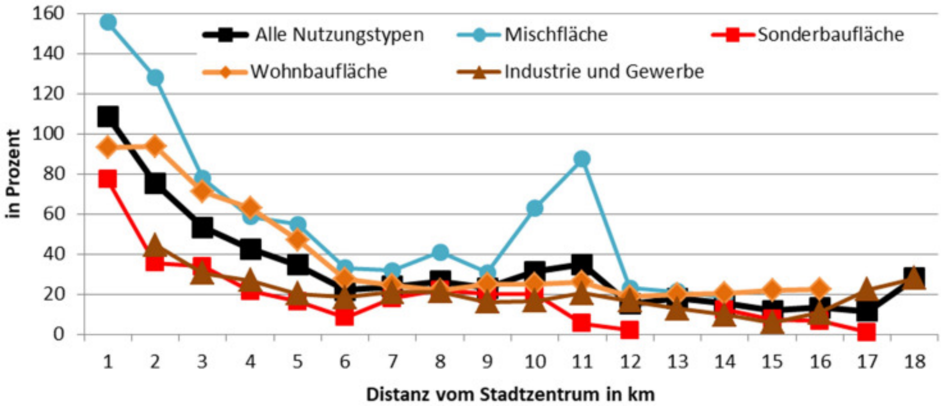


Abb. 8: Nutzungsintensität verschiedener Flächennutzungstypen nach Distanz vom Stadtzentrum Köln (Nutzungsintensität: planungsrechtlich mögliche GFZ nach BauGB versus GFZ-Schätzung über das DOM)

Bei der Interpretation dieser Ergebnisse ist zu berücksichtigen, dass eine hohe Nutzungseffizienz nicht zwangsläufig wünschenswert ist. Neben ökologischen Aspekten wie der Stadtklimatologie oder dem Hochwasserschutz sind selbstverständlich auch die Freiraumversorgung und Durchgrünung der Stadt sowie die städtebauliche Qualität und der Bebauungscharakter von Wohnquartieren zu berücksichtigen, die häufig im Konflikt mit einer höheren Ausnutzung der zulässigen Geschossflächenzahl stehen. Aus dieser Perspektive liegt der Wert der vorliegenden Analyse in einer Beschreibung des Ist-Zustandes. Um einen konkreten Mehrwert für die Stadtplanung zu erzeugen, sind weiterführende Analysen zu Nachverdichtungspotenzialen unerlässlich. Die vorliegenden Datengrundlagen können hier lediglich informatorisch unterstützen.

5 Fazit und Ausblick

Der vorliegende Beitrag zeigt, dass mit Hilfe von Fernerkundungsdaten die Bereitstellung gebäudescharfer 3D-Informationsgrundlagen aus technischer Sicht qualitativ hochwertig möglich ist. Die dabei erzeugten Daten zu Baumassen und Bauvolumen schließen eine Lücke für das Monitoring der Stadtentwicklung, denn insbesondere die stadtregional vergleichbare Berechnung von Geschossflächen- und Bebauungsdichten war bislang nur mit bedeutend höherem Aufwand realisierbar. Für eine flächendeckende Umsetzung der beschriebenen Methoden sind der Kostenaufwand für die Akquise und die Prozessierung der Erdbeobachtungsdaten derzeit zwar nach wie vor relativ hoch. Es kann aber mit zukünftigen Effizienzsteigerungen gerechnet werden, die schon heute gewisse Investitionen in die Methodenentwicklung rechtfertigen.

Diesbezüglich muss festgehalten werden, dass die Vernetzung von 3D-Stadtmodellen, Geobasisdaten und räumlicher Statistik methodisch noch in den Anfängen steckt. Die Harmonisierung von Datenformaten und der organisatorische Datenaustausch stellen den Anwender vor große Herausforderungen, und man ist hier von der Entwicklung wünschenswerter standardisierter Prozesse noch weit entfernt. Gleichzeitig verdeutlichen die dargestellten thematischen Anwendungen aber den universellen Nutzen derartig kombinierter Datenquellen in der Form kleinräumiger Dichtedaten.

Sowohl aus planungspraktischer als auch aus raumwissenschaftlicher Perspektive eröffnen sich damit vielfältige Nutzungsoptionen. Beispielhafte Anwendungsbezüge für das Monitoring der Dichte bieten sich in

- der Stadtklimatologie und hier insbesondere bei der methodischen Weiterentwicklung von Vulnerabilitätsstudien (z. B. Berechnung von Verschattungsverhältnissen),
- der Planung des Stadtumbaus, indem unter anderem Rückbauoptionen auf ihre infrastrukturellen Implikationen vertiefend untersucht werden,
- der Bewertung von Nachverdichtungsmaßnahmen mit ihren positiven und negativen Auswirkungen (z. B. Verbesserung der Infrastruktureffizienz, Verringerung der Freiraumversorgung) oder
- der Durchführung von Energieverbrauchs- und -einsparszenarien im Gebäudebereich, für die belastbare Daten zu Gebäudemassen und -formen von großer Bedeutung sind.

Als grundsätzlich sinnvoll wird die Ergänzung konventioneller Monitoringsysteme auf kommunaler und regionaler Ebene eingeschätzt, indem Dichteindikatoren integriert und mit anderen Indikatoren kombiniert werden können. Der Vorteil der hier aufgezeigten Methoden liegt vor allem darin, dass ein multidimensionales Dichtemonitoring für größere Gebietskulissen bei regelmäßiger Fortschreibung der Daten mit vertretbarem Aufwand leistbar ist. Die damit erleichterte Verfügbarkeit teilgemeindlicher Daten ermöglicht auch interregional vergleichende Analysen siedlungsstruktureller Zustände und Entwicklungen, die für Deutschland so bisher nicht möglich waren. Auch im Hinblick auf erwartbare Steigerungen der Kosteneffizienz der fernerkundlichen Verfahren kann eine Weiterentwicklung und Adaption der hier vorgestellten Methoden für die Stadtforschung und angrenzende Disziplinen deshalb nur empfohlen werden.

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Polyzentralität in deutschen Stadtregionen – eine integrierte Bestandsaufnahme

Angelika Krehl

Zusammenfassung

Der zahlenmäßige Rückgang der Arbeitsplätze in den Kernstädten westlicher Industriestaaten geht einher mit der Entstehung randstädtischer und peripherer Arbeitsplatzagglomerationen. Das Zentren-Subzentrengefüge verschiebt sich, polyzentrische Strukturen bilden sich heraus. Vor diesem Hintergrund sucht der vorliegende Beitrag Antworten auf die Frage nach dem morphologischen Verhältnis zwischen Kernstadt und Subzentren. Dazu werden vier exemplarische Stadtregionen im Hinblick auf ihre polyzentrische Raumstruktur untersucht und miteinander verglichen. Die Kombination von Daten der Fernerkundung mit denen zu sozialversicherungspflichtig Beschäftigten ermöglicht dabei eine integrierte Analyse der raumstrukturellen Prägung der jeweiligen Stadtregion. Die Ergebnisse weisen auf recht ausgeprägte Hierarchien hin; in allen Regionen dominiert die Kernstadt trotz teilweise sehr deutlich sichtbarer Subzentren im Umland. Im Vergleich zum überkommenen Zentrum sind die Subzentren jedoch wenig maßgeblich in der raumstrukturellen Prägung der einzelnen Regionen.

17.1 Einleitung

Sind die Innenstädte von Kernstädten „Auslaufmodelle“? In der stadtregionalen Entwicklung insbesondere westlicher Industriestaaten ist seit den 1970er-Jahren ein zahlenmäßiger Rückgang der Arbeitsplätze in den etablierten Zentren der Kernstädte zu verzeichnen. Zugleich entstehen an randstädtischen und peripheren Standorten neue Arbeitsplatzagglomerationen (vgl. unter anderem Anas et al. 1998; Siedentop et al. 2003; Bontje und Burdack 2005; Riguelle et al. 2007; Knapp und Volgmann 2011). Diese teilweise hoch verdichteten peripheren Arbeitsplatzstandorte sind es, die den Bedeutungsverlust der Kernstadt maßgeblich befördern. Vor allem in US-amerikanischen Stadtregionen ist in diesem Zusammenhang von der Entstehung sogenannter *edge cities* die Rede (Garreau 1992; vgl. auch Kap. 11). *Edge cities* bezeichnen großflächige Büro- und Einzelhandelsagglomerationen an peripheren Standorten, die unter anderem durch ihre weitgehende Monofunktionalität und schlechte Einbettung in den städtischen Kontext bei gleichzeitig guter Verkehrsanbindung geprägt sind. Ebenso wird angemerkt, dass diese *edge cities* lediglich ein Übergangsphänomen auf dem Weg hin zu einer völligen Dispersion von Arbeitsplätzen (*edgeless cities*) sein können (vgl. unter anderem Lang und LeFurgy 2003; Lee 2007). Die entstandene Zentren-/Subzentrenstruktur wäre demnach kein stabiles räumliches Gleichgewicht sondern eher ein Zwischenstadium. Gewisse Einigkeit in dem Diskurs besteht lediglich darin, dass in der stadtregionalen Entwicklung noch kein – wie auch immer geartetes – räumliches Gleichgewicht erreicht ist.

Ein in diesem Diskurs vielfach verwendeter Begriff ist *Polyzentralität*. Diesem liegt keine einheitliche Definition zugrunde, sondern er wird im jeweiligen Kontext neu gedacht und definiert (vgl. unter anderem Kloosterman und Lambregts 2001; Davoudi 2003; Green 2007). Während funktionale Polyzentralität auf die ökonomischen oder verkehrlichen Verflechtungen zwischen Zentren und Subzentren abstellt, bezieht sich morphologische Polyzentralität zumeist auf die sozioökonomische Dimension von Aktivitäten an einem Standort innerhalb der Untersuchungsregion. Gemeinsam ist allen Definitionsversuchen, dass es sich bei Polyzentralität um eine auf mehrere Zentren eines Untersuchungsraums konzentrierte Verteilung zumeist ökonomischer Aktivität handelt. In diesem – zugegebenermaßen unscharfen – Sinne wird der Begriff Polyzentralität in dem vorliegenden Beitrag eingesetzt. Die Herausbildung weiterer (Sub-)Zentren neben dem beziehungsweise den überkommenen Zentrum/Zentren wird dabei als Kerncharakteristikum morphologischer Polyzentralität verstanden. Je nachdem ob es sich um intra- oder interurbane Polyzentralität handelt, liegen eines oder mehrere überkommene Zentren vor. Bei intraurbaner Polyzentralität handelt es sich um eine Stadtregion, die durch eine Kernstadt geprägt war und aufgrund regionsinterner Dekonzentrationsprozesse zu einer mehrkernigen Region wurde. Interurbane Polyzentralität hingegen adressiert Städteregionen, die historisch aus mehreren einzelnen Städten bestanden und erst im Lauf der Zeit zu einer Stadtregion zusammengewachsen sind. Funktionale Polyzentralität im Sinne verkehrsmäßiger Verflechtungen oder ähnliches (vgl. Green 2007) wird hier nicht betrachtet. Uneinigkeit herrscht jedoch dahingehend, ob es in polyzentrischen Regionen eine hierarchische Struktur zwischen Zentrum und Subzentrum geben darf, wie es das Begriffspaar Zentrum ↔ Subzentrum suggeriert oder ob eine Struktur vorliegt, in der das (historische) Zentrum als *primus inter pares* bezeichnet werden kann. Erste empirische Ergebnisse dazu sind unter anderem bei Riguelle et al. (2007) oder Garcia-López und Muñiz (2010) zu finden, die auf eine nach wie vor existierende Hierarchie in polyzentrischen Stadtregionen hinweisen. Eine Nivellierung der „Wichtigkeit" beziehungsweise eine weitergehende Dispersion von Bevölkerung und Beschäftigung sei ihrer Ansicht nach bisher nicht zu beobachten. Aus der Fernerkundung können diese Befunde in Bezug auf die bauliche Struktur einer Stadtregion visuell bestätigt werden (vgl. Kap. 10).

Vor diesem Hintergrund sollen in dem vorliegenden Beitrag vier exemplarische Untersuchungsregionen im Hinblick auf ihre polyzentrische Raumstruktur untersucht und nach Möglichkeit miteinander verglichen werden. Dazu erfolgt zunächst eine erste Annäherung an die räumliche Verteilung von ökonomischer Aktivität und Geschossfläche in den einzelnen Untersuchungsregionen. Hinter der Wahl der Geschossfläche als Analysegröße steht die Annahme, dass Beschäftigung irgendwo „stattfinden" muss und dies mehrheitlich auf Büro- oder Produktionsflächen geschieht. Die zugrundeliegende Vermutung ist daher, dass zwischen Geschossfläche und Beschäftigung ein positiver und möglicherweise auch proportionaler Zusammenhang herrscht.

Darauf aufbauend wird in einem zweiten Schritt versucht, eine Einschätzung hinsichtlich der hierarchischen Prägung einer Region zu geben. Die Kombination von Daten der Fernerkundung mit denen zu sozialversicherungspflichtig Beschäftigten ermöglicht erstmals eine integrierte Analyse der raumstrukturellen Prägung einer Stadtregion. Diese vergleichende Betrachtung generiert einen zusätzlichen Erkenntnisgewinn aus der Verknüpfung sozioökonomischer und fernerkundlicher Daten und stellt damit eine Inwertsetzung der Daten der Fernerkundung dar. In der internationalen Stadtforschung hat der skizzierte Ansatz bisher keinen Einzug gehalten, und für Deutschland war er aufgrund fehlender Daten nicht durchführbar. Der vorliegende Beitrag stößt damit sowohl empirisch als auch methodisch in eine Forschungslücke und trägt zu einem tieferen Verständnis der raumstrukturellen Konfiguration von Stadtregionen bei.

Die diesem Beitrag zugrundeliegende Hypothese lautet: In der morphologischen Betrachtung der raumstrukturellen Konfiguration lässt sich eine eindeutige Hierarchie zwischen den überkommenen Zentren und Subzentren nachweisen, unabhängig davon, ob es sich um Monozentralität, intra- oder interurbane Polyzentralität handelt. Definitionsgemäß sind lediglich die Grade der Polyzentralität unterschiedlich stark ausgeprägt. Die Subzentren sind demnach Nebenzentren von untergeordneter Bedeutung, welche auf der räumlichen Ebene unterhalb der Gemeinden ein anderes Muster aufweisen können als auf der der Städte und Gemeinden. Zu vermuten ist jedoch, dass auch dort die Vorrangstellung gewachsener Zentren (Innenstadt/Central Business District) bestätigt wird (vgl. Kap. 11).

Der Aufbau dieses Beitrags ist folgendermaßen angelegt: Abschn. 17.2 stellt den Dateneinsatz und die Untersuchungsregionen vor und ermöglicht damit einen Eindruck der jeweiligen raumstrukturellen Konfiguration. In Abschn. 17.3 folgen die Analyse der unterschiedlichen Konzentrationen von Beschäftigung und Geschossfläche. Abschnitt 17.4 widmet sich der Frage nach möglichen Hierarchien und Abschn. 17.5 fasst die Erkenntnisse zusammen und versucht eine Einschätzung der raumstrukturellen Prägung der einzelnen Untersuchungsregionen. Ein Ausblick auf methodische und konzeptionelle Weiterentwicklungsmöglichkeiten schließt den Beitrag (Abschn. 17.6).

17.2 Untersuchungsgegenstand

17.2.1 Dateneinsatz und Raumbezug

Die vier Untersuchungsregionen Frankfurt/Main, Köln/Bonn, München und Stuttgart wurden auf Basis der den Kernstädten zugehörigen Arbeitsmarktregionen des Bundesinstituts für Bau-, Stadt- und Raumforschung (BBSR) abgegrenzt und in einem zweiten Schritt mit den Großstadtregionen des BBSR verschnitten (Details zur jeweiligen Abgrenzung siehe BBSR 2012a und BBSR 2012b, Stand jeweils 31.12.2011). Als Untersuchungsraum wird jeweils die Region bezeichnet, die innerhalb der Arbeitsmarktregion liegt und gemäß den Großstadtregionen als Kernstadt, Ergänzungsgebiet zum Kern oder engerer Pendlerverflechtungsbereich klassifiziert ist.

Um dem *Modifiable Areal Unit Problem* (MAUP) Rechenschaft zu tragen und die Verfügbarkeit kleinräumiger Daten aus unterschiedlichen Quellen zu nutzen, werden die Analysen sowohl mit Daten auf der Gemeindeebene als auch mit Rasterdaten mit einer Kantenlänge von 1000 m durchgeführt. Das Raster ist gemäß des europäischen Gitters INSPIRE (Infrastructure for Spatial Information in the European Community) verortet. Dabei wird erwartet, dass die grobkörnige Struktur der administrativen Grenzen durch die Ergänzung mit untergemeindlichen Daten zwar im Gesamteindruck bestätigt, jedoch differenzierter dargestellt werden kann. Tabelle 17.1 ermöglicht einen Größeneindruck über die so generierten Regionen. Anstatt der absoluten Zahlen wird die Beschäftigungsdichte verwendet, da sie eine Flächennormierung der Beschäftigung darstellt und somit zwischen Raumeinheiten unterschiedlicher Größe und unterschiedlicher Zuschnitte besser vergleichbar ist.

Tab. 17.1: Überblick über die vier Untersuchungsregionen

	Region Frankfurt/Main	**Region Köln/Bonn**	**Region München**	**Region Stuttgart**
	Gemeindeebene			
Größe in km²	4843	2812	3277	2844
Anzahl Gemeinden,	168	39	119	137
davon Kernstädte	4	2	1	1
Anzahl der sozialversicherungspflichtigen Beschäftigung (SVB) gesamt, in 1000	1457	980	1080	960
Beschäftigungsdichte (SVB pro km²)	300,8	348,5	329,6	337,5
	Rasterebene, Kantenlänge 1000 m			
Anzahl mit SVB gefüllten Rasterzellen	2914	2293	2464	2029
Durchschnittliche Beschäftigungsdichte[a]	494,3	443,6	511,6	535,4
Baumasse in Millionen m³	695,7	1046,5	684,3	472,7
Geschossfläche in Millionen km²	237,6	356,5	199,7	162,0

[a] Per Definition identisch mit der durchschnittlichen Anzahl SVB pro Rasterzelle.
(Quelle: Eigene Berechnungen auf Basis der Daten der BA und der georeferenzierten Integrierten Erwerbsbiografien des IAB, jeweils zum Stand 30.06.2009)

Die Daten der Geschossfläche stammen aus der Fernerkundung und wurden im Rahmen eines DFG-Projekts am Deutschen Fernerkundungsdatenzentrum (DFD) im Deutschen Zentrum für Luft- und Raumfahrt e.V. (DLR) verarbeitet (für Details siehe Wurm et al. 2014; Fina et al. 2014). Für die nachfolgende Analyse und Interpretation der Ergebnisse ist zu berücksichtigen, dass alle Geschossflächen betrachtet werden, auch solche, die wohnlich genutzt sind. Dies kann zu Verzerrungen bei der gemeinsamen Betrachtung von Beschäftigung und Geschossfläche führen. Alle Werte zur Beschäftigung auf Gemeindeebene sind Daten der Bundesagentur für Arbeit (BA) zum Stichtag 30.06.2009 und beziehen sich auf die sozialversicherungspflichtig Beschäftigten am Arbeitsort. Die Datengrundlagen zur Beschäftigung auf Rasterebene sind die georeferenzierten Integrierten Erwerbsbiografien des Forschungsdatenzentrums der Bundesagentur für Arbeit im Institut für Arbeitsmarkt- und Berufsforschung (FDZ) zum Stichtag 30.06.2009 (für Details siehe Scholz et al. 2012). Erfasst und in den rasterbasierten Analysen verwendet werden die Angaben für alle sozialversicherungspflichtig Beschäftigten (SVB), geringfügig Beschäftigte werden nicht berücksichtigt. Die Daten zur Beschäftigung unterliegen einer datenschutzbedingten Zensur, bei der unter anderem alle Zellen geschwärzt werden, in denen weniger als drei Beschäftigte in weniger als drei Betrieben registriert sind (für eine vollständige Darstellung der Datenschutzrichtlinien siehe Bundesagentur für Arbeit 2014). Diese zensierten Daten wurden manuell auf den Wert 1 gesetzt, wissend, dass dies teilweise eine massive Verzerrung nach unten zur Folge haben kann. Tabelle 17.2 ermöglicht eine quantitative Einschätzung der Datenschutzproblematik. Gegenüber den Daten der BA enthalten die prozessierten Daten des FDZ technisch bedingt nur zwischen 73% und 83% der insgesamt registrierten sozialversicherungspflichtig Beschäftigten.

Tab. 17.2: Überblick über datenschutzbedingte Zensurproblematik in den Rasterdaten

	Region Frankfurt/Main	**Region Köln/Bonn**	**Region München**	**Region Stuttgart**
Durchschnittliche Anzahl SVB[a] je Rasterzelle	494,3	443,6	511,6	535,4
Median Anzahl SVB[a] je Rasterzelle	288	214	151	337
Durchschnittliche Anzahl zensierter Personen[b] je Rasterzelle	9,0	9,2	9,0	8,6

[a] Bezogen auf nicht zensierte Rasterzellen. [b] Berechnet als Anzahl zensierter Personen geteilt durch Anzahl zensierter Rasterzellen. Der Median konnte nicht berechnet werden, da die Häufigkeitsverteilung aus Datenschutzgründen nicht zugänglich war. Lediglich die Summen standen zur Verfügung.
(Quelle: Eigene Berechnungen sowie Auszählungen des FDZ, jeweils auf Basis der georeferenzierten Integrierten Erwerbsbiografien des IAB)

Aus diesen Daten sowie der Information, dass in über 99% der Fälle (in der Region Frankfurt/Main 100%) die Schwärzung aufgrund einer Primärsperrung, das heißt zu wenig Beobachtungen, erfolgte, lässt sich folgendes ableiten: Vermutlich werden nur wenige einzelne Rasterzellen beziehungsweise Zellverbünde sehr hoher Beschäftigungsdichte aufgrund der datenschutzbedingten Zensur nicht erfasst. Die Rasterdaten bezüglich der sozialversicherungspflichtig Beschäftigten erscheinen demnach hinreichend genau, um Auskunft über die raumstrukturelle Prägung der einzelnen Untersuchungsregionen sowie möglicher Hierarchien innerhalb derselben geben zu können. Lediglich die stark monozentrisch geprägte Region München ist im Gegensatz zu den übrigen in erhöhtem Maße von der Zensur aus Dominanzgründen betroffen, sodass einzelne Rasterzellen hoher Beschäftigungsdichte nicht erkannt werden. Dominanzgründe sind solche, in denen die Zensur vorgenommen wird, weil ein Unternehmen innerhalb der Rasterzelle zu viele Beschäftigte (> 50 beziehungsweise 75%) auf sich vereint (für Details siehe Bundesagentur für Arbeit 2014). Die Unterschätzung durch die manuelle Ersetzung der zensierten Werte fällt hierbei besonders stark ins Gewicht.

17.2.2 Charakterisierung der Untersuchungsregionen

Eine erste Einschätzung der vier Untersuchungsregionen auf der Gemeindeebene weist auf deren unterschiedliche raumstrukturelle Konfiguration bezogen auf die Beschäftigungsdichte hin. Auffällig ist insbesondere die Struktur der Regionen München und Stuttgart: Die Kernstädte dominieren jeweils die

Region, aber auch außerhalb existieren Gemeinden mit hoher Beschäftigungsdichte. Ob dies bereits als intraurbane Polyzentralität gewertet werden kann, muss zunächst offen bleiben. Die Region Frankfurt/Main weist hingegen eine offensichtlich mehrkernige Struktur auf, die unter anderem durch das Vorhandensein von vier Kernstädten (Darmstadt, Frankfurt/Main, Mainz, Wiesbaden) erklärbar ist. Aber auch neben diesen Städten gibt es weitere mit auffällig hohen Beschäftigungsdichtewerten. Die Region Köln/Bonn zeichnet sich schließlich durch eine aus den Kernstädten Köln und Bonn geformte, bipolare Struktur aus.

Werden anstelle der Gemeindedaten die Rasterzellen mit einer Kantenlänge von 1000 m betrachtet (vgl. Abb. 17.1), erscheint der visuelle Eindruck der Raumstruktur differenzierter, wenngleich die grundlegenden Erkenntnisse aus der Gemeindeebene erhalten bleiben. Es zeigt sich, dass auch innerhalb von Gemeinden sehr hoher Beschäftigungsdichte Gegenden existieren, in denen keine Beschäftigung registriert ist. Dazu zählen unter anderem Grünflächen aber auch Straßenzüge oder Gewässer. Bezeichnenderweise sind die höchsten Dichten der jeweiligen Regionen, sofern in den Daten als nicht zensierte Werte enthalten, weiterhin in den Kernstädten registriert. Dasselbe gilt für die Geschossfläche pro Rasterzelle, wie in Abb. 17.1 vergleichend dargestellt. Dies spricht zunächst für eine eher hierarchische Struktur der vier Untersuchungsregionen. Die *edgeless cities*-Hypothese, wie sie von Lang und LeFurgy (2003) formuliert wurde, kann für die hier betrachteten Regionen noch nicht endgültig bestätigt oder widerlegt werden. *Edge Cities*, wie von Garreau (1992) beschrieben, scheinen für die deutschen Stadtregionen hingegen nicht zu existieren.

Zu Abb. 17.1 ist anzumerken, dass die teilweise niedrigen Geschossflächendichten (GFD) auf erhebungstechnische Gründe zurückzuführen sind: (1) Die Rasterzellen beinhalten auch Straßen, Grün- und Freiflächen neben den Gebäuden. (2) Es werden stets alle Gebäude beziehungsweise ihre Geschossfläche auf eine Rasterzelle von 1 km² umgelegt, sodass insbesondere in Gebieten lockerer Bebauung „künstlich" niedrige GFDs entstehen, die als Bruttodichten zu interpretieren sind. Folglich sind die genannten GFDs als eine Art Untergrenze zu verstehen und sind in der Realität und vor allem bezogen auf die in der Nettoberechnung korrekterweise betrachteten Grundstücksflächen höher, als es auf der Rasterebene der Fall ist. Um welchen Faktor sie höher liegen, kann mit dem aktuell vorliegenden Datenmaterial noch nicht abgeschätzt werden. Für die weitere Forschung ist das jedoch geplant. In den Kernstädten, und dort im Stadtzentrum, liegen wie erwartet die Rasterzellen mit den regional höchsten GFDs. Für die schraffierten Flächen im Nordosten und Südwesten der Region Köln (Abb. 17.1, zweite Zeile rechts) liegen aufgrund von Wolken zum Zeitpunkt der Aufnahme keine Daten aus der Fernerkundung vor, sodass Lücken geblieben sind, die etwa 8,7% der Gesamtfläche umfassen.

In einem ersten Zwischenfazit kann daher festgehalten werden: Die überkommenen Zentren, definiert als die Kernstädte der Untersuchungsregionen, sind geprägt durch sowohl die höchsten Beschäftigungsdichten als auch die höchsten GFDs. Auf der Gemeindeebene ist dies für die Beschäftigung recht eindeutig, wohingegen sich das Bild auf der Rasterebene differenzierter darstellt. Dies liegt unter anderem daran, dass eine Unterscheidung in Flächen mit und ohne Beschäftigung möglich ist.

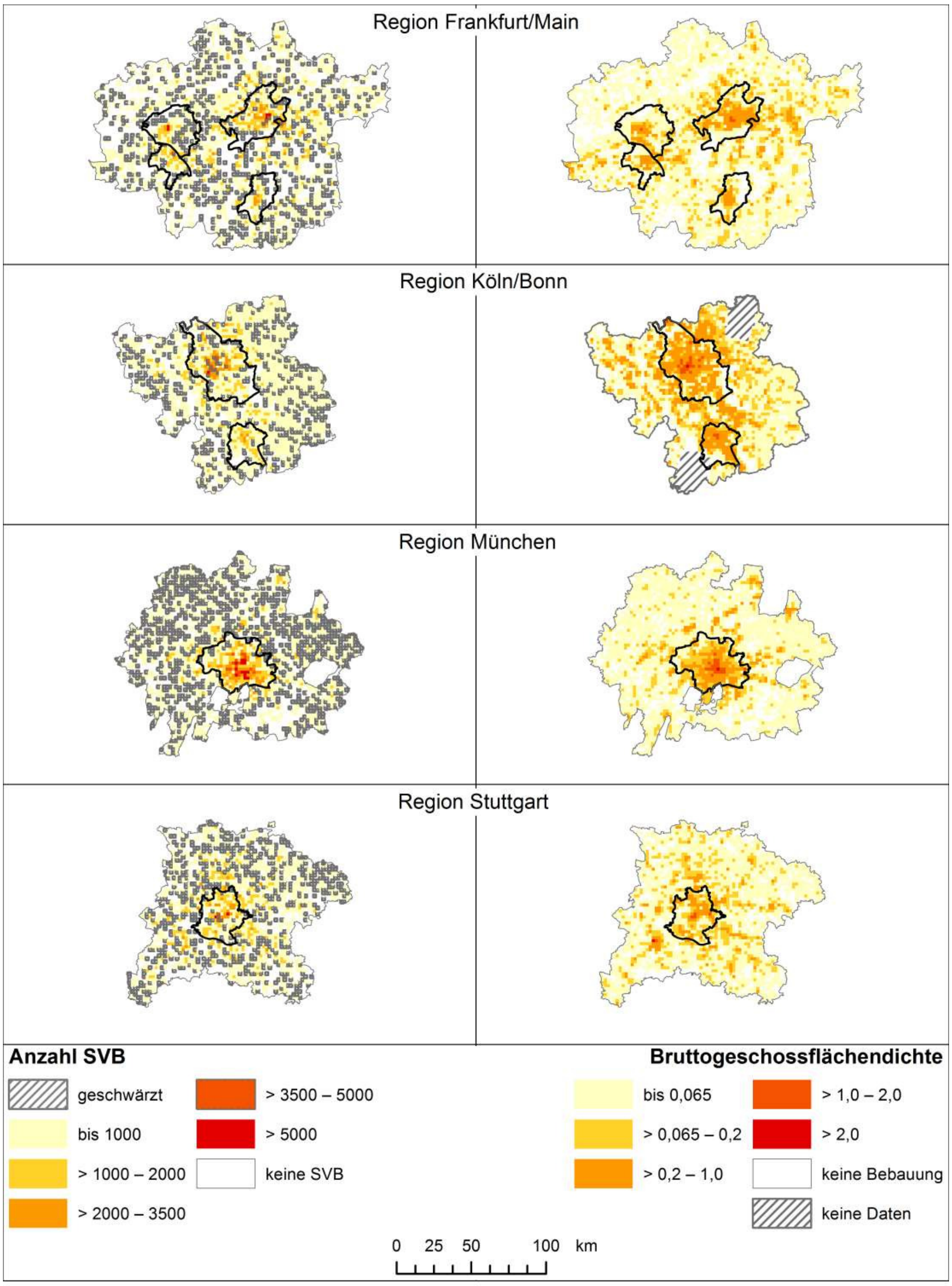

Abb. 17.1: Gegenüberstellung von Beschäftigungsdichte (links) und Geschossflächendichte (rechts) auf Rasterebene in den vier Untersuchungsregionen (Quelle: Eigene Darstellung auf Basis der georeferenzierte Integrierten Erwerbsbiografien des IAB sowie auf Basis der Daten des DLR; vgl. Kap. 10)

17.3 Konzentration in den Regionen als Maß zur Abschätzung ihrer polyzentrischen Struktur

Zur Klassifikation einer Region und zur Klärung der Frage inwiefern sie möglicherweise polyzentrisch geprägt ist, erfolgt eine Analyse der Konzentration von Beschäftigungs- und Geschossflächendichte. Die Vorgehensweisen zur Konzentrationsmessung in der Stadt- und Regionalforschung sind sehr vielfältig. Eine gute Übersicht über die gebräuchlichsten Konzentrationsmaße bieten z. B. Pereira et al. (2013). Neben der Vielfalt der Messmethoden wird auch diskutiert, welche Anforderungen gültige Maße erfüllen müssen und wie Gültigkeit für die einzelnen Maße definiert wird (unter anderem Combes und Overman 2004; Duranton und Overman 2005). Ein neuer Ansatz ist in diesem Zusammenhang die Anwendung bekannter, aus der Ökonomie stammender Konzentrationsmaße auf die Daten der Fernerkundung.

Eine Darstellung der Ungleichverteilung – und damit auch Konzentration – der absoluten Beschäftigung kann mithilfe der sogenannten *Lorenzkurve* umgesetzt werden. Dafür werden zunächst die Anteile der Beschäftigung jeder Gemeinde an der Gesamtbeschäftigung in der Untersuchungsregion berechnet und in aufsteigender Reihenfolge sortiert. Um von den Anteilen zur Lorenzkurve zu gelangen, wird, basierend auf der aufsteigenden Sortierung der Beschäftigungsanteile, zudem der kumulierte Beschäftigungsanteil berechnet. Für die grafische Darstellung wird in einem kartesischen Koordinatensystem auf der Abszisse der kumulierte Beschäftigungsanteil abgetragen, auf der Ordinate der kumulierte Flächenanteil. Je weiter eine Kurve von der Gleichverteilungskurve (dargestellt durch die 45°-Linie) entfernt ist, umso größer ist die Ungleichverteilung. Die Abb. 17.2a und b stellt dies für die Beschäftigung in den vier Untersuchungsregionen dar. In Abb. 17.2c ist mit derselben Methode die Geschossflächenkonzentration abgebildet.

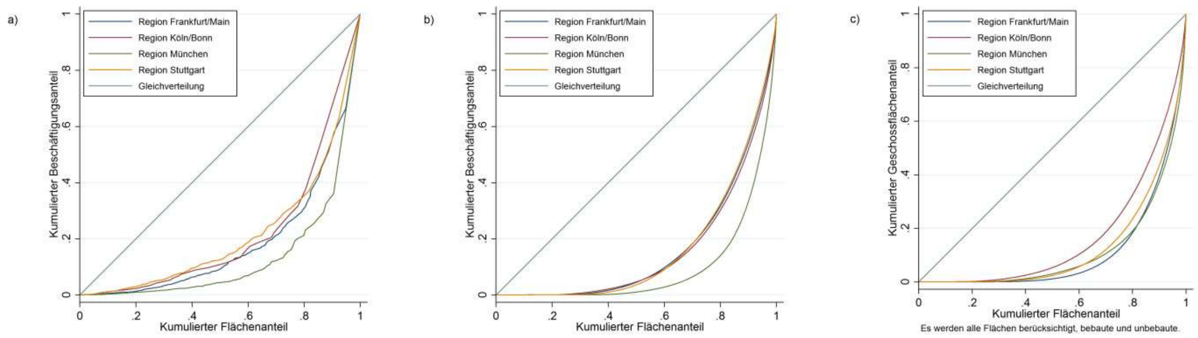

Abb. 17.2: **a** Lorenzkurven der Beschäftigtendaten auf Gemeindeebene für 2009 (Quelle: Eigene Berechnung auf Basis der Daten der BA), **b** Lorenzkurven der Beschäftigtendaten auf Rasterebene für 2009 (Quelle: Eigene Berechnung auf Basis der georeferenzierten Integrierten Erwerbsbiografien des IAB), **c** Lorenzkurven der Geschossfläche auf Rasterebene (Quelle: Eigene Berechnung auf Basis der Daten des DLR)

Damit verfestigt sich der Eindruck, dass in der Region München die räumlich am stärksten konzentrierte Beschäftigung vorliegt. Weiterhin scheint bezüglich der Beschäftigung die Region Frankfurt/Main die am zweitstärksten konzentrierte Untersuchungsregion zu sein. Da sich die Lorenzkurven für die vier Untersuchungsregionen jedoch schneiden, ist allein auf dieser Basis eine Rangliste der Regionen hinsichtlich ihrer Beschäftigungskonzentration nicht zulässig. Zu berücksichtigen ist darüber hinaus, dass die Kurve keine Verortung der (beschäftigungsstarken) Gemeinden beziehungsweise Rasterzellen ermöglicht. Diese kann sowohl über die gesamte Untersuchungsregion verteilt sein, als auch konzentriert in einem Teil der Untersuchungsregion. Für die Region München dürfte letzteres zutreffen, wohingegen in der Region Frankfurt/Main eher ersteres der Fall ist. Dort liegen vier Kernstädte mit jeweils hohen Beschäftigungszahlen vor, sodass die Beschäftigung auf wenige Orte konzentriert ist, diese Orte jedoch über die Region verteilt sind – ein Charakteristikum interurbaner Polyzentralität. Die Betrachtung der Rasterebene (Abb. 17.2b) scheint keine gesicherte Aussage zu ermöglichen bis auf die Bestätigung, dass die Region München die am stärksten konzentrierte Beschäftigung aufweist. Werden anstelle der Beschäftigten die Geschossflächen betrachtet (Abb. 17.2c), erscheint der Eindruck modifiziert. Konzentration dominiert zwar das Bild und ist in etwa gleich stark ausgeprägt wie die der Beschäftigung, auffällig ist jedoch der Verlust der Stellung Münchens als am sichtbar stärksten konzentrierte Region. Dies mag mit planungsrechtlichen Rahmenbedingungen zusammenhängen, die gleichermaßen für alle Regionen unter anderem maximale Geschossflächenzahlen festlegen. Gleichwohl gilt auch hier, dass ein Regionsvergleich aufgrund der sich schneidenden Lorenzkurven unzulässig ist.

Die zugehörigen *Gini-Koeffizienten* sind in der nachstehenden Tabelle (Tab. 17.3) dargestellt. Sie werden berechnet als Anteil der Fläche zwischen Lorenz- und Gleichverteilungskurve an der Gesamtfläche unterhalb der Gleichverteilungskurve. Je höher der Wert des Gini-Koeffizienten, desto konzentrierter ist die betrachtete Verteilung.

Tab. 17.3: Gini-Koeffizienten der SVB sowie der Geschossflächen in den vier Untersuchungsregionen

	Region Frankfurt/Main	**Region Köln/Bonn**	**Region München**	**Region Stuttgart**
	Gemeindeebene Sozialversicherungspflichtig Beschäftigte			
Gini-Koeffizient, ungewichtet	0,822	0,748	0,854	0,775
Gini-Koeffizient, flächengewichtet	0,872	0,848	0,955	0,881
	Rasterebene, Kantenlänge 1000 m Sozialversicherungspflichtig Beschäftigte			
Gini-Koeffizient, alle Rasterzellen[a]	0,815	0,763	0,870	0,785
Gini-Koeffizient, nur gefüllte Zellen[b]	0,674	0,685	0,809	0,673
	Rasterebene, Kantenlänge 1000 m Geschossfläche			
Gini-Koeffizient, alle Rasterzellen	0,789	0,686	0,787	0,763
Gini-Koeffizient, nur gefüllte Zellen	0,713	0,643	0,743	0,710

[a] Die zensierten Zellen sind mit dem Wert eins, Rasterzellen ohne Beschäftigung mit dem Wert null in die Berechnung eingegangen. [b] Die zensierten Zellen sind mit dem Wert eins in die Berechnung eingegangen, Rasterzellen ohne Beschäftigung wurden vor der Berechnung aus dem Datensatz eliminiert.
(Quelle: Eigene Berechnungen auf Basis der Daten der BA, der georeferenzierten Integrierten Erwerbsbiografien des IAB sowie der Daten des DLR)

Das Betrachten der Gemeindedaten verdeutlicht die Bedeutung der Gemeindefläche bei der Konzentrationsmessung. Wird selbige nicht berücksichtigt (Zeile 1 in Tab. 17.3), ist die Ungleichverteilung deutlich weniger stark ausgeprägt als wenn sie berücksichtigt wird. Die Berücksichtigung erfolgt, indem die Gemeinden nicht nur abgezählt, sondern gemäß ihrer Flächenanteile aufsteigend sortiert werden. Mit dem Wechsel auf die räumlich niedrigere Ebene der Rasterzellen relativiert sich das Bild ein wenig gegenüber den flächengewichteten Gemeindewerten, der Gesamteindruck bleibt jedoch erhalten. Für die Interpretation von Tab. 17.3 bezüglich der Rasterdaten sind zwei Aspekte zu beachten: (1) Die datenschutzbedingte Zensur auf der Ebene der Rasterdaten macht eine manuelle Ersetzung der betroffenen Werte notwendig. Folglich sind die berechneten Gini-Koeffizienten lediglich eine Näherung an die tatsächlichen Werte. (2) Dort, wo Beschäftigung registriert ist, ist sie gleichmäßiger verteilt, als es auf Gemeindeebene der Fall ist (siehe Tab. 17.3, Vergleich der 3. mit der 4. Zeile). In Bezug auf die vermutete Raumstruktur ist es wenig überraschend, dass die Konzentration von Beschäftigung und Geschossfläche in der Region München unabhängig von der räumlichen Ebene am stärksten ausgeprägt ist.

Es lässt sich daher zeigen, dass Lorenzkurve und Gini-Koeffizient zwar etwas über Konzentrationen aussagen, sie jedoch die für die Polyzentralitätsanalyse notwendige räumliche Verortung nicht abbilden können. Auch eine mögliche räumliche Kongruenz zwischen Beschäftigungs- und Geschossflächenkonzentration kann nicht allein mit diesen Methoden nachgewiesen werden, auch wenn die reinen Konzentrationswerte auf einen positiven Zusammenhang hindeuten. Diese Erkenntnis ist nicht neu: Diverse Autoren haben bereits angemerkt, dass eine Weiterentwicklung der einfachen Konzentrationsmaße notwendig ist, um diesen unter anderem eine regionale Komponente zur Seite zu stellen und auch statistische Tests hinsichtlich der Signifikanz zu ermöglichen (z. B. Ellison und Glaeser 1997; Combes und Overman 2004; Duranton und Overman 2005). Dieser Problematik wird in Teilen begegnet, indem das Konzentrationsmaß trotz bekannter Schwächen berechnet und seine Ergebnisse im folgenden Abschnitt mit weiteren Methoden validiert werden.

17.4 Hierarchien als (Konter-)Inzidenz für morphologische Polyzentralität

Einen ersten Eindruck hinsichtlich der Hierarchie der einzelnen Gemeinden einer Untersuchungsregion ermöglicht die *rank-size rule*. Ursprünglich wurde diese Methode angewendet, um unter anderem die Regelmäßigkeit der Bevölkerungsverteilung in Städtesystemen zu visualisieren. In einem von Zipf (1949) empirisch nachgewiesenen Spezialfall der *rank-size rule* gilt, dass der Bevölkerungszahl nach absteigend sortierte Städte sich durch inverse Proportionalität zwischen Bevölkerungszahl und Position in der Rangliste auszeichnen. Diesem Gesetz folgend zählt die zweitgrößte Stadt nur 50% der Einwohner der größten Stadt, die drittgrößte Stadt besitzt 1/3 der Einwohner im Vergleich zur ersten Stadt usw. (vgl. unter anderem Gabaix und Ioannides 2004; Lalanne 2013). Zur empirischen Überprüfung wird meistens ein doppelt logarithmisches Modell geschätzt, um den beschriebenen Sachverhalt zu linearisieren: Der logarithmierte Rang einer kommunalen Gebietseinheit kann erklärt werden mit einer Konstanten zuzüglich einem Vielfachen der logarithmierten Bevölkerungsanzahl. Ist dieses Vielfache gleich dem Wert −1, kann der von Zipf formulierte Spezialfall bestätigt werden. Im Folgenden soll geprüft werden, ob anstelle der Bevölkerungsverteilung auch die Beschäftigungs- und die Geschossflächenverteilung diese Regelmäßigkeit aufweisen. Ließe sich dies bestätigen, wäre die *rank-size rule* ein Maß zur vergleichenden Analyse größenbezogener hierarchischer Strukturen (vgl. dazu Bröcker und Herrmann 2012) in unterschiedlichen Untersuchungsregionen und auf Basis unterschiedlicher Variablen. In einer polyzentrischen Region würde eine flachere Hierarchie erwartet werden als in einer monozentrischen. Der Zipf'sche Wert −1 und seine Interpretation deuten jedoch auf recht ausgeprägte hierarchische Strukturen, wie sie in eher monozentrisch geprägten Regionen vorliegen. Anzumerken ist hierbei, dass es unterschiedliche Auffassungen darüber gibt, ob Hierarchien über absolute Zahlen abgebildet werden können oder ob sie nur in relationalen Beziehungen wie zum Beispiel Pendlerverflechtungen oder Güterströmen zum Ausdruck kommen (Taylor 1997). Der vorliegende Beitrag stellt lediglich auf morphologische, nicht jedoch auf funktionale Polyzentralität ab. Folglich werden auch relationale Verflechtungen nicht betrachtet, weshalb angenommen wird, dass ein Größenvergleich auch etwas über die Hierarchie aussagt.

Beginnend mit der Betrachtung aller Gemeinden einer Untersuchungsregion weist die Anwendung der *rank-size rule* im Großen und Ganzen das erwartete Verhältnis zwischen Beschäftigungsanzahl und Rangposition auf. Allerding kann anstelle des von Zipf postulierten, linearen Zusammenhangs lediglich ein monoton fallender Zusammenhang nachgewiesen werden. Folglich ist bei der Berücksichtigung aller Gemeinden einer Untersuchungsregion kein einheitliches, der *rank-size rule* entsprechendes Muster zu beobachten. Wird die Beschäftigung unter Auslassung des unteren Quartils betrachtet, verändert sich das Bild (vgl. Abb. 17.3): Die Regressionsgeraden werden steiler als bei der Berücksichtigung aller Gemeinden. Steilere Regressionsgeraden bedeuten eine weniger stark ausgeprägte Hierarchie (vgl. Lalanne 2013). Diese weniger stark ausgeprägte Hierarchie nach dem Weglassen von Gemeinden mit niedrigerer Beschäftigung war zu erwarten, da durch die Eliminierung der beschäftigungsschwächeren Gemeinden eine „Nivellierung" erfolgt. Der nicht lineare Verlauf der Datenpunkte in Abb. 17.3 verdeutlicht, dass es keine Gesetzmäßigkeit für Beschäftigte auf Gemeindeebene gibt, wie sie von Zipf formuliert und unter anderem von Bröcker und Herrmann (2012) für die Bevölkerung nachgewiesen wurde. Zu berücksichtigen ist, dass die hier generierten Ergebnisse auf der Gemeindeebene speziell für die Region Köln aufgrund niedriger Fallzahlen verzerrt sein können.

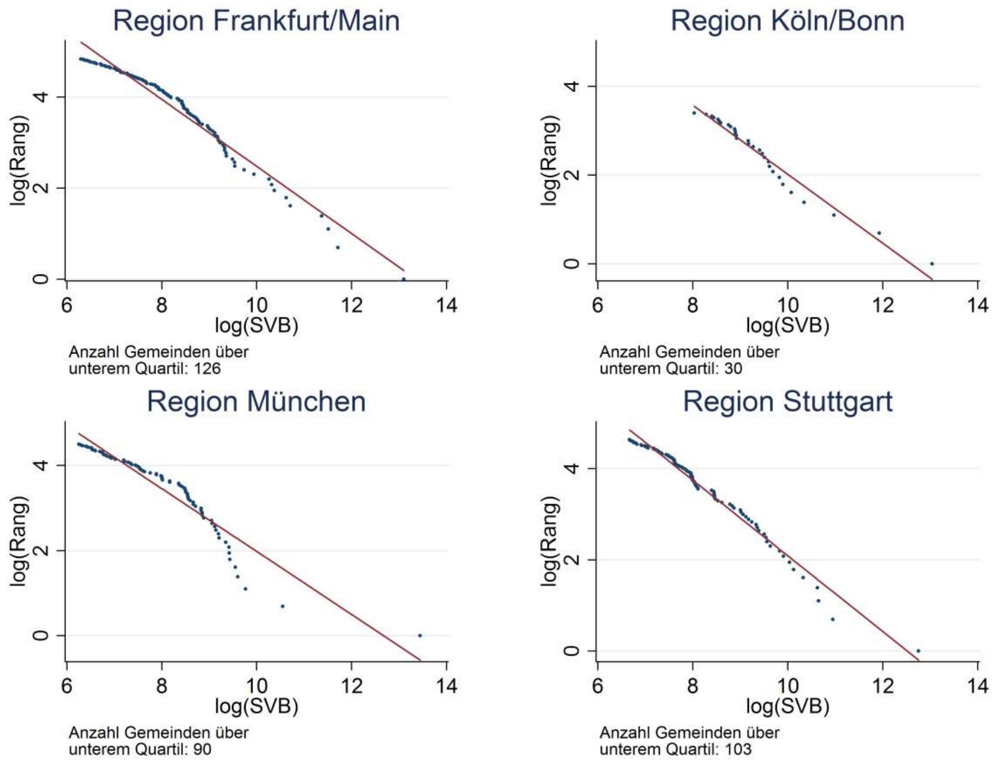

Abb. 17.3: Darstellung der *rank-size rule* für die Untersuchungsregionen, jeweils bezogen auf die beschäftigungsstärksten 75% der Gemeinden (Quelle: Eigene Berechnungen auf Basis der Daten der BA)

Es fällt auf, dass die *rank-size rule* für sozialversicherungspflichtig Beschäftigte auf Ebene der Rasterdaten (Abb. 17.4) ebenfalls keine Gültigkeit besitzt, obwohl auch hier nur das obere Ende der Verteilung betrachtet wird, so wie es auch Gabaix und Ioannides (2004) oder Bröcker und Herrmann (2012) handhaben. Die hier nicht dargestellte Abbildung unter Berücksichtigung aller Rasterzellen zeigt ein ähnliches Bild. Eine deutlich flachere Hierarchie in der Beschäftigungsverteilung, als sie gemäß *Zipf's Law* zu erwarten gewesen wäre, zeichnet sich in den Regionen Frankfurt/Main ($\beta_1 = -1{,}547$), Köln/Bonn ($\beta_1 = -1{,}380$) und Stuttgart ($\beta_1 = -1{,}686$) ab. Lediglich die Region München weist mit einem Koeffizienten von $\beta_1 = -0{,}980$ nahezu eine Zipf'sche Proportionalität im Hinblick auf Beschäftigung auf. Ein der Bevölkerungsgrößenverteilung auf Gemeindeebene entsprechendes Verhältnis scheint auf kleinräumiger Ebene und für Beschäftigung und vor allem in a priori polyzentrischen Regionen demnach nicht zu existieren.

Werden bei der Abbildung der Geschossfläche mithilfe der *rank-size rule* alle bebauten Flächen berücksichtigt, liegt ebenfalls kein linearer Zusammenhang zwischen logarithmierter Geschossfläche und logarithmiertem Rang vor. Auffällig ist jedoch der fast perfekte Zusammenhang, wenn anstelle aller Rasterzellen nur solche mit einer GFD größer 0,4 berücksichtigt werden. Dies bestätigt zunächst die Einschätzung, dass es sinnvoll ist, lediglich das obere Ende der Verteilung zu betrachten. Inwiefern eine GFD von mehr als 0,4 hier inhaltlich begründet werden kann, muss zunächst offen bleiben. Berücksichtigt werden muss, dass es sich bei den hier genannten GFD-Werten um Bruttowerte handelt, da jede Rasterzelle neben Gebäuden und deren zugehörigen Grundstücken auch Verkehrswege, Grünflächen etc. beinhaltet. Gegenüber dem Spezialfall, wie er für die Bevölkerung auf Gemeindeebene bereits nachgewiesen werden konnte, ist die Hierarchie der GFDs jedoch deutlich flacher. Die Regressionskoeffizienten betragen zwischen $\beta_1 = -3{,}059$ (Region Frankfurt) und $\beta_1 = -2{,}103$ (Region München). Die Region München ist folglich weniger stark konzentriert als die Region Frankfurt/Main. Es muss an dieser Stelle jedoch explizit berücksichtigt werden, dass ein Ausschluss der wohnbaulich genutzten Flächen aus dem Datenmodell nicht möglich war, sodass in der Region München wie auch in allen anderen Regionen eine gewisse Verzerrung in den hier vorgestellten Analysen beinhaltet ist. Einerseits ist die weniger starke Konzentration der Region München gegenüber der der Region Frankfurt/Main überraschend, da die vermutete Kongruenz zwischen sozialversicherungspflichtig Beschäftigten und Geschossfläche nicht so ausgeprägt ist. Andererseits muss aufgrund der Nichtverortung der betreffenden Rasterzellen davon ausgegangen werden, dass die *rank-size rule* zwar eine Hierarchie, nicht aber zwangsläufig räumliche (De-)Konzentration angibt.

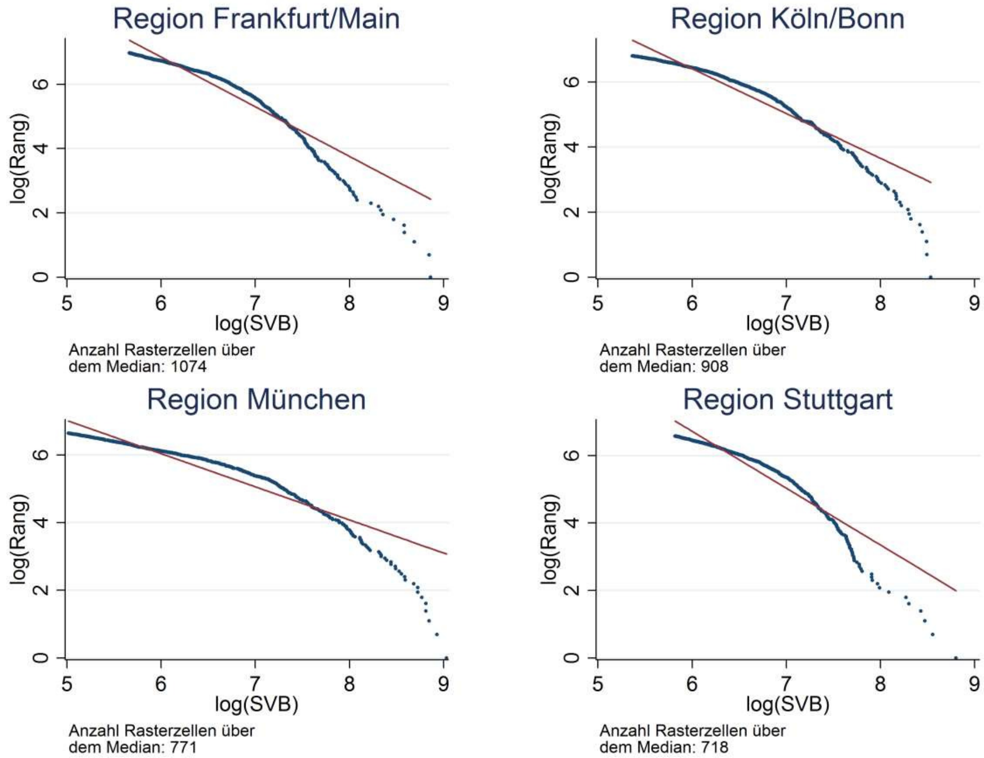

Abb. 17.4: Darstellung der rank-size rule für die Untersuchungsregionen im Jahr 2009, jeweils bezogen auf die beschäftigungsstärksten 50% der Rasterzellen (Quelle: Eigene Berechnungen auf Basis der georeferenzierten Integrierten Erwerbsbiografien des IAB)

Die Hierarchie von Zentren und Subzentren lässt sich mithilfe der Abb. 17.2–17.4 in ihren Grundzügen charakterisieren. Jeweils am unteren rechten Bildrand der Graphen in den Abb. 17.3 und 17.4 sind einzelne Datenpunkte unterhalb der Regressionslinie identifizierbar. Werden daraus die 20 am weitesten rechts unten liegenden Punkte abgeleitet, das heißt die 20 „größten“ Rasterzellen, mit statistischen Kennzahlen belegt (Tab. 17.4) und in einer Karte verortet (Abb. 17.5), kann für die einzelnen Regionen Folgendes konstatiert werden:

Tab. 17.4: Beschäftigung und Geschossfläche in den jeweils 20 „größten“ Rasterzellen

	Region Frankfurt/Main	Region Köln/Bonn	Region München	Region Stuttgart
	20 beschäftigungsstärkste Rasterzellen			
Flächenanteil in %	0,4	0,7	0,6	0,7
Beschäftigungsanteil in % [a]	7,7	9,4	14,3	8,4
Anzahl SVB	81.753	76.013	113.998	65.137
Geschossflächenanteil in %	5,7	6,1	9,8	5,3
Geschossfläche in km²	13,7	22,6	19,6	8,6
	20 geschossflächenstärkste Rasterzellen			
Flächenanteil in %	0,4	0,7	0,6	0,7
Beschäftigungsanteil in %	5,7	6,5 [b]	10,6	3,1
Anzahl SVB	60.330	52.221	84.535	24.315
Geschossflächenanteil in %	7,6	8,1	13,3	12,5
Geschossfläche in km²	18,1	28,9	26,6	20,2

[a] Da die Summe aller SVB je Untersuchungsregion zur Verfügung stand, tritt eine datenschutzbedingte Verzerrung der Werte hier nicht auf. [b] Eine von 19 Zellen ist zensiert, sodass hier eine datenschutzbedingte Verzerrung auftritt.
(Quelle: Eigene Berechnungen auf Basis der georeferenzierten Integrierten Erwerbsbiografien des IAB sowie auf Basis der Daten des DLR)

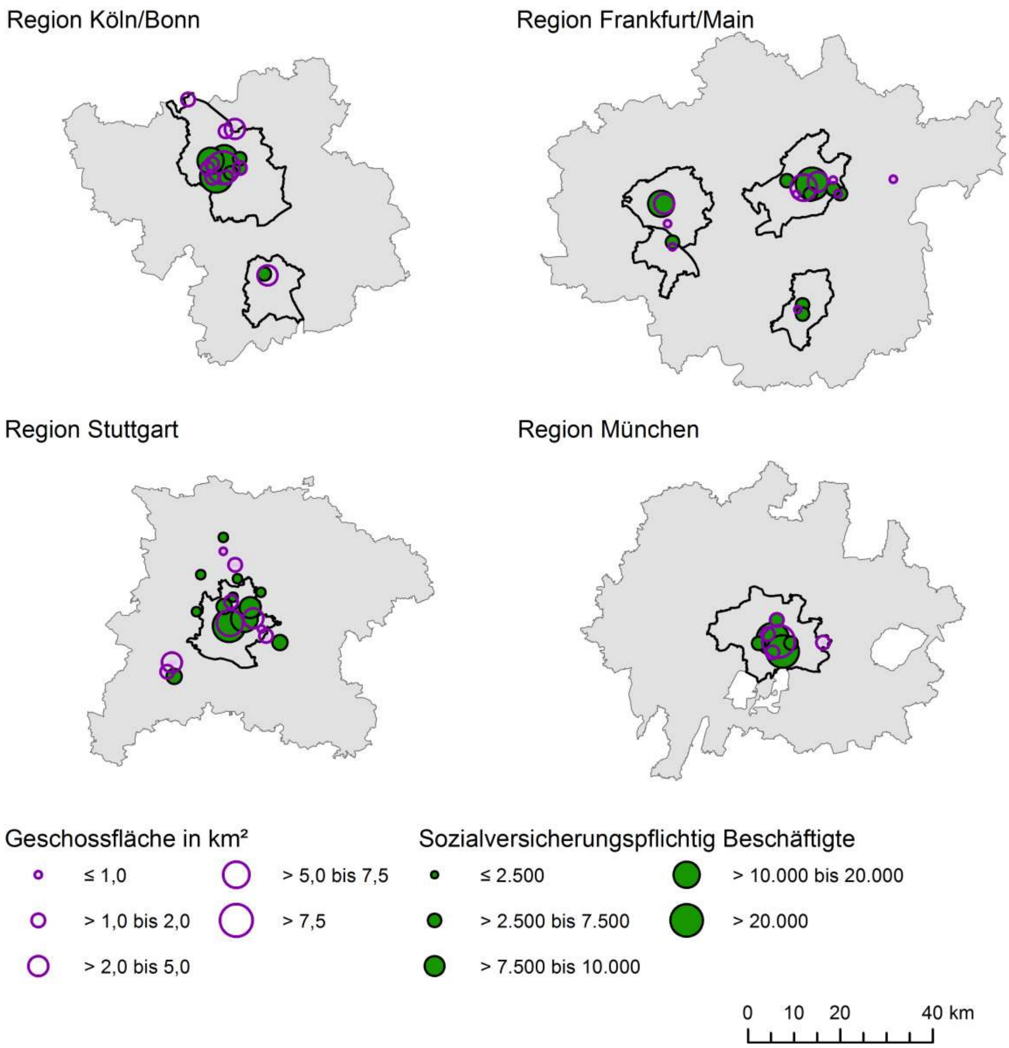

Abb. 17.5: Verortung und Größenordnung der 20 „größten“ und bei Vorliegen gemeinsamer Grenzen zusammengefassten Rasterzellen (Quelle: Eigene Darstellung auf Basis der Daten des DLR sowie auf Basis der georeferenzierten Integrierten Erwerbsbiografien des IAB)

1. 17 der 20 beschäftigungsstärksten Rasterzellen der *Region Frankfurt/Main* liegen in einer der vier Kernstädte. Die übrigen drei befinden sich in der Stadt Offenbach und dort nahe der Stadtgrenze zur Stadt Frankfurt/Main. Der Mittelwert dieser 20 Werte ist zehnmal so groß wie

der Mittelwert aller verbleibenden Rasterzellen der Region. Auch die Geschossfläche ist dort stärker vertreten (5,7%, vgl. Tab. 17.4) als es bei Gleichverteilung der Fall wäre.

2. 19 der 20 betrachteten Rasterzellen der *Region Köln/Bonn* befinden sich in der erweiterten Kölner Innenstadt sowie auf dem gegenüberliegenden Messeufer. Die verbleibende Rasterzelle ist in Bonn lokalisiert. Der Mittelwert dieser 20 Werte ist neunmal so groß wie der Mittelwert aller verbleibenden Rasterzellen der Region. Bezüglich der Geschossfläche zeichnet sich ein ähnliches Bild wie in der Region Frankfurt/Main, wenngleich dort prozentual weniger Geschossfläche als Beschäftigung verortet ist.
3. Die betrachteten 20 Rasterzellen in der *Region München* liegen in der Kernstadt und sind dort auf den Stadtkern konzentriert. Der Mittelwert dieser 20 Werte übersteigt den Mittelwert aller verbleibenden Rasterzellen der Region um das Zwölffache. Auch bezüglich der Geschossfläche wird deutlich, dass auf diesen 0,6% der Fläche überproportional viel Geschossfläche (9,8%) vorliegt.
4. In der *Region Stuttgart* sind nur 13 der betrachteten 20 Rasterzellen in der Kernstadt verortet. Die übrigen sieben verteilen sich auf mehrere unterschiedliche Gemeinden, die direkt an die Kernstadt angrenzen und liegen dort jeweils recht zentral. Der Mittelwert dieser 20 Werte übersteigt den Mittelwert aller verbleibenden Rasterzellen der Region lediglich um das Fünffache. Die Geschossfläche ist mit 5,3% im Vergleich zu den anderen Regionen eher niedrig, was die Ergebnisse der Beschäftigungsbetrachtung unterstützt.

Wird diese Untersuchung umgekehrt und werden die 20 geschossflächenstärksten Rasterzellen betrachtet, zeichnet sich ein der Beschäftigung ähnliches, wenngleich auch nicht deckungsgleiches Bild (vgl. Abb. 17.5). In Tab. 17.4 sind die zugehörigen Anteile und Absolutwerte zusammengefasst. Diese weisen sehr anschaulich nach, dass auch bei der Geschossfläche eine deutliche Konzentration vorliegt, jedoch in weniger stark ausgeprägtem Maße als bei der Beschäftigung. Damit bestätigen sich auch die Ergebnisse der Gini-Koeffizienten.

Bezüglich einer visuellen Einschätzung der Hierarchie der Zentren und Subzentren in den Untersuchungsregionen liefert Abb. 17.5 weitere Einblicke und ergänzt die bisherigen Erkenntnisse. Benachbarte Rasterzellen wurden dabei zu größeren Polygonen zusammengefasst, um die Struktur der einzelnen Zentrenstandorte besser herausarbeiten zu können.

Die Beschäftigungs- und Geschossflächenhierarchie in den Regionen München, Frankfurt/Main und Köln/Bonn ist deutlich stärker ausgeprägt als die in der Region Stuttgart. Die *rank-size rule* hatte dies schon ohne konkrete räumliche Verortung angedeutet. Mit der Verortung der 20 ranghöchsten Rasterzellen kann neben einer Hierarchie in der Gesamtregion auch eine deutliche Konzentration nachgewiesen werden. Dies bestätigt sich auch, wenn anstelle der oben genannten Anzahlen entsprechende Anteile verortet werden (vgl. Tab. 17.4). Bezüglich der Region München ist zu erwähnen, dass hinter den beiden größten Werten (größte grüne Punkte in der Region München in Abb. 17.5) über 35.000 beziehungsweise über 63.000 Beschäftigte stehen. In keiner der anderen drei Untersuchungsregionen werden zusammenhängende Rasterzellen in dieser Größenordnung gefunden, weder bezüglich der Beschäftigung noch hinsichtlich ihrer der räumlichen Nähe zueinander.

Werden analog zur Beschäftigung die 20 geschossflächenreichsten Rasterzellen im Falle der Nachbarschaft zusammengefasst, entsteht das in Abb. 17.5 mithilfe der violetten Ringe präsentierte Muster. Im Gegensatz zur Beschäftigung existieren insbesondere in der Region Köln/Bonn weniger zusammenhängende Rasterzellen: Die Geschossfläche ist stärker im Raum verteilt. Nichtsdestotrotz können in den übrigen drei Regionen Geschossflächenkonzentrationen an eher innerstädtischen und meist auch innerhalb der Kernstädte gelegenen Standorten konstatiert werden. Eine gewisse Kongruenz zwischen Beschäftigung und Geschossfläche lässt sich ebenfalls nachweisen. In der Region Frankfurt/Main scheint bezüglich der „größten" Rasterzellen Deckungsgleichheit zu herrschen, wohingegen in der Region Köln ein gewisses Auseinanderfallen zu beobachten ist. Dahinter können jedoch erhebungstechnische Aspekte stehen. Die Region Stuttgart weist erwartungsgemäß eine polyzentrische Struktur auf, und in der Region München bestätigt sich das Bild einer eher monozentrischen Region.

17.5 Einordnung und Interpretation der Ergebnisse

Wie ist dieser Befund bezüglich der *edge* oder *edgeless cities*-Debatte einzuordnen und was trägt er im Hinblick auf die Polyzentralitätsdebatte zum Verständnis der Raumstruktur in den Untersuchungsregionen bei? Deutlich geworden ist die ungebrochene Dominanz der Kernstädte aller vier deutschen Untersuchungsregionen gegenüber ihrem Umland. Dies spiegelt sich nicht nur in den Konzentrationsindizes wider, sondern wird auch bei der Betrachtung der Hierarchie sowie ihrer kartografischen Visualisierung deutlich. Der Hypothesenteil hinsichtlich der Kernstadtdominanz kann folglich als bestätigt angesehen werden. In den einzelnen Untersuchungsregionen sind die Ausprägungen jedoch, wie erwartet, unterschiedlich.

Nichtsdestotrotz ist insbesondere in der Region Stuttgart auch hohe Beschäftigung außerhalb des überkommenen Zentrums (der Innenstadt) lokalisiert und kann daher in ihrer Intensität als nachgeordnetes Subzentrum bezeichnet werden. Die Konzentrationsmaße sind für diese Stadtregion ebenfalls niedriger als z. B. für die Region München, sodass – ohne eine eindeutige Definition zu verwenden – die Region Stuttgart eine relativ polyzentrische Raumstruktur aufweist. Auf der Rasterebene ist dies deutlich besser sichtbar als auf der Gemeindeebene. Auf letzterer könnte für die Region Stuttgart auch von „erweiterter Monozentralität" im Sinne von „positiven Beschäftigungsdichteausreißern an den Rändern der Kernstadt" (analoges gilt für die Geschossfläche) gesprochen werden. Aufgrund dieses Befundes kann intraurbane Polyzentralität festgestellt werden. Zentrum ist die Kernstadt beziehungsweise die dort verorteten Rasterzellen und die Subzentren im Südwesten, Norden und Osten der Kernstadt haben noch einen Weg vor sich bevor sie als gleichrangige Subzentren bezeichnet werden können. In den Regionen Frankfurt/Main und Köln/Bonn ist das Bild nicht so eindeutig wie in München und Stuttgart. Ein Charakteristikum interurbaner Polyzentralität? Die Verteilung der Geschossfläche und speziell der 20 geschossflächenstärksten Rasterzellen in der Region Köln/Bonn fällt als einzige ein wenig aus dem Rahmen. Sie zeigt eine eher disperse Struktur. Dies kann Ausdruck einer schwachen interurbanen Polyzentralität sein. Ausgeprägt polyzentrische Strukturen können abgesehen von definitorisch mehreren Kernstädten nicht eindeutig nachgewiesen werden. Desgleichen scheinen keine charakteristischen Büro- und damit implizit Beschäftigungsstandorte in nicht innerstädtischen Lagen zu existieren, sodass die von Garreau (1992) geprägte Formulierung der *edge cities* sich nicht zur Beschreibung der hier vorliegenden raumstrukturellen Muster eignet. Interessant, wenngleich auch zu erwarten, aber noch nicht quantitativ nachgewiesen, ist die auffällige *Kongruenz zwischen Beschäftigung und Geschossfläche*. Der Blick der Fernerkundung „von oben" ermöglicht eine Visualisierung der Wirkungen der Beschäftigungsverteilung auf die baulich-physische Struktur einer Stadtregion, oder vice versa. Die Frage nach Ursache und Wirkung kann mit der vorliegenden Analyse jedoch nicht beantwortet werden.

17.6 Fazit

Gibt es *primae inter pares* in den einzelnen Stadtregionen wie es in polyzentrisch geprägten Stadtregionen zu erwarten wäre? *Primae* – ja. In allen Regionen dominiert die Kernstadt trotz teilweise sehr deutlich sichtbarer Subzentren im näheren Umland. Die Konzentrationsindizes weisen ebenfalls darauf hin. *Inter Pares* – nein. Subzentren liegen in allen Regionen in unterschiedlichem Maß vor, wie die Konzentrationsindizes und ein Stück weit auch die Visualisierungen der *rank-size rule* zeigen. Im

Vergleich zum überkommenen Zentrum sind sie jedoch noch kleine Gewichte in der raumstrukturellen Prägung der einzelnen Regionen. Das Vorliegen von *edgeless cities*, deren Entstehung unter anderem Lang und LeFurgy (2003) für Nordamerika prognostizieren, kann nicht bestätigt werden. Die Ergebnisse von Riguelle et al. (2007) beziehungsweise Garcia-López und Muñiz (2010) finden jedoch in den hier durchgeführten Untersuchungen Entsprechung: Hierarchie ist in allen Stadtregionen (noch?) gegeben und die Innenstädte der Kernstädte weisen nach wie vor eine hohe Bedeutung auf.

Der nächste Schritt wäre nun, die für die Beschäftigung zum Zeitpunkt 2009 erhaltenen Ergebnisse im Zeitverlauf zu analysieren. Diese Analyse würde es ermöglichen, Polyzentralität als raumstrukturellen Prozess aufzufassen und ihre langfristige Ausformung zu betrachten. Im Bereich der Fernerkundung ist dies bereits heute in Ansätzen möglich, da erste Zeitreihen verfügbar sind (vgl. Kap. 10). Deren systematische Analyse weist noch reichlich Forschungsbedarf auf und bietet damit die Möglichkeit, die raumstrukturelle Entwicklung von Stadtregionen kleinteilig nachzuzeichnen. Für die Beschäftigungsdaten wären Zeitreihen ebenfalls wünschenswert, sind im deutschen Kontext jedoch noch nicht so feinkörnig verfügbar wie es für eine sinnvolle Untersuchung polyzentrischer Strukturen notwendig wäre. Wie eingangs angesprochen, ermöglicht nicht nur die hier vorgenommene zeitpunktbezogene integrierte Betrachtung von sozioökonomischen Daten und Daten der Fernerkundung erheblichen Mehrwert. Insbesondere die Verknüpfung dieser Daten in einer räumlichen Panelstudie bietet noch viel Potenzial für weitergehende Forschungen.

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Urban spatial structure: an interaction between employment and built-up volumes

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This paper employs socioeconomic and remote sensing data to develop a novel approach to analysing the morphological urban spatial structure in select German city-regions. Furthermore, the suggested multidimensional procedure facilitates the analysis of the implications of different urban spatial structures in terms of physical urban form. All analyses are conducted on the spatial scale of 1 km² grid cells to allow for spatially detailed results and to account for intra-municipality differences in the urban spatial structures in the study regions. The results indicate fundamental differences among the study regions' distribution of employees and built-up volumes and, as a result, among their urban spatial structures. Both employees and built-up volumes are found to be highly spatially clustered primarily within the core cities but with notable exceptions, which thus qualifies the regions as polycentric. This finding is consistent with prior research but also reveals that built-up volumes can be understood as physical manifestations of proximity advantages to which firms and employees are subject.

Keywords: urban spatial structure; polycentricity; employment; built-up volumes; spatial clustering; Germany

Introduction

Urban spatial structure is a term frequently used to denote and discuss the distribution of activity within a metropolitan area. A discussion has persisted until this day regarding present and future urban spatial structures with respect to employment and population, in particular. It seems clear that a continuing dispersal of employment and population has been occurring, particularly in economically advanced countries (e.g., Bontje & Burdack, 2005; Coffey & Shearmur, 2001; McMillen & McDonald, 1998; Pfister, Freestone, & Murphy, 2000; Siedentop, Kausch, Einig, & Gössel, 2003). Although there is also an ongoing debate about present and future economic recentralization processes (e.g., Glaeser & Gottlieb, 2006; Scott, 2008), it seems that a decidedly dispersive suburbanization process has occurred in recent decades, which has become manifest in terms of spatial construction. However, scholars have assessed this process's direction and its intensity differently: some argue that previously *monocentric* city-regions have become *polycentric* (e.g., Anas, Arnott, & Small, 1998; Garcia-López & Muñiz, 2010; Kloosterman & Musterd, 2001), some expect a complete dispersal will ensue and result in *edgeless city*-regions without any centre or densification (Gordon & Richardson, 1996; Lang & LeFurgy, 2003),

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whereas still others have posited the formation of *edge cities* (Garreau, 1992). This brief discussion and its diverging assessments reveal both the great variety of conceptualizations of urban spatial structures, including conceptualizations of the spatial scale that it is addressed to, and the question of the actual spatial occurrence (for details, see the second section). Focusing on the latter, this paper provides a multidimensional representation of the urban spatial structure in Germany and, as a result, an assessment of the status quo.

The notion of urban spatial structure is multifaceted, consisting of the distribution of population, employment, built-up volumes, transportation networks and land uses (cf. Parr, 2014). To complement the understanding of urban spatial structure, this morphological dimension can be completed by functional features, such as flows of goods and services, interactions between people and infrastructure, and/or face-to-face contacts among people (cf. Farber & Li, 2013), and additional features include topography, resource endowment and path dependence (cf. Hohenberg, 2004). Because this paper's objective is to analyse urban spatial structure in its morphological occurrence, it focuses on the distribution of employees and built-up volumes.[1]

Until now, there seems to have been no study that empirically addresses the interplay between the distribution of employees and urban form. Whereas polycentricity has mostly been analysed in its socioeconomic dimension alone (i.e., with respect to the distribution of employees), this paper aims for a more realistic depiction that also considers the physical dimension represented by built-up volumes. Thus, it is the first study to analyse the implications of polycentricity in terms of physical urban form. The advantage of this approach compared with solely looking at employees is found in the more encompassing understanding of urban spatial structure and the notion that built-up volumes are the physical manifestation of proximity advantages – such as knowledge spillovers – to which employees are subject. Hence, an assessment of this relationship is possible for the first time, and analysing the influence of the land intensity of different industrial sectors on the built-up environment is also now feasible.

This paper's empirical starting point is thus the proposition that employees mainly work in buildings. The expectation is that urban spatial structure is morphologically similar with respect to employees and built-up volumes. However, because different types of industries require different amounts of space, the patterns are likely to be generally similar but differ in their details. For example, manufacturing firms typically have large production halls in which comparatively few people work. Conversely, people working in offices frequently share one room and thus work in a much denser environment than their manufacturing colleagues. With this in mind, it is anticipated that the correlation will be higher between the number of office employees and built-up volumes than the corresponding correlation between the numbers of all employees and built-up volumes. For that reason, it is appropriate to use a multidimensional approach that combines socioeconomic variables (different groups of employees) with constructional variables (built-up volumes). Therefore, this paper contributes to the research on urban spatial structure in the following two ways: it presents the benefits of using a multidimensional data set and analysis procedure to enable a multidimensional representation of urban spatial structure, and it provides novel insights into four German city-regions.

The remainder of this paper is organized as follows. The second section provides the theoretical background with particular reference to different research objectives and research frontiers in different countries. The third section introduces the methods applied, and the fourth section follows with a presentation of the empirical results. The paper concludes in the fifth section with a summary and prospects for future research.

Literature survey

Urban spatial structure in its morphological dimension is frequently addressed in the literature and polycentricity is a widely used term in this context. When employed as an analytical rather than a political-normative concept, polycentricity means that a region has more than one centre. How many centres and/or sub-centres a region needs to be polycentric, how these are defined, and in what relation to one another they should be are questions that have not yet been agreed upon (e.g., Davoudi, 2003; Hall & Pain, 2006; Kloosterman & Musterd, 2001). This notion and the discussion surrounding it did not 'appear from nowhere' but resulted from the current and ongoing spatial suburbanization process. Suburbanization has led to a 'scattered' distribution of economic activity that is neither perfectly monocentric nor edgeless, 'flat', with no centre or densification (e.g., Anas et al., 1998; McMillen & Smith, 2003; Muñiz & Garcia-López, 2010).

When investigating this discussion, particularly as it applies in the US, we can see continuing research efforts, both empirically and theoretically (e.g., Anas & Kim, 1996; Arribas-Bel & Sanz-Gracia, 2014; Carruthers, Lewis, Knaap, & Renner, 2010; Giuliano & Small, 1991; McDonald, 1987; McMillen, 2001; Meijers & Burger, 2010).[2] Moreover, the use of data on small spatial scales, such as transport analysis zones, census tracts or spatial grids, has been established for more than a decade (e.g., Craig & Ng, 2001; Glaeser, Kahn, & Chu, 2001; McMillen, 2001; McMillen & McDonald, 1997). Small-scale data have also been applied in research on European countries' urban spatial structures (e.g., Baumont, Ertur, & Le Gallo, 2004; Larsson, 2014; Riguelle, Thomas, & Verhetsel, 2007; Smith, 2011). However, with respect to Germany, official data on employment below the spatial scale of municipalities have only recently become available (Scholz, Rauscher, Reiher, & Bachteler, 2012). Thus, until now, urban and regional research on this issue in Germany has relied on municipality data (Einig & Guth, 2005; Siedentop, 2008; Siedentop et al., 2003) or data compiled for commercial purposes (Knapp & Volgmann, 2011). This newly available official data on employment will thus enable more detailed analyses, which can be complemented and enhanced with data on built-up volumes derived from remote sensing; this paper aims to exploit the combination of these newly available and valuable data. The data combination is not only innovative in German research, but also it has only recently been able to be exploited in the international context (e.g., Smith, 2011).

Both conceptual fuzziness of polycentricity and the lack of a clear measurement approach are reflected in an impressive number of empirical studies aiming to detect urban spatial structure (e.g., Agarwal, Giuliano, & Redfearn, 2012; Arribas-Bel & Schmidt, 2013; Carruthers et al., 2010; Einig & Guth, 2005; Kneebone, 2009; Siedentop et al., 2003; Yang, French, Holt, & Zhang, 2012) or to discuss methods of sub-centre identification (e.g., Craig & Ng, 2001; Giuliano & Small, 1991; McDonald, 1987; McMillen, 2001; Riguelle et al., 2007). These objectives are not mutually exclusive, and measurement approaches change when the spatial scale under consideration changes (e.g., Davoudi, 2003; Kloosterman & Musterd, 2001). Nonetheless, some general statements are possible: if the objective is to detect urban spatial structure, both global and local measures are feasible, whereas sub-centre identification relies only on local measures. Global measures are those that provide information on the *degree of (spatial) dispersion*, such as Gini coefficients, relative dispersion coefficients, or the global Moran's *I*, to name only a few (e.g., Adolphson, 2009; Riguelle et al., 2007; Romero, Solís, & Ureña, 2014). Conversely, local measures allow for a site-specific analysis because their objective is to detect *local spatial densifications,* which are often called sub-centres. These measures include the application of threshold values, whether densities or accessibilities, kernel densities or locally weighted regressions, or measures of local spatial association (e.g., Giuliano & Small, 1991; McMillen, 2001; Redfearn, 2007; Riguelle et al., 2007).

Addressing issues related to data choice and research objectives in a discussion about the theoretical underpinnings of urban spatial structure leads to questions involving the cause, effect and trajectory of urban development. As briefly discussed in the introduction, there are several opposing but not necessarily mutually exclusive notions regarding the current urban spatial structure. In any of these notions, the corresponding explanation patterns roughly comprise economic agglomeration effects causing centre and sub-centre formation, on the one hand, and topographic and accessibility issues, on the other. Both of these are reasonable and referred to in the literature, as aptly discussed by Arribas-Bel and Sanz-Gracia (2014, p. 982). However, explanatory patterns cannot be empirically addressed in this study but will be used qualitatively to support certain findings. Accordingly, their quantitative assessment remains a task for future research.

In summary, much empirical research has been conducted, but this approach is novel: whereas data on small spatial scales are nothing new in recent international research, these data have not been available in Germany. Moreover, the suggested approach that combines employees and built-up volumes is insightful both empirically and theoretically. It is insightful empirically because each is a core element of urban morphology, and it is insightful theoretically because agglomeration economies, with their physical representation in built-up volumes, are likely to both evolve from and reinforce face-to-face interactions and knowledge spillovers among employees in office agglomerations.

Research design

Data and regional scale

The study regions are four German city-regions: Cologne, Frankfurt, Munich and Stuttgart (Figure 1). These regions were roughly delineated on the basis of regional labour markets defined by the Federal Institute for Research on Building, Urban Affairs and Spatial Development.

The analyses are conducted on the spatial level of grid cells with a side length of 1 km and located in accordance with the European grid INSPIRE (Infrastructure for Spatial Information in the European Community). Compared with municipality boundaries that are frequently used, grid cells allow for a more detailed picture and should help avoid false conclusions resulting from administrative boundary artefacts.

Data concerning employees are taken from the georeferenced Integrated Employment Biographies (georeferenced IEB), as of 30 June 2009, which are provided by the Research Data Centre of the Federal Employment Agency at the Institute for Employment Research (RDC). Originally, these are point data but these points must be aggregated into grid cells before the RDC may distribute them under German privacy laws (for aggregation details, see Scholz et al., 2012). Moreover, these aggregated data are subject to censoring also under German privacy laws. All grid cells with either less than three employees belonging to less than three firms ('minimum case') or one firm accounting for more than 50% or 75% of all employees ('dominance case') were

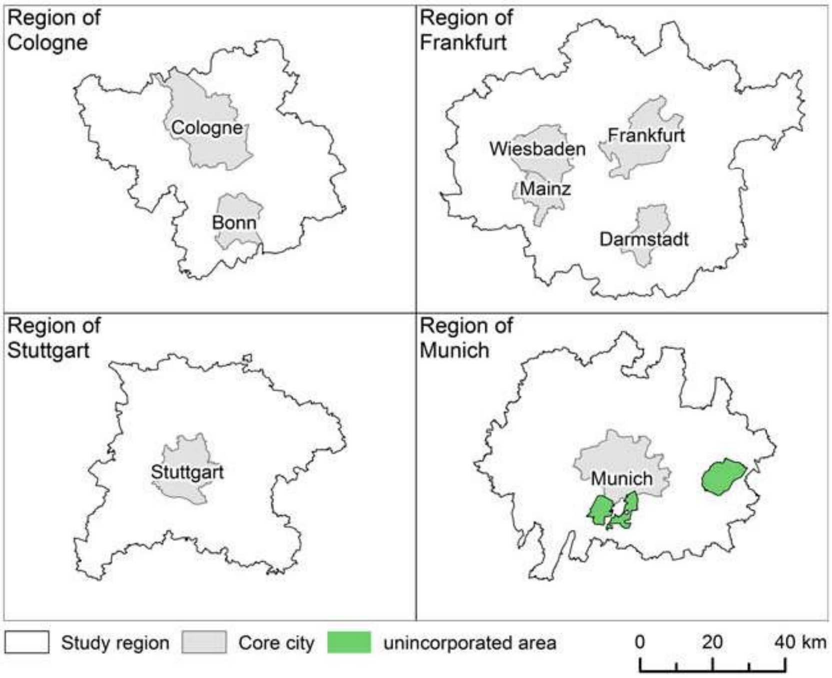

Figure 1. Study regions and core cities.
Source: Author.

censored (for details, see Bundesagentur für Arbeit, 2014). Thus, these grid cells had to be manually set to one, i.e., one employee, to avoid even more severe downward bias from completely excluding them from the analyses. However, the censored cells only contain 0.5–1.0% of all employees and 2.0–3.0% of the employees in service sectors in each study region. Employees in service sectors are those registered in sections J–N or S according to the Classification of Economic Activities, issue 2008 (WZ 2008).[3] Employees who are either not subject to social insurance or marginally employed were excluded because data on these groups were not available. For ease of reading, the term 'employees' will be used henceforth. It might be argued that these 'subsets' of all employees and the censoring spoil the validity of the analyses. However, the official data used herein are complete under German privacy laws. An imputation of employees not subject to social insurance,[4] such as self-employed persons, and rescaling them into grid cells would probably validate the comprehensive database but would not necessarily increase the quality of the analyses.

Earth observation images have shown the ongoing scattering of built-up areas for quite some time (e.g., Huang et al., 2007; Schneider & Woodcock, 2008). Recently developed methods allow for the derivation of built-up volumes (m^3 per m^2 built-up area) from these images. Their computation was made possible for the first time on a fine spatial scale and over a large study region. Built-up volumes were calculated for the INSPIRE grid cells based on large-area three-dimensional building models for entire urban regions. These models were generated by fusing information from building footprints derived from topographic maps at a scale of 1:25 000 and building heights derived from these footprints with height measurements from stereoscopic satellite imagery (for details, see Wurm, d'Angelo, Reinartz, & Taubenböck, 2014). These models directly facilitate addressing the physical distribution of densities, which is one core element of morphological urban spatial structure (cf. the second section).

However, these data also contain built-up volumes for residential use only, which might bias the results. With the help of additional data from the Authoritative Topographic–Cartographic Information System (ATKIS Basis-DLM, shortly ATKIS), it was possible to eliminate these shares of 'residential use only' from the built-up volumes. Each ATKIS polygon is originally attributed with a type of use and when aggregating these polygons into the grid cell, the respective areas for each type of use are added together. Thus, the grid cell is assigned a value in m² for each type of use, out of which percentages per grid cell can be calculated. If ATKIS identifies x% of a grid cell's built-up area to be designed for residential use, then the amount of built-up volumes in that grid cell is multiplied by $(100-x)/100$ to 'remove' the share of built-up volumes for residential use only. A point to ponder is that ATKIS and remote sensing data do not perfectly match, i.e., there are grid cells for which remote sensing identifies built-up volumes but ATKIS does not attribute any type of use. However, this mismatching accounts for at most 0.03% of the entire built-up area of a study region; thus, this limitation is considered negligible.

Empirical procedure and methods

The empirical procedure to detect spatial concurrence between employment and built-up volumes consists of two steps. First, spatial concurrence is analysed with the visual comparison of *density maps* and supported with *Spearman's rank correlation coefficients* between employees, employees in service sectors, and built-up volumes, in addition to a coefficient on spatial autocorrelation, the *global Moran's I*. Second, a statistical procedure based on exploratory spatial data analysis (ESDA) is applied to identify local spatial densifications ('sub-centres') taking into account spatial spillovers and statistical significance.

Density, as applied in the first step, means that the absolute number of employees in each spatial entity is divided by that entity's area. Thus, it allows values for entities of different geographical size to be compared with one another.[5] Density is equal to absolute numbers here, as all grid cells are sized and shaped equally. However, there is an exception for those located at the regions' fringes that are not fully covered: They are smaller than 1 km², but the qualitative and quantitative differences between density and absolute values are small in these particular cases. Spearman's rank correlation coefficient is calculated using pairwise deletion and approximate p-values. Its significance is based on two-tailed tests without further adjustment. The global Moran's I is calculated in accordance with Anselin (1995) by applying 9999 permutations and a pseudo-significance level of $\alpha = 0.001$. Its formula is given in equation (1):

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij} z_i z_j}{\sum_{i=1}^{n} z_i^2}$$

where I denotes the global Moran's I for the region under consideration; and n is the number of spatial entities forming the study region. The spatial weights matrix consists of $n \times n$ row-standardized spatial weights ω_{ij}. Row standardization means that each ω_{ij} is divided by the row sum, which is equal to the number of non-zero row elements if a binary weight matrix is chosen. S_0 is the double sum of the weights, which is equal to n in case of row standardization. z_i and z_j are the respective observations measured in deviations from the mean, i.e., the mean $\bar{x}$ of the study region's observation value is subtracted from the spatial entity's observation value x_i. The neighbourhood is defined as a second-order queen contiguity, which implies that entities sharing a common border or vertex with the one under consideration are assigned a ω_{ij} of 1. Additionally, these neighbouring entities' direct neighbours are also assigned a ω_{ij} of 1. All others get no weight. Second-order queen contiguity was chosen because spatial spillovers are likely to have a larger influence than within a radius of approximately 1 km.[6]

The global Moran's I ranges between –1 and +1. These extremes imply perfect negative spatial autocorrelation, i.e., a 'chequered' pattern, and perfect clustering of similar values, respectively. A significantly positive value thus indicates that similar values are spatially grouped together, and a negative global Moran's I indicates that rather different values are located in a common neighbourhood. However, a significantly positive global Moran's I does not reveal information regarding whether high or low values are clustered. Values around zero imply that the spatial pattern is random.

Many of the methods used for the analysis of urban spatial structure thus far are mainly derivatives of monocentric city models. However, several scholars have shown that monocentricity is not the prevalent urban form, and some even argue that monocentric models might not even be relevant anymore (e.g., Arribas-Bel & Sanz-Gracia, 2014; Garcia-López & Muñiz, 2013). The application of an ESDA acknowledges this. It allows the identification of spatial patterns without an a priori assumption about their true nature. Independence from decisions regarding the locations of central business districts or threshold values is another advantage of ESDA, as it also reduces arbitrariness. Moreover, ESDA enables comparisons involving different spatial patterns in different regions because it only requires the choice of 'framing parameters', such as significance levels and/or neighbourhood definitions. In this study, ESDA is applied to both employees and built-up volumes to detect their respective spatial clustering and to thus draw conclusions regarding the study regions' spatial configurations. Furthermore, theoretical contributions suggest that agglomeration economies such as knowledge spillovers are responsible for the spatial clustering of service sector employees, in particular (cf. Agarwal et al., 2012; Coffey & Shearmur, 2002; Muñiz & Garcia-López, 2010). Hence, a method that is able to detect spatial clusters seems reasonable.[7]

Therefore, the measure of choice is the *local Moran's I* as developed by Anselin (1995), one method of ESDA. This measure allows for the detection of clusters with high and low values, as well as spatial outliers, i.e., low values surrounded by high values and vice versa. This feature makes the local Moran's I measure more attractive here than, for example, the application of the Getis and Ord's G_i or G_i* statistic, which only identify spatial clusters but not spatial outliers. To describe extensively the urban spatial structure, it is necessary to identify both positive (clusters) and negative dependencies (outliers). Of course, applying ESDA cannot be the final step in analysing the morphological urban spatial structure. Instead, it is appropriate to analyse new data and to provide a descriptive assessment of their spatial distribution, which then should be further evaluated with respect to the forces causing it, for example. Because it is an exploratory method, the local Moran's I reveals spatial patterns but does not offer a causal interpretation. It evaluates each spatial entity (in this case, each grid cell) in relation to its predefined neighbourhood, and its formula is presented in equation (2):

$$I_i = n \frac{z_i \sum_{j=1}^{n} \omega_{ij} z_j}{\sum_{i=1}^{n} z_i^2}$$

where I_i denotes the local Moran's I for the spatial entity i. All other formula elements are the same as defined for equation (1). The neighbourhood definition again is according to second-order queen contiguity. Other scholars applying the local Moran's I choose both similar (e.g., Arribas-Bel & Sanz-Gracia, 2014) and different neighbourhood definitions, such as the k-nearest or the average number of neighbours (e.g., Guillain & Le Gallo, 2010; Riguelle et al., 2007). This choice makes a difference if spatially irregularly shaped data are used but is of less relevance for grid cells because they are shaped regularly and sized equally. Differences in the number of neighbours for grid cells occur in the data used here in two cases: (1) when grid cells are located at the region's edge and (2) when a non-empty grid cell is spatially adjacent to an empty cell because the latter are omitted from these calculations for technical reasons. Apart from that, the choice of the correct significance level in the presence of spatial autocorrelation is quite an issue. In the analysis below, it will be addressed as follows: First, local Moran's I values are computed by applying 9999 permutations, as suggested by Anselin (1995) and later used by Arribas-Bel and Sanz-Gracia (2014). The resulting pseudo-significance level is set to $\alpha = 0.05$ by convention. All results are saved and further processed to apply a false discovery rate, as suggested by Caldas de Castro and Singer (2006) based on the pseudo-p-value of $\alpha = 0.05$.

The local Moran's I results include four types of spatial dependence: spatial clusters of high values surrounded by high values (high–high) or low values surrounded by low values (low–low). In this context, 'high' means above average ($x_i > \bar{x}$), and 'low' means below average ($x_i < \bar{x}$). Outliers are the opposite of the clustering of similar values, i.e., a high value surrounded by low values (high–low) or a low value is surrounded by high values (low–high). Interpreting the results requires some consideration as the local Moran's I evaluates each grid cell's variable against a local context defined by the weights matrix. Thus, areas without high values in absolute numbers but that have high values in relation to their neighbours can be considered high–high clusters, and vice versa. The same logic applies to spatial outliers: they are significantly different from their neighbours but not necessarily high or low in comparison with the entire study region.

The combination of these measurement approaches sheds new light on the urban spatial structure in Germany. Whereas the first step aims at inspecting the distribution of employees and built-up volumes – thus deriving hints about spatial clustering – the second step's objective is to further support the results from the first step with the help of a statistically based measure that takes local contexts into account. The identified patterns will be presumptively explained with agglomeration economies, accessibility and topographic aspects. Establishing causal relationships based on the empirical analyses, however, is neither an objective nor a possibility.

Empirical findings

Location and correlation

Density maps (Figure 2) visualizing the location of employees and built-up volumes indicate obvious differences between the study regions' urban spatial structure. Whereas the Stuttgart region shows a pattern that is quite dispersed in terms of employment and built-up volumes, the Munich, Cologne and Frankfurt regions are rather concentrated. The pattern in the Munich region is focused on the city of Munich, whereas the regions of Cologne and Frankfurt are characterized by the highest densities being located in the respective core cities. Therefore, from a visual assessment, it might be posited that

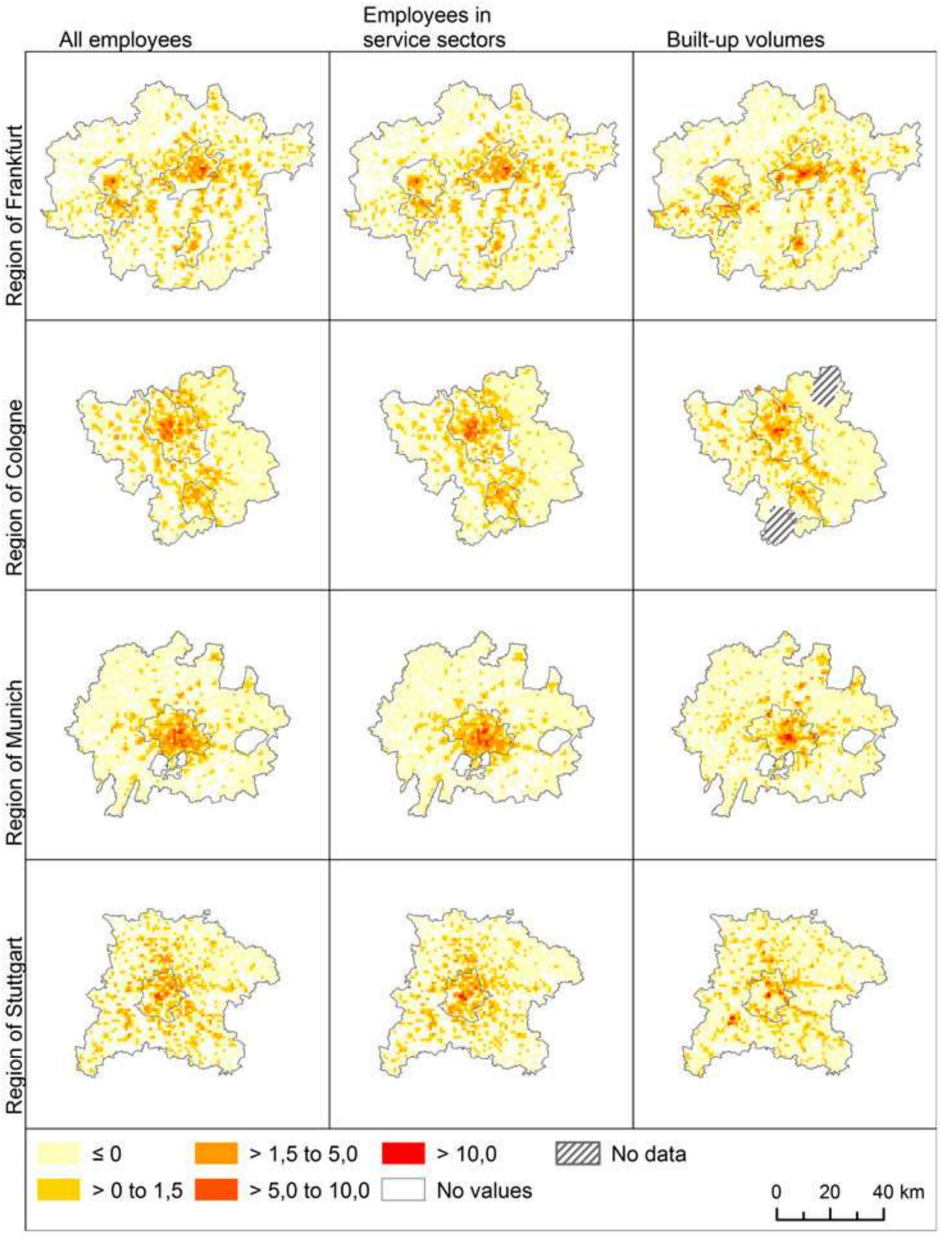

Figure 2. Standardized densities.
Source: Author's own calculations based on the georeferenced IEB and data on built-up volumes.

Stuttgart is dispersed, that Frankfurt and Cologne are somewhat polycentric, and that Munich is monocentric. However, the polycentricity in both the Frankfurt and Cologne regions is also a matter of definition because both these regions consist of multiple core cities.

All data in Figure 2 were standardized into *z*-scores to make the variables and regions comparable. The colouring is identical for all maps: density increases as the colour changes from yellow to red. White areas do not contain the respective variable, and diagonally hatched areas indicate that remote sensing data were not available. Dark grey circled areas represent the core cities' municipal boundaries.

A closer examination of Figure 2 reveals the spatial concurrence between employment and built-up volumes in the Frankfurt region. High densities are found in the core cities, whereas low densities are located in the region's northern section, which is a low, mountainous area. The Cologne region shows similar patterns: the Bergisches Land area in the region's eastern section contains only low numbers of employees and built-up volumes, whereas the highest densities are located in or near the core cities. The Cologne region and the Frankfurt and Stuttgart regions exhibit clustering tendencies within the core cities, which might hint at effective agglomeration economies. The Munich region clearly reveals a monocentric spatial configuration, although some outliers are discernible. The highest densities in the Stuttgart region are located along major roads and the River Neckar, which suggests a strong influence of accessibility issues and topography. Notably, the core city is not visually identifiable from the distribution of employees or built-up volumes. The urban spatial structure quite clearly shows a dispersed configuration with respect to employees and a quite obviously axial system with respect to built-up volumes, which is not particularly pronounced in any other region. To some extent, these consequences might ensue from topography: the region has been structured by several valley-like river canyons and ranges of hills surrounding the core city.

Furthermore, the impression of all density maps suggests that the level of spatial clustering is slightly higher for employees in service sectors than for all employees, whereas the concentration of built-up volumes is much higher than that of employees. The global Moran's *I* values, which yield information regarding the degree of spatial association, provide quantitative evidence for this (Table 1). In contrast to the local Moran's *I*, however, the global Moran's *I* cannot distinguish the clustering of positive values from the clustering of negative values. Spatial association would be high in both cases because similar values are located together.

All values in Table 1 are positive and statistically significant implying significant spatial association in all study regions. The rather dispersed nature of the Stuttgart region is reflected in markedly lower global Moran's *I* values than in the other regions. Conversely, the Munich region scores highest in all variables, which supports its position as 'most monocentric' region among the regions considered. However, the global Moran's *I* does not reveal any information about the spatial concurrence of employees and built-up volumes. Thus, Spearman's rank correlation coefficients are calculated to evaluate this issue (Table 2). All coefficients are also positive and statistically significant. The values for all employees and built-up volumes range between 0.65 in the

Table 1. global Moran's *I* values.

	All employees	Employees in service sectors	Built-up volumes
Region of Cologne	0.4501	0.5074	0.4765
Region of Frankfurt	0.2981	0.3806	0.4149
Region of Munich	0.5828	0.6063	0.5999
Region of Stuttgart	0.2484	0.3282	0.2642

Note: All values are significant at the 0.1% pseudo-significance level after 9999 permutations.
Source: Author's calculations based on the georeferenced IEB and data on built-up volumes.

Table 2. Spearman's rank correlation coefficients.

	Built-up volumes
Region of Cologne	
All employees	0.6475
Employees in service sectors	0.6337
Region of Frankfurt	
All employees	0.6458
Employees in service sectors	0.6311
Region of Munich	
All employees	0.6717
Employees in service sectors	0.6423
Region of Stuttgart	
All employees	0.7061
Employees in service sectors	0.6825

Note: All values are significant below the 1% significance level.
Source: Author's calculations based on the georeferenced IEB and data on built-up volumes.

Cologne and Frankfurt regions and 0.71 in the Stuttgart region. The Munich region scores 0.67. These values indicate medium correlations in all the regions. Thus, the proposition that employees are predominantly registered in grid cells containing built-up volumes and that their respective values are positively correlated (cf. the first section) is true.[8]

A closer look at Table 2 reveals that correlations among all employees and built-up volumes are higher than those between employees in service sectors and built-up volumes. These differences, however, are quite small within a region. One reason for this result, which contradicts the hypothesis expressed in the first section, might be found in the incomplete removal of built-up volumes for residential use. ATKIS helped remove shares that were for residential use only. However, there are many mixed-use areas in all the study regions, in particular, employees in service sectors are often located in mixed-use buildings. However, the built-up volumes for residential use in these buildings cannot be cleared by ATKIS. Thus, each employee is assigned more built-up volumes than she actually occupies, which yields lower correlations between the amount of built-up volumes and the number of service sector employees. All employees are also subject to this, but those who are not service sector employees are likely to be located in areas for industrial use only, which means that they are affected less and is further supported by small differences in the correlation coefficients (Table 2).

Exploratory analysis

Density maps (Figure 2), the global Moran's I values (Table 1), and the correlation coefficients (Table 2) shed light on the spatial concentration and concurrence of high and low values of the variables under consideration but do not account for their local context. Thus, the next step is to detect statistically significant spatial clusters, which is essential for a full understanding of the urban spatial structure in a study region: density maps are likely to suffer from subjectivity because they only visualize values. Correlation coefficients shed light on coincidences of values, and spatial correlation coefficients yield information about the clustering of similar values. However, nothing is revealed about their spatial location and their actual and statistically significant pattern, and nothing can be said thus far about the actual existence, size and location of sub-centres.

Figure 3 visualizes the spatial clusters derived from the local Moran's I values. Red-coloured areas indicate high–high clusters and blue-coloured areas indicate low–low clusters, whereas light red and light blue areas represent positive and negative outliers. White areas signify grid cells in which the values are either not registered or statistically insignificant. Grey areas indicate that the respective grid cell does not have a neighbour with a positive value (i.e., the neighbours are empty). Finally, remote sensing data were not available for diagonally hatched areas.

All study regions are characterized by the clustering of positive and negative values (bright red and blue areas in Figure 3), which is consistent with the significantly positive global Moran's I values (cf. Table 1). There are also spatial outliers, but they do not occur excessively and thus do not substantially shape the urban spatial structure. The overall impression is of an urban spatial structure formed by significant high–high clusters mainly located in the core cities, which is particularly true for the Munich region[9] and also holds for the other regions. A closer look further reveals that there are more high–high clusters for all employees than for employees in service sectors. Therefore, the latter seem to be more concentrated, which might be an indication that they are either more exposed to positive – or suffer less from negative – agglomeration economies.

The Frankfurt region is characterized by a polycentric structure as the result of its four core cities. Furthermore, it is striking that there is a high–high building cluster in the region's east (city of Hanau) that is not reflected in a high–high employee cluster. One explanation for this phenomenon might be that the number of employees is not markedly higher there than in neighbouring grid cells, thus yielding the local Moran's I's statistical insignificance. The density maps speak in favour of this explanation. The disappearance of a high–high cluster located between the Frankfurt region's core cities when moving from all employees to those in service sectors is the result of industrial structure because that cluster captures an area in which the automotive sector is dominant. A 'reverse' situation applies to the municipalities of Eschborn, Schwalbach and Sulzbach, located directly north of the city of Frankfurt: although there is a small high–high cluster for all employees, it is much larger when employees in service sectors are considered, which is not surprising, because these municipalities host many offices and company headquarters. Furthermore, a comparison of the density maps (Figure 2) reveals that the high–high clusters coincide well with high-density areas. From an economic point of view, one might presume that agglomeration economies are effective both for all employees and those in service sectors, but the latter profit more.

When comparing the Frankfurt region with the Cologne region, the geographically larger amount of clustering in the latter is the most striking difference. Although there is an employment cluster north-east of Bonn if all employees are considered, this cluster disappears if only service sector employees are considered. To some extent, the same also applies to a high–high cluster in the city of Leverkusen, in which the chemical industry is predominantly located. These findings have the same background as in the Frankfurt region: after removing all the service sector employees, the remaining employees are too few to be significantly different from those in the neighbouring grid cells. The high–high clusters of built-up volumes match well with those for employees, which is further proof of the proposition that there is spatial concurrence between employees and built-up volumes.

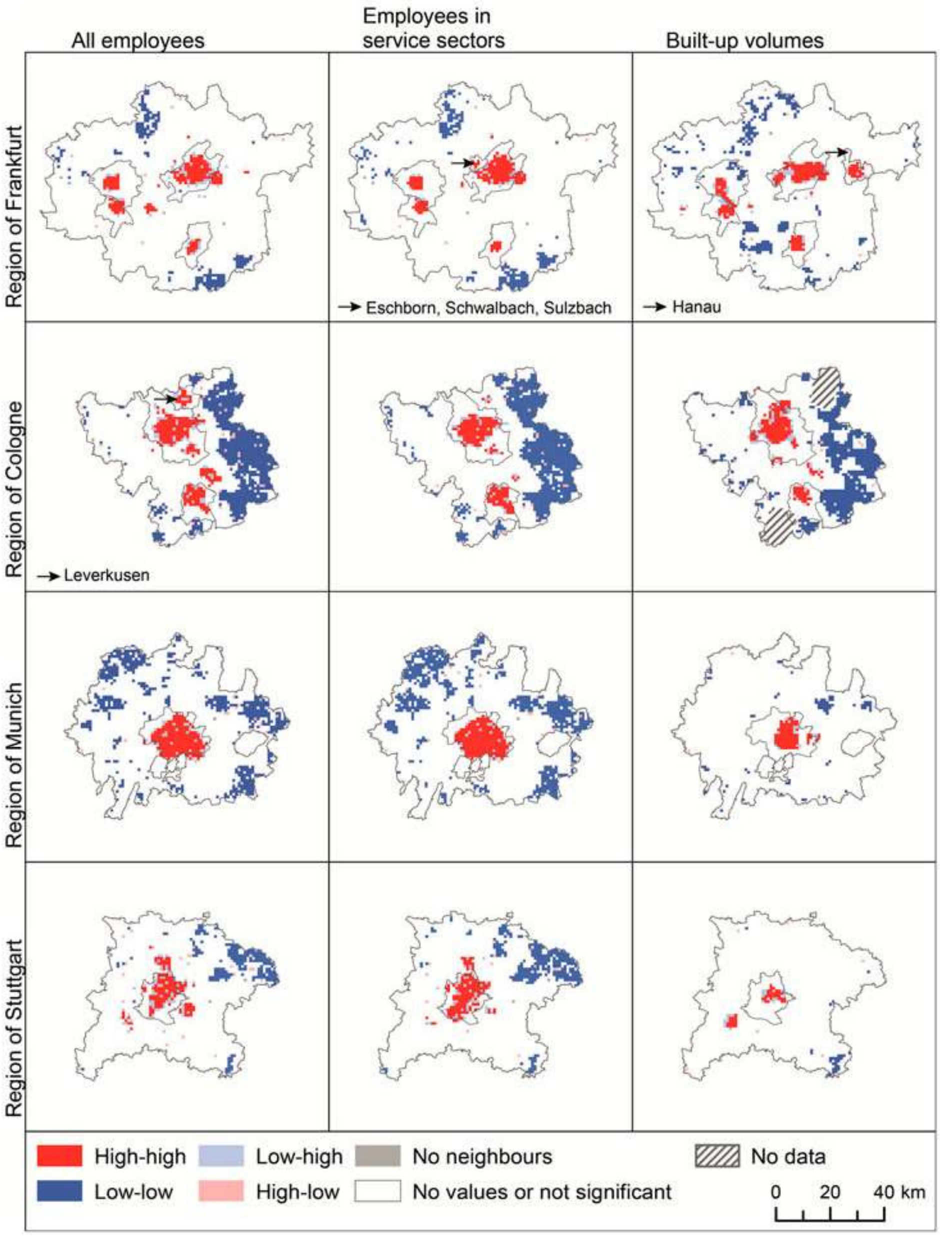

Figure 3. Cluster maps.
Source: Author's own calculations based on the georeferenced IEB and data on built-up volumes.

An examination of the Munich region confirms that monocentricity characterizes the region. In contrast to the other study regions, this pattern does not change between all employees and employees in service sectors. However, the difference in the area covered by the high–high clusters is striking, for which the local Moran's *I* does not provide a causal explanation, unfortunately. It might yet be assumed that positive agglomeration economies shape this distribution of employees. The lower clustering of built-up volumes – indicating a more equal distribution – might be the result of planning laws regulating the maximum amount of built-up volumes per square meter of ground floor.

The maps for the Stuttgart region speak in favour of a polycentric spatial structure. All variables exhibit significant positive clustering outside the core city. Although – or because – the automotive industry is dominant, the differences between the clustering of all employees and those in service sectors are comparatively small. However, the clustering patterns for built-up volumes are notably different. Although the spatial distribution of employees is polycentric, that of built-up volumes appears to be bipolar. It should be remembered that the area surrounding the clusters is not 'empty' but is rather not significant. Thus, this result suggests a rather dispersed urban spatial structure with two significant densifications of built-up volumes.

Synthesis and interpretation

The previous analyses show that the four study regions differ in their respective morphological urban spatial structures. Whereas the Stuttgart region is rather polycentric in terms of employees and seemingly bipolar in terms of built-up volumes, the Munich region clearly shows a monocentric pattern. The Frankfurt and Cologne regions are mainly characterized by their multiple core cities and economic structures in which the industrial sector is concentrated in certain areas of the region. Thus, these regions can be considered polycentric. However, their polycentricity is somewhat by definition because they consist of more than one core city (and thus more than one centre) rather than being characterized by actual sub-centre existence. A *sub-centre* is an area consisting of at least one grid cell being a statistically significant high–high cluster and either located outside the core city's centre or in spatial distinction from the core city. From this perspective, all regions show polycentric patterns to different extents. From a theoretical point of view, one might thus argue that the Cologne and Frankfurt regions are inter-urban polycentric, whereas the Munich and Stuttgart regions tend to show intra-urban polycentricity (cf. Kloosterman & Musterd, 2001).

The combination of employees, employees in service sectors, and built-up volumes revealed insufficient detection of morphological urban spatial structure if not all these variables are considered. Although they show spatial concurrence, their distributions differ in details. The cluster maps (Figure 3) visualized this result and the two correlation coefficients (Tables 1 and 2) additionally support it. Thus, one variable suffices to gain a rough, but sometimes misleading, impression of a region's urban spatial structure. However, important details resulting from the region's industrial structure might remain unrevealed, such as in the Stuttgart region, which seems polycentric in terms of employees but is rather bipolar in terms of built-up volumes. We also observed some evidence of these differences in the Frankfurt region, where the three variables' clusters differ markedly. In the quite monocentric region of Munich, additional information from two out of three variables seems negligible, which might lead to the conclusion that the more monocentric a region, the less important it is to have an encompassing data set. However, it is not a priori certain that monocentricity will occur (for all variables). In other words, because urban spatial structure in general and polycentricity in particular are complex concepts, their analysis requires a rich set of variables and indicators that extend beyond solely socioeconomic variables. This paper's empirical results support this claim.

Conclusions and prospects

The analyses herein provided detailed insight into the urban spatial structure of four selected German city-regions. A high correlation of employees and built-up volumes was found, and their interplay certainly shapes the urban spatial structure. Although spatial concurrence between the variables considered applies for all regions under consideration, the respective outcomes differ. Whereas the Stuttgart region is polycentric for employees and – to a limited extent – for built-up volumes, the results for the Frankfurt and Cologne regions are not as unambiguous. Both regions show polycentric patterns but with obvious core city dominance. The Munich region is characterized by a strong core city and is thus monocentric, although there are single high–low outliers in the region's periphery. Furthermore, it is remarkable that all the sub-centres in the regions are located in close proximity to a core city. These sub-centres differ markedly from American edge cities with respect both to their sizes – American edge cities are much larger spatially – and their location – American edge cities are mostly located at the edges of regions. An edgeless city pattern, sometimes considered 'beyond polycentricity' (Gordon & Richardson, 1996), does not yet exist in any study region study herein. Even in the most dispersed study region, Stuttgart, clusters of activity remain, and considering the urban spatial structure 'flat' would not appropriately reflect reality.

The empirical procedure employed herein and its results are unique in national research. Moreover, an integrated approach combining socioeconomic and remote sensing data has found its way into international research only fairly recently. The data on employees and built-up volumes are helpful in identifying clusters and outliers – which are similar in certain respects but different in others – jointly shaping the morphological urban spatial structure. However, the results gained here are just an approximation because the employment data utilized in this study suffer from both a rough classification of economic activity and censoring due to German privacy laws. Additionally, a more thorough removal of built-up volumes for residential use would further enhance the results' quality and also open up routes for in-depth analyses of land use and land intensity in different industrial sectors.

Given the newly available data, it is now feasible to compare the actual location of employees and built-up volumes with planning goals, e.g., reaching the legally defined maximum inner city densities of built-up volumes. Moreover, combining employees and built-up volumes into one indicator (employees per m^3 of built-up volumes) would enable the distinction between retail and office agglomerations, for example, shedding light on the quality of densifications and also likely on their economic resilience. However, a discussion of vacancies and of past, present and future industry structure, among other topics, would be required. All this work, unfortunately, requires much more comprehensive data than the data available for this study. To fully capture the urban spatial structure, it would also be revealing to consider population. The same applies to the use of panel rather than cross-sectional data. Development processes yielding the current urban spatial structure could not be analysed here but had to remain for further research. Finally, all the analyses conducted above are descriptive and exploratory but do not explain causalities. Thus, the next step would be to conduct regression analyses to reveal (mutual) causalities and to explicitly consider topics such as the influence of planning regulations and policies on the regions' urban spatial structure.

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Notes

1. The data on population data were, unfortunately, not available.
2. This list is far from exhaustive and contributions on topics such as sprawl, transportation and car dependence, or planning policies are not acknowledged because these aspects are beyond the scope of this paper.
3. These include information and communication (section J); financial and insurance activities (K); real estate activities (L); professional, scientific and technical activities (M); administrative and support service activities (N); and other service activities (S).
4. If all Germany is considered, employees subject to social insurance account for more than 75% of all people employed (Statistisches Bundesamt, 2008). Spatially disaggregated information on the distribution of the remaining 25% is not available.
5. For a discussion about 'density', see Fina, Krehl, Siedentop, Taubenböck, and Wurm (2014).
6. This is also implicitly assumed in other scholar's work if they use a first-order queen contiguity on geographically larger entities.
7. Whether agglomeration economies are the true causes for the clusters that ESDA identifies is presumptive from a strictly quantitative point of view.
8. Spurious correlations are possible but this issue cannot be directly addressed with the data available. Nonetheless, there are reasons to believe that the correlations are robust and not driven by a 'third party'.
9. Munich was more severely hit from censoring due to the 'dominance case' than the other regions, which must be considered when interpreting the results.

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Urban subcentres in German city regions: Identification, understanding, comparison*

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Abstract. Whereas many studies exist regarding urban subcentre identification, systematic analyses of these methods' characteristics are scarce. This paper addresses and reflects these issues for one selected method, the locally weighted regression (LWR) approach. Methodologically the study concludes that no 'one size fits all' method exists, but that the LWR is a sensitive means to identify urban subcentres. Content-wise the study finds that German city regions are fairly monocentric, as all identified subcentres are of local relevance only. Comparisons to the urban spatial structure in US metro areas, to which the same LWR is applied, however, prove to be fairly complicated.

JEL classification: C14, R11, R12

Key words: Employment subcentre identification, locally weighted regression (LWR), metropolitan areas, comparative urban research, Germany

1 Introduction

Urban settlement structures have been transforming over the last decades. Although there is not much solid knowledge of the actual distribution of employees or residents, especially in European city regions, it seems clear that a continuing dispersal of economic activity has been occurring, particularly in economically advanced countries (e.g., McMillen and McDonald 1998; Pfister et al. 2000; Coffey and Shearmur 2001; Shearmur and Coffey 2002; Lang and LeFurgy 2003; Siedentop et al. 2003; Bontje and Burdack 2005; Adolphson 2009; Kim et al. 2014). Taking a closer look at these processes, however, reveals that the changes are not

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unambiguously oriented towards dispersion and urban sprawl. Rather, a spatial reconfiguration process is taking place resulting in a differentiation of urban spatial structure: deconcentration processes (e.g., dispersion, sprawling) are overlapping with (re-) concentration processes (e.g., subcentre formation, reurbanization). Additionally, functional specialization of newer (sub-) centres coincides with a multi-functional orientation of other, mostly established, centres (e.g., Batty et al. 2004; Einig and Guth 2005; Zhong et al. 2015).

A major issue in most considerations is the means of identifying and quantifying the urban spatial structure: what does dispersion actually mean? What characterizes a subcentre? These are issues not only for time-series but also for comparative-static analyses. Researchers have not yet agreed on a consistent and internationally comparable evaluation scheme regarding urban spatial structure. One central element of urban spatial structure are employment densifications, such as central business districts (CBDs) or (sub-) urban subcentres. The spectrum of methodologies developed to identify these local spatial densifications ranges from density maps and gradients (e.g., Anas et al. 1998; Kim 2007) to normatively influenced cutoff values (e.g., Giuliano and Small 1991; Kim et al. 2014) and more advanced analytical techniques, such as regression analysis (e.g., Craig and Ng 2001; McMillen 2001; Carruthers et al. 2010; Wheeler 2014; Roca Cladera et al. 2009 provide an extensive overview) and spatial statistics (e.g., Riguelle et al. 2007; Guillain and Le Gallo 2010; Krehl 2015b).

Another issue in the quantitative analysis of urban spatial structure is the spatial scale. Whereas analyses of small spatial scales, such as census tracts, grid cells or points have been established in the United States for years (e.g., Anas et al. 1998; Craig and Ng 2001; Glaeser et al. 2001a; McMillen 2004a; Redfearn 2007), such spatially detailed analyses have not been feasible for Germany due to data unavailability until recently (e.g., Knapp and Volgmann 2011; Krehl 2015b). The spatial data availability in other European countries is better but far less comprehensive than that found in the US (e.g., Baumont et al. 2004; Adolphson 2009; Smith 2011; Larsson 2014), in terms of spatial grain and time-series' length, for example (Redfearn 2009).

Against this background, it is not surprising that the quantitative analysis of morphological urban spatial structure has been significantly influenced by the research conducted in North America (cf. Shearmur and Coffey 2002; Duranton and Puga 2015).[1] Numerous methods applied internationally have been developed and tested in metropolitan regions of the US. This means that the methods could be influenced by North (US-)American peculiarities such as fairly large geographical size, rather pronounced car dependence and less public transportation supply and demand, a younger average age as compared to European cities, etc. What is missing is more research on non-US metro areas, precisely other regions than the well-researched Los Angeles or Chicago regions, and cross-national comparative studies regarding urban spatial structure, its history and its recent changes (cf. Bogart and Ferry 1999; Duranton and Puga 2015).

Considering the remarkable differences in both the data availability and the urban spatial structure itself, it has not been settled whether the methods briefly outlined above can be directly applied to regions other than those for which they were designed. The assignability of a method depends on several aspects: assumptions underlying the method; normative determinations, such as the study region's delineation; data availability; and the research objective. Thus, this paper's contribution is threefold:

1. it discusses these assignability issues with respect to one selected method, the so-called locally weighted regression (LWR) presented in McMillen (2001);

[1] This holds despite the fact that much spatial economic theory was developed in Germany (Arnott 2012) and that the concept of city regions emerged in Europe before it was taken up in the US (Hall 2009).

2. it provides a fine-grained insight into the spatial configuration of selected German city regions; and
3. it qualitatively juxtaposes aspects regarding the number, size and location of urban (sub-) centres identified by the LWR, both in Germany and in the US.

Precisely, the LWR will be applied to four German city regions, and its results will be compared to the results for those US metro regions for which the method was originally designed. Additionally, some modifications to the McMillen (2001) LWR will be made to account for both the smaller geographical size of German city regions and their different urban spatial structures. The idea behind these additional modifications is to gain insight into the relationship between the method and the spatial pattern identified. Thus, a deeper understanding of the urban spatial structure in the case study regions will be presented. Compared to other studies that have been conducted for Germany, this study additionally offers insights into the intra-municipality polycentric structure of four German city regions because it operates on the spatial scale of 1 km^2 grid cells. Thus, this paper's results contribute to a place rather than a municipality-based analysis. They also provide an empirical base to discuss whether the term 'subcentre' is appropriate for urban densifications measured at any spatial scale or if another term might be more suitable. Finally, the challenges of cross-national comparative urban research are touched upon.

The empirical findings indicate that the urban spatial structure in German city regions shows less pronounced spatial disparities than that in US metro regions. In addition to the predefined CBD, only local subcentres are identified. These subcentres do not influence the entire region's spatial employee distribution but only the spatial employee distribution in the closer neighbourhood. Large concentrations of employees outside the CBD, the so-called edge cities that characterize many US metro regions (cf. Garreau 1992; Lee 2007),[2] are not identified. Rather, persisting core city and CBD dominance are observed in German city regions. This dominance also exceeds the core city's relevance in US metro regions, especially if those regions have characterizing subcentres. Thus, German subcentres tend to be local spatial densifications of employment whose influence is masked by CBD dominance rather than mimicking 'mini-CBDs'. This finding holds for both the direct application of the LWR following McMillen and several modifications; it is also consistent with previous analyses for Germany (e.g., Knapp and Volgmann 2011; Krehl 2015b) and for other European countries (e.g., Riguelle et al. 2007; Adolphson 2009; Garcia-López and Muñiz 2010; Martínez Sánchez-Mateos et al. 2014).

Based on this insight, this paper's methodological contribution is to show that an identification procedure that was originally designed for a large study region with pronounced subcentres is also feasible for subcentre identification in geographically smaller regions that show a spatially more equally distributed employment density. Concerning the different spatial patterns identified in Germany and those found in the literature for the US: differing location preferences of land users and land use regulations on each side of the Atlantic Ocean might be possible explanations.

The remainder of this paper is organized as follows: Section 2 provides an overview of the state of the research and outlines the challenges in analysing spatial disparities. The methodology, the data and the study regions are introduced in Sections 3 and 4. The empirical results are presented in Section 5 and discussed in Section 6. The paper concludes with a brief summary and suggestions for further research (Section 7).

[2] A discussion continues whether edge cities still exist in the US (cf. Gordon and Richardson 1996; Giuliano et al. 2007; Lee 2007), but that is not this paper's focus.

2 State of the research

2.1 Why considering subcentres?

Duranton and Puga (2015, p. 545) offer a remarkably simple depiction of urban (sub-) centres: ‘In fact, subcenter formation and diffuse employment decentralization should not be seen as a binary dichotomy. Reality is about a continuum ranging from small isolated facilities, to groups of several offices in a strip-mall, to small industrial parks with a couple hundred workers, to full-fledged business subcenters with tens of thousands of employees’. This depiction might explain why no agreement has been reached regarding a consistent definition of urban subcentres. This lack of agreement applies not only to (formerly) monocentric city regions in which further spatial densifications apart from the historic CBD emerge but also to polycentric city regions (cf. Craig et al. 2015, p. 27).

At the same time, the continuity of urban spatial structures challenges quantitative and qualitative investigations. Issues are to identify urban centres and subcentres, to explain their emergence and growth, to understand their qualitative nature or to relate their economic relevance to their administrative context. These issues are still under debate as consistent explanations and means of identification are still somewhat missing (see subsection 2.2 for a more extensive review of the literature).[3]

Though the literature on subcentre identification issues is fairly large, little research has been conducted for German city regions. This especially applies to studies based on disaggregated spatial scales. Analysing city regions at fine-grained spatial scales provides a much deeper insight into their urban spatial structure and reveals patterns that remain undetected in classic analyses at the municipality level. Intra-municipality subcentres will be identified here, which adds to the debate (*i*) another spatial scale and thus (*ii*) a modified understanding of urban subcentres. Finally, this paper also adds to the international state of research by adding insights of urban spatial development in non-North American city regions.

2.2 Means of identifying subcentres

A well-established method is the definition of density thresholds (e.g., Giuliano and Small 1991; Anas et al. 1998; McMillen and McDonald 1998; Gaschet 2002; Siedentop et al. 2003; Kim et al. 2014). Any regional entity exceeding *a priori* defined cutoff value, threshold, is considered a (sub-) centre. However, any threshold definition is somewhat arbitrary, which is criticized by Craig and Ng (2001), McMillen (2001) or Redfearn (2007). Moreover, these thresholds are hardly useful for subcentre identification in regions other than those for which they were designed. The reason for this limited transferability is the thresholds’ crucial dependence on the level and range of variables for which they were initially calculated. Hence, threshold values calibrated for economically strong metro regions might not be suitable for identifying subcentres in economically weaker regions, although substantial local spatial densifications exist. For that reason, agreement on a unique threshold value any local spatial densification must exceed to be a ‘true’ subcentre has not been reached.

Another means of detecting urban subcentres is exploratory. Exploratory methods roughly comprise Q-Q, box and scatter plots. If a spatial component is explicitly considered, they also include spatial statistics, such as local Getis *Gi* / *Gi** and local Moran’s *I*

[3] A remarkable amount of literature exists discussing the type of jobs/firms that relocate from the CBD to a subcentre, about residential sub and re-urbanization, about subcentres’ specialization vs. mimicking the CBD, etc., but these aspects are – although interesting and highly relevant – beyond this paper’s scope.

(e.g., Baumont et al. 2004; Riguelle et al. 2007; Guillain and Le Gallo 2010; Arribas-Bel and Sanz-Gracia 2014; Kim et al. 2014; Krehl 2015b) or the geographically weighted regression (GWR). Whereas the first two methods mentioned are truly exploratory in nature, GWR is formally a non-parametric regression approach. It is similar to weighted least squares regression, but the spatial weights are based on geographic co-ordinates and the corresponding weights matrix results from kernel estimation (cf. McMillen 2004b; Wheeler 2014). For that and for its objective to identify spatially varying beta coefficients, the GWR can also be considered an exploratory approach.

LWR is slightly different but is also used to identify subcentres (e.g., McMillen 2001; Redfearn 2007). From a formal point of view, LWR is the general case of GWR. The main difference between these two is that the latter only considers the spatial dimension by defining the weights matrix, whereas LWR allows the geographic co-ordinates to be explanatory variables of their own (McMillen 2004b). Further regression based methods for analysing urban spatial structure are density gradients (e.g., Heikkila et al. 1989; Anas and Kim 1996; Craig and Ng 2001; Roca Cladera et al. 2009; Barr and Cohen 2014), kernel density estimations (e.g., Adolphson 2010; Knapp and Volgmann 2011) and additional specifications of employment density functions (e.g., McMillen and Lester 2003; Carruthers et al. 2010).

Unlike exploratory approaches, regression based analyses are rooted in theory and usually imply a hypothesis. Most regression models in the urban context rely on the assumption that a dominant CBD is characterized by the highest regional employment densities. This assumption follows the classic monocentric city model in which all employment is concentrated in the CBD, and the population is located around it (cf. Alonso 1964). However, the monocentric city model can nevertheless be proven to be relevant to explaining today's urban spatial structure, which is characterized by several spatial densifications apart from the dominant CBD (e.g., Bogart and Ferry 1999; Kim 2007; Garcia-López and Muñiz 2010; Agarwal et al. 2012; Arribas-Bel and Sanz-Gracia 2014; Barr and Cohen 2014; Krehl 2015a; see Arnott 2012 for a comprehensive discussion).

2.3 Germany and the US – how similar are their urban configurations?

Empirical studies using the methods drafted in subsection 2.2 have found remarkable similarities in metro regions' overall urban spatial structures. These studies conclude that urban centres and subcentres exist in German, European and North American metro regions. However, their size and location, functional specialization and characterization and relevance regarding the entire urban spatial structure in a metro region seem to differ essentially both within and across nations (e.g., Glaeser et al. 2001b; Shearmur and Coffey 2002; Einig and Guth 2005; Behrens and Bougna 2015; Zhong et al. 2015; see Duranton and Puga 2015 for a comprehensive overview).

Limiting the focus to studies of the US and Germany reveals both similarities and differences in the formation and development of urban settlement patterns (cf. Gordon and Cox 2012). Hohenberg (2004) describes the development patterns for European city regions, explaining that their roots often are found in the Middle Ages. This explanation contrasts with the story Anas et al. (1998) tell for the US: they identify settlements' initial locations around transportation nodes as focal points in the development of cities. Redfearn (2009) points at similarities in the development of urban centres and subcentres by offering path dependence, durability of infrastructure investments and related inertia in land use changes as main explanatory factors. Of course, today's urban spatial structures are not only driven by historical situations but also by current planning policies and several other aspects. One of these aspects is the different attitudes towards land use and zoning that are reflected in different settlement patterns today (McMillen and McDonald 1999; Hirt 2007; Schmidt and Buehler 2007; Duranton and

Puga 2015). These different starting points and attitudes manifest in rather compact and dense urban environments in Germany, whereas the US metro regions are rather deconcentrated and dispersed and, thus, characterized by lower average densities (Garreau 1992; Nivola 1998; Gordon and Cox 2012).

Whereas comparisons between land-rich countries such as the US and Canada have been conducted (e.g., Shearmur and Coffey 2002), similar comparisons between land-rich and land-scarce countries are rare. This lack of research is not only a German-American issue but is also reflected in the scarcity of transatlantic studies of the urban spatial structure. Therefore, this study seeks to provide first insights into this kind of research by comparing the empirical results for Germany with literature-based results for the US. This comparison seems appropriate for both methodological and knowledge-driven reasons. The first applies to suitability issues: can methods be transferred? If so, what is the outcome and how sensitive do these outcomes react to parameter changes? The second reason applies to aspects of understanding and comparing spatial patterns: are the patterns qualitatively or quantitatively similar? These aspects are framed by touching upon the challenges of cross-national comparative urban research.

3 Empirical procedure

3.1 The choice of a locally weighted regression approach

As briefly discussed in Section 2, a myriad of measurement approaches exists for subcentre identification. This paper's research objective is to consistently identify employment subcentres applying a method that meets the following requirements (cf. McMillen 2001): it identifies subcentres in different study regions without imposing any threshold value or requiring any local knowledge. It is theory based to permit the derivation of (hypothetical) explanations of the identified patterns. It is feasible to assess the statistical significance of a potential subcentre and that subcentre's influence on the region's entire employment density surface, that is, the spatial distribution of employees within a given region. The essence of these requirements is that neither normatively influenced methods nor exploratory methods are feasible. Though regression-based methods meet these requirements, it needs to be discussed to which extent they actually identify consistent spatial patterns. Or are their results also prone to parameter settings?

Starting from theory, the first issues are the definition of a subcentre and the distinction between a subcentre and the CBD. These issues are followed by a second concern about the actual subcentre identification. Just as the name suggests, a subcentre is less or, at a maximum, as relevant as the centre (CBD) in shaping the employment density surface. Hence, a monocentric spatial structure is initially assumed. However, this structure will be altered to account for multiple centres later. To be able to capture a multiple centre structure, locally weighted regression is the preferred option. Other methods include regression lines with various distance-based measures as exogenous variables (for a good overview, see Roca Cladera et al. 2009). One particular regression model, the traditional negative exponential model, has been disregarded for the analyses here because it is not as flexible as the LWR approach in modeling the density surface. While the latter requires separating the distance north and east of the CBD, the aforementioned model only allows for one distance. This one-directional distance produces rings around the CBD, thus implying a symmetric spatial pattern that is generally unlikely to occur. Still, the negative exponential model will serve as a benchmark model to compare the LWR results.

3.2 LWR for subcentre identification

In the McMillen (2001) formulation, the non-parametric LWR approach allows for non-symmetry around the CBD, as it includes both the distance north and the distance east of the CBD. This two-directional distance introduces 'spatial flexibility' into the model, thus enabling it to nearly perfectly adapt to the employment density surface. Nevertheless, spatial flexibility implies a trade-off between adapting to the actual and smoothing the estimated density surface (cf. Redfearn 2007). McMillen (2001) exploits this trade-off. He uses the LWR for subcentre identification, suggesting a two-step procedure. The first step identifies the so-called candidate sites, and the second step identifies the actual subcentres from among these candidates. In step 1 the LWR is applied and employment density is regressed on the distances north and east of the CBD. The estimated regression line is:

$$y_i = g(DCBD_i), \tag{1}$$

where y_i is the logarithm of employment density in grid cell i, and employment density is employees per square kilometre. $DCBD_i$ is a vector containing the distances north and east of the CBD. Both distances are measured according to the great circle formula. This first step is also called 'initial smooth' because the regression line provides estimates of y_i that reflect a fairly smooth employment density surface in which outliers, that is, the positive residuals, are considered subcentre candidates. Equation (1) is estimated by the LWR procedure based on a tri-cube weighting kernel (for details on the calculus, see McMillen 2001, 2013). The window size, which defines the share of geographically closest observations to get a weight in the estimation, is 50 per cent to obtain a fairly smoothed employment density surface. Candidate sites are those having a statistically significant positive residual at the 5 per cent significance level, that is, they greatly exceed the smoothed employment density surface. Regarding the actual identification of subcentres in step 2, McMillen (2001) suggests including only those candidate subcentres of step 1 that score the highest $g(DCBD_i)$ value within a 3-mile radius to avoid multicollinearity. This suggestion is followed here. So, the remaining subcentre candidates – which are minimum 3 miles apart from each other – enter the following equation in the second step:

$$y_i = \beta_0 + \beta_1 h(DCBD_i) + \sum_{j=1}^{S}\left(\delta_{1j}D_{ij}^{-1} + \delta_{2j}D_{ij}\right) + u_i, \tag{2}$$

where S is the number of candidate sites, D_{ij} is the distance between each subcentre candidate j and grid cell i, and u_i is the error term. Including both inverse and level forms of D_{ij} permits the distinction of subcentres that merely have a local effect on the employment density surface (inverse form) from subcentres that have an effect on the entire study region (level form). While the window size chosen for estimating Equation (1) was 50 per cent, it is 1.0 per cent for estimating $h(\cdot)$ in Equation (2). 1.0 per cent was chosen according to the cross-validation criterion and this small window size best captures the employment density surface. $h(\cdot)$ is estimated with a LWR, but as McMillen (2001) explains, the key issue is to choose a highly flexible estimation procedure and not necessarily a LWR. The point in estimating $h(\cdot)$ is less to obtain a smoothed density as in Equation (1) but to also approximate the employment distribution best possible. For that, the window sizes are not identical. After obtaining $h(\cdot)$ non-parametrically, the full Equation (2) is estimated by ordinary least squares (OLS).

The final list of subcentres is obtained from repeatedly estimating Equation (2) and stepwise deleting the subcentre candidate whose coefficient scores the lowest t-value, regardless of whether this coefficient is statistically significant. This stepwise procedure is ended as soon as all subcentre candidates are significant at the 20 per cent level, in either level or inverse form.

Thus, any significant δ_{1j} or δ_{2j} indicates a true subcentre. If δ_{1j} is significant, the subcentre is called a 'local' subcentre, as the coefficient is followed by the inverse distance to subcentre j. A statistically significant δ_{2j} indicates that the subcentre is 'global'.

Because the employment density is fairly disperse in each study region analysed here, the employment density enters Equations (1) and (2) in level instead of log form. This decision is reasonable because employment densifications in Germany are less pronounced than in the US. Using the log form in German study regions would level out most spatial densifications (see Figures 2 and 3). The original McMillen-model, which requires log instead of level form, has been tried in several versions but it yielded econometrically worse results than the level-specification finally used. For that, it was not considered further although theoretical considerations call for a log-specification and the mapped results do not differ substantially.[4] Nevertheless, Equations (1) and (2) with y_i in level form are referred to as the original model in the remainder of this paper.

3.3 Modifications to the original model

Technically, a more fundamental modification than using the level instead of the log form is to vary the distance that any two subcentre candidates must be apart from each other (cf. step 1): 1-mile to 5-miles will be used to evaluate whether a 3-mile radius, as suggested by McMillen (2001), is appropriate for German city regions. The 3-mile radius might be either too large (the regions are much smaller and employees distributed more equally than in the US) or too small (less likely).

The third set of modifications is to alter the window size in Equation (1). Whereas small window sizes result in 'jagged' but well-fitting curves, large window sizes produce a more general curve representing some spatial trend in the data. Modifying this window size and choosing one smaller than 50 per cent is expected to better reflect each study region's employment density surface. The reasoning for this expectation is that a smaller window size permits the detection of smaller, more local subcentres. Choosing a window size larger than 50 per cent, on the contrary, results in an even smoother density surface and thus limits the number of subcentre candidates to grid cells that score very high numbers of employees.

Furthermore, the regions of Frankfurt and Cologne are estimated twice because both contain more than one core city.[5] The Frankfurt region includes four core cities, one of which is the municipality of Frankfurt, and the Cologne region has two core cities, the municipalities of Cologne and Bonn. Two versions of $g(DCBD_i)$ and $h(DCBD_i)$ are used in these multi-core city regions. Version one calculates $DCBD_i$ as the distance north and the distance east of the region's *largest* core city's CBD. These largest cities are those of Cologne and Frankfurt. Version two uses the distances north and east of the *closest* core city's CBD to calculate $DCBD_i$. The latter version is used to capture the inherently inter-urban polycentric structure of the Cologne and Frankfurt regions. It is expected that this modification yields better results than only considering the distance to the largest city's CBD.

3.4 Benchmark models

Finally, two further models are estimated for comparison and benchmarking purposes. They are meant to evaluate whether the sophisticated LWR procedure markedly improves the results. The

[4] This could set a stage for discussing what actually needs to be fulfilled to qualify a grid cell/site/etc. to be a subcentre. However, analysing this in-depth is beyond this paper's scope.

[5] The details for all study regions follow in subsection 4.2.

first benchmark model is a pure linear model, where employment density is the dependent variable and the distance to the CBD (as the crow flies) is the independent variable. The regression line thus is:

$$y_i = \beta_0 + \beta_1 DCBD_i + \varepsilon_i. \tag{3}$$

A linearized version of the negative exponential model, sometimes called the standard model in literature, serves as a second benchmark model. Its equation is:

$$ln(y_i) = \beta_0 - \beta_1 DCBD_i + \varepsilon_i. \tag{4}$$

Both of these equations are estimated by OLS. The main differences between these models are in the assumed distribution of employment density and in the interpretation of the coefficients. Whereas the coefficients in Equation (3) have an absolute unit interpretation, the coefficients in Equation (4) have a semi-elasticity interpretation.

4 Data and study regions

4.1 Data sources

All analyses are based on the georeferenced Integrated Employment Biographies (georeferenced IEB) as of 30 June 2009, which are provided by the Research Data Centre of the Federal Employment Agency at the Institute for Employment Research. Employees are counted at their places of work in this data set. These employee data do neither capture self-employed persons nor civil servants, which results in capturing 75 per cent of all employed persons on a Germany-wide average (Statistisches Bundesamt 2008). The missing 25 per cent are not available on the spatial level of grid cells, which is the spatial entity applied here. Their size is 1 km^2, their shape is quadratic and they are located in accordance with the European Grid INSPIRE (Infrastructure for Spatial Information in the European Community). Thus, the number of employees equals the number of employees per km^2, the latter also called employee density.

Furthermore, censoring occurred in the georeferenced IEB due to German privacy laws: numbers must not be reported either if there are fewer than three individuals in a grid cell (‘minimum case’) or if one firm dominates in a grid cell (‘dominance case’). Individuals may be both firms and employees and if any of these scores less than three in a grid cell, then the number of employees – which are used here – is censored. To dominate, on the contrary, means that one firm accounts for a substantial number of all employees within a grid cell (see Bundesagentur für Arbeit 2014 for details regarding all censoring issues). Table 1 provides both the numbers and the shares of grid cells and employees ‘lost’ due to these censoring issues. While the share of censored grid cells is rather high, the share of employees ‘lost’ is fairly low. All censored grid cells were manually assigned one employee to avoid even more severe downward bias that would result had the censored grid cells been completely excluded from the analyses. It should be noted, however, that the majority of censoring occurred for minimum case reasons in all study regions. Therefore, the data are considered appropriate for subcentre identification.

As previously discussed, the LWR approach requires the calculation of distances. Thus, all grid cells were turned into points by aggregating the information in each grid cell into that grid cell’s centroid. All distances are calculated between these centroids. Whereas the LWR in Equation (1) requires the distance north and the distance east of the CBD, Equation (2) only requires a

Table 1. Characterizing the study regions

	Frankfurt region	Cologne region	Munich region	Stuttgart region
Area (km^2)	4843	2812	3277	2842
Number of core cities	4	2	1	1
Employees (million 2009)	1.06	0.80	0.79	0.77
Residents (million 2011)	3.51	2.77	2.41	2.35
Grid cells containing employees	2914	2293	2462	2029
Number of censored grid cells	774	481	923	596
Share of censored grid cells (%)	26.6	21.0	37.5	28.0
Share of employees 'lost' due to censoring (%)[a]	0.7	0.5	1.0	0.7
Censoring for dominance reasons[a]				
Number of grid cells[b]	0	1	6	3
Number of employees 'lost'[b]	0	64	7411	5184
Average employee density	363	351	320	378
Median employee density	142.5	117	41	147
Average employee density, excluding censored grid cells	494	444	512	535
Median employee density, excluding censored grid cells	288	214	151	337

Source: Own calculations based on the georeferenced IEB and Eurostat (2014).
Notes: [a]Numbers provided by the FDZ. [b]Information on these grid cells' location unavailable.

one-directional distance. That one-directional distance is as the crow flies. The location of the CBD is chosen according to the location of town halls and central market places registered in the 'Geographical Names 1:250 000 (GN250)' as of 31 December 2013 (BKG 2014).

4.2 Study regions

The study regions are four German city regions: Frankfurt, Cologne, Munich and Stuttgart. These regions were delineated based on regional labour markets (*Arbeitsmarktregionen*) and metropolitan areas (*Großstadtregionen*), which are both defined by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR 2012a, 2012b). Thus, it can be expected that the regions sufficiently capture the regional economic system, making the analysis of employment centres and subcentres meaningful.

The fairly small number of just four study regions is the consequence of the project setting, in which the employment data were obtained. That project setting also included the analysis of spatial base data, which were not accessible for the whole of Germany. For that reason, a most similar systems design (MSSD; for that technique's details, see Yin 2009) with a small number of four regions was decided on.

One could argue at this point that a Europe-wide comparison would be more insightful than comparing four German city regions. This is true. However, a European comparison was discarded mainly but not solely due to data issues although all analyses are conducted on the spatial level of grid cells. This grid-oriented spatial scale would favour a comparative approach but it also complicates the data availability as providing employment data on a 1 km^2 basis is not yet standard. Thus, data is not available for all years in all, or at least several, European countries. Moreover, the definition of employees subject to social insurance (which is used here) varies among different countries. This variation is accompanied by different privacy laws and, hence, censoring practices. Consequently and for the sake of consistency the decision for a solely German consideration was made.

As briefly mentioned above, the choice of regions was made according to a MSSD aiming for the analysis of polycentricity in selected German city regions. A MSSD requires that the chosen regions should be similar in all but one characteristic. Due to these requirements, metro areas such as Berlin or Hamburg have not been included in the sample; their population and their endowment with employees are by far greater than that of Frankfurt or Stuttgart, for example. Table 1 shows that the four study regions used here are comparable in most variables except for the number of core cities. That number serves as our *a priori* identifier for the polycentricity of a region.

Each region's core city is defined in accordance with the definition of core cities given in the metropolitan areas provided by the BBSR. Core cities have more than 100 000 inhabitants and an incommuter-outcommuter relation greater than 1 (BBSR 2012b). While the Munich and Stuttgart regions are characterized by one core city (the cities of Munich and Stuttgart), the Frankfurt and Cologne regions host four and two core cities, respectively. Thus, the sample consists of a region that is expected to be monocentric (Munich); a region that is supposedly monocentric but where local knowledge leads one to expect a polycentric, or even dispersed, urban spatial structure (Stuttgart); and two regions consisting of multiple core cities, implying inter-urban polycentricity by definition (Cologne and Frankfurt). Figure 1 visualizes each study region and its location in Germany.

Figures 2 and 3 present the four study regions and their distribution of employees. All numbers in these figures are standardized into z-scores to establish comparability among the regions. A z-score below 0 implies that the respective grid cells is below the regional

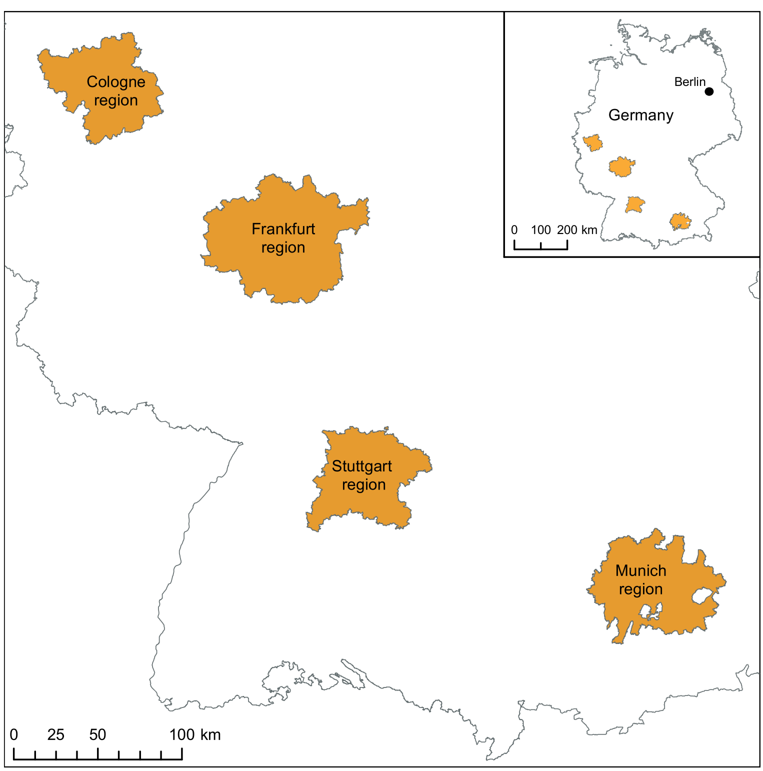

Fig. 1. Location of the study regions in Germany

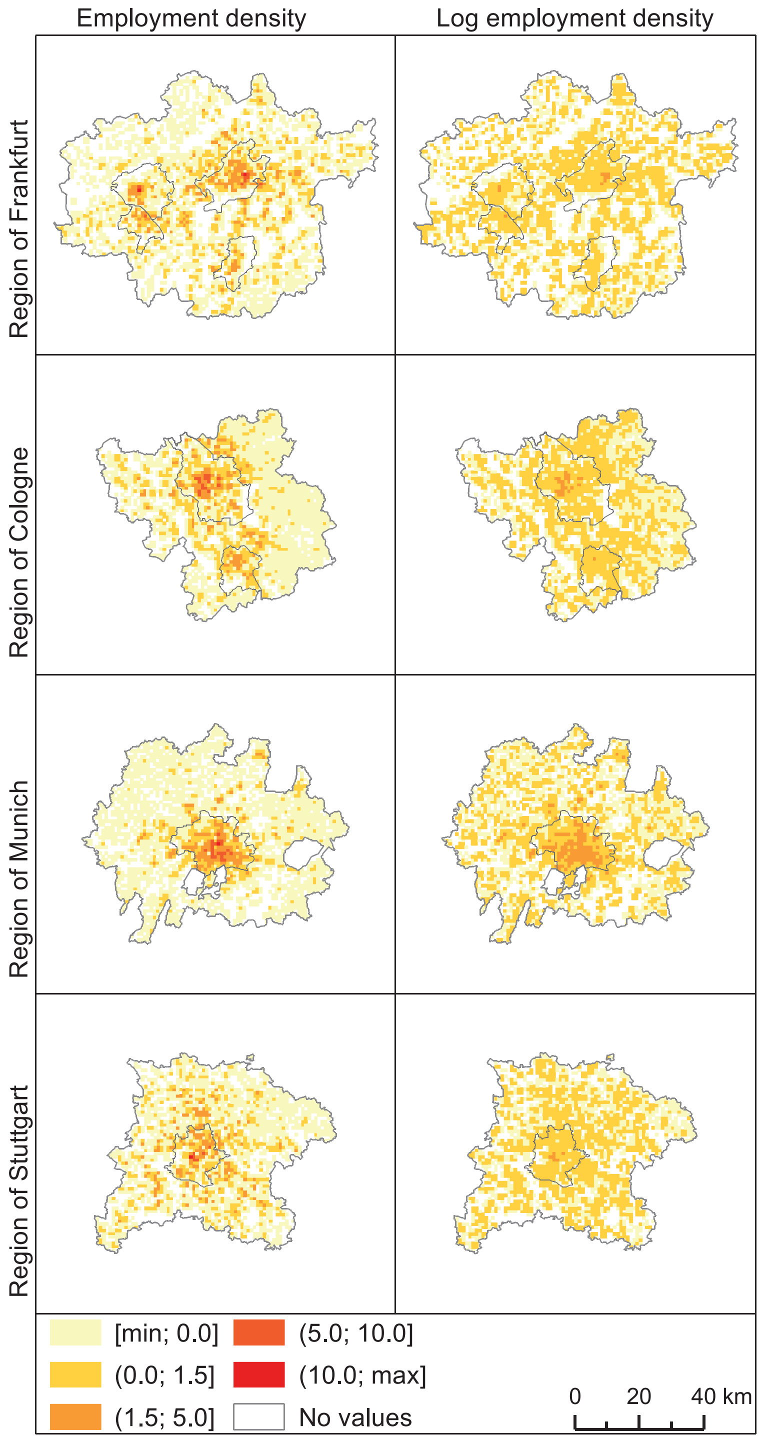

Fig. 2. Standardized employment densities
Source: Own elaboration based on the georeferenced IEB.

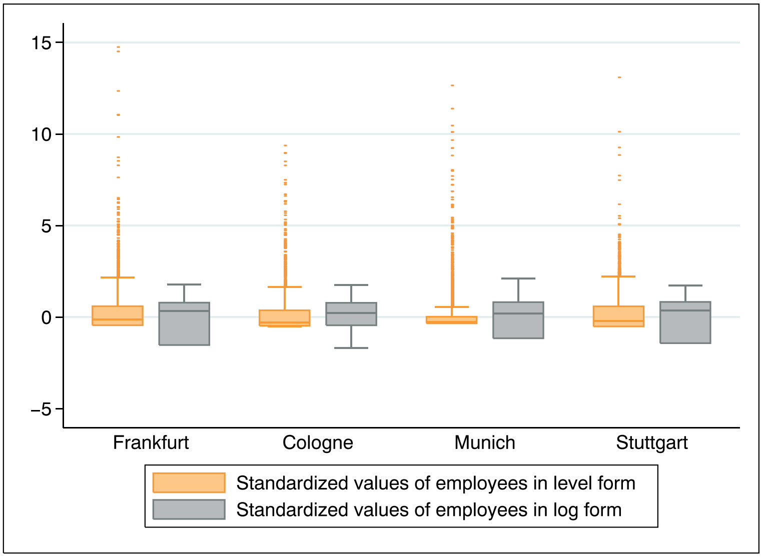

Fig. 3. Box plots of the standardized number of employees in each study region
Source: Own calculations based on the georeferenced IEB.

mean, z-scores between 0 and 1.5 indicate scoring at max 1.5 standard deviations above the mean, and so on. In Figure 2, employment density increases as the colour changes from yellow to red. White (hollow) grid cells do not host any employees and grey circled areas within each region denote the core cities' administrative area. All white (empty) grid cells are omitted from the regression analyses. The left column of Figure 2 shows the number of employees in level form, whereas the right column contains their natural logarithm.

The most striking impression is that employment densifications are much more obvious in level than in log form. Whereas one can easily form expectations regarding the number and location of subcentres based on the maps in the left column, this identification is hardly possible based on the maps in the right column. While the left column of Figure 2 shows the employment densifications in all core cities' centres and along major roads or rivers, no axial system or otherwise interpretable pattern of employment density can be detected in the right column. This finding gives rise to the first hypothesis that employment densities are more dispersed in German than in US metro regions.

Moreover, the maximum values of the z-scores of employees in level form are between 9.4 and 13.8, but they score only from 1.7 to 2.1 in log form (Figure 3). This further proves the comparatively dispersed employment distribution in suburban areas in Germany, especially if a log-transformation is performed. Non-core city subcentres are assumed to be characterized by high employment densities and are visible as outliers in Figure 3. While there are numerous outliers in level form, there are none in log form. For these reasons, and due to the aim of subcentre identification, the non-logarithmized number of employees is applied here.

Furthermore, the core cities are focal points of employment densifications. This core city dominance is presumably stronger in German than in US metro regions. A general dispersion of employment cannot be derived from the figures shown so far. Detecting or claiming a region-wide dispersion of employees would furthermore contrast with previous findings (cf. Section 2). However, analyses below the spatial level of municipalities are scarce in German research. Thus, the possibility of not identifying any local spatial densification cannot be ruled out *a priori*. The LWR approach and its modifications described in Section 3 will be used to reduce this scarcity.

Table 2. Comparing the goodness-of-fit measures between the benchmark and the original models

		Frankfurt region	Cologne region	Munich region	Stuttgart region
			Adjusted R^2 values		
Distance to CBD	OLS regression	0.08	0.17	0.25	0.15
	Linear version of negative exponential model	0.03	0.10	0.18	0.09
	Full LWR model	0.50	0.67	0.74	0.50
	LWR with $h(DCBD_i)$ only[a]	n.a.	n.a.	n.a.	n.a.
	Full LWR excluding $h(DCBD_i)$	0.02	0.07	0.04	0.04
			Number of subcentres		
	Full LWR model	9	15	20	12

Source: Own calculations based on the georeferenced IEB.
Notes: n.a. = not available. [a]Including only $h(DCBD_i)$ assumes monocentricity as D_{ij} and D_{ij}^{-1} are excluded.

5 Evidence from German city regions

5.1 Applying the original model

Table 2 provides an overview of the original LWR models and their goodness-of-fit measures as well as the comparison of the two benchmark models.[6] Rows 1–2 compare traditional gradients obtained from estimating Equations (3) and (4). Rows 3–5 discuss the monocentric city model and its extension to a multi-core city model. These regressions are based on the LWR introduced above using employment density in level form.

Comparing the model fit of the full LWR models to that of the models omitting the CBD-distance variable $h(DCBD_i)$ evinces the subcentres' limited explanatory power regarding the employment density surface in the study regions (rows 3 and 5 in Table 2). This finding holds despite all models' overall significance and the subcentre coefficients' significance. Admittedly, the versions of Equation (2) that do not consider $h(DCBD_i)$ suffer from omitted variable bias. The main reason for these to still be included here is to verify the CBD's influence on the employment density surface.

The analyses summarized in Table 2 reveal that statistically significant subcentres exist in each study region (the last row in Table 2). However, these subcentres only have local influences on the entire employment density surface. Based on these results, one can conclude that the LWR approach seems appropriate for subcentre identification. This appropriateness is further supported by comparing the full LWR models to the benchmark models presented in rows 1–2. The adjusted R^2 values are markedly higher in the semiparametric regression procedure including the subcentres than in the simple linear models. The LWR goodness-of-fit measures are, furthermore, similar to those McMillen (2001) obtains for six US metro regions. However, this quantitative similarity is not sufficient evidence of the general (un-)suitability of McMillen's LWR approach to identify the subcentres of German city regions. For that reason, further modifications were designed and applied.

[6] In addition, the Akaike and Bayesian information criteria have been calculated for all (semi-) parametric models. These criteria's values confirm the findings based on the adjusted R^2 for all models, except the negative exponential one. The diverging results for the latter are likely to be due to the levelling-out of outliers by taking the logs of the independent variable.

5.2 *Applying the modifications*

5.2.1 Next CBD

The first modification to the original McMillen-procedure is to include the next CBD (*nCBD*) instead of the largest CBD (*DCBD*). The expectation is that this next CBD model formulation yields better results, as it more precisely reflects the underlying urban spatial structure. This expectation is based on the fact that all core cities are weighted equally because they are all considered in the initial smooth $g(\cdot)$ and core city relevance $h(\cdot)$. Equal weighting seems reasonable from the notion that an inter-regionally polycentric region has several, roughly equivalent centres. For that reason, it is surprising that using $nCBD_i$ instead of $DCBD_i$ negatively affects the results: the adjusted R^2 values decrease by 0.12 (Frankfurt: 0.50 decreases to 0.38) and 0.15 (Cologne: 0.67 decreases to 0.52), respectively (see Table 3). This implies that the defined core cities are not of equal relevance but that the largest core city's CBD is the region's centre.

Table 3, in combination with Table 2, proves that models considering only the largest (in the notion of most important) CBD have a better overall fit than models 'weighting' all CBDs equally. Contrary to the assumption that including all CBDs in an inter-urban polycentric region would improve model quality, it has to be noted that the opposite is the case. One reason for this result could be that considering all CBDs equally introduces more disturbances into the model than does only considering the most important CBD. Thus, the largest CBD specification is more appropriate than the multi-core specification. Therefore, distinct inter-regional polycentricity does not exist in the Frankfurt and Cologne regions.

5.2.2 Altering the radius

The second set of modifications refers to the minimum distance between any two candidate sites. Altering this distance provides the insight that its influence on the number of subcentres is immense, whereas its influence on explanatory power is limited. Figure 4 visualizes the relationships among the radius, the adjusted R^2 values and the number of subcentres in each study region.

The employment density distribution in the Munich region is extremely well explained by any of the radii tested, as the adjusted R^2 values always score 0.74. Because the share of explained variance does not change when the radius is changed but the number of subcentres changes markedly, one can conclude that the subcentres do not characterize the employment density pattern in the entire region. This is reasonable recalling that again all subcentres are

Table 3. Comparing the goodness-of-fit measures in the next CBD specifications

		Frankfurt region	Cologne region
		Adjusted R^2 values	
Distance to nCBD	OLS regression	0.09	0.20
	Linear version of negative exponential model	0.02	0.13
	Full LWR model	0.38	0.52
	LWR with $h(nCBD_i)$ only[a,b]	n.a.	n.a.
	Full LWR excluding $h(nCBD_i)$	0.25	0.33
		Number of subcentres	
	Full LWR model	30	33

Source: Own calculations based on the georeferenced IEB.
Notes: nCBD = next CBD; n.a. = not available. [a]Including only $h(nCBD_i)$ assumes monocentricity, as D_{ij} and D_{ij}^{-1} are excluded. [b]The window size is 2.0%, according to the cross-validation measure. All else remains unchanged.

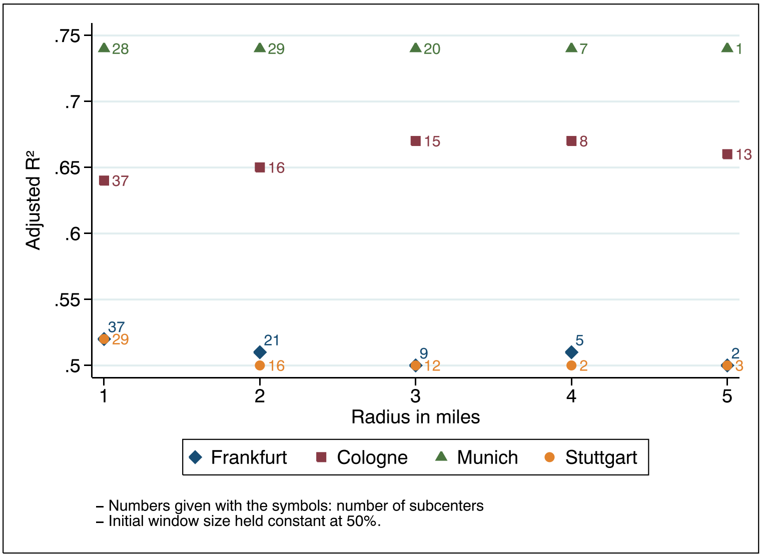

Fig. 4. Relationships among radius, goodness-of-fit and number of subcentres
Source: Own calculations based on the georeferenced IEB.

local. The same holds for the Frankfurt and Stuttgart regions: all subcentres are local; the adjusted R^2 values are fairly independent of the chosen radius; and the number of subcentres changes dramatically when the radius changes. This finding proves that the subcentres do not add much explanatory power to the model. Otherwise, the number of subcentres would have more substantially influenced the goodness-of-fit measures. The best model fit for the region of Cologne is obtained using a 3 or 4-mile radius, and again, all subcentres are local.

Averaging the goodness-of-fit measures over all study regions shows that a 1 mile or a 4-mile radius seems most appropriate. However, the differences in the adjusted R^2 values are very small, thus implying that the radius does not play a key role. This non-pivotal role of the radius could hint that the LWR approach requires ‘minimum spatial disparities’ in the underlying data to identify subcentres. From that point of view, one could argue that the LWR is not suitable for subcentre identification in regions having rather dispersed employment density distributions or where no subcentres exist. Following this line of argumentation, the identification of solely local subcentres in the four study regions seems reasonable: whereas the local subcentres are relevant in their direct neighbourhood, their effect on the entire study region is negligible.

5.2.3 Altering the initial window size

The third set of modifications outlined in subsection 3.3 includes variation of the initial window size. It is expected that a smaller initial window size yields more precise results in comparatively disperse regions. Using three different window sizes provides the results summarized in Figure 5.

The comparatively small window size of 25 per cent yields the highest adjusted R^2 values, on average. However, the differences between these measures in the respective specifications are negligible as they vary by 0.005 within each study region. The number of subcentres, in contrast, changes if the window size is changed. In any specification, all statistically significant subcentres are local, implying that they are rather weak and effective solely in a local context.

These results suggest that varying the initial smooth seems less relevant than varying the minimum distance between any two subcentres. Combining these findings supports the results

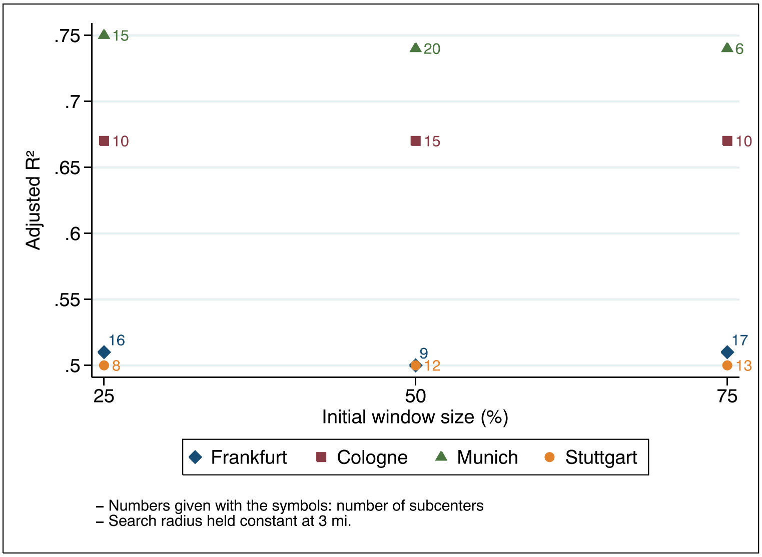

Fig. 5. Relationships among initial window size, goodness-of-fit and number of subcentres
Source: Own calculations based on the georeferenced IEB.

summarized in Table 2, also suggesting that urban subcentres do not characterize the employment density surface in any of the study regions. Characterizing subcentres of regional importance, thus, do not exist in the regions analysed.

5.3 Subcentres in German city regions

The analyses have been somewhat a-spatial, as their results have been presented in tables and diagrams only. Figure 6 illustrates the best LWR approaches regarding the initial window size and the distance any two subcentre candidates must be located apart from each other. Based on the results in Figures 4 and 5, a window size of 25 per cent and a radius of 3 miles have been chosen, and their results are spatially overlaid with the results obtained from a window size of 50 per cent and a radius of 1 mile. The *nCBD* specifications are not considered in the maps, as they turned out to disturb rather than qualify the models (cf. row 3 in Tables 2 and 3). For ease of interpretation, the standardized employment densities are also mapped.

The subcentres in the Munich region reveal that the LWR model specification is not crucial for the overall urban spatial structure because many of the subcentres and their areas covered by the radius coincide. This finding is in contrast with the subcentre locations in the Cologne and Stuttgart regions, as subcentre coincidences are less prominent there. The Frankfurt region is somewhere in between these.

Analysing the identified subcentres reveals that the subcentres plus their ‘spheres of influence’ (radii) account for about 7–11 per cent of each region’s employee endowment. Whereas these shares are fairly stable in the two most appropriate model specifications, the shares of area covered vary substantially: 7–20 per cent in the 1 mile, 50 per cent specification and 17–27 per cent in the 3 mile, 25 per cent specification. When interpreting these numbers, it should be noted that the shares provided do not cover the CBD but only the subcentres. Based on these findings and the location of the subcentres, a CBD-dominance interpretation seems natural. This is not only reflected in the low shares of employees but also in the substantially lower employment densities in the subcentres than in the entire region. Comparing these numbers and the standardized densities in Figure 6 provides further support for persistent core city dominance in all study regions.

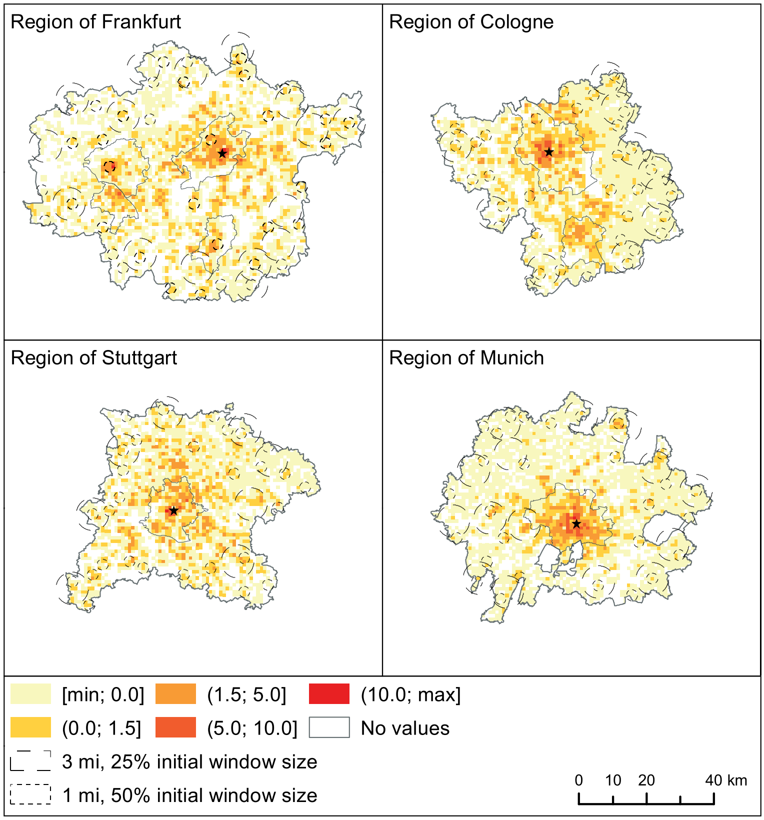

Fig. 6. Subcentres in German city regions
Source: Own elaboration based on the georeferenced IEB.

A closer look at the subcentres' locations is surprising at first, as nearly all of them are located in the regions' peripheries and the underlying employment densities are not necessarily high. This finding, however, supports the regression results indicating that all statistically significant subcentres are local. Thus, they do not shape the regions' entire employment density surfaces. The subcentres' local nature also implies that the CBD, whose coefficient is large and highly significant, dominates the study regions. One could thus hypothesize that if each region's CBD had not been that important, there would likely have been more subcentres closer to the region's geographical centre.

However, it is still reasonable to consider the subcentres because they add explanatory power to the underlying model: once taken into account, the mean square error (MSE)[7] decreases in each study region. The polycentric model (Table 4, row 3) is more powerful than the monocentric one. This finding applies to both the comparison with the simple linear (row 1) and the comparison with the nonparametric (row 4) specifications. The CBD's strong influence is further reflected in the very high MSE values if only subcentres are taken into account (row 5). This is also in line with the descriptive statistics regarding the subcentres: both the share of employees and the employment densities are fairly low because the CBD is omitted from those analyses. Consequently, CBD dominance seems to mask much of the spatial variation

[7] Adjusted R^2, AIC and BIC are not available for nonparametric models. Thus, the MSE is listed in Table 4. The comparatively very low values for the linear version of negative exponential model (row 2) are somewhat misleading because taking the log of y_i mitigates the outliers.

Table 4. Comparing the Mean Square Error of all models specified

		Frankfurt region	Cologne region	Munich region	Stuttgart region
		Mean Square Error			
Distance to CBD	OLS regression	296544	267639	434579	267482
	Linear version of negative exponential model	6.91	5.51	6.25	7.10
	Full LWR model	154331	107021	148324	153486
	LWR with $h(DCBD_i)$ only[a]	192989	135268	181822	203109
	Full LWR excluding $h(DCBD_i)$	300761	299916	544500	297998

Source: Own calculations based on the georeferenced IEB.
Notes: [a]Including only $h(\cdot)$ assumes monocentricity, as D_{ij} and D_{ij}^{-1} are excluded.

in the employment density surface and strongly influential spatial densifications cannot be identified with the LWR approach.

As compared to many other studies, subcentres identified here are small (1 km^2) and independent of political designations such as municipalities. Whereas much research has been conducted on essentially administratively motivated area delineations, research on geometry-based spatial delineations, such as grid cells, is fairly novel. This geometry-based approach makes the interpretation of the identified subcentres more complicated because designations such as satellite cities cannot be used easily. Rather, core and other areas of substantial spatial densifications occur within the same municipality – regardless of whether that municipality is a core or a peripheral one.

One consequence of the empirical analyses obtained here is the question whether it is appropriate to use the term ‘subcentre’ to describe the identified local spatial employment densifications in German city regions. These densifications’ influence is so small that the term ‘centre’ could be misleading. Referring back to the subcentre characteristics regarding the share of employment and area covered, the term indeed is somewhat misleading as only small shares are covered. Additionally, these shares of employees are not markedly higher as the shares of area they are located in. For that, it is to be discussed whether the identified subcentres are ‘true’ subcentres, whether they are comparable to the subcentres identified in other parts of the Global North, and whether the notion and character of these subcentres is similar.

6 Discussion

Several issues arise in the quest for explanation: Are the methods appropriate for the research objective of identifying urban subcentres? How can the urban spatial structure in German city regions be explained? Why does it fundamentally differ from the results other researchers obtained for the urban spatial structure in the US? What does this imply for internationally comparative studies?

6.1 Methodology and data

Concerning the urban spatial structure of German city regions, the easiest reasoning is that censoring due to privacy laws causes the urban subcentres’ weakness. However, most censoring occurred for ‘minimum case’ reasons and should not influence the existence of subcentres.

The next possible explanation of the identified patterns is related to the choice of methods. It could be argued that the LWR applied here is not sufficiently sensitive to detect urban subcentres in rather polycentric-disperse environments. This argumentation would support the initial thought that methods for one region cannot be easily transferred to another region. There are two aspects that weaken this line of reasoning: First, any method – statistical, explorative or normative – can be modified to yield the expected results (which would be the existence of marked spatial disparities here). However, aiming for a research verification bias should not be the basic motivation. The choice of methods should rather be based on theory or hypotheses formulated *a priori*. As discussed in Section 1 and subsection 3.1, the LWR approach is both based on theory and satisfies the requirement of producing inter-regionally and internationally comparable results. Second, the LWR approach has not been uncritically adopted from previous research but has thoroughly been tested and slightly modified. The modifications were necessary to take into account the geographical predefinitions (smaller regions) and to mitigate the peculiarities of the available data and methods. Based on this reasoning, the finding that few subcentres exist should be correct and not methodology driven. Additionally, these modifications provided a better understanding of the relationship between the method's parameter settings and the identified spatial patterns.

Furthermore, the LWR results obtained here match previous findings: Krehl (2015b) used the same data and applied an exploratory spatial data analysis approach. She identified geographically large subcentres located in close proximity to the core city in all study regions. Moreover, almost the entire core cities are considered one continuous employment hotspot. These seemingly contrasting results, large geographical entities vs. local subcentres in the regional periphery, are in fact complements. The detection of spatially connected subcentres is not aimed for with point-data oriented methods. Additionally, the notion of the subcentre is different. While the LWR approach searches for points (grid cells' centroids in this particular case) exceeding a smoothed employment density surface, the exploratory approach applied in Krehl (2015b) looks for broader spatial associations. Hence, an 'exploratory subcentre' may comprise of several continuous grid cells of high employment density, whereas an 'LWR subcentre' significantly influences the local or global employment density surface.

Therefore, once sensibly adjusted, the LWR is appropriate for urban subcentre identification. Furthermore, the LWR's results for these four selected German city regions are consistent with previous findings. Although the differences in the results obtained in Section 5 are marked regarding the number of subcentres, they are small regarding the models' quality. This result leads to the conclusion that applying more than one model specification pays off. Put differently, there is no 'one size fits all' method for every region.

6.2 Urban spatial structure in Germany and in the US

The remaining question is why are there no subcentres similar to those in many US metro regions? A knowledge-driven explanation refers to land use regulation patterns, especially zoning practices. There is evidence in the planning literature that zoning in the US is far more functionally exclusive than in Germany (e.g., McMillen and McDonald 1999; Hirt 2007). Land use patterns in US metro regions are characterized by a clustered distribution of certain land use types with spatially separated residential, commercial and industrial areas (Ewing et al. 2002). In contrast, German land use patterns are much more shaped by multi-functional urban areas and a fine-grained mix of land uses. Moreover, comparatively restrictive German density regulations usually do not allow high-density commercial or office buildings with floor area ratios above 2.4. This may also explain the lack of statistically significant employment density peaks in suburban locations and hence the identification of only comparatively weak local subcentres.

Figure 7 illustrates the number of employees per number of residents in Germany to indirectly support these differences in land use patterns. This employee-resident ratio increases as the colour changes from yellow to red. White (hollow) areas indicate that neither of them is registered in the respective grid cell and grey circled areas within each region denote the core cities' administrative area.

Figure 7 reveals that almost no grid cell exists where the majority is employees, that is, a value larger than one. Recalling that the number of residents also contains those who are either

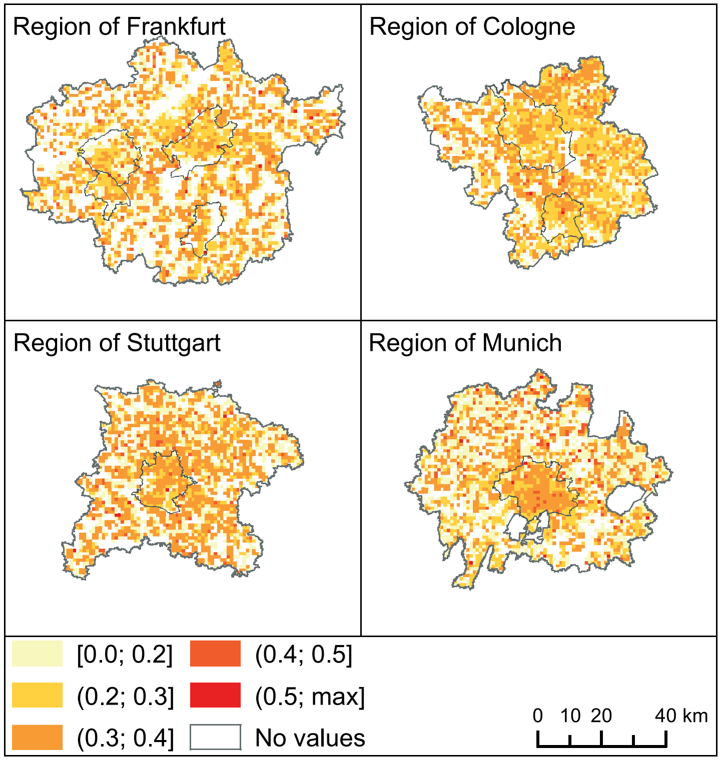

Fig. 7. Employees per number of residents
Source: Own elaboration based on the georeferenced IEB and the GEOSTAT data.

too young or too old to work, this is not especially surprising. However, a 1:2 employee-resident ratio is also rare. This finding implies that employment density is dispersed and often reflected in a considerable number of residents. With that in mind, the hypothesis is supported that mixed land use patterns might be responsible for the different results between German and US metro regions. Moreover, employment and residential densities are remarkably similar in the four German city regions analysed here. This similarity implies that either mixed-use areas are predominant or industrial and residential land use areas are rather small and thus coexist in a 1 km^2 grid cell. Of course, some 'hotspots' exist in which employees almost outweigh residents, thus indicating 'employment surplus'. However, these hotspots do not excessively characterize the study regions, which is in line with the findings obtained from the LWR approaches applied earlier in this paper.

Another line of argumentation regarding the spatial differences between Germany and the US refers to the endowment with land. Whereas the US is fairly land-rich, Germany is rather land-scarce. Thus, one would expect higher average densities on a regional basis in Germany than in the US. Regarding subcentre densities, however, the opposite is likely to be true.

The entire Los Angeles metropolitan statistical area (LA MSA), for example, is as large as the sum of the four study regions used here. Comparing the employment densities between the LA MSA[8] and the four German city regions shows that both LA and Orange County score much higher employment densities. The remaining MSA counties, however, are comparable to the

[8] The numbers are taken from Redfearn (2009, p. 228) and McMillen (2001, p. 455). It should be noted that the US data are as of 1990 (McMillen) and 2000 (Redfearn) and for this and other reasons not fully comparable to the 2009 data used here.

study regions used here in terms of employment density. Similar results can be obtained if the McMillen (2001) data and results, for which the LWR was originally designed, are considered. Region sizes and densities in transport analysis zones (TAZ) are larger in those six metro areas than in the regions analysed here. The region-wide employment densities, however, are lower than the employment densities in the four German city regions.

Regarding the number and location of urban subcentres, McMillen (2001) concludes that several subcentres exist within each study region, but their location is more evenly spread and in greater distance to the predefined CBD than in the study regions analysed here. Thus, his findings differ from those obtained by applying the same methodology for German city regions. However, these differences are not too surprising for reasons of region size, unit of analysis, endowment with land or land use and zoning practices. But these reasons are still hypothetical. For a closer discussion of outcomes and possible driving forces in the development of urban spatial structure in Germany (or Europe) and North America, more in-depth cross-national comparisons are necessary. Unfortunately, these are not easily conducted due to different spatial reference systems and data sources (see also Siedentop and Fina 2012 regarding such challenges).

Based on these seemingly diverging results, one could ask whether the term ‘subcentre’ means the same in these two studies. One striking technical difference is that most US analyses cited here are based on tract or TAZ level, whereas the spatial scale of 1 km^2 grid cells is much more fine-grained. Thus, 1 km^2 subcentres are smaller and potentially located closer to each other (despite the predefined minimum distances). For these technical aspects, 1 km^2 subcentres do not necessarily have the same characteristics as TAZ or tract subcentres, although it cannot be ruled out here that high-density core city centres or subcentres are similar. Therefore, different notions of the term ‘subcentre’ are likely though not necessary.

7 Conclusions and prospects

The paper opened with a brief discussion of the most common methods of subcentre identification. All methods share one characteristic: they depend – to different extents – on the researchers’ interests, their qualitative understanding of a subcentre, and the way this understanding is operationalized into quantitative measures. Nevertheless, the literature review proved that qualitative understandings of subcentres are quite similar among researchers and regions. Their translation into quantitative measures, however, varies substantially and so does the methodology-induced interpretation of the identified results (cf. discussion of LWR vs. exploratory subcentres in subsection 6.1). Thus, one definition and subcentre identification procedure cannot usually be transferred 1:1 to another region. This finding is common knowledge for normative methods, such as thresholds. However, the same applies to statistical and theory-based approaches. Whereas normative approaches can be easily modified to obtain the desired result, exploratory and theory based methods are more robust but not parameter-invariant.

The application of a well-established and theory based approach proved to be not only generally unique and robust but also sensitive to modifications (see Figures 4 and 5). To better understand that sensitivity, several modifications were applied, which proved to be very informative, although the overall patterns remained similar (Figure 6). Considering both the non-uniqueness in the details of the LWR results and their global similarity, the relevant finding for further research is that the LWR is feasible for analysing urban spatial structure and identifying densifications in the spatial distribution of employees, and that it is prone to modifications such as window sizes or the distance any two subcentre candidates must be apart from each other. Its results, however, are still valuable. The highly flexible LWR approach provides an informative picture of a study region's urban spatial structure. Its weakness of being prone to model specification is counterbalanced by its flexibility and its ability to model entire study regions' patterns.

The content and knowledge-driven findings are that the spatial disparities in German city regions are substantial when comparing the core city area to its surroundings. However, the disparities excluding the core cities are small and reflected in the non-existence of global subcentres. The empirical results prove spatial densifications, but they are somewhat masked by both the CBD and an often fairly evenly distributed suburban employment distribution. This could be interpreted as a hint of edgeless cities in a Lang and LeFurgy-style, although these authors had in mind much larger regions than those analysed here (Lang and LeFurgy 2003, p. 436). Obviously polycentric structures and the existence of edge cities, which are characteristic for US metro regions, cannot be identified here. From the perspective of urban configuration, all study regions appear to be monocentric.

This finding is also in line with the analyses done by McMillen and Smith (2003), who numerically show that a city region's first subcentre emerges as soon as the city region's population exceeds about 2.7 million residents.[9] Using their notion of subcentres the Munich and Stuttgart regions are monocentric, that is, without any subcentre, whereas the regions of Cologne and Frankfurt are indeed polycentric with their subcentres being the 'non-largest' core cities. Given these results, core city dominance seems to better characterize the urban spatial structure than mono- or polycentricity or dispersion.

Furthermore, the empirical results obtained here are in line with other European studies' results (e.g., Bontje and Burdack 2005; Riguelle et al. 2007; Adolphson 2009). If polycentric patterns and subcentres exist, these are limited in their influence on the entire employment density surface. Thinking these issues further, future work could fruitfully concentrate on identifying subcentres by applying a LWR approach to consider the entire urban spatial structure, that is, to analyse whether not only subcentres but also 'anti-centres' exist, the latter having a negative influence on employment density. The existence of these anti-centres could lead to a more comprehensive understanding of spatial disparities, thus facilitating a more detailed analysis of the employment density distribution (and possible economic implications) in metro regions.

Apart from further, probably more detailed (sub-) centre identification procedures, future work could also focus on understanding the spatial patterns identified earlier. Questions such as 'Why do densifications exist at certain locations?', 'What is their main characteristic?', 'How are they related to the CBD and/or to other subcentres in the region?' are yet unresolved. Some of these issues are currently dealt with, whereas others are still waiting for consideration in empirical work.

The comparison between the city regions analysed here and those in selected US-American studies proved to be fairly complicated. Although qualitative similarities and differences could be touched upon, the discussion is far from a systematic, context-sensitive comparison. An interesting issue would have been to quantitatively compare the identified subcentres' endowments with residents and employees both in Germany and in the US. Unfortunately, the necessary information is not provided in the study by McMillen (2001) and re-doing his analyses here was not feasible and would also have been beyond this paper's scope. However, it would be interesting for future research, not only from a content-oriented point of view but also regarding the challenges and prospects of comparative urban research: analyses often suggest that German city regions' spatial development tends to follow that of US metro regions (e.g., Richardson and Bae 2004; Gordon and

[9] This number is sensitive to the definition and numerical estimation of traffic congestion. If congestion is higher, subcentres emerge at lower numbers of residents.

Cox 2012) and persistent core city dominance can be identified in both German and US metro areas (cf. Redfearn 2009 for the US). What is still somewhat missing is a quantitative and cross-national comparative study of the subcentring in several urban regions that is based on: (*i*) the same spatial scale and delineation of study regions; (*ii*) the same data and (*iii*) the same methodological framework.

A similar strand of future research could be to apply the LWR not only to cross-sectional data but also to panel data, which would facilitate the monitoring of city regions. Issues could be the extent of spatial and socioeconomic dynamics regarding the emergence and development of subcentres. Another interesting aspect would be the convergence and divergence of urban spatial structure in the US and in Germany. Systematically discussing these processes could provide the basis for a quantitative debate on whether there is currently an 'Americanization' process: an increase in deconcentration and dispersion of economic activity in space and its reflection in the urban form of German city regions.

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A Comprehensive View on Urban Spatial Structure: Urban Density Patterns of German City Regions

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Abstract: Urban density must be considered a key concept in the description of a city's urban spatial structure. Countless studies have provided evidence of a close relationship between built density and activity densities, on the one hand, and urban environmental conditions or social practices, on the other hand. However, despite the concept's common use in urban research, urban density is a rather fuzzy and highly complex concept that is accompanied by a confusing variety of indicators and measurement approaches. To date, an internationally-accepted standard for the implementation of density indicators that permits a robust comparison of different countries, regions or cities is widely missing. This paper discusses the analytical opportunities that recent remote sensing data offer in regard to an objective and transparent measurement of built density patterns of city regions. It furthermore clarifies the interrelations between built and activity densities. We apply our approach to four German city regions to demonstrate the analytical capacity of spatially-refined density indicators for the purposes of comparative urban research at a regional scale. In so doing, we contribute to a more encompassing and robust understanding of the urban density concept when analyzing regional morphology.

Keywords: urban spatial structure; remote sensing; density measures; built density; floor area ratio; built-up volume; land use metrics; city region; Germany

1. Introduction

In urban research and planning, the spatial densification of human activities and their physical manifestation as built density are key factors in describing the form and structure of the built environment [1–5]. The density of built structures is a precondition for the spatial proximity of individuals and actors—residents, employees, inventors, entrepreneurs or creative people—and proximity in turn has a complex influence on urban behavioral patterns and processes of economic and social interaction.

In recent years, great progress has been made in better understanding the relationships between the built structures of urban areas and the variegated socioeconomic processes. Research into this topic has taken place within a wide variety of scientific disciplines. Numerous empirical studies in the fields of urban planning and transportation have been able to demonstrate close relationships between built density and corresponding activity densities (such as population or job densities), on the one hand, and individual mobility behavior, on the other hand [6–10]. With an increase in the built density of a city, the number of trips that are made on foot, by bicycle or public transportation increases, as the average trip distance decreases and the quality of transit services increases, everything else being equal [2,7,11,12]. Furthermore, the greater degree of physical activity in denser urban neighborhoods in comparison to suburban areas with lower densities has positive effects on the health of a population [13–15]. The positive relationship between built density and energy consumption that has already been demonstrated for mobility also applies to the construction sector. Here, studies have shown that the demand of energy for heating and cooling purposes in large-volume buildings is lower than in smaller buildings owing to a more favorable surface-to-volume ratio [16,17].

Economic sciences have also addressed the impact of the size and density of urban areas in recent years. Studies in this field emphasize the topic's relevance for the prosperity and innovation capacity of economic systems [2,18–23]. Empirical studies have been able to show that higher densities facilitate the exchange of ideas and knowledge between individuals and firms. Density creates positive returns to scale, and it is exactly this reason why knowledge-intensive business services, which are especially dependent on spatial proximity and knowledge spillovers, can particularly be found in urban centers [24–27]. However, these returns to scale are not just applicable to spatial proximity and the corresponding advantages in labor market economics: it can also be stated that specific costs for the provision of infrastructure services decrease when demand density increases, since high capital expenditures, particularly those related to technical infrastructure, can be allocated to a greater number of users (see [28] (p. 6 *et seqq.*) with further references [29,30]).

Meanwhile, high densities also carry disadvantages, as they might be accompanied by high rent and property prices, transportation system congestion [27,31,32], low air quality and a discomforting urban microclimate [33,34]. For instance, the vulnerability of dense urban areas regarding summer heat waves and the health risks related to this are significantly higher than in suburban or rural settlement areas [35]. Historically, high densities were also critically examined from a military perspective and for reasons of social hygiene. The often extreme population densities that were evident during times of industrialization (and that are still present today in the metropolises of the Global South) are considered to be partially responsible for the emergence and spread of epidemics and other diseases [36,37].

Against this backdrop, it must be surprising that, despite the remarkable significance attributed to the density of a city or city region as an explanation for environmental conditions, social practices and economic relationships, few empirical studies of urban and regional density patterns exist [38–41]. Compared to other measures of the built form of cities—for instance, the "concentration" and "mixture" of urban functions or the "compactness" of the physical settlement area—built density appears at first glance to be a simple, objective, easily understood and manageable measure. Upon closer inspection, however, it is clear that a simple empirical approach alone fails to fully embrace the concept [36]. In this regard, Churchman pointed out at the end of the 1990s that no internationally-recognized measure of built density existed to date and that indicators of built density for various countries, regions and cities are generally not comparable (or only comparable to a limited extent) if they come from different sources [3] (p. 390). This assessment is still true today.

The empirical study of the density of a city or city region is fraught with challenges that are, on the one hand, conceptual, but can, on the other hand, also be explained by restrictions to the availability of basic data (see Section 2 for a more detailed discussion). In this way, the validity and interpretability of density indicators often suffer from a lack or an unclear definition of a spatial relationship ([8], p. 3). Frequently, it is also not clear whether density should be interpreted as a gross or net value, since it is not obvious which types of area (plot area, public spaces or the total settlement areas) have been considered in the density calculation. Rather practical problems emerge in the analysis of density values, as the necessary data are not always available [16]. This especially concerns the assessment of built densities at the level of built-up properties, blocks or neighborhoods. However, population or job densities can also not always be determined with the desired spatial resolution, since the availability of demographic and employment data at the sub-municipal level is often limited; see also [24].

In this context, the extensive and increasingly affordable availability of remote sensing data, with which not only land use, but also the height of built structures can be modeled, offers entirely new opportunities. Large-scale volume calculations can be made, from which density measures, such as the floor area ratio, can be derived. Further benefits ensue as a result of: (i) the objectivity of the density calculation, since building heights and volumes can be reliably determined; (ii) the high spatial resolution of the data and the possibility to aggregate them at will into spatial reference systems (such as ring zones or grid cells) that are independent of local administrative units; (iii) the extensive availability at comparatively moderate costs; and (iv) the ability to easily link data with demographic and socioeconomic data at the sub-municipal level.

Consequently, in recent years, an increasing number of studies have used remote sensing data or respective derivate products to approach the concept of urban density. Most of these studies have addressed two-dimensional settlement densities as proxies for the analysis of the spatial configuration of built structures [42–45]. The latest developments, however, allow for morphologic density analyses using 3D city models, while overcoming the restriction of limited area coverage [46,47].

This article addresses the analytical opportunities of new geodata in determining the multifaceted density patterns of urban areas. These issues are pursued by elaborating three main objectives:

1. To present a novel method for a region-wide detection of built densities.
2. To demonstrate the practical feasibility of our approach based on four German city regions. In doing so, we illustrate the analytical capacity of fine-grained spatial density data for the characterization of urban spatial structure.
3. To shed light on the interrelations between built and activity densities.

With the methodological approach introduced here, it is, for the first time, possible to conduct a region-wide, detailed analysis of the urban spatial structure that also considers built densities. Previous studies in this field only illustrate urban morphology in a two-dimensional space using socioeconomic and land use data, whereas our approach achieves a higher level of analytic depth. In this way, the relationship between socioeconomic processes and built physical structures can also be examined more closely. Thus, this paper supports a more encompassing and robust understanding of the urban density concept and its variegated applications in urban research and planning practice.

The remainder is organized as follows: After a short discussion of the scientific background of the topic (Section 2), we introduce our methodological approach to generating high-resolution density data. We then address in detail the analysis of fine-grained geospatial basic data using Earth observation methods (Section 3). The aim of this is to create a comprehensive image of the morphology of a city region. In Sections 4 and 5 we illustrate and discuss this using the examples of four case study regions (Frankfurt/Main, Cologne, Munich and Stuttgart). This article concludes with a short summary regarding potential explanatory factors of urban density patterns (such as topography, urbanization history or economic structures) and future applications of spatially-differentiated density data (Section 6).

2. Conceptualization of Built Density

The discussion surrounding the "appropriate" density of a city is perhaps as old as the discipline of urban planning itself, and it can certainly be seen as one of the most controversial issues within this field. "Density" is a distinct interdisciplinary concept [48], whose significance has always been prone to change over time. It is indisputable that the perception and valuation of density is largely subject to cultural and social values (e.g., [5] (p. 6), [36] (p. 2)). An objective benchmark that can classify built or use-related densities into "high" and "low" or "good" and "bad" labels does not exist.

Dealing with the concept of density is, however, not only challenging from a normative urban planning perspective: the objective measurement of urban density is also subject to various restrictions. It is indisputable that density represents a measure of the relation of objects (which can include, among others, residents, buildings, dwellings or jobs) and a reference area upon which these objects are located. Density is expressed by using a fraction in which the number of objects is the numerator and the size of the reference area is the denominator. A general distinction can be made between built densities and use or activity densities: built densities are related to the ratio of built structures (such as the number of buildings, floor space or the number of dwelling units) to a reference area, while activity densities express the intensity of human use on built-up areas. The former are of a rather static nature, since built structures, at least in a larger spatial context, only change very slowly. In contrast, activity densities are subject to constant change, as they are underpinned by dynamic, often discontinuous, demographic and socioeconomic processes. Table 1 provides an overview of the urban density indicators that are frequently found in research and planning practice.

Table 1. Urban density indicators and their meanings.

Indicator	Scale	Meaning/Measurement	Included Land Resources
Metropolitan density	Region	People, jobs or dwelling units per land area unit	Administrative area
Urban (residential) density	City, city district	People, jobs or dwelling units per land area unit	Urbanized area
Gross residential density	Neighborhood, urban block	People or dwelling units per land area unit	Residential area (including streets, pavements, local community services and public open spaces)
Net residential density	Neighborhood, urban block	People or dwelling units per land area unit	Residential area (not including streets, local community services public open spaces)
Site density	Plot, property	Dwelling units per land area unit; floor area per land area unit	Single plot, property
Occupation density	Dwelling unit	People per dwelling unit	Single dwelling unit
(Source: own compilation based on information and definitions provided in [3,41])			

Beyond this general understanding, however, the measurement of built densities poses a couple of empirical problems that are positively correlated with the spatial level of the respective observation. Especially the property, block or neighborhood levels frequently lack precise and up-to-date density values. The reason for this is that data at the property or block level are usually not covered by official statistical surveys (such as censuses). Studies based on one's own data collection (e.g., using site visits) or private geodatabases are of limited use owing either to their complexity or to the lack of transparency in the data. Until now, density studies have mostly been carried out in the form of individual municipal analyses or collections of case studies [41,49] whose results are often only comparable in a limited way with other municipalities or territorial units. These challenges potentiate themselves when attempting to conduct international comparative density analyses.

The modeling of urban density surfaces and structures therefore suffers in particular from a low degree of spatial granularity. This not only has negative effects on planning practice (e.g., in the modeling of noise pollution or climate vulnerability), but also interferes with urban and spatial research. The significance of built density as a factor in explaining the spatial variance of particular phenomena, such as modal split or infrastructure costs, places high demands on the quality of available data. In many studies, however, simple activity density measures (such as gross population density) must be applied, since more precise structural density indicators are unavailable. Such restrictions greatly limit the performance of descriptive and explanatory research.

Built density can be determined in a number of ways as Table 1 demonstrated. Frequently, corresponding indicators address the relationship between a building's floor space or volume to the plot area. Here, a standard indicator is the floor area ratio (FAR; also referred to as the floor area density or floor-space index) [3,5,46]. It is commonly defined as the amount of floor space of building divided by that building's plot area. Still, determining the floor area ratio is a complex task, since official surveys of building metrics (e.g., floor number, volume or height data) are typically not available. While many studies do provide ranges for built density figures at the level of selected building and development types (e.g., the FAR; *cf.* [41]), the results of such studies are often not comparable, since various definitions of density are applied or the approaches to data collection differ.

This directs our focus to a second, rather conceptual, problem: the use of density indicators often suffers from an imprecise definition of the reference area [41]. In this regard, it is not always clear whether the entire surface area of a territorial unit or only the area that is being occupied by a certain use (e.g., residential) has been considered in the calculation. In such cases, it often remains unclear whether figures are to be interpreted as gross or net densities. In net density calculations, the number of countable objects is related to the relevant useable area (e.g., the number of residents to residentially-used plots). Other land uses, such as roads and sidewalks or public green spaces, are not taken into consideration. Net density calculations provide information about the "reality" of densification in a much more appropriate way, since they are less dependent on a spatial definition of the study area. The so-called "modifiable areal unit problem" [50], when the aggregated measurement results of spatial phenomena vary with the size of the basic study area, can be alleviated by applying net density values. However, most density studies that can be found in the literature offer gross density values.

The remainder of this article presents methods for determining and describing the density characteristics of cities and city regions at a high spatial resolution and using new kinds of data from remote sensing, as well as population and employment statistics.

3. Measuring Built Density

3.1. Remote Sensing-Based Measurement of Built-Up Volume and the Number of Floors

Recent developments in Earth observation allow satellite-based remote sensing technology to derive large-area information on urban features with a well-balanced trade-off between cost-effectiveness and accuracy. Today, a broad range of imaging sensors and methods for the determination of geometrically high-resolution measurements of the urban spatial structure exists. Three-dimensional (3D) data, which include information about height, are decisive in the extraction of information on the physical urban morphology. Height can be determined either by using stereoscopic aerial images or airborne laser scanning and, more recently, by satellite-based stereo images. The main difference between aerial and space-borne data acquisition is that airborne imaging is, on the one hand, less flexible in terms of spatial coverage and can be rather cost-intensive for large areas, but its geometric resolution, on the other hand, can be as fine as a few centimeters. Greater flexibility is provided by new satellite-based stereoscopic measurements, such as QuickBird, WorldView-2 or Pléiades, which are also capable of deriving geometrically very high-resolution stereo models. However, the same disadvantage of spatial limitation in the context of large-area acquisitions also applies to these data. For the desired height information in our analysis, both of these data sources were ruled out beforehand because we aim at comparing four different city regions with a total area of about 14,000 km^2, which is larger than the entire Los Angeles metropolitan area.

To overcome the restrictions in terms of imaged area and degree of detail, in the current analysis, we used stereo images acquired by the Indian Remote Sensing Satellite (IRS), which employs the Cartosat-1 stereo sensor on board. This sensor (IRS-P5) has the advantage that images are almost constantly acquired all over the world, as it was specifically designed for large-scale and large-area stereo mapping and the generation of digital surface models (DSM). The acquired stereo images cover a swath of 27 km and at a pixel spacing of 2.5 m, which can be exploited to generate DSMs with 5-m spacing [51,52]. Since the launch of Cartosat-1 in May 2005, large parts of the Earth have been mapped, including a coverage of Europe. In light of these characteristics, Cartosat-1 meets both the spatial and the geometric requirements for an area-wide and cost-effective derivation of height information from various large urban regions. The geometric accuracy of Cartosat-1 height measurements in the context of urban analysis at the spatial level of individual buildings has been analyzed in a few studies and demonstrated to be between a 3- and a 3.5-m standard deviation [47,53]. For an overview of the steps performed in modelling built density, please refer to Figure 1. This figure summarizes the steps performed in building modelling using Cartosat-1 stereo images and building footprints for the generation of 3D building models and ancillary data, such as INSPIRE (Infrastructure for Spatial Information in the European Community) grid geometries and land use data from the Basis DLM, to derive the desired built density.

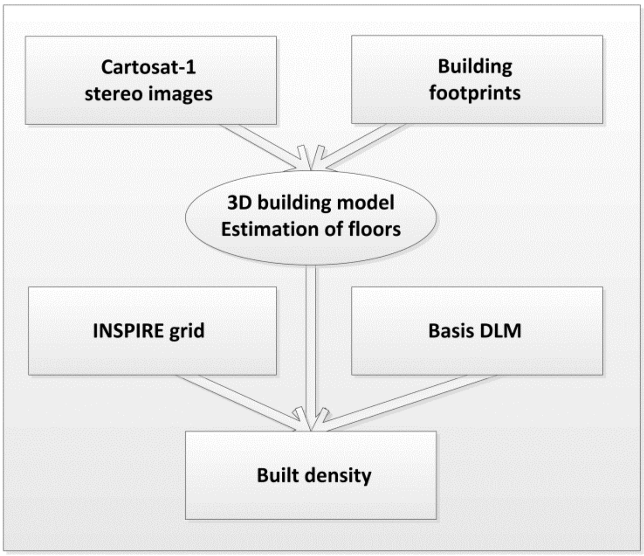

Figure 1. Flowchart of the steps performed for modeling the built densities.

In the process of modeling built-up volume for the four city regions, 3D building models were generated using Cartosat-1 DSMs. These were derived by applying an adapted semi-global matching procedure (see [54]) from a total of 129 Cartosat-1 stereo pairs over all four city regions at a pixel spacing of 5 m with a mean error of less than 0.5 m. The DSM was normalized (nDSM) using a reference digital terrain model. Then, the building models were generated by combining nDSM heights with building footprints, which were extracted from digital topographic maps at a scale of 1:25,000. By doing this, we obtained a mapping of individual building footprints that were merged with height data from Cartosat-1 in the subsequent step (see Figures 2 and 3). A detailed description of the method for DSM generation and building modeling is described in [47].

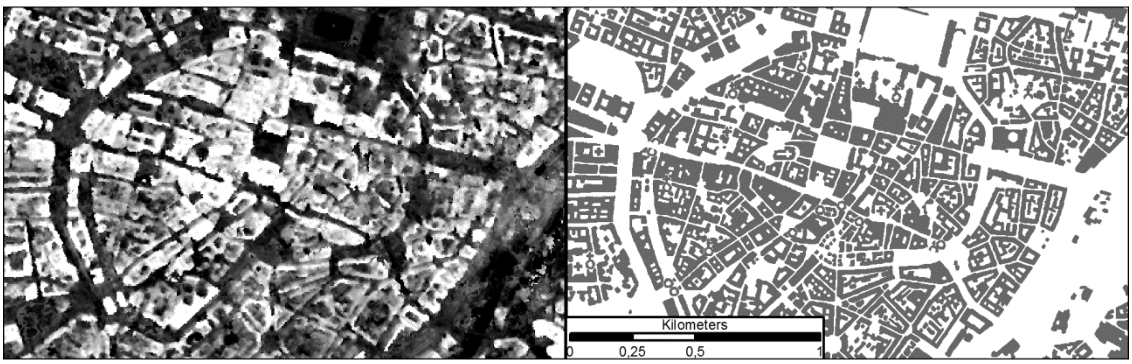

Figure 2. Spatial data input for the generation of the 3D building models using the example of the center of the Munich city region; left: normalized digital surface model; right: extracted building footprint objects from the topographic map DTK25-V. Topographic map: © GeoBasis-DE/BKG (2010), cf. [55].

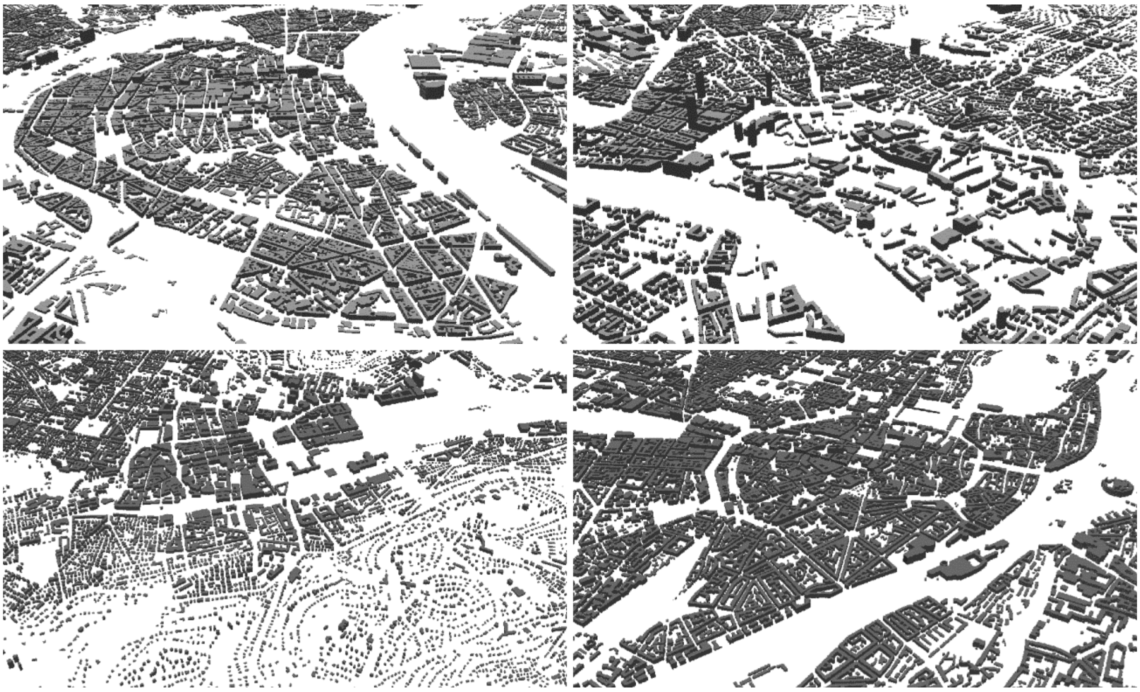

Figure 3. Perspective view of 3D building models derived from space-borne Cartosat-1 height measurements and building footprints from digital topographic maps (top left: Cologne; top right: Frankfurt; bottom left: Stuttgart; bottom right: Munich). Topographic map: © GeoBasis-DE/BKG (2010), cf. [55].

In a further step, the large-area 3D building models at the Level of Detail 1 (LoD1) were generated using a combination of the building footprints and height values from the nDSM. LoD1 means that each building is represented by a single building height. A perspective view of the 3D building models of the historic centers of the four city regions is depicted in Figure 3.

In a thorough performance evaluation analysis of official cadastral reference data, the generated 3D building models were checked for their accuracy and geometric detail [47]. The results of the study report that, due to generalization procedures in the production process of the map, individual building footprints may be larger than the reference buildings. This effect especially accounts for smaller buildings with footprints of less than 300 m^2 whose areal deviation is comparatively much larger than that of larger buildings. An overall agreement of a kappa value of 0.71 could be observed in the study. Cohen's kappa coefficient κ is a measure used for the evaluation of accuracy. The kappa statistic incorporates the off-diagonal elements of the error matrix; in other words, omission and commission errors are included. The value of κ shows the randomness of the results, meaning $\kappa = 0$ denotes complete statistical randomness, while $\kappa = 1$ indicates perfect positive statistical connectivity [56].

Regarding the accuracy of building height, the study reports the following outcomes: first, an overall agreement between the modeled building heights and the reference data shows a standard deviation of 3.67 m and a mean absolute error of 3.21 m at the spatial level of individual buildings. In a structured analysis, no significant correlation between the building footprint area and the accuracy of the building height could be observed, apart from buildings with very small areas (less than 300 m^2; see Figure 4).

A second experiment reveals correlations between accuracy and building height. This means that the deviations between the modeled heights and the reference data can be observed alongside increasing building heights. The metric error tends to be smaller for low-rise buildings (around a 2-m standard deviation for buildings with a height of less than 6 m) and rises with increasing building heights: up to a 5-m standard deviation for buildings with a height of 20 m. Thus, the observed error in the building model is also higher for taller buildings. This effect can be explained by the acquisition geometries of the stereo images and can be overcome either by using more stereo images that provide better stereo angles or by applying linear correction models. The latter can be used to correct the models, since the correlation of height errors is a linear function of a building's height. The same effect applies for the derived built-up volume, which is calculated at the spatial level of buildings. In the present analysis, these effects are of minor importance, since all buildings are affected in the same way. Thus, from a relative perspective, the building heights and therefore also the built-up volume can be compared between the four city regions. However, attention has to be paid when the derived volumes and floor area ratios are compared to "real-world" reference values, since experiments have demonstrated that volumes and floor area ratios tend to be slightly underestimated. It is observed that a general underestimation of 3–4 m applies for the derived building models.

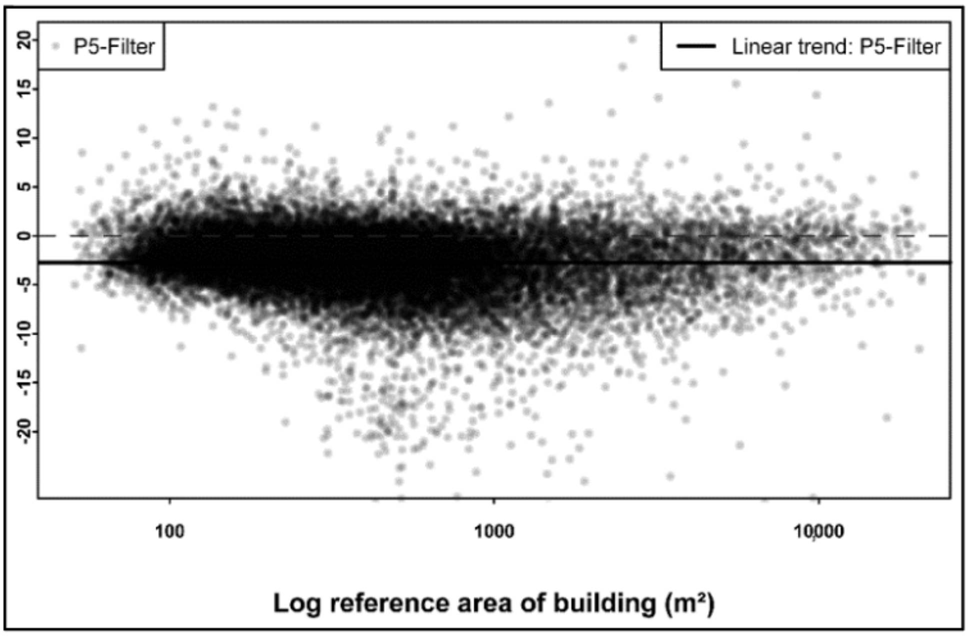

Figure 4. Correlation between building area and the deviation of building height against the reference data.

To quantify the quality of the derived built-up volume on the spatial level of grid cells, a third evaluation exercise has been performed. Comparisons with the reference building model are in line with the observations from the prior accuracy assessments on the building level: since the estimated building heights are lower than the reference building heights, built-up volume on the grid cell level deviates relatively by approximately 10% with higher deviations for lower built-up volumes.

Our 3D building models permit the measurement of built-up volume at the level of individual buildings. While built-up volume can be seen as an easily understandable measure, its dimensions are difficult to compare. Thus, in urban planning and the analysis of the urban spatial structure, the FAR is a well-established and widely-accepted measure of urban density (see Section 2). However, the calculation of the FAR requires information on or an estimation of the number of floors [38,57,58]. Therefore, the number of floors is modeled based on building height. In this way, we use empirically-estimated quantitative relationships between the building height and the number of floors applied in prior studies to establish a function of floors and height [47,59]. The accuracy of the relationship between the building height and the number of floors has proven to be accurate for 60% of buildings at an error of zero floors. If an error of one floor is acceptable (due to varying definitions of floors regarding roofs), the exact number of floors can even be derived for 90% of all buildings [46,59].

Based on the 3D building model, built-up volume and floor area are separately calculated for each individual building as the product of the building's footprint, height and number of floors.

3.2. Derivation of Urban Density per Grid Cell: Built-Up Volume and FAR

The aforementioned 3D building model including the estimated number of floors represents the number of elements per spatial unit in the density calculation. The spatial unit can be chosen from manifold options, such as plots or urban blocks, which are widely used in research studies and practical urban development applications. However, these units can be too small in terms of data availability for the integration of ancillary socioeconomic data, such as population sizes or the number of employees (see Section 2), and therefore implicate shortcomings in the spatial transferability of the proposed approach. Thus, we calculate the FAR at the spatial level of regular cells of the INSPIRE grid [60], which is a standardized dataset containing grid cells covering the countries of the European Union (EU27). Thus, for the derivation of urban densities, we related built-up volume and floor area from the derived building block models to the 1 × 1-km grid cells as a reference plane.

The derived urban density value (the FAR) represents a net density, implying that the reference area, that is, each grid cell, is reduced to its built-up area (in contrast to gross density, where the entire grid area represents the reference area). In this way, vegetation areas and land used for transportation are excluded from the 1-km^2 grid cells, resulting in varying reference areas for the calculation of the FAR. Thus, only "areas dominated by buildings" per grid cell are used for the calculation of the FAR. These areas are integrated from the German digital landscape model (DLM), which is provided by the Federal Agency for Cartography and Geodesy [61]. In this way, the built-up volume per INSPIRE grid cell results from the cumulative building volumes in all "areas dominated by buildings" within the particular INSPIRE grid cell. The FAR is calculated as the sum of the total floor area divided by the total built-up area as outlined by the DLM within an INSPIRE grid cell. For buildings that are crossed by the border of one or more grid cells, only the volume of the respective part of the building is taken into account. A graphical depiction of the calculation of built-up volume and FAR is presented in Figure 5 below.

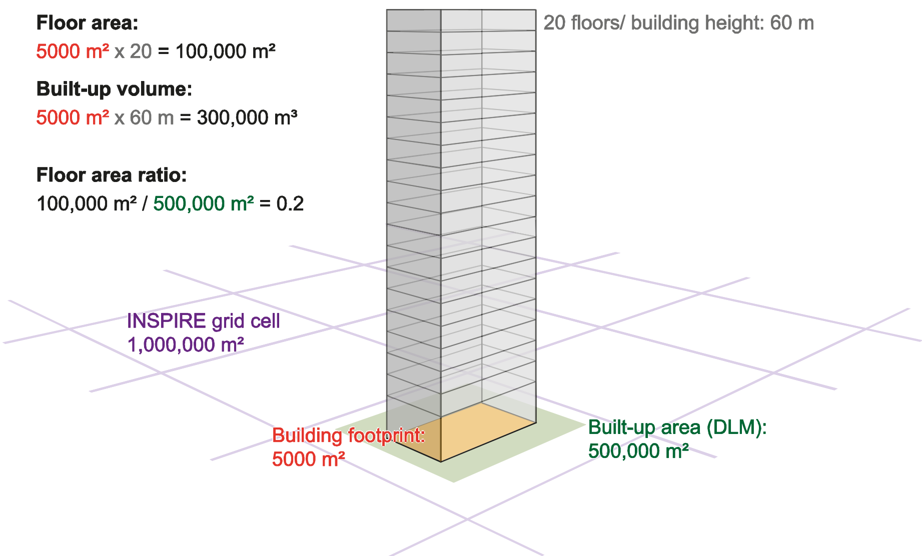

Figure 5. Calculation of built-up volume and FAR per INSPIRE grid cell.

4. Patterns of Built Densities and Their Relation to Activity Densities

As already mentioned in the Introduction (Section 1), the methodological approach introduced here permits a region-wide, detailed analysis of urban spatial structure that also considers built densities. We thus achieve a higher level of analytic depth than previous studies and examine the relationship between socioeconomic processes and built physical structures more closely. The following discussion provides a more detailed picture of this relationship using a comparison of four German city regions. At the same time, it highlights both the complex concept of urban density and the prospects of still providing inter-regionally comparative measure of the same.

Table 2 provides an overview of the central parameters of urban spatial structure in these regions. All regions can be classified as highly urbanized, as evidenced by the above-average population density (the average value in Germany is just under 230 residents per km^2). We estimate the total regional built stock to have values of around 660 million m^3 (Stuttgart region) and 1160 million m^3 (Cologne region) built-up volume and 216 million m^2 (Stuttgart region) and 374 million m^2 (Cologne region) of floor area. The values for both of the other urban regions, Munich and Frankfurt, score between these figures.

Table 2. Overview of spatial indicators.

Indicator	City Region			
	Cologne	Frankfurt	Munich	Stuttgart
Area (km^2)	2812	4843	3277	2842
Population (million residents)	2.81	3.57	2.43	2.40
Employment (million jobs)	0.99	1.46	1.09	0.96
Built-up area (km^2)	623	807	535	505
Built-up volume (million m^3)	1159	1029	942	659
Floor area (km^2)	374	335	328	216
Population density (people per km^2)	1000	736	742	845
Mean floor area ratio (FAR)	0.60	0.41	0.61	0.43
Floor area per resident and job (m^2)	99	67	93	64
Built-up volume per resident and job (m^3)	305	205	268	197

Employment data are taken from the Federal Employment Agency, "Beschäftigungsstatistik, Sozialversicherungspflichtig Beschäftigte nach Wohn- und Arbeitsort mit Pendlerdaten, Nürnberg, Stichtag 30. Juni 2010" [62]; population data are data on the spatial level of municipalities as of 31 December 2010, taken from "Statistische Ämter des Bundes und der Länder", version as of 2013; and called "Bevölkerungsstand: Bevölkerung nach Geschlecht, Stichtag 31.12. regionale Tiefe: Gemeinden, Samt-/Verbandsgemeinden" [63] Both employees and residents have been summarized into the regional delineations used in this study.

These global values already display surprisingly clear differences in built density, which cannot be explained by regional population and employment figures alone. This becomes apparent when considering the average FAR, which was calculated by dividing the total floor area by the total built-up area of the regions (see Section 3.2). While values of around 0.6 were obtained for the rather monocentrically characterized regions of Munich and Cologne, the average built density in Frankfurt and Stuttgart is significantly lower, scoring values of just over 0.4.

The complexity of the relationships between socioeconomic characteristics and the built environment also becomes apparent when considering the intensity of the use of the urbanized area. This relationship is addressed here by relating the number of residents and jobs to a certain floor area (→ floor area per resident and job) and built-up volume (→ built-up volume per resident and job) (Table 2). The larger the floor area or built-up volume per resident and job, the lower is the intensity of use. While it can generally be assumed that density increases alongside the size of a region, density is apparently also influenced by regionally- and locally-effective factors, such as topography, economic structure, prosperity level or urban and regional planning. We discuss these relationships in greater detail in the following paragraphs.

Our results show that the regions of Cologne and Munich have the highest built densities among all regions included (considering the average FAR values), while the intensity of use in the regions of Frankfurt and Stuttgart is noticeably higher. This finding can possibly be explained by the different land use efficiency of certain economic sectors. Furthermore, varying levels of infrastructural provision in regional centers, such as trade fairs and event and congress centers, could also account for this finding. Such services mostly encompass large-volume building complexes.

An analysis of our data at the spatial level of grid cells furthermore indicates that the density distribution has an upwards bias in all regions owing to extremely high values in a few spatial units. The following box plots illustrate this issue, considering the fact that the vast majority of grid cells have very low FAR and built-up volume values. When regarding standardized values, it becomes apparent that the median value is in part distinctly lower than the mean value. This also hints at the upwardly-biased distribution owing to outliers. The median built-up volume in all regions is lower than 0.1 million m^3, while the FAR is under 0.3. In contrast, central locations display values that sometimes reach over 5 million m^3 per km^2 of reference area or FAR values of over 4.0.

These box plot results indicate that extreme disparities exist in all study regions. Comparing the left and right columns in Figure 6 supports this finding. Omitting the outliers, that is all grid cells with built-up volume (upper row) or FAR (lower row) values greater than 1.5-times the inter-quartile range, shows that the remaining grid cells are built at a much lower density and land use intensity. However, nothing is revealed regarding the outliers' spatial location. Therefore, characterizing the regions as monocentric or polycentric is not feasible using this kind of information alone.

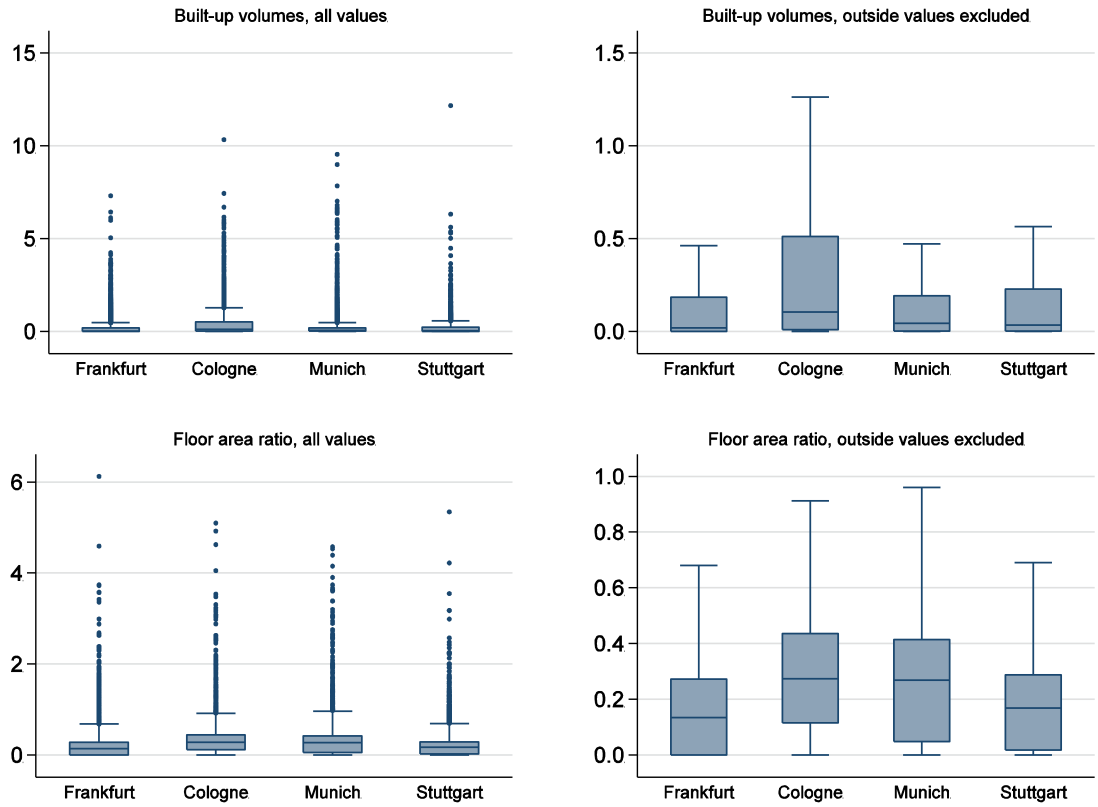

Figure 6. Box plots of built-up volumes (million m^3) and floor area ratios.

Figure 6 also suggests that the data are log-normally distributed. However, log-transforming the data is not helpful here, as it considerably narrows the data's range. The logs also cause differences between consecutive values to diminish as the values grow larger. Thus, disparities are not as prominent in logs as they are in levels. On the one hand, this "leveling-out" is what is intended when doing such a transformation. On the other hand, this transformation eliminates much of the variability in the data that we actually need to characterize the density patterns: for that, we use the levels instead of the logs.

Having these results in mind, Figure 7 provides further insight into this by illustrating the built-up volumes and the average FAR of the four study regions at the spatial level of grid cells (1 km^2). Clearly recognizable are the different basic settlement patterns in the regions. For instance, the axial structure of the Stuttgart region stands in clear contrast to the monocentric Munich region. The latter is characterized by a strongly densified core, while in bands of density, the Stuttgart region can be observed stretching from the inner city along the regional rail corridors into the hinterland. By way of contrast, the Frankfurt region is characterized by a rather polycentric and dispersed land use pattern, evident in the concentration of high built-up volume in the inner cities of the four core cities (Frankfurt, Darmstadt, Mainz and Wiesbaden). Upon closer observation, however, it becomes apparent that extremely high built-up volume of over 5 million m^3 per km^2 can only be encountered in the inner city of Frankfurt. The other three core cities of this polycentric region display consistently lower built-up volumes.

These analyses are supported by Krehl [24], who calculated global and local indicators of spatial association for selected variables of activity and built density. It can be shown that the global Moran's I values are positive and statistically significant below the 5% significance level, indicating positive spatial autocorrelation, *i.e.*, a spatially-concentrated urban pattern, in all study regions. The corresponding local Moran's I values support the polycentric notion of the Frankfurt and Stuttgart region, respectively.

It also becomes apparent that all regions are characterized by a significant core-periphery gradient in built density. Even the core cities' fringes (not to be confused with the regions' periphery) are characterized by rather low-density urban areas, whose FARs are mostly below a value of 0.5. Here, predominantly low-density commercial uses and residential areas with detached single-family homes can be observed. However, the spatial extent of the dense core areas of the regions varies markedly. In Munich and Cologne, a larger, more compact urban core is visible, while the dense inner cities of Frankfurt and especially Stuttgart give way to lower-density construction within a few kilometers (see also Figure 8 or [64] for further insights into this). Thus, the diverse density structures within each of the four city regions considered here can also be explained by the varying spatial extent of the compact regional core (see also [24]).

Figure 8 stresses this using an east-west cross-section through each region. It illustrates the built-up volumes (left scale) and the average FAR (right scale) of those grid cells that are located on the same latitude as the grid cell of each regional center. These figures are related to the distance from the center in both eastern and western direction (recorded on the x-axis). Similar results have been obtained by Siedentop *et al.* [65] (p. 185) for a similar dataset. These authors considered the average floor area ratio in rings of 0–2, 2–5 and 5–10 km around the central business district. While these average rings shed light on a rather "smoothed" urban density surface, the analyses in Figure 8 (below) shed light on the density surface of a selected cross-section within each region. These patterns certainly cannot be generalized to the entire urban spatial structure. Sensitivity analyses, however, have shown that they provide a robust picture. Additionally, the qualitative findings of Siedentop *et al.* [65] and the analyses presented here are complementary to each other.

In the rather monocentric regions of Munich and Cologne, the highly densified area along the east-west plane extends across approximately ten kilometers, while this area only reaches across seven to eight kilometers in the Frankfurt region and only two to three kilometers in the Stuttgart region. Accordingly, the defined regional core is indeed relevant in the polycentric regions and displays comparable built-up volume and floor area ratios, but its spatial extent is markedly smaller than in monocentric regions. While the monocentric regions display a spatially-expansive core, (sub)urban settlement patterns are already apparent within a radial distance of about five to ten kilometers from the center in both rather polycentric regions. These (sub)urban settlement patterns include both peripheral urban settlement areas and, somewhat further away, the historic inner cities of mid-sized regional centers (see also Figure 7).

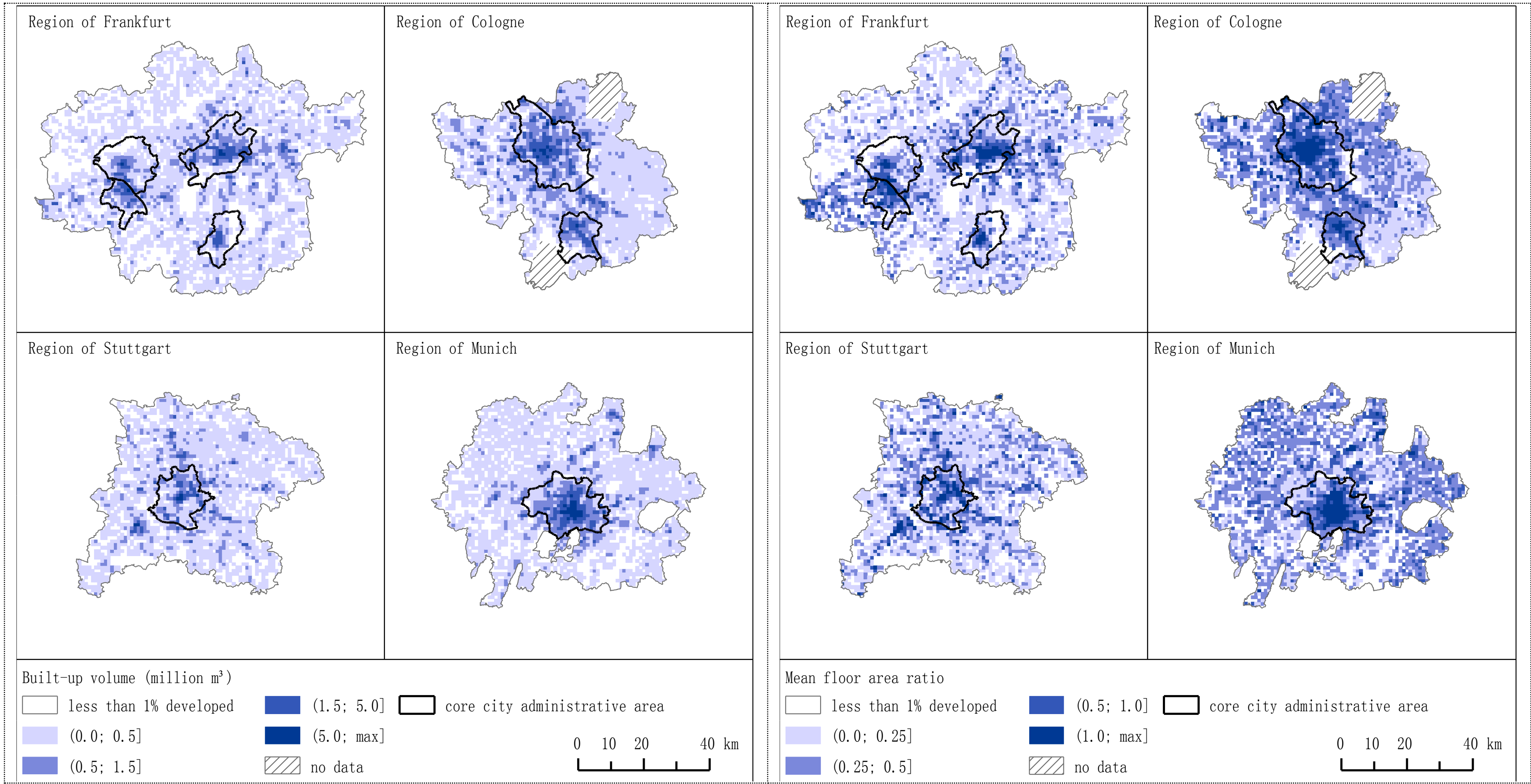

Figure 7. Patterns of built densities represented by built-up volume (**left**) and mean floor area ratio (**right**) for 1-km^2 grid cells.

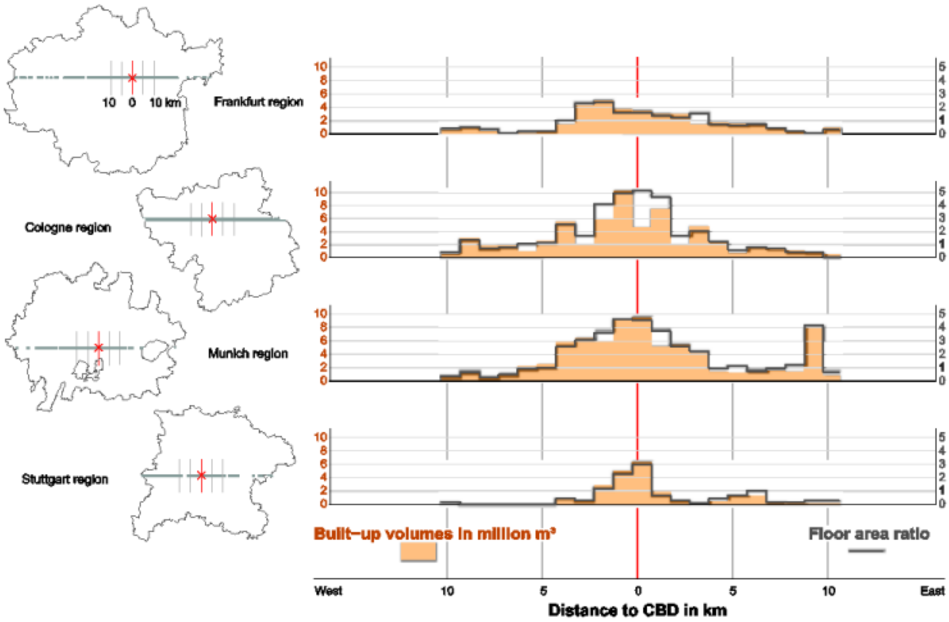

Figure 8. Selected density profiles of the case study regions; built-up volume and floor area ratio values for the grid cells located along the respective core city's latitude, the latter indicated by the town hall's geographic location.

Finally, our comprehensive dataset also permits an analysis of the relationship between urban morphology and the distribution of socioeconomic activity. To briefly exploit this and also gain deeper insight into the relation between the two map series in Figure 7, we calculated Spearman's rank correlation coefficients between the FAR, built-up volume and the number of employees and residents per grid cell. These variables are complemented by two further variables: the average floor space per building and the number of buildings per grid cell. Our *a priori* expectation is that the five variables should be highly and positively correlated on a region-wide average. This expectation is supported by the results displayed in Table 3. All rank correlations are statistically significant below the 0.1% significance level and are also positive.

Table 3. Spearman's rank correlation coefficients for several density measures.

	City Region			
	Cologne	**Frankfurt**	**Munich**	**Stuttgart**
	Floor area ratio (FAR)			
Average floor space per building	0.69	0.61	0.62	0.55
Built-up volume	0.70	0.66	0.53	0.66
Number of buildings	0.41	0.39	0.30	0.38
Number of residents and employees	0.43	0.38	0.33	0.38
	Number of residents and employees			
Floor area ratio (FAR)	0.43	0.38	0.33	0.38
Average floor space per building	0.27	/	/	−0.06
Built-up volume	0.82	0.83	0.88	0.86
Number of buildings	0.90	0.92	0.95	0.95

Employment data are taken from georeferenced Integrated Employment Biographies (georeferenced IEB) as of 30 June 2009, which are provided by the Research Data Centre (FDZ) of the Federal Employment Agency (BA) at the Institute for Employment Research (IAB) (for details and documentation, see [66]); population data as of 2011, provided by Eurostat [67].

The correlations between the FAR and the buildings' average floor space score higher values (0.55–0.69) than the correlations between the FAR and the number of buildings (0.30–0.41). This finding implies that high floor area ratios are not necessarily the result of many (individual) buildings within a grid cell. Very high correlations can be observed if the number of residents and employees and the absolute density values, such as the built-up volume or the number of buildings, are considered. The correlations between the FAR and the employee-resident value, however, are much smaller. Figure 9 visualizes these relationships using scatterplot matrices. It provides evidence of positive relationships among the built density indicators and positive, but less clear-cut relationships between the built and the activity densities.

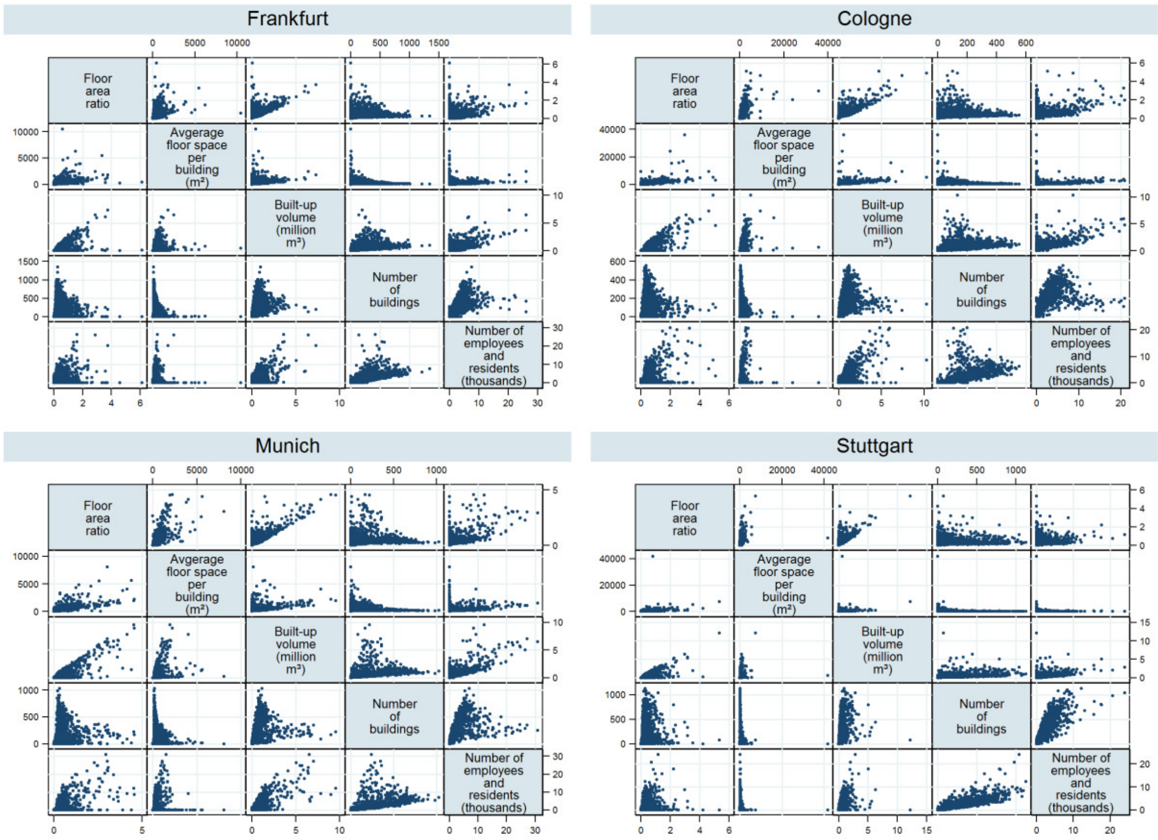

Figure 9. Scatterplot matrices showing the relationship between built and activity densities (both measured in levels). Employment data are taken from georeferenced Integrated Employment Biographies (georeferenced IEB) as of 30 June 2009, which are provided by the Research Data Centre (FDZ) of the Federal Employment Agency (BA) at the Institute for Employment Research (IAB) (for details and documentation, see [66]).

Thus, if there is a great deal of built-up volume in a grid cell, socioeconomic activity in this grid cell tends to be high. Floor area ratios and the socioeconomic activity's correlations are positive, but much smaller. Explanations for this could be that people work and live in buildings, but that this fact is not necessarily associated with a linear/proportional amount of land or floor area demand (one may think of examples such as individual preferences for certain types of housing or the production needs of manufacturing firms compared to those of knowledge-intensive business services). However, going into greater detail on this topic is beyond the scope of this paper.

5. Discussion

The empirical findings introduced in the previous section reveal regionally-specific morphological structures. We have shown that urban density cannot be solely considered either by built or by activity densities. Rather, these have to undergo a joint consideration in order to better understand urban spatial structure. As all analyses are descriptive, detecting significant causalities is beyond this paper's scope.

To briefly contextualize our results, we draft some strands of explanations. We assume that the identified patterns can be partially explained by topographical situations and transportation infrastructure. The Stuttgart region is a fairly good example of this. Previous studies regarding the density patterns of built-up volume and employees have shown an axial system that follows regional development axes, such as highways and rivers. Similar patterns can also be observed in the Cologne region along the river Rhine [24].

Additionally, historical path dependencies of economic and settlement history or regional and urban planning practices might also have contributed to these patterns. Thus, varying levels of built density could be the result of industrialization or urbanization processes that started at different times. Waves of urbanization towards the end of the 19th century produced higher built densities than later phases of urban growth characterized by residential and commercial suburbanization.

By the same token, the economic structure and its development could also explain the regional differences in density. The respective composition of the manufacturing and service industries manifests itself in a specific land use efficiency (*i.e.*, as used area per employed person), which in turn influences the built density situation. Looking at the Frankfurt or Stuttgart region provides evidence of this relation: whereas the correlation between the sum of employees and residents, on the one hand, and built-up volume, on the other hand, is fairly high (Table 3: 0.83 for Frankfurt and 0.86 for Stuttgart), the density maps of employees, employees in service sectors and built-up volumes clearly indicate that this global value is distorted by local peculiarities. The reasons for this are the concentration of employees in service sectors in the regions core city centers, who work in offices, and the concentration of employees, in the manufacturing sectors, in rather suburban areas, such as Russelsheim, where the automotive sector is strong. Similar patterns can be identified for the Stuttgart region, where the manufacturing sector is concentrated along the river Neckar and in the municipalities of Böblingen/Sindelfingen (see [24,64] for details).

Complementary data also show that suburban settlements from the 1950s to the 1970s, whose establishment was facilitated by mass motorization and low land prices, have apparently undergone very little subsequent densification [68]. For this reason, the transition from a compact regional core to a more scattered suburban environment still characterizes the settlement structure of the regions to this day. In this way, low built densities and therefore also low population-job densities are quite often evident, even in inner-city locations or in close proximity to stations along rail-based transportation corridors. The densification of such areas, which has been vigorously supported by urban planners (see the discussion in [69–71]), is subject to the provisions of planning law designed to protect existing structures and is also very rarely consistently sought after for reasons of low social acceptance.

A final factor can be seen in urban planning regulations. Urban density in Germany is regulated by municipal land use and development planning. The essential legal provisions for this (Baunutzungsverordnung, the Federal Land Use Ordinance) set a maximum limit for floor area ratio at 1.2 for residential uses and 3.0 for certain commercial uses. While higher densities may be allowed in particular exceptional cases, German planning law tends to restrict rather than support strong densification. Additionally, regional and local planning cultures and practices vary greatly. For instance, high-rise development is not permitted in the City of Munich, whereas this has long been a common practice in Frankfurt. The radial structure of density in the Stuttgart region appears not only to be an expression of topographical conditions, but also of the regulations made by regional planning.

The approach introduced here and the data generated in this manner offer improved analytical opportunities for the future understanding of the complex relationships between economic and social, as well as built structures and changes in urban regions. In this context, our analyses also show that there is not one perfect measurement of density. Rather, the complexity and diversity of the urban spatial structure reveals itself when considering multiple, conceptually different density figures, such as the FAR, the built-up volume or the density of socioeconomic use. Correlations between the individual variables are certainly sometimes high (see Table 3 or also [24]), but this does not apply in all cases. Future research endeavors will certainly contribute to both a better understanding of the causational factors of these relationships and a better estimation of their implications for humans and their environment.

6. Conclusions and Outlook

The present discussion shows that it is possible to generate region-wide built density models using remote sensing data. In this way, a significant gap in the ongoing observation of processes of urban and regional development can be narrowed.

To date, available mapping products, such as the European Urban Atlas, provide data regarding density for two dimensions to a limited extent. Analyses of urban morphology and form, however, are related to the built-up volume and, thus, to the third dimension. In this context, our approach described and applied above presents a framework for the generation of spatial built densities for very large areas at low costs compared to other DSM acquisition technologies by the multi-source combination of digital surface models and building footprints. The integration of building footprints allows for the derivation of 3D building models with high accuracies for such large areas as the four city regions presented in our study. Current and future Earth observation missions, such as TanDEM-X or Cartosat, with their large area data acquisition to global coverage, will add to this capability for 3D monitoring. Thus, remote sensing will be able to systematically monitor the built environment of cities over time. In this way, the consistency of the data may permit international comparative urban studies.

The availability of fine-grained density data offers new possibilities, both from a practical planning perspective and from a scientific view. Applications can be found, for example, in urban climatology and ecology and especially in exposure studies. Precisely, vulnerability evaluation methods and models could be refined. Examples are the application of built-up volume as triggers of local heat island phenomena or their influence on local wind systems [72]. Noise transmission calculations can also be methodologically refined by taking into account the exact geographic location and height of buildings. Another issue is that the planning of urban revitalization could also profit from building and density data in that strategies of planned shrinkage and demolition of vacant buildings, among others, can be investigated regarding their effects on infrastructure [73,74]. The same applies to the evaluation of densification projects with their positive and negative impacts (e.g., the improvement of infrastructural efficiency, reduction of open space). In this way, the potential for densifications around subway or commuter rail stations, for example, can also be determined.

Fina *et al.* [46] furthermore point out that the expansion of conventional spatial monitoring systems offers chances for a multidimensional observation of urban and regional development, since density indicators can be integrated and combined with other statistics and metrics. The resulting improved availability of sub-municipal data also allows for an interregional comparative analysis of the conditions and developments in urban areas that has not yet been possible in Germany.

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Abbreviations

The following abbreviations are used in this manuscript:

FAR	floor area ratio
IRS	Indian Remote Sensing Satellite
DSM	digital surface models
BKG	Bundesamt für Kartographie und Geodäsie (Federal Agency for Cartography and Geodesy)
INSPIRE	Infrastructure for Spatial Information in the European Community
DLM	digital basis landscape model
nDSM	normalized DSM
DTK25-V	Digitale Topographische Karte 1:25 000, Vorläufige Ausgabe (georeferenced digital topographic maps)
LoD1	Level of Detail 1
WZ 2008	Klassifikation der Wirtschaftszweige 2008 (Classification of Economic Activities, 2008 edition)
FDZ	Forschungsdatenzentrum (Research Data Centre)
BA	Bundesagentur für Arbeit (Federal Employment Agency)
IAB	Institut für Arbeitsmarkt- und Berufsforschung (Institute for Employment Research)

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Morphologische Polyzentralität der Beschäftigung in deutschen Metropolregionen – Aktuelle Befunde und Veränderungen seit 1970

Zusammenfassung

Der Beitrag widmet sich den Veränderungen der morphologischen Polyzentralität im Hinblick auf die Beschäftigung in ausgewählten Metropolregionen Deutschlands zwischen 1970 und 2010. Ausgehend von einer Diskussion des Konzepts der morphologischen Polyzentralität und einer Literatursynthese werden unterschiedliche Erfassungskonzepte vorgestellt und in ihren jeweiligen Eigenschaften diskutiert. Im Anschluss erfolgt die empirische Untersuchung elf deutscher Metropolregionen über einen Zeitraum von fast 40 Jahren auf Ebene der Städte und Gemeinden sowie eine Analyse der Metropolregion und der Stadt Stuttgart basierend auf 1 km² Gitterzellen. Die Ergebnisse zeigen eine abnehmende Konzentration der Beschäftigung auf Gemeindeebene bei nahezu unveränderter Kernstadtdominanz sowie erste Anzeichen ökonomischer Reurbanisierungsprozesse. Auffällig ist, dass bestehende suburbane Arbeitsplatzkonzentrationen in ihrer Bedeutung stärker geworden, neue größere Subzentren im Sinne von „Edge Cities" jedoch nicht entstanden sind. Die Betrachtung der räumlichen Ebene der Gitterzellen bestätigt die grundsätzlichen Ergebnisse der Gemeindeebene. Sie weist aber auch nach, dass innerhalb von Gemeinden bedeutsame raumstrukturelle Unterschiede vorherrschen. Die intra-urbane Polyzentralität der Metropolregion Stuttgart tritt im Gegensatz zur Betrachtung der Gemeindeebene deutlich hervor. Der Beitrag schließt mit einer Zusammenfassung der empirischen Ergebnisse sowie methodischer Weiterentwicklungsmöglichkeiten.

1 Einführung

Bereits in den 1970er- und 1980er-Jahren wurden in den größeren Stadtregionen westlicher Industriestaaten Anzeichen einer tiefgreifenden siedlungsstrukturellen „Re-Konfiguration" festgestellt (Leven 1978; Griffith 1981; Gordon, Richardson & Wong 1986; Freestone & Murphy 1998). Die bis dahin überwiegend monozentrisch geprägten Siedlungssysteme wandelten sich sukzessive in polyzentrische Raumgebilde, in denen die ökonomische Dominanz der Kern- und Innenstädte mehr und mehr schwand, was sich insbesondere an Veränderungen der räumlichen Arbeitsplatzverteilung zeigen lässt (Anas, Arnott &

Small 1998; Kloosterman &Musterd 2001; Hall & Pain 2006; Siedentop 2015: 15).

Während in der Stadt- und Regionalforschung Einigkeit dahingehend besteht, dass ökonomische Dekonzentrationsprozesse, verbunden mit der Herausbildung polyzentrischer Standortkonfigurationen bei der Beschäftigung, als universelle Merkmale der jüngeren raumstrukturellen Entwicklung anzusehen sind, existiert über das in verschiedenen Ländern und Regionen erreichte Ausmaß dieses Prozesses und ein mögliches „Equilibrium" noch wenig gesichertes Wissen. Allenfalls kann als empirisch evident gelten, dass die Suburbanisierung der Beschäftigung in Europa und Deutschland weniger stark ausgeprägt ist als in Nordamerika. Zwar wurden auch für europäische und deutsche Stadtregionen bedeutsame Dekonzentrationsprozesse und die Entstehung suburbaner Beschäftigungszentren nachgewiesen (Siedentop et al. 2003; Einig & Guth 2005; Siedentop, Lanzendorf & Kausch 2006; Riguelle, Thomas & Verhetsel 2007; Siedentop 2007; Garcia-López & Muñiz 2010; Burger et al. 2011; Knapp & Volgmann 2011; Krehl 2015b). Zugleich ist aber zu konstatieren, dass vergleichbare Standortagglomerationen an suburbanen Standorten, wie Joel Garreau sie in seinem Buch „Edge Cities" (Garreau 1992) für Nordamerika beschrieben hat, in Europa und in Deutschland bislang nicht entstanden sind (Bontje & Burdack 2005; Krehl 2015a). Verglichen mit dem Niveau nordamerikanischer Stadtregionen ist der Grad räumlicher Konzentration der Beschäftigung, insbesondere bei wissensintensiven Wertschöpfungsformen, immer noch hoch (Riguelle, Thomas & Verhetsel 2007; Garcia-López & Muñiz 2010; Krehl 2015b).

Derartige Bewertungen sind jedoch nicht allgemein gültig, denn empirische Studien folgen unterschiedlichen Verständnissen von Polyzentralität, woraus unterschiedliche Arbeitsdefinitionen und Messkonzepte resultieren. In Deutschland ist die Erforschung polyzentrischer Raumstrukturen u.a. aufgrund der spärlichen Verfügbarkeit untergemeindlicher Daten sowie aufgrund der hohen Datenschutzanforderungen besonderen Schwierigkeiten ausgesetzt. Bisherige Studien operieren vornehmlich mit Gemeindedaten, während die meisten Forschungsarbeiten aus den USA und zum Teil auch aus europäischen Nachbarländern disaggregierte Daten einsetzen (McMillen & McDonald 1998; McMillen 2003; Adolphson 2009; Kneebone 2009). Aus all dem ergeben sich Einschränkungen in der Vergleichbarkeit empirischer Befunde.

Vor diesem Hintergrund ist es Anliegen dieses Beitrages, zu einer empirischen Schärfung der Debatte um Polyzentralität beizutragen. Polyzentralität wird dabei als Beschäftigungspolyzentralität interpretiert und allein in ihrer morphologischen Dimension betrachtet. Funktionale Polyzentralität im Sinne von Green (2007), die auf relationale Verbindungen zwischen räumlich getrennten Regionen abstellt, kann hier nicht thematisiert werden. Vielmehr wird untersucht, welches Maß an morphologischer Polyzentralität in ausgewählten deutschen Metropolregionen feststellbar ist und wie sich dieses im Zeitverlauf verändert. Dazu wird eine Datenbasis eingesetzt, die erstmals die Erfassung von raumstrukturellen Veränderungen über einen Zeitraum von knapp 40 Jahren ermöglicht. Zur Messung der Polyzentralität werden ausgewählte Methoden verwendet und in ihren analytischen Möglichkeiten verglichen.

Die in diesem Beitrag vorgestellten statistischen Analysen erfolgen auf zwei räumlichen Ebenen: Für insgesamt acht Metropolregionen der alten Bundesländer werden Beschäftigungsdaten auf der Gemeindeebene über einen Zeitraum von 1970 bis 2007 ausgewertet, für drei weitere Metropolregionen der neuen Bundesländer über einen Zeitraum von 1999 bis 2007. Im Anschluss werden mit Daten zur Beschäftigung auf der Ebene von Gitterzellen für die Metropolregion Stuttgart die kleinräumigen Verteilungsmuster analysiert. Hierbei kann erstmals auf eine Datenbasis des Forschungsdatenzentrums der Bundesagentur für Arbeit im Institut für Arbeitsmarkt- und Berufsforschung (im Folgenden kurz FDZ genannt) zurückgegriffen werden, die auf adressscharfen Beschäftigtendaten basiert.

Der Beitrag gliedert sich wie folgt: Im ersten Teil (Abschnitt 2) wird ein Überblick über den internationalen Meinungsstand zur Messung von Polyzentralität gegeben. Dabei werden die wichtigsten Methoden mit ihren Stärken und Schwächen dargestellt. In Abschnitt 3 werden die eingesetzten Datengrundlagen, die Vorgehensweise bei der Abgrenzung der Untersuchungsräume und die Methodenauswahl erläutert. Anschließend erfolgt eine Diskussion der erarbeiteten Befunde. Der Beitrag schließt mit einer Zusammenfassung und einem Ausblick auf weiteren Forschungsbedarf (Abschnitt 4).

2 Methoden zur Abbildung von Polyzentralität

Polyzentralität ist kein einfach zu messendes Konzept. Zwar wurden in der Vergangenheit vielfältige Versuche unternommen, die Zentrenstruktur von Metropol- oder Stadtregionen qualitativ und quantitativ zu erfassen, aber weder hat sich dabei ein eindeutiges Begriffsverständnis herausgebildet (Davoudi 2003: 979f.; Hall & Pain 2006: 4; Green 2007: 2078), noch gibt es eine Übereinkunft, wie Polyzentralität (geo)statistisch abbildbar ist (Kloosterman & Lambregts 2001: 724; Kloosterman & Musterd 2001: 622; Veneri & Burgalassi 2012: 1019ff.). Erschwerend wirkt, dass Polyzentralität je nach Betrachtungswinkel auf unterschiedlichen Ebenen untersucht und gemessen wird (Kloosterman & Musterd 2001: 626ff.; Davoudi 2003: 979; Hall & Pain 2006: 4, 12; Veneri & Burgalassi 2012: 1019ff.) und dass neben einem empirisch-analytischen auch ein politisch-normativ geprägtes Verständnis anzutreffen ist (Davoudi 2003: 979, 988f.). Beides hat die Bandbreite des Begriffsverständnisses gedehnt und eine erhebliche Unschärfe des Konzepts der „polyzentrischen Region“ erzeugt.

2.1 Räumliche Bezugsebenen

Bei einem methodisch orientierten Vergleich wissenschaftlicher Arbeiten in diesem Themenbereich können trotz der angesprochenen Vielfalt einige Gemeinsamkeiten identifiziert werden. Dies betrifft die Vorgehensweise bei der äußeren Abgrenzung von Regionen, die als mono- bzw. polyzentrisch bezeichnet werden, und die innere Struktur der Regionen in Form von administrativen und nicht-administrativen Gebietseinheiten.

2.1.1 Regionsabgrenzung

Die Frage nach der Regionsabgrenzung geht eng einher mit der Frage, wie sich der inter-urban polyzentrische Raum von seinem Umland abgrenzt. Gemäß der in diesem Buch zugrundeliegenden Definition von Polyzentralität (siehe hierzu den Beitrag von Münter, Danielzyk & Wiechmann) beinhaltet ein inter-urban polyzentrischer Raum mehrere Kerne, die eine hohe Konnektivität untereinander aufweisen.

Zur Abgrenzung eines Untersuchungsraums eher unüblich ist die Verwendung politisch-administrativer Verwaltungseinheiten wie Landkreise, Regierungsbezirke oder Raumordnungsregionen. Verbreitet sind vielmehr funktionale Regionen, die nach dem „Verflochtenheitsprinzip“ (Sinz 2005: 921) abgegrenzt werden. Meistens stellt dies auf Kriterien wie Pendlerverflechtungen oder wirtschaftliche Beziehungen ab. Vorteilhaft für die räumliche Analyse ist, dass es sich bei der Abgrenzung nach funktionalen Kriterien um Räume handelt, deren Außengrenzen weniger willkürlich sind. Ungeachtet dessen sind Regionsabgrenzungen immer normativ, da auch hier Schwellenwerte eingesetzt werden müssen, um den Regionsrand vom weiteren Umlandraum zu trennen (siehe u.a. Kropp & Schwengler 2008). Schwierigkeiten bereitet auch die Aufgabe, ein Mindestmaß an funktionaler Interaktion zwischen verschiedenen Kernstädten zu definieren, damit diese mit ihrem Umlandraum als (inter-urban) mehrkernige Metropolregionen angesehen werden können. Erwähnt werden soll an dieser Stelle auch die Normativität der Klassifizierung von lokalen Gebietskörperschaften als „Kernstädte“.

2.1.2 Interne Regionsgliederung

Neben den Außengrenzen ist für die Analyse polyzentrischer Strukturen die Binnengliederung des Untersuchungsraums relevant. Während die inter-urbane Polyzentralität meistens mit Gemeindedaten ermittelt wird, benötigt die Erfassung von intra-urbaner Polyzentralität Daten unterhalb der Gemeindeebene. In der Literatur werden hier verschiedene statistische Gebietseinheiten wie Baublöcke, Verkehrszellen oder die Zähleinheiten der Volkszählungen (z.B. Census Tracts) eingesetzt (siehe z.B. Anas, Arnott & Small 1998; Gaschet 2002; Berliant & Wang 2007; Redfearn 2007; Gilli 2009; Carruthers et al. 2010; Fina et al. 2014).

Eine weitere Methode zur internen Regionsgliederung bedient sich unterschiedlicher „Schablonen“ wie z.B. Gitterzellen. Dieser Ansatz unterscheidet sich grundlegend von den übrigen, da er mit festen geometrischen Formen agiert und dabei keine Rücksicht auf morphologische, funktionale, politische oder geographische (Binnen)Gliederungen nimmt. Adolphson (2009: 24) verwendet beispielsweise Rasterdaten mit Kantenlängen von 200 Metern, um strukturelle, kleinteilige morphologische Veränderungen darzustellen und von diesen auf den Grad der Polyzentralität zu schließen. Auch McMillen & McDonald (1997), Batty et al. (2004), Adolphson (2010: 556) und Krehl (2015b: 292) setzen in ihren Arbeiten auf Rasterdaten. Eine ähnliche Regionsgliederung verwendet Gilli (2009: 1398), indem er den Untersuchungsraum in gleichgroße Hexagone aufteilt.

Festzuhalten ist bezüglich der Raumabgrenzung, dass (1) die Form der zu analysierenden Polyzentralität – intra- oder inter-urban – im Prinzip simultan mit der Raumabgrenzung festgelegt wird und dass (2) intra-urbane Polyzentralität innerhalb einer inter-urban polyzentrischen Region angetroffen werden kann, während es umgekehrt nicht der Fall ist.

2.2 (Geo-)Statistische Erfassungsmethoden

Nicht nur bei der Festlegung der Außengrenzen und der inneren Gliederung des betrachteten Raumes, sondern auch beim Einsatz von (geo)statistischen Messmethoden zur Ermittlung von Polyzentralität lässt sich eine große Vielfalt erkennen. Nichtsdestotrotz können auch hier Gemeinsamkeiten erkannt und zu Kategorien zusammengefasst werden.

2.2.1 Schwellenwerte

Eine häufig zum Einsatz kommende, relativ einfache Methodenkategorie ist die Schwellenwertbildung. Für einen definierten Gesamtraum werden z.B. Dichteschwellenwerte gebildet. Dichte bezieht sich in den meisten Studien auf die Anzahl der Arbeitsplätze je Referenzfläche.[1] Die Schwellenwerte werden derart operationalisiert, dass sie einen Wert angeben, den eine Teilregion des Gesamtraumes überschreiten muss, um als potenzielles (Sub)Zentrum bezeichnet zu werden (Giuliano & Small 1991: 166f.; Small & Song 1994: 297; Anderson & Bogart 2001: 149; Gaschet 2002: 68f.; Gilli 2009: 1398; Kim, Yeo & Kwon 2014 359)[2].

Eine der Schwellenwertmethode sehr ähnliche Vorgehensweise bezieht sich auf Entfernungen und umfasst Erreichbarkeiten sowie die Definition von Ringzonen um einen festgelegten Mittelpunkt, meist die Innenstadt (Central Business District, CBD). Bei letzterer Methode ist die Ortskenntnis von besonderer

1 Für eine Diskussion des vermeintlich einfachen Maßes der Dichte siehe Fina et al. (2014).
2 Gute Übersichten bieten Agarwal, Giuliano & Redfearn 2012: 441f. und Fernández-Maldonado et al. 2014: 1957.

Bedeutung, da die Festlegung des CBD sowie der jeweiligen entfernungsbasierten Ringzonen stets Auswirkungen auf die Ergebnisse hat (Siedentop et al. 2003: 10ff.). Bezüglich dieser Methode kann eingewendet werden, dass Subzentren nicht zwangsläufig symmetrisch um den CBD verteilt sein müssen bzw. dass dies je nach geografischer Situation der betrachteten Region zu signifikanten Verzerrungen führen kann.[3]

Einen weitergehenden Ansatz verfolgen McMillen & McDonald (1997), Anas, Arnott & Small (1998) und Anderson & Bogart (2001), die Beschäftigungsdichten mit einer erforderlichen Mindestausstattung an Arbeitsplätzen kombinieren. Damit soll vermieden werden, dass beschäftigungsstarke, aber absolut betrachtet kleine Räume als Subzentren identifiziert werden. Siedentop (2007: 111f.) verwendet absolute Werte als Schwellenwerte und kombiniert diese mit normativen Aspekten wie dem Status als sogenannter Zentraler Ort. Weitere Möglichkeiten beschreiben u.a. Siedentop et al. (2003: 68f.) und Einig & Guth (2005: 446). Der Vorteil aller Schwellenwertmethoden ist gleichzeitig ihr größter Nachteil: Für jede Region können den lokalen Gegebenheiten angepasste Schwellenwerte definiert werden. Dadurch kann einerseits auf die jeweiligen räumlichen Bedingungen Rücksicht genommen werden. Andererseits bedeutet es aber auch, dass insbesondere absolute Schwellenwerte eher willkürlich und damit nicht als allgemeingültige Messkonzepte geeignet sind (McMillen & McDonald 1997: 600; Craig & Ng 2001: 101; McMillen 2001a: 449, 463; McMillen 2001b: 18; Redfearn 2007: 520f.). Folglich können die auf Basis unterschiedlicher Schwellenwerte identifizierten Zentren zwischen den Regionen nicht verglichen werden.

2.2.2 Schätzverfahren

Eine Weiterführung und Ergänzung der angesprochenen Methoden sind parametrische und nicht-parametrische Schätzverfahren.[4] Dazu zählen u.a. die Berechnung von Dichtegradienten, Kernel-Density Schätzungen oder Locally Weighted Regressions. Dichtegradienten werden berechnet, indem z.B. die Beschäftigungsdichte einer Gebietseinheit als Funktion ihrer Entfernung zur Innenstadt beschrieben wird (Anas, Arnott & Small 1998: 1436; McMillen 2001a: 451; McMillen 2001b: 17; McMillen 2004: 227). Eine gute Übersicht über unterschiedliche Spezifikationen bieten Roca Cladera, Marmolejo Duarte & Moix (2009).

Ähnlich wie bei der Methode der Ringzonen wird bei der Anwendung von Dichtegradienten eine Konzentration der Beschäftigung in der Innenstadt bzw. eine konzentrisch zum Rand hin abnehmende Beschäftigungsdichte angenommen. Im Ergebnis entstehen Radien um ein vordefiniertes Zentrum, auf denen

3 Als Beispiel hierfür kann die San Francisco Bay Area genannt werden. Die Kernstadt San Francisco liegt direkt am Meer und hat damit kein westliches Umland. Wird mit einer Ringzone gearbeitet, können folglich Verzerrungen auftreten.

4 Eine gute Übersicht über letztere bieten Büning & Trenkler (1994).

sich potenzielle Subzentren befinden. Für die Identifikation der auf diesen Ringen liegenden Subzentren ist die oben angesprochene Ortskenntnis erforderlich. Diese Methode kann so abgewandelt werden, dass nur solche Gebiete als Subzentren in Frage kommen, deren Residuen positiv und zusätzlich geclustert sind (Anas, Arnott & Small 1998: 1433; McMillen & Smith 2003: 326). Craig & Ng (2001: 102) entwickeln eine ähnliche Methode, die lediglich auf die oberen Quantile der Beschäftigungsdichte abstellt. Damit soll sichergestellt werden, dass nur solche Teilräume als Subzentren identifiziert werden, die auch absolut betrachtet hohe Werte aufweisen.

Eine weitere Methode, Subzentren zu identifizieren und damit Aussagen über das Vorhandensein polyzentrischer Strukturen zu generieren, ist die Kernel-Density Methode. Dabei werden für jeden Datenpunkt (z.B. die Adresse eines Unternehmens mit Beschäftigten) die über einen Suchradius festgelegten nächsten Nachbarn betrachtet. Für die Verteilung dieser Daten wird eine Kerndichtefunktion berechnet (Leslie 2010: 211; Knapp & Volgmann 2011: 311). Wie Adolphson (2010: 557f.) zeigt, kann diese Methode in unterschiedlichen Spezifikationen angewendet werden. Der Vorteil nicht-parametrischer gegenüber parametrischer Schätzverfahren ist, dass die funktionale Form der Datenverteilung nicht a priori bekannt sein muss. Bei der Verwendung der Locally Weighted Regression, einer Weiterentwicklung der Kernel-Density Methode, wird das Datenrelief derart geschätzt, dass bezogen auf einen Datenpunkt immer nur die nächsten Nachbarn berücksichtigt werden. Anschließend werden in einem zweiten Schritt die Subzentren mithilfe einer nicht-parametrischen Schätzung identifiziert (für Details siehe z.B. McMillen 2001b). Es werden die Teilräume immer in Abhängigkeit ihrer direkten Umgebung betrachtet, so dass auch die Subzentren relativ zu ihrer Umgebung erfasst werden und die Symmetrie um den CBD aufgehoben wird (McMillen 2001b: 18). Redfearn (2007: 521) weist darauf hin, dass diese Methode auch Ausreißer als Subzentren identifiziert. Daher schlägt er eine Modifikation vor, bei der eine sehr kleine Window Size verwendet und diese mehrfach unterschiedlich partitioniert wird. Die Auswahl der bestmöglichen Window Size erfolgt mithilfe weiterer ökonometrischer und statistischer Testverfahren.

2.2.3 Räumliche Statistiken und Indikatoren

Die bisher vorgestellten Methoden eignen sich in erster Linie zur Identifikation kleinräumiger, intra-urbaner Polyzentralität. Es existieren darüber hinaus jedoch weitere Ansätze, die neben der intra- auch die inter-urbane Polyzentralität adressieren. Riguelle, Thomas & Verhetsel (2007), Arribas-Bel & Sanz-Gracia (2014) oder auch Krehl (2015b) gehen beispielsweise davon aus, dass eine Region dann polyzentrisch ist, wenn sie eine im weitesten Sinne statistisch signifikant ungleich verteilte Beschäftigung aufweist. Dazu verwenden sie Indikatoren wie den Hoover-Index oder das globale Moran's I. Sie verstehen unter einem Subzentrum ein Cluster der Beschäftigungsdichte, den sie mithilfe der sogenannten Local Indicators of Spatial Association (LISA) identifizieren. Guillain & Le Gallo (2010: 963) verwenden zudem eine Variation des in der räumlichen Analyse weit verbreiteten Gini-Koeffizienten, den Locational Gini-Index. Begründet wird die Verwendung dieser Methoden damit, dass sie sich nur auf die vorhandenen Daten beziehen, keine Ortskenntnis voraussetzen, ohne Schwellenwerte auskommen und damit nicht willkürlich sind (Riguelle, Thomas & Verhetsel 2007: 200). Ein weiterer Vorteil ist die allgemeine Anwendbarkeit der Methode: Sie eignet sich für Räume unterschiedlicher Ausdehnung, interner Struktur und Bevölkerungs- bzw. Beschäftigungsdichte. Um sinnvolle Vergleiche der berechneten Werte für unterschiedliche Untersuchungsregionen zu ermöglichen, ist jedoch weiterhin auf eine möglichst ähnliche Binnengliederung zu achten.

Weiterhin existieren zahlreiche Indikatoren, die zur Messung von Polyzentralität herangezogen werden, jedoch keine räumlichen Übertragungseffekte berücksichtigen. Eine große Gruppe bilden darin (globale) Ungleichheitsmaße wie Gini-Koeffizient, Herfindahl Index, relativer Dispersionskoeffizient oder Zipf's law/rank-size rule (Alpkokin et al. 2005: 3836ff.; Meijers 2008: 2332ff.; Adolphson 2009: 22; Gilli 2009: 1393; Lalanne 2014: 1728; González-Val et al. 2015: 179ff.; Krehl 2015a: 163ff.). Diese Koeffizienten zeichnen sich im Gegensatz zu den bereits beschriebenen Methoden dadurch aus, dass ihre Ergebnisse etwas über den Grad der Ungleichverteilung (Polyzentralität, Dispersion) aussagen. Mit ihnen können jedoch keine Raumeinheiten als Zentren oder Subzentren identifiziert werden.

2.3 Zwischenfazit

Es wurde gezeigt, dass die angewendeten Raumbezüge und Messmethoden äußerst vielfältig sind und in unterschiedlicher Weise zweckbezogen miteinander kombiniert werden. Die Identifikation von Subzentren und die Ermittlung ihrer Anzahl sind maßgeblich von der Wahl des räumlichen Bezugssystems sowie den gewählten Methoden abhängig (Anas & Arnott & Small 1998: 1440; McMillen 2001b: 17; Adolphson 2010: 553). Tabelle 1 gibt einen Überblick über die meistverwendeten Erfassungskonzepte sowie deren Charakteristika im Hinblick auf die empirische Adressierung von Polyzentralität.

Zusammenfassend lässt sich festhalten: Einige Methoden zeichnen sich dadurch aus, dass sie etwas über das grundsätzliche Vorliegen polyzentrischer Strukturen aussagen, indem Standorte als (potenzielle) Zentren identifiziert werden. Globalmaße wie beispielsweise das globale Moran's I sind hingegen geeignet, den Grad der Polyzentralität anzugeben, ohne dabei genauere Aussagen über die räumliche Ausformung der Zentrenstruktur zuzulassen. Lokalmaßstäblich operierende Maße wie u.a. LISA sind für Letzteres besser geeignet, da sie angeben können, ob an einem bestimmten Standort eine Abweichung vom Datenrelief (Schwelle, statistische Signifikanz etc.) vorliegt oder nicht. Diese

Lokal- und Globalmaße können sowohl für die intra- als auch für die inter-urbane Polyzentralitätsabschätzung eingesetzt werden.

Methode	Anzeige der Existenz polyzentrischer Strukturen (standortspezifische Betrachtung)	Angaben über den Grad der Polyzentralität (regionsweite Betrachtung)
Schwellenwerte		
• Dichte	x	
• Erreichbarkeiten	x	
• Ringzonen	x	
Schätzverfahren		
• Gradienten	x	
• Kernel-Density Methode	x	
• LWR	x	
Räumliche Statistiken und Indikatoren		
• LISA	x	
• Gini-Koeffizient		x
• Global Moran's I		x
• Herfindahl-Index		x
• Hoover-Index		x
• Relativer Dispersionskoeffizient		x
• Zipf's Law/rank-size rule		x

Tabelle 1: Charakteristika der zur empirischen Erfassung von Polyzentralität verwendeten Methoden (Quelle: eigene Zusammenstellung)

Insgesamt wird deutlich, dass die Methoden zur Erfassung intra-urbaner und inter-urbaner Polyzentralität nicht sauber unterschieden werden können. Darüber hinaus muss festgehalten werden, dass keine Methodik zu existieren scheint, die in der Lage ist, eindeutig zwischen intra- und inter-urbaner Polyzentralität zu differenzieren. Ein Stück weit dürfte dies definitionsbedingt sein, da intra-urbane Polyzentralität in inter-urban polyzentrischen Regionen auftreten kann.

Eine Kombination der Methoden und räumlichen Bezugsebenen kann dieses Problem jedoch entschärfen und ein detailliertes, auf unterschiedlichen räumlichen Ebenen angesiedeltes Bild der Polyzentralität eines Untersuchungsraumes liefern. Der empirische Teil dieses Beitrags widmet sich eben dieser Fragestellung. Aufbauend auf einem „Trichterkonzept“ gibt er einen Einblick in einige Kombinationsmöglichkeiten.

3 Beschäftigungspolyzentralität und ihre Entwicklung in deutschen Metropolregionen

Ziel der nachfolgenden empirischen Analysen ist es, ein neuartiges methodisches Instrumentarium zu erarbeiten und zu erproben, das die Ausprägung polyzentrischer Beschäftigungsstrukturen und ihre historische Genese unter Einsatz hochauflösender räumlicher Daten erlaubt. Das hier zur Anwendung kommende „Trichterkonzept“ (vgl. Abb. 1) hat einen gestuften Aufbau und ist aus mehreren Gründen innovativ:

- Es vereint unterschiedliche methodische Ansätze: Global- und Lokalmaße.
- Es erlaubt Längsschnittaussagen für eine Spanne von fast 40 Jahren.
- Es operiert auf unterschiedlichen räumlichen Ebenen: Gemeinden und Gitterzellen.

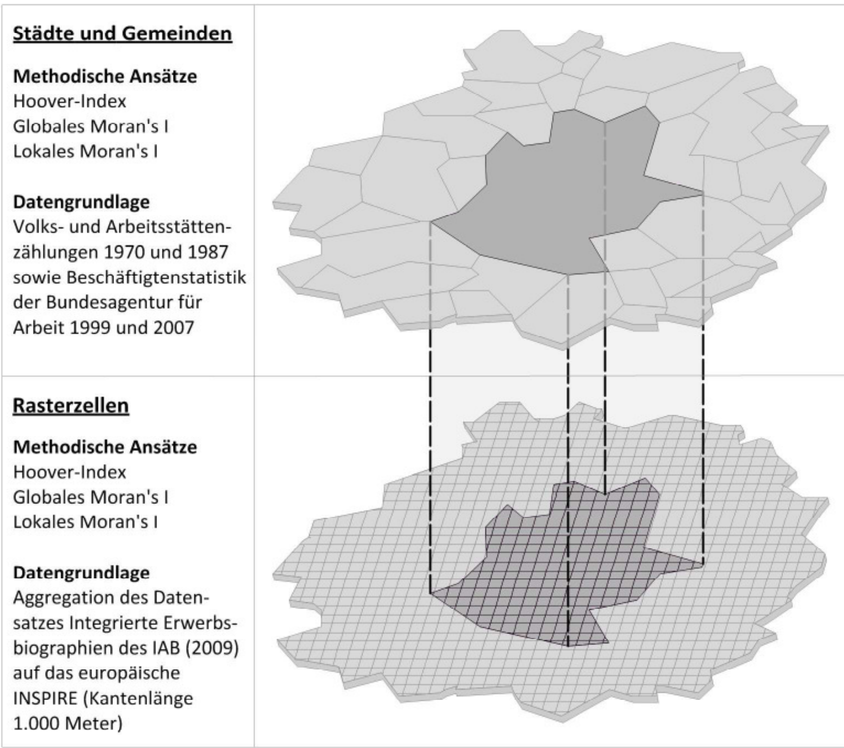

Abbildung 1: Schematische Darstellung des Analysekonzepts am Beispiel eines Ausschnittes aus der Metropolregion Stuttgart (Quelle: eigene Darstellung)

Erwartet werden im Ergebnis drei „Klassen“ von Metropolregionen: inter-urban polyzentrisch, stark monozentrisch und überwiegend monozentrisch. Von den elf betrachteten Metropolregionen können Rhein-Ruhr, Rhein-Main sowie die Metropolregion Nürnberg als explizit inter-urban polyzentrisch bezeichnet werden. Stark monozentrisch geprägt sind die Metropolregionen Berlin, Hamburg und München, überwiegend monozentrisch die Metropolregionen Bremen, Dresden, Leipzig und Hannover. Die Metropolregion Stuttgart nimmt vermutlich eine gewisse Sonderrolle ein, da die polyzentrische Struktur dieses Raumes in hohem Maße durch die Beschäftigungsstärke der die Kernstadt umgebenen Mittelzentren begründet ist.

3.1 Methodik und Dateneinsatz

3.1.1 Methodische Ansätze

Die nachfolgenden empirischen Ergebnisse berufen sich zum Teil auf die von Riguelle, Thomas & Verhetsel (2007) vorgestellte Vorgehensweise zur Bewertung der Polyzentralität. Sie stellen zugleich einen Ausschnitt der Arbeiten auf der untergemeindlichen Ebene von Krehl (2015b) dar. Diese im Folgenden eingesetzte Vorgehensweise verbindet klassische Konzentrationsmaße mit neueren Methoden der explorativen räumlichen Datenanalyse. Zur ersten Gruppe zählt der Hoover- bzw. Dissimilarity-Index, der einen ersten Überblick über die räumliche Verteilung der Beschäftigung innerhalb der Untersuchungsräume vermittelt (Bähr, Jentsch & Kuls 1992: 57). Er ist in den Raumwissenschaften etabliert und zählt zu den sog. Globalmaßen – ein einzelner Indexwert charakterisiert wie stark oder schwach sich die Beschäftigten auf die Merkmalsträger (z.B. Gemeinden) eines räumlichen Systems (z.B. eine Region) konzentrieren. Der Wertebereich des Hoover-Index liegt zwischen Null und 1: je näher bei 1, desto stärker die Konzentration. Ein klarer Vorteil gegenüber anderen Konzentrationsmaßen liegt in der sehr intuitiven Interpretation des Maßes. Es gibt den Anteil der Beschäftigung an, der innerhalb der Gesamtheit der Merkmalsträger umverteilt werden müsste, um eine Gleichverteilung zu erlangen (Riguelle, Thomas & Verhetsel 2007: 199).

Ein zweites hier eingesetztes Maß ist das globale Moran's I, das zu den Werkzeugen der explorativen räumlichen Datenanalyse zählt (eine Übersicht über diese Techniken liefern Ertur & Le Gallo 2003: 56ff.). Das globale Moran's I zeichnet sich dadurch aus, dass es räumliche Übertragungseffekte (spatial spillovers) berücksichtigt. Es dient zugleich der Bewertung der globalen Verteilung der Beschäftigung, indem es „simultan sowohl die räumliche Konfiguration der territorialen Einheiten als auch deren Attributwerte“ (Kranabether, Helbich & Knoflacher 2012: 23) einbezieht. Das globale Moran's I gehört zu den sog. räumlichen Autokorrelationsstatistiken, die Hinweise auf räumliche Cluster liefern (O'Sullivan & Unwin 2010: 205). Dessen Wertebereich reicht von –1 bis +1 (Goodchild 1986: 16). Ist das I-Maß größer als Null und statistisch signifikant, liegt positive räumliche Autokorrelation vor, d.h. benachbarte Merkmalsträger weisen ähnlich hohe oder geringe Werte auf. Ist das I-Maß kleiner als Null und statistisch signifikant, liegt negative räumliche Autokorrelation vor – Merkmalsträger mit hohen Werten sind von Nachbarn mit niedrigen Werten umgeben oder umgekehrt. Liegt das Maß sehr nahe an Null, ist das räumliche Muster ein Ergebnis des Zufalls (keine räumliche Autokorrelation).

Die vorgestellten Globalmaße haben eine gemeinsame Schwäche: Beide analysieren die Eigenschaft des Verteilungsmusters für den Untersuchungsraum insgesamt (Helbich 2009: 99), ohne dabei die lokalen Beschäftigungszentren im Einzelnen zu identifizieren. Um nähere Aussagen bezüglich der räumlichen Lage von Zentren bzw. Subzentren tätigen zu können, wird mit dem lokalen Moran's I auf einen dritten Indikator zurückgegriffen. Das Maß lässt sich als disaggregierte Variante des globalen Moran's I interpretieren (Anselin 1995: 98). Üblicherweise werden die Ergebnisse kartographisch in sog. LISA-Cluster-Maps visualisiert (Anselin 2005: 141). Mit den Karten lassen sich vier unterschiedliche Typen räumlicher Assoziation aufdecken:

- Ist ein Merkmalsträger mit hohen Werten, z.B. Werte für die Beschäftigungsdichte, von Nachbarn mit ebenfalls hohen Werten derselben Variablen umgeben, spricht man von einem räumlichen High-High-Cluster (Anselin, Syabri & Smirnov 2002: 6).
- Ist ein Merkmalsträger mit niedriger Beschäftigungsdichte von Nachbarn mit ebenfalls niedriger Beschäftigungsdichte umgeben, spricht man von einem räumlichen Low-Low-Cluster.
- Ist ein Merkmalsträger mit hoher Beschäftigungsdichte von Nachbarn mit niedriger Beschäftigungsdichte umgeben, spricht man von einem räumlichen High-Low-Ausreißer.
- Ist ein Merkmalsträger mit niedriger Beschäftigungsdichte von Nachbarn mit hoher Beschäftigungsdichte umgeben, spricht man von einem räumlichen Low-High-Ausreißer.

Mit den hier zum Einsatz kommenden Kennziffern erhöhen sich Schritt für Schritt die Aussagemöglichkeiten bezüglich des Polyzentralitätsgrades der Untersuchungsräume und ihrer jeweiligen räumlichen Ausprägungen.

3.1.2 Dateneinsatz

Die nachfolgend dargestellten empirischen Ergebnisse operieren mit verschiedenen Datengrundlagen, die Querschnitt- und Längsschnittanalysen ermöglichen. Dies ist für Analysen in Deutschland bisher nicht durchgeführt worden und stößt somit in eine Forschungslücke.

Längsschnittanalysen

Die Längsschnittanalysen erfolgen für einen Zeitraum von 37 Jahren (Metropolregionen der alten Bundesländer) bzw. acht Jahren (Metropolregionen der neuen Bundesländer), der an vier bzw. zwei Zeitpunkten evaluiert wird. Datengrundlage sind die gemeindescharfen Ergebnisse der Volks- und Arbeitsstättenzählung 1970 und 1987 sowie die Statistik der sozialversicherungspflichtig Beschäftigten (SVB) der Jahre 1999 und 2007. Die Volkszählungen wurden als Primär- und Vollerhebungen der westdeutschen Wohnbevölkerung durchgeführt, beziehen sich allerdings nur auf die alten Bundesländer. Die Beschäftigtenstatistik der Bundesagentur für Arbeit berücksichtigt die erwerbstätige Bevölkerung des bundesdeutschen Gebietes nach heutigem Zuschnitt und umfasst nur meldepflichtige Erwerbspersonen, die Beiträge an die gesetzliche Kranken-, Pflege- und Arbeitslosenversicherung entrichten (also keine Beamten, Selbstständigen und deren mithelfende Familienangehörige); sie enthält daher nur etwa 75 % aller Erwerbstätigen Deutschlands (Statistisches Bundesamt 2007: 6). Um eine größtmögliche Vergleichbarkeit der Volkszählungs- und Bundesagenturdaten herzustellen, wurden die Datengrundlagen modifiziert. Hierzu wurden aus der digital verfügbaren Volkszählung 1987 sämtliche Erwerbspersonen ausgeschlossen, die keiner sozialversicherungspflichtigen Tätigkeit nachkommen (Details dazu siehe Link & Guth 2010). Eine Modifikation des 1970er-Zahlenmaterials nach diesem Schema konnte nicht erfolgen, da kein verlässliches Schätzverfahren für einen nachträglichen Ausschluss der Beamten und Selbstständigen aus den Originaldaten existiert. Die Beschäftigtenzahlen für 1970 sind daher nicht deckungsgleich mit den Daten der folgenden Jahre. Diese Schwäche wird hier zugunsten der Längsschnittbetrachtung in Kauf genommen.

Querschnittanalysen

Die Querschnittanalysen beziehen sich auf den 2009er-Querschnitt der Integrierten Erwerbsbiografien (IEB) des Forschungsdatenzentrums der Bundesagentur für Arbeit im Institut für Arbeitsmarkt- und Berufsforschung (FDZ). Dieser wurde in einem separaten, dort angesiedelten Projekt mit den georeferenzierten Adressdaten Bund gekoppelt (Details siehe Scholz et al. 2012: 4ff.). Im Ergebnis liegen am FDZ georeferenzierte Informationen über ca. 2,5 Millionen Betriebe mit insgesamt ca. 36,2 Millionen Beschäftigten bundesweit vor. Aus Datenschutzgründen konnten diese Individualdaten nicht bezogen und weiterverarbeitet werden. Stattdessen wurden Shapefiles für die Metropolregion Stuttgart an das FDZ gesendet und in diese die Anzahl der Beschäftigten[5] eingespielt, so dass aggregierte Daten anstelle der Individualdaten verwendet wurden. Des Weiteren mussten alle Polygone zensiert werden, die zu wenig Betriebe oder einen dominanten Betriebe enthielten (Details dazu siehe Bundesagentur für Arbeit 2012b). Für die Analyse der Beschäftigungspolyzentralität der Metropolregion Stuttgart bedeutet dies, dass bei den Rasterdaten bezüglich der Beschäftigten (SVB) 596 von 2029 Zellen zensiert sind. Um diese trotzdem in den Analysen berücksichtigen zu können, wurden die jeweiligen Werte manuell auf eins, d.h. einen sozialversicherungspflichtig Beschäftigten,

5 Unter Beschäftigte verstehen wir alle SVB zum Stichtag 30.06.2009.

gesetzt, wissend dass dies im Einzelfall eine massive Verzerrung nach unten bedeuten kann.[6] Da es jedoch die besten verfügbaren untergemeindlichen Daten sind, wurde diese Verzerrung in Kauf genommen. Bei der Interpretation der Ergebnisse ist zudem zu beachten, dass das Arbeitsstättenkonzept nicht immer greift. So dürfen Unternehmen, die an mehreren Standorten innerhalb einer Gemeinde agieren, alle Mitarbeiter an einer Stelle innerhalb dieser Gemeinde melden. Dies ist jedoch mit der Einschränkung versehen, dass die Mitarbeiter dann in demselben Wirtschaftszweig (5-Steller) angemeldet sein müssen. Dadurch kann es sein, dass die Beschäftigungskonzentration überschätzt wird.

3.1.3 Raumbezüge

Die empirischen Untersuchungen bewegen sich auf zwei räumlichen Ebenen: Auf der Ebene der Städte und Gemeinden (Längsschnittanalysen) und auf der untergemeindlichen Ebene von Gitterzellen (Querschnittanalysen).

Städte und Gemeinden

Die den Analysen zugrundeliegende äußere Begrenzung der Untersuchungsräume stützt sich auf die vom Initiativkreis Europäische Metropolregionen in Deutschland definierten Metropolregionen (IKM 2010: 7). Ausgehend von den dort genannten Kernstädten wurden die Metropolregionen verkleinert: Zunächst wurde eine Ringzone mit 50 km-Radius um die Kernstädte gezogen; anschließend wurden alle (Land)Kreise erfasst, die zu mehr als 50 % von der durch den Radius beschriebenen Fläche bedeckt wurden. In einigen Fällen musste manuell eingegriffen werden, um unplausible Raumzuschnitte zu vermeiden.[7] Die so entstehenden Raumgebilde formen in der unten stehenden Analyse die Metropolregionen, im Folgenden IKM50-Regionen genannt. Die Abgrenzung erfolgte aufgrund der notwendigen Kompatibilität mit anderen Raumabgrenzungen in diesem Band auf Kreisebene, auch wenn innerhalb der Metropolregionen mit gemeindescharfen Daten operiert wird.[8]

Gitterzellen

Um tiefer gehende Analysen zu ermöglichen, wird in einem zweiten Schritt auf die untergemeindliche Ebene gewechselt. Eingesetzt wird ein Raster mit 1.000

6 Auszählungen durch das FDZ ergaben, dass durch die Schwärzung der Rasterzellen (29,4 % aller Zellen, die SVB beinhalten) lediglich 0,7 % aller SVB im Untersuchungsgebiet betroffen sind. Die Schwärzungen erfolgten zudem in allen bis auf drei Fällen aufgrund zu geringer Fallzahlen (weniger als 3 Betriebe oder weniger als 3 Beschäftigte). Diese drei aus Dominanzgründen gesperrten Zellen enthalten zusammen lediglich 160 SVB.

7 Dies war z.B. der Fall in Berlin, das anderenfalls kein südliches, west- und östliches Umland gehabt hätte.

8 In Vorbereitung der Abgrenzung der Metropolregionen haben wir mit unterschiedlichen Angrenzungsmethoden „experimentiert". Die Variante 50 km Radius und mindestens 50 % Überdeckung der Gemeinden durch den Radius hat das plausibelste Ergebnis generiert.

Meter Kantenlänge (basierend auf dem europäischen Gitter INSPIRE), das mit den IEB-Daten aus dem Jahr 2009 verschnitten wurde.

Die untergemeindlichen Rasteranalysen erfolgen im Gegensatz zu den Gemeindeanalysen dabei nicht mehr für alle Metropolregionen, sondern nur beispielhaft für die Stadt und die Metropolregion Stuttgart, deren Außengrenze dabei nicht mit den Außengrenzen der IKM50-Region übereinstimmt.[9] Die Abgrenzung der im Blickpunkt stehenden Metropolregion Stuttgart erfolgte in einem mehrstufigen Prozess: Aus den Arbeitsmarktregionen des Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) wurden alle Gemeinden ausgewählt, deren Hauptpendlerziel die Stadt Stuttgart ist. Anschließend wird jeder dieser Gemeinden mithilfe der Großstadtregionen des BBSR eine Bereichstypik zugeordnet. In der Analyse werden lediglich Gemeinden betrachtet, die als Kernstadt definiert sind, im Ergänzungsbereich oder im engeren Pendlerverflechtungsbereich der Kernstadt liegen.

3.2 Ergebnisse auf Ebene der Städte und Gemeinden

3.2.1 Einordnung der Metropolregionen in den gesamtdeutschen Kontext

Die elf IKM50-Regionen weisen erwartungsgemäß erhebliche raumstrukturelle Unterschiede auf, die in unterschiedlichen Merkmalen zum Ausdruck kommen (vgl. Tabelle 2).

In diesem Beitrag stehen die Beschäftigung und ihre räumliche Verteilung im Fokus. Abbildung 2 erlaubt erste Aufschlüsse bezüglich der Beschäftigungsgrundstrukturen der IKM50-Regionen. Zu betonen ist dabei, dass die hier zum Ausdruck kommenden Unterschiede zugleich das Ergebnis unterschiedlicher Gemeindeflächenstrukturen in den Bundesländern sind (vgl. auch Tabelle 2). Auf gemeindescharfen Datengrundlagen basierende Regionsvergleiche sind daher nur als „tendenzielle Aussagen“ möglich und echte Vergleiche aufgrund unterschiedlicher Gemeindestrukturen nicht zulässig. Beides steht jedoch nicht im Blickpunkt dieses Beitrags.[10]

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9 Der abweichende Raumzuschnitt wurde nötig, da für die IKM50-Abgrenzung nicht flächendeckend untergemeindliche Daten zur Verfügung standen.

10 Unkritisch sind die im Fokus dieser Untersuchung stehenden Längsschnittanalysen. Diese operieren über den gesamten Zeitstrahl mit konstanten Gebietszuschnitten, so dass die von Bundesland zu Bundesland unterschiedlichen Gemeindeflächengrößen hier keine Rolle spielen.

IKM50-Region	Gesamt-fläche	Gemeinden		Bevölkerung		Beschäftigung	
	km²	An-zahl	Ø km²	Mio.	EW je km²	Mio.	Beschäftig-te je km²
Bremen	7.797	152	51,3	1,47	188,4	0,46	59,0
Hamburg	7.244	414	17,5	3,16	436,8	1,12	155,2
Hannover	7.066	140	50,5	2,06	291,3	0,66	92,8
München	7.174	224	32,0	2,81	391,6	1,16	161,8
Nürnberg	10.112	295	34,3	2,17	214,5	0,78	77,3
Rhein-Main	17.260	986	17,5	7,74	448,4	2,76	160,1
Rhein-Ruhr	19.793	559	35,4	13,67	690,9	4,20	212,1
Stuttgart	7.935	322	24,6	4,09	516,1	1,49	187,8
ABL	84.379	3.092	27,3	37,18	440,6	12,6	149,7
Berlin	20.284	271	74,8	5,18	255,2	1,54	75,9
Dresden	7.194	182	39,5	1,58	219,5	0,53	73,7
Leipzig	7.559	325	23,3	1,75	231,9	0,56	73,8
NBL	35.037	778	45,0	8,51	242,8	2,63	75,0

ABL: Alle IKM50-Regionen der alten Bundesländer; NBL: Alle IKM50-Regionen der neuen Bundesländer

Tabelle 2: Strukturdaten der elf IKM50-Regionen für das Jahr 2007 (Quelle: eigene Berechnungen nach Daten der laufenden Raumbeobachtung des Bundesinstituts für Bau-, Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung sowie nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 2007)

Darüber hinausgehende Einsichten erlaubt eine Betrachtung der (Veränderung der) Beschäftigungsanteile nach den einzelnen Metropolregionen (vgl. Tabelle 3). Die Anteile der acht westdeutschen IKM50-Regionen an der Gesamtbeschäftigung der alten Bundesländer schwanken im Jahr 2007 zwischen 2,1 % (Bremen) und 19,3 % (Rhein-Ruhr), in den drei ostdeutschen Metropolregionen schwanken diese Anteile zwischen 10,4 % (Dresden) und 30,1 % (Berlin). In vier von acht westdeutschen Metropolregionen haben die Beschäftigungsanteile seit 1970 abgenommen (Bremen, Hamburg, Hannover, Rhein-Ruhr). Für die Metropolregionen München, Nürnberg, Rhein-Main und Stuttgart kann hingegen ein Anteilsgewinn der Beschäftigung festgestellt werden. Zusammengenommen erfuhren die acht westdeutschen Metropolregionen zwischen 1970 und 2007 jedoch einen Anteilsverlust der Beschäftigung, der maßgeblich auf die Entwicklung in der Metropolregion Rhein-Ruhr zurückzuführen ist. Im Umkehrschluss konnten die nicht-metropolitanen Räume zwischen 1970 und 2007 Beschäftigungsanteilsgewinne verbuchen. Erkennbar wird somit ein großräumiger Dekonzentrationsprozess der Beschäftigung, der sich allerdings in den 2000er-Jahren abgeschwächt oder sogar umgekehrt hat, ließe man die Metropolregion Hannover und Rhein-Ruhr außer Acht.

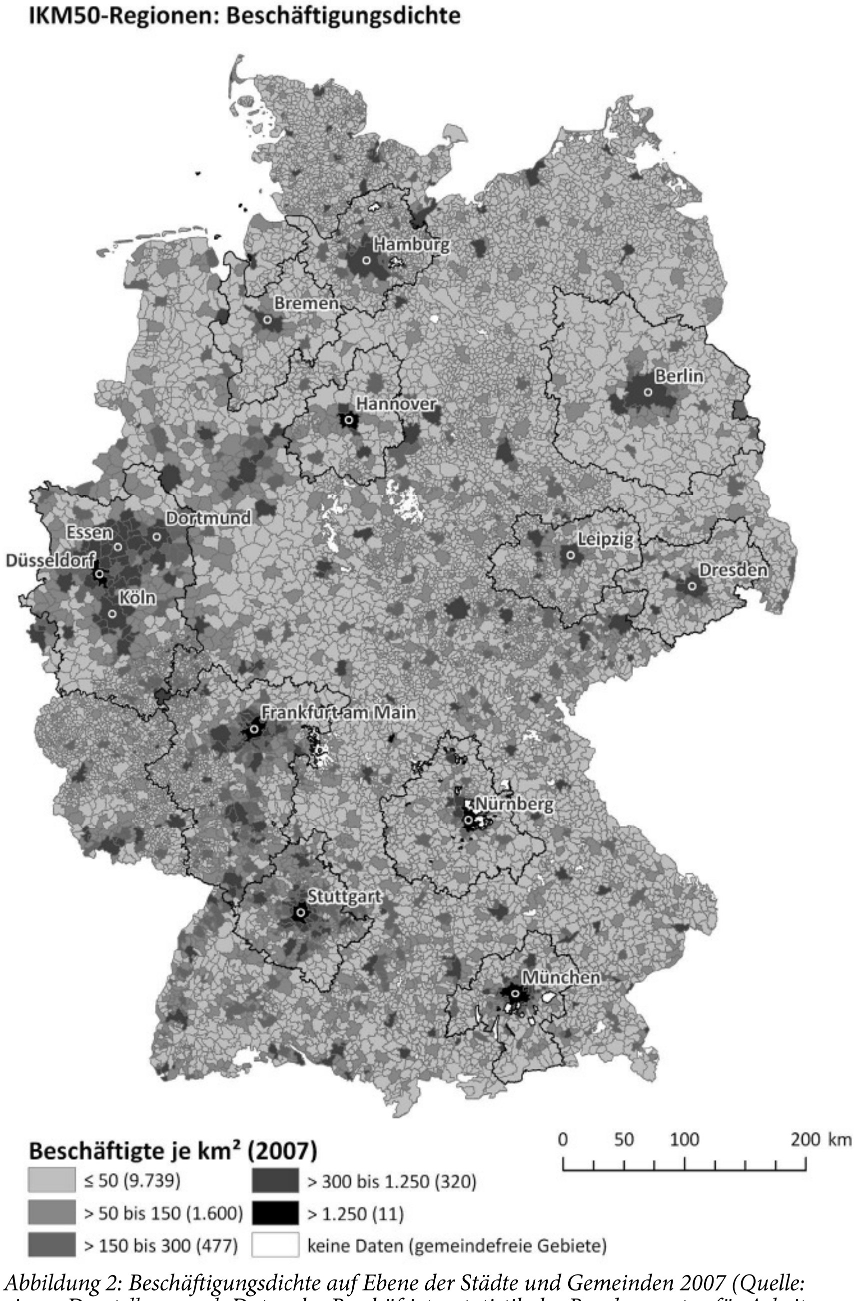

Abbildung 2: Beschäftigungsdichte auf Ebene der Städte und Gemeinden 2007 (Quelle: eigene Darstellung nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 2007)

IKM50-Region	Anteil der Beschäftigten an allen Beschäftigten der alten/neuen Bundesländer (in %)				Jährliche Veränderung des Beschäftigungsanteils (in % / a)			
	1970	1987	1999	2007	70-87*)	87-99	99-07	70-07*)
Bremen	2,2	2,0	2,1	2,1	-0,47	0,36	-0,08	-0,12
Hamburg	5,3	4,8	5,1	5,2	-0,54	0,38	0,30	-0,06
Hannover	3,6	3,2	3,2	3,0	-0,71	-0,09	-0,55	-0,47
München	4,3	5,0	5,0	5,3	0,88	0,10	0,74	0,60
Nürnberg	3,3	3,5	3,5	3,6	0,39	-0,04	0,30	0,23
Rhein-Main	12,5	12,9	12,6	12,7	0,18	-0,18	0,11	0,05
Rhein-Ruhr	22,6	20,7	20,0	19,3	-0,54	-0,25	-0,46	-0,43
Stuttgart	6,7	7,2	6,8	6,9	0,39	-0,40	0,05	0,06
ABL	60,5	59,3	58,3	58,1	-0,12	-0,13	-0,05	-0,11
Berlin	(-)	(-)	28,6	30,1	(-)	(-)	0,62	(-)
Dresden	(-)	(-)	9,9	10,4	(-)	(-)	0,51	(-)
Leipzig	(-)	(-)	11,1	10,9	(-)	(-)	-0,25	(-)
NBL	(-)	(-)	49,7	51,4	(-)	(-)	0,41	(-)

ABL: Alle IKM50-Regionen der alten Bundesländer; NBL: Alle IKM50-Regionen der neuen Bundesländer
*) Ein Vergleich der gekennzeichneten Veränderungsraten ist mit Vorsicht zu treffen, da die Grundgesamtheiten nicht identisch sind (vgl. Kap. 3.1.2)

Tabelle 3: Entwicklung der Beschäftigungsanteile im Zeitraum (1970-1987-) 1999-2007 (Quelle: eigene Berechnungen nach Daten der Volks- und Arbeitsstättenzählung 1970 und 1987 sowie nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 1999 und 2007)

3.2.2 Beschäftigungspolyzentralität der Metropolregionen

Erste Einschätzungen zum Grad und zur Veränderung der Beschäftigungspolyzentralität der Metropolregionen vermittelt der Hoover-Index, den wir analog zu Riguelle, Thomas & Verhetsel (2007: 199) als berechnen. Dabei repräsentiert den Anteil der Beschäftigung in Gemeinde an der Gesamtbeschäftigung der Metropolregion und den Flächenanteil der Gemeinde an der Gesamtfläche aller Gemeinden der Metropolregion.

Die Werte für das Jahr 2007 belaufen sich in den eher monozentrischen Metropolregionen mit einer dominanten Kernstadt (Berlin, Hamburg, München) auf 0,730, 0,677 und 0,687, womit 73,0 %, 67,7 % bzw. 68,7 % der Beschäftigung umverteilt werden müsste, um eine „flächenproportionale“ Beschäftigungsverteilung in den Untersuchungsräumen zu erlangen (vgl. Tab. 3). In den eher polyzentrischen Metropolregionen mit mehreren Kern- und beschäftigungsstarken Mittelstädten ist der Hoover-Index erwartungsgemäß deutlich niedriger, aber dennoch recht hoch mit Werten von ca. 0,5. Die angenommen raumstrukturellen Konfigurationen lassen sich folglich mit den Hoover-Indizes auch quantitativ nachweisen.

IKM50-Region	Hoover-Index: Absolute Beschäftigung				Jährliche Veränderung des Hoover-Index (in % / a)			
	1970	1987	1999	2007	70-87*)	87-99	99-07	70-07*)
Bremen	0,656	0,628	0,597	0,594	-0,26	-0,42	-0,05	-0,27
Hamburg	0,729	0,698	0,678	0,677	-0,26	-0,24	-0,02	-0,20
Hannover	0,585	0,576	0,559	0,557	-0,09	-0,25	-0,05	-0,13
München	0,732	0,713	0,690	0,687	-0,15	-0,27	-0,06	-0,17
Nürnberg	0,675	0,656	0,630	0,631	-0,17	-0,34	0,03	-0,18
Rhein-Main	0,573	0,566	0,555	0,558	-0,07	-0,16	0,07	-0,07
Rhein-Ruhr	0,547	0,515	0,498	0,493	-0,35	-0,28	-0,12	-0,28
Stuttgart	0,548	0,533	0,510	0,511	-0,15	-0,38	0,03	-0,19
Berlin	(-)	(-)	0,720	0,730	(-)	(-)	0,18	(-)
Dresden	(-)	(-)	0,572	0,587	(-)	(-)	0,33	(-)
Leipzig	(-)	(-)	0,574	0,588	(-)	(-)	0,30	(-)

*) Ein Vergleich der gekennzeichneten Veränderungsraten ist mit Vorsicht zu treffen, da die Grundgesamtheiten nicht identisch sind (vgl. Kap. 3.1.2).

Tabelle 4: Entwicklung des Hoover-Index im Zeitraum (1970-1987-)1999-2007 (Quelle: eigene Berechnungen nach Daten der Volks- und Arbeitsstättenzählung 1970 und 1987 sowie nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 1999 und 2007)

Der Hoover-Index sinkt im Zeitverlauf in allen westdeutschen Metropolregionen. Gravierende Unterschiede zwischen eher mono- und eher polyzentrisch geprägten Metropolregionen äußern sich nicht. Dies ist Ausdruck der über Jahrzehnte wirkenden Beschäftigungssuburbanisierung. Am stärksten fiel die Dekonzentration der Beschäftigung in den Metropolregionen Bremen und Rhein-Ruhr aus, was sicher auf den wirtschaftlichen Strukturwandel und die starken Beschäftigungsverluste im produzierenden Sektor, weniger auf das Wachstum der suburbanen Beschäftigung zurückgeht.

Eine Differenzierung der einzelnen Zeitabschnitte weist auf eine Abschwächung der Dekonzentrationstendenz in der letzten Bilanzperiode hin (1999-2007). In fünf von acht westdeutschen Metropolregionen sinkt das Maß weiter, allerdings mit deutlich geringerer Intensität (Bremen, Hamburg, Hannover, München, Rhein-Ruhr), in den übrigen drei steigt es sogar (Nürnberg, Rhein-Main, Stuttgart). Auch in den drei ostdeutschen Metropolregionen nimmt der Hoover-Index zwischen 1999 und 2007 zu, womit sich die Beschäftigung in dem achtjährigen Beobachtungszeitraum zunehmend ungleich verteilt. Interessant ist, dass der steigende Hoover-Index lediglich in einigen polyzentrischen Regionen zu verzeichnen ist, die klassisch monozentrischen hingegen weiter von Dekonzentrationsprozessen betroffen sind.

Weitere Aufschlüsse ermöglicht das globale Moran's I. Es deutet in allen Metropolregionen und Zeitpunkten auf eine signifikante, positive Autokorrelation hin (vgl. Tabelle 5). Zu berücksichtigen ist, dass es im Gegensatz zum

Hoover-Index für die Beschäftigungsdichte und nicht für die absoluten Zahlen berechnet wurde.[11] Die Beschäftigungsverteilung der Städte und Gemeinden neigt gemäß den Hoover-Indizes zu räumlicher Konzentration. Städte und Gemeinden mit ähnlichen Beschäftigungsdichtewerten liegen darüber hinaus tendenziell in räumlicher Nähe zueinander und formen Cluster (vgl. Moran's I). Im Längsschnitt nimmt das globale Moran's I in allen westdeutschen Untersuchungsräumen zwischen 1970 und 2007 teils beträchtlich zu. Auch hier zeigt sich ein „Luftholen“ zwischen 1999 und 2007. In fünf von acht Metropolregionen nimmt die Kennziffer ab (Bremen, Nürnberg, Rhein-Main, Rhein-Ruhr, Stuttgart), in den verbleibenden drei nimmt sie zu (Hamburg, Hannover, München). In den ostdeutschen Metropolregionen Berlin und Dresden nimmt sie zwischen 1999 und 2007 ebenfalls zu, in Leipzig nimmt sie ab. Inwiefern die Diskrepanz zwischen Hoover-Index (Abnahme) und globalem Moran's I (Zunahme) in den monozentrischen Metropolregionen Hamburg und München ein Artefakt der unterschiedlichen Berechnungsgrundlagen ist, soll an dieser Stelle nicht im Detail weiter verfolgt werden. Denkbar ist, dass die Beschäftigungsdichte stärker räumlich konzentriert ist als die absolute Beschäftigung. In beiden Metropolregionen weisen die Kernstädte einen sehr hohen Flächenanteil an der Gesamtregion auf, während aber innerhalb der Gemeinde auch Gegenden sehr niedriger Beschäftigung existieren, so dass das Dichtemaß nicht in dem Ausmaß auffällig ist wie die absoluten Zahlen.

Die im Zeitverlauf überwiegend steigenden Werte des globalen Moran's I lassen sich auch als Herausbildung eines polyzentrischen Standortmusters der Beschäftigungsdichte interpretieren. Wie sich diese Standortmuster dabei konkret verorten lassen, kann das globale Moran's I nicht darstellen. Letzteres kann mit dem lokalen Moran's I und den korrespondierenden LISA-Cluster Maps deutlicher herausgearbeitet werden.

Abbildung 3 zeigt am Beispiel der Metropolregion Stuttgart die absoluten Werte bezüglich der Beschäftigungsdichte sowie die angesprochene Visualisierung der lokalen Moran's I Werte. Im unteren Teil ist die räumliche Verteilung der Gemeinden dargestellt, die gemäß der False Discovery Rate (FDR) statistisch signifikant sind, basierend auf einem pseudo-p-Wert < 0,05 und nach 9.999 Permutationen u.a. als High-High-Cluster (schwarz) oder High-Low-Ausreißer (mittelgrau) bewertet wurden und damit als potenzielle Zentren bzw. Subzentren anzusehen sind.[12]

11 Hierdurch werden die unterschiedlichen Flächengrößen der Städte und Gemeinden relativiert. Beim Hoover-Index war dies inhaltlich nicht sinnvoll.

12 Für Details zur Begründung und Berechnung der FDR siehe Caldas de Castro & Singer (2006: 186), zum Permutationsansatz und resultierenden pseudo-p-Wert siehe Anselin (1995: 102).

IKM50-Region	Globales Moran's I: Beschäftigungsdichte				Jährliche Veränderung des globalen Moran's I (in % / a)			
	1970	1987	1999	2007	70-87*)	87-99	99-07	70-07*)
Bremen	0,144	0,122	0,180	0,162	-0,96	3,28	-1,30	0,32
Hamburg	0,215	0,297	0,299	0,339	1,92	0,05	1,58	1,24
Hannover	0,076	0,109	0,186	0,197	2,16	4,57	0,70	2,62
München	0,346	0,431	0,522	0,535	1,30	1,62	0,30	1,19
Nürnberg	0,311	0,349	0,370	0,331	0,68	0,48	-1,37	0,17
Rhein-Main	0,393	0,477	0,504	0,498	1,14	0,47	-0,17	0,64
Rhein-Ruhr	0,537	0,571	0,572	0,568	0,36	0,02	-0,09	0,15
Stuttgart	0,347	0,376	0,410	0,399	0,47	0,72	-0,31	0,38
Berlin	(-)	(-)	0,442	0,473	(-)	(-)	0,83	(-)
Dresden	(-)	(-)	0,212	0,216	(-)	(-)	0,21	(-)
Leipzig	(-)	(-)	0,117	0,113	(-)	(-)	-0,37	(-)

Alle pseudo p-Werte < 0,001 nach 9.999 Permutationen. Als Nachbarschaftsdefinition wurde die sogenannte Queen contiguity erster Ordnung verwendet, bei der Gemeinden mit gemeinsamer Grenze oder gemeinsamem Knoten als benachbart gelten.
*) Ein Vergleich der gekennzeichneten Veränderungsraten ist mit Vorsicht zu treffen, da die Grundgesamtheiten nicht identisch sind (vgl. Kap. 3.1.2).

Tabelle 5: Entwicklung des globalen Moran's I im Zeitraum (1970-1987-)1999-2007 (Quelle: eigene Berechnungen nach Daten der Volks- und Arbeitsstättenzählung 1970 und 1987 sowie nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 1999 und 2007)

Deutlich wird bei der Betrachtung der (oberer Teil), dass sich in dem Metropolregionskern ein zusammenhängender Standortraum, bestehend aus Gemeinden mit hoher Beschäftigungsdichte, herausgebildet hat. Dessen räumliche Konfiguration hat sich seit 1970 nicht tiefgreifend verändert. Zwar hat gemäß der in Tabelle 6 zusammengestellten Auszählungen die Anzahl der High-High Gemeinden neben Stuttgart in fast allen Metropolregionen zwischen 1970 und 2007 zugenommen, was Ausdruck einer räumlichen Expansion des verdichteten oftmals bereits in Ansätzen polyzentrisch strukturierten Kernraums ist. Gemessen an der Gesamtzahl der jeweils regionszugehörigen Gemeinden fallen die Verschiebungen der relativen Positionen der einzelnen Gemeinden aber moderat aus, denn es handelt sich um einen Zeitraum von fast 40 Jahren (vgl. unterer Teil). Insgesamt bestätigen diese Analysen und die Abbildung 3 für den Stuttgarter Raum frühere Arbeiten, wonach sich die Entstehung bzw. Verfestigung suburbaner Beschäftigungszentren häufig auf einen räumlich vergleichsweise eng begrenzten Randbereich um die Kernstädte erstreckt (siehe z.B. Siedentop et al. 2003).

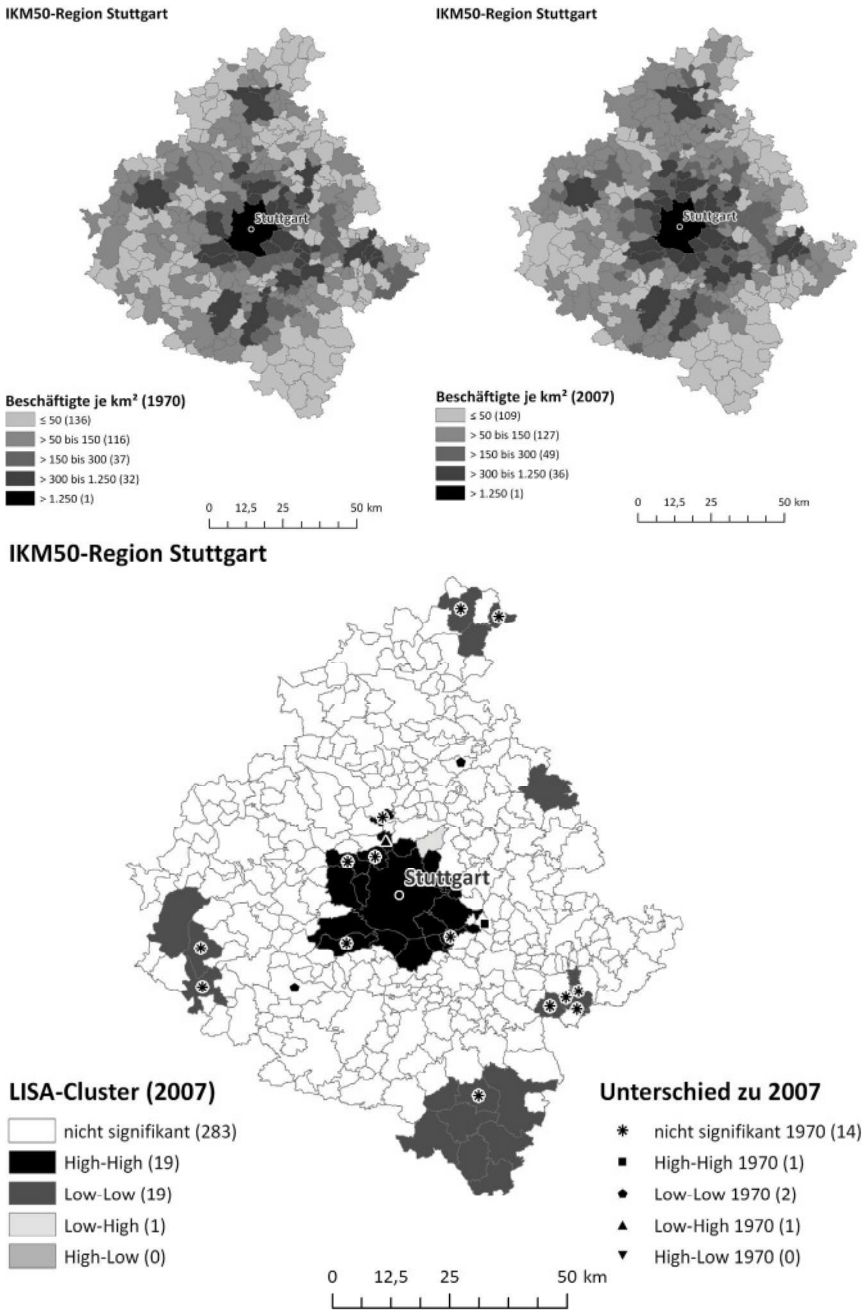

Abbildung 3: Beschäftigungsdichte für die Jahre 1970 und 2007 und LISA-Cluster-Map 2007 für die Metropolregion Stuttgart (Quelle: eigene Darstellung nach Daten der Volks- und Arbeitsstättenzählung 1970 sowie nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 2007)

IKM50-Region	*Anzahl der Gemeinden in der Region*	*Anzahl der Gemeinden im LISA-Cluster*							
		High-High		*Low-Low*		*Low-High*		*High-Low*	
		1970	*2007*	*1970*	*2007*	*1970*	*2007*	*1970*	*2007*
Bremen	*152*	*3*	*5*	*0*	*0*	*2*	*0*	*1*	*0*
Hamburg	*414*	*16*	*16*	*4*	*4*	*3*	*5*	*0*	*0*
Hannover	*140*	*0*	*5*	*4*	*3*	*0*	*1*	*0*	*1*
München	*224*	*17*	*17*	*2*	*4*	*4*	*0*	*2*	*0*
Nürnberg	*295*	*5*	*7*	*1*	*3*	*0*	*1*	*0*	*0*
Rhein-Main	*986*	*37*	*30*	*47*	*55*	*2*	*1*	*6*	*4*
Rhein-Ruhr	*559*	*45*	*46*	*42*	*47*	*1*	*1*	*1*	*3*
Stuttgart	*322*	*14*	*19*	*12*	*19*	*2*	*1*	*0*	*0*

Die Differenz zur Gesamtzahl aller Gemeinden einer Region gibt die Anzahl der Gemeinden an, die als statistisch nicht signifikant betrachtet und damit keinem LISA-Cluster zugeordnet wurden.

Tabelle 6: Entwicklung der Beschäftigungsdichte in den IKM50-Regionen der altenBundesländer zwischen 1970 und 2007 am Beispiel der absoluten Veränderung der einem LISA-Cluster zugehörigen Gemeinden (Quelle: eigene Berechnungen nach Daten der Volks- und Arbeitsstättenzählung 1970 und 1987 sowie nach Daten der Beschäftigtenstatistik der Bundesagentur für Arbeit 1999 und 2007; Zuordnung der Gemeinden zu LISA-Clustern gemäß False Discovery Rate, basierend auf einem pseudo-p-Wert < 0,05 und nach 9.999 Permutationen)

3.3 Ergebnisse auf Basis von Gitterzellen

3.3.1 Regionsebene

Die Metropolregion Stuttgart wird nun zusätzlich mithilfe untergemeindlicher Daten auf ihre polyzentrische Raumstruktur untersucht. Abbildung 4 gibt einen ersten Überblick über die Verteilung der sozialversicherungspflichtig Beschäftigten. Die Globalmaße Hoover-Index und globales Moran's I ermöglichen darüber hinaus quantitative Einblicke in die Verteilung der absoluten Beschäftigung sowie der Beschäftigungsdichte innerhalb der Metropolregion.[13] Der Wert des Hoover-Index beträgt 0,52: Es müssten folglich 52 % der SVB umverteilt werden, um eine „flächenproportionale" Beschäftigung zu erreichen. Daraus kann zunächst geschlossen werden, dass die Beschäftigungsdichte in der Metropolregion recht konzentriert ist. Das globale Moran's I ist für die Untersuchungsregion signifikant zum 0,1 %-Niveau (pseudo-p-Wert nach 9.999 Permutationen) und weist auf positive räumliche Autokorrelation hin. Dies bestätigt die Ergebnisse des Hoover-Index und ergänzt sie dahingehend, dass es Cluster hoher und niedriger Beschäftigungsdichte innerhalb der

13 Im Fall der hier vorliegenden Gitterzellen sind die Beschäftigung je km^2 (Beschäftigungsdichte) und die Absolutwerte der Beschäftigung je Rasterzelle konstruktionsbedingt identisch, da jede Rasterzelle 1 km^2 umfasst. Abweichungen ergeben sich lediglich am Regionsrand, wo die Zellen nur unvollständig erfasst werden.

Metropolregion gibt. Beides bestätigt ebenso die visuellen Einschätzungen basierend auf Abbildung 4.

Mithilfe des lokalen Moran's I und seiner Darstellung in einer LISA-Cluster-Map kann die räumliche Lage der Cluster sichtbar gemacht werden (Abb. 5).[14] In unserer Analyse betrachten wir lediglich High-High und High-Low als potenzielle Beschäftigungszentren bzw. Subzentren.

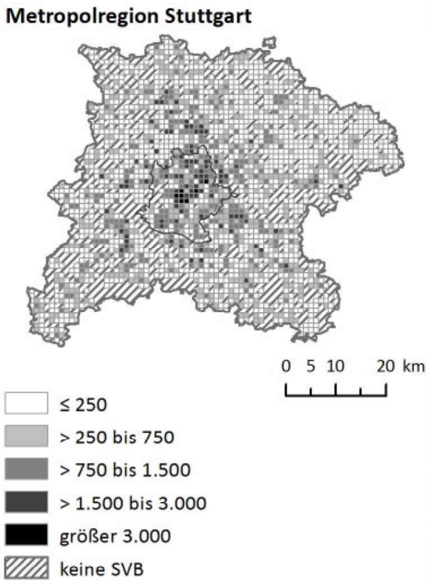

Abbildung 4: Sozialversicherungs-pflichtige Beschäftigung in der Metropolregion Stuttgart (Quelle: eigene Darstellung nach Daten der georeferenzierten IEB des Querschnitts 2009)

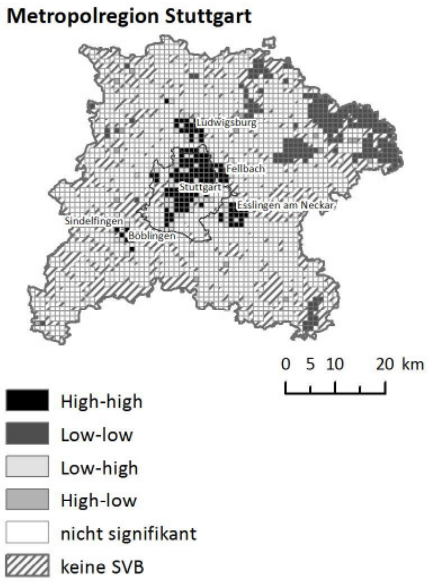

Abbildung 5: LISA-Cluster-Map auf Basis von Gitterzellen in der Metropolregion Stuttgart (Quelle: eigene Darstellung nach Daten der georeferenzierten IEB des Querschnitts 2009)

Es zeigt sich, dass die Beschäftigung insbesondere in der Stadt Stuttgart (vgl. Gemeindeumrisse Abb. 4 und 5) sowie in einigen Clustern benachbarter Gemeinden konzentriert ist. Hierbei handelt es sich hauptsächlich um die Mittelzentren Böblingen/Sindelfingen, Esslingen, Fellbach und Ludwigsburg. Ein zweites Ergebnis bezieht sich auf die Verteilung der SVB innerhalb der Kernstadt. Eine Konzentration auf die historische Innenstadt und ihren unmittelbaren Randbereich ist nicht erkennbar. Vielmehr haben sich auch randstädtische

14 Die Signifikanz wird ebenfalls mit der FDR basierend auf einem pseudo-p-Wert < 0,05 und 9.999 Permutationen festgestellt. Als Nachbarschaft wurde die queen contiguity zweiter Ordnung gewählt. Damit haben räumliche Übertragungseffekte annahmegemäß einen größeren Einflussbereich als ca. 1 km Umkreis (queen contiguity erster Ordnung, angewendet auf 1 km² große Gitterzellen). Als Nachbarn werden hier folglich der erste und zweite Ring um die jeweils betrachtete Rasterzelle bezeichnet.

Lagen (z.B. Vaihingen am Südrand der Kernstadt) als intra-städtische Subzentren mit erheblichen Beschäftigungsdichten etablieren können.

3.3.2 Stadtebene

Dieses Bild wandelt sich, wenn von der regionalen auf die städtische Ebene gewechselt wird. Dies liegt daran, dass der Fokus jetzt auf einem Gebietsausschnitt liegt, in dem viele beschäftigungsreiche Gitterzellen liegen. Der Hoover-Index sinkt auf einen Wert von 0,40 und weist damit auf eine weniger stark konzentrierte Beschäftigungsverteilung in der Stadt Stuttgart im Vergleich zur Metropolregion Stuttgart hin, was auch den Erkenntnissen aus Abbildung 6 entspricht.

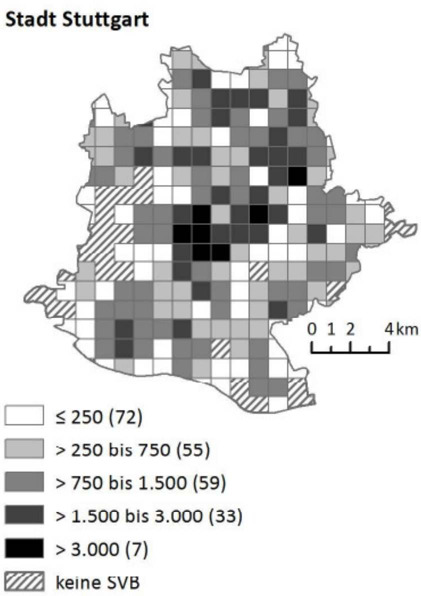

Abbildung 6: Sozialversicherungs-pflichtig Beschäftigte in der Stadt Stuttgart (Quelle: Eigene Darstellung nach Daten der georeferenzierten IEB 2009)

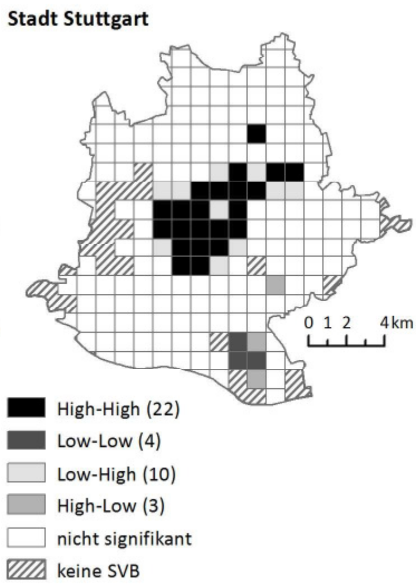

Abbildung 7: LISA-Cluster-Map auf Basis von Gitterzellen für die Stadt Stuttgart (Quelle: Eigene Darstellung nach Daten der georeferenzierten IEB 2009)

Das globale Moran's I ist auch hier signifikant zum 0,1 %-Niveau (pseudo-p-Wert nach 9.999 Permutationen) und zeigt positive räumliche Autokorrelation an. In der LISA-Cluster-Map (Abb. 7) fällt auf, dass im Vergleich zur Regionsanalyse in der Stadt Stuttgart deutlich weniger Gitterzellen als High-High-Cluster ausgewiesen werden. Dies liegt unter anderem daran, dass eine veränderte Datengrundlage (226 statt 2.029 Gitterzellen) verwendet wurde. Auf der untergemeindlichen Ebene – das zeigt die LISA-Cluster-Map – tritt die Dominanz des historischen Zentrums als Beschäftigungsschwerpunkt viel deutlicher hervor als auf der regionalen Ebene. Der Südrand der Stadt fällt in der LISA-

Cluster-Map trotz seiner hohen Beschäftigungsdichte nicht als signifikant auf. Dies liegt daran, dass das lokale Moran's I jede Rasterzelle im Kontext ihrer definierten Nachbarschaft betrachtet und nur dann Signifikanz anzeigt, wenn die betrachtete Rasterzelle sich deutlich von ihren Nachbarn abhebt. Das ist hier nicht der Fall (vgl. auch Abb. 5). Weiterhin muss die vermutete Überschätzung der Konzentration aufgrund der oben angesprochenen Erfassung der Arbeitsstätten der Beschäftigten bei der Interpretation berücksichtigt werden. Dies könnte sich auf innerstädtischer Ebene deutlicher bemerkbar machen als auf Ebene der Metropolregion und ein Grund für die ausgeprägtere Innenstadtdominanz sein.

4 Zusammenfassung und Ausblick

In diesem Beitrag wurden verschiedene Methoden zur Messung der Polyzentralität der Beschäftigungs(dichte)verteilung vorgestellt und für elf deutsche Metropolregionen angewendet. Unterschieden wurden dabei Methoden, die den Grad der Polyzentralität in einer Maßzahl ausdrücken (Globalmaße) und Methoden, mit denen sich eine binnenräumlich differenzierte Charakterisierung der Zentrenstruktur eines Raumes vornehmen lässt (Lokalmaße). Die verfügbare Datenbasis erlaubt zum einen eine längsschnittanalytische Betrachtung der raumstrukturellen Veränderungen auf Ebene von Städten und Gemeinden über einen Zeitraum von fast 40 Jahren, zum anderen differenzierte Analysen der Standortstrukturen auf untergemeindlicher Ebene.

Die erzielten empirischen Ergebnisse belegen einen Trend der Beschäftigungsdekonzentration, der mit einer tendenziellen Verfestigung polyzentrischer Raumstrukturen auf der Gemeindeebene einhergeht. In allen untersuchten Metropolregionen war der Grad der Beschäftigungskonzentration im Jahr 2007 geringer als im Jahr 1970. In dieser Zeit entstanden neue suburbane Beschäftigungszentren oder die im Jahr 1970 bereits existierenden (Sub)Zentren konnten ihre Bedeutung behaupten bzw. ausbauen. Die Daten deuten ferner darauf hin, dass diese Subzentren häufig in enger Nachbarschaft zueinander bzw. zur Kernstadt entstanden sind. Während die absolute Beschäftigung auf Ebene der Gitterzellen nach visueller Einschätzung sowohl als polyzentrisch als auch als eher dispers gewertet werden kann, zeigt sich bei der Betrachtung der LISA-Cluster-Map eine recht eindeutig polyzentrische Struktur, wenngleich sich die identifizierten Beschäftigungsschwerpunkte auch – ähnlich wie auf der Gemeindeebene – auf die Kernstadt sowie ihre engere Nachbarschaft konzentrieren.

Zugleich muss konstatiert werden, dass die Bedeutung der Kernstädte als regionale Beschäftigungszentren nach wie vor hoch ist. Nach einer vergleichsweise stürmischen Phase der Suburbanisierung in den 1990er Jahren ist die Dekonzentration der Beschäftigung in den Jahren zwischen 1999 und 2007 in der Mehrzahl der Metropolregionen weitgehend zum Stillstand gekommen; in einigen Metropolregionen lassen sich sogar leichte Konzentrationsprozesse ausmachen. Ob letzteres als ein Indiz für eine ökonomische Reurbanisierung zu werten ist, muss an dieser Stelle offen bleiben. Für deutsche Metropolregionen kann allerdings nicht von einer weiteren „Auflösung" der Raumstrukturen im Sinne einer immer stärker dispers geprägten Beschäftigungsdichteverteilung ausgegangen werden. Die räumliche Verteilung der Beschäftigung zeigt vielmehr eine bemerkenswerte Persistenz, was aus ökonomischer Perspektive als andauernde Wettbewerbsfähigkeit der Standorte interpretiert werden kann, die sich historisch als Beschäftigungsschwerpunkte etablieren konnten. Kurz gefasst: Die Metropolregionen sind in den 1970er bis 1990er Jahren polyzentrischer geworden, ohne dass dies aber die bereits bis 1970 herausgebildete Zentrenstruktur maßgeblich überformt hätte.

Mit Blick auf den sich seit 1999 abzeichnenden Trendbruch erscheint es fraglich, ob für die Zukunft von einer weiteren Dekonzentration und Dispersion der Beschäftigung auszugehen ist. Aufgrund der zunehmenden Bedeutung von „Wissen" als Produktionsfaktor in der post-industriell geprägten Ökonomie (siehe z.B. Storper & Venables 2004) könnte auch ein Bedeutungsgewinn der überkommenen Zentrenstandorte, vor allem der Kern- und Innenstädte mit ihrer hohen sozialen Kontaktdichte, erwartet werden. Wie für Stuttgart exemplarisch aufgezeigt, haben sich neben den Kern- und Innenstädten aber auch suburbane Gemeinden mit guter Erreichbarkeit im Standortwettbewerb behauptet. Diese genießen durch ihre zentrumsnahe räumliche Lage offenbar Agglomerationsvorteile, ohne von typischen Agglomerationsnachteilen wie hohen Immobilienpreisen, Flächenknappheit oder Verkehrsproblemen wie die Innenstadtlagen betroffen zu sein. Wahrscheinlich ist somit insgesamt ein Konsolidierungsprozess der Raumstruktur, der mit graduellen Bedeutungsverschiebungen innerhalb des Zentrensystems, weniger dagegen mit der Entstehung ganz neuer Zentrenstandorte, einhergehen wird.

Ein weiteres Hauptergebnis dieses Beitrages ist, dass inter-urban polyzentrische Metropolregionen und solche mit stärkerer monozentrischer Prägung keine auffälligen Unterschiede hinsichtlich der Dynamik von Dekonzentrationsprozessen zeigen. Wohl aber lässt sich zeigen, dass die räumliche Ausdehnung des High-High-Clusters in polyzentrischen Räumen deutlich größer ist. Desgleichen scheinen erste Anzeichen ökonomischer Reurbanisierungsprozesse – identifiziert über ein in der letzten Bilanzperiode steigenden Hoover-Index – sich eher in polyzentrisch geprägten Regionen zu zeigen.

Des Weiteren konnte mit dem Vergleich der unterschiedlichen räumlichen Ebenen die Skalenabhängigkeit der Polyzentralität exemplarisch für Stuttgart nachgewiesen werden. Während sich auf regionaler Ebene der Gemeinden ein High-High-Cluster in enger räumlicher Nähe abzeichnet, zeigt sich auf der intra-regionalen Ebene der Gitterzellen ein deutlich inhomogeneres Bild. Betätigt wird dieser visuelle Eindruck von den Globalmaßen Hoover-Index und globa-

lem Moran's I. Diese Ergebnisse finden sich auch in anderen Untersuchungen zu sowohl morphologischer als auch hier nicht betrachteter funktionaler Polyzentralität (vgl. Vasanen 2013: 412).
Ein Nachteil der in diesem Beitrag präsentierten Ergebnisse ist ihre eingeschränkte Belastbarkeit für querschnittanalytische Fragestellungen. Da die Gemeindegrößenstrukturen in erheblicher Weise Einfluss nehmen auf den errechneten Grad der Polyzentralität, unterliegen Vergleiche zwischen Metropolregionen erheblichen Einschränkungen. Die stärkere Nutzung rasterbasierter Anwendungen könnte dies allerdings mittel- bis langfristig überwinden.

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Erratum zum Band „Polyzentrale Metropolregionen“

Die gedruckte Version der ersten Auflage des Bandes enthält (gegenüber der Originalversion) bedauerlicherweise in zwei Beiträgen Fehler.

Stefan Siedentop, Angelika Krehl, Dennis Guth & Christian Holz-Rau: Morphologische Polyzentralität der Beschäftigung in deutschen Metropolregionen – Aktuelle Befunde und Veränderungen seit 1970, S. 45-75

1) Seite 62, erster Absatz des Kapitels 3.2.2: In diesem Absatz fehlt eine mathematische Formel. Die korrekte Fassung des Absatzes lautet (Korrekturen sind in Fettdruck hervorgehoben):

Erste Einschätzungen zum Grad und zur Veränderung der Beschäftigungspolyzentralität der Metropolregionen vermittelt der Hoover-Index, den wir analog zu Riguelle, Thomas & Verhetsel (2007: 199) als $H = 0{,}5 * \sum_{(i=1)}^{n} |X_i - Y_i|$ berechnen. Dabei repräsentiert $\boldsymbol{X_i}$ den Anteil der Beschäftigung in Gemeinde $\boldsymbol{i}$ an der Gesamtbeschäftigung der Metropolregion und $\boldsymbol{Y_i}$ den Flächenanteil der Gemeinde $\boldsymbol{i}$ an der Gesamtfläche aller Gemeinden der Metropolregion.

2) Seite 62, zweiter Absatz des Kapitels 3.2.2: In diesem Absatz wird auf eine falsche Tabelle verwiesen. Die korrekte Fassung des Absatzes lautet (Korrekturen sind in Fettdruck hervorgehoben):

Die Werte für das Jahr 2007 belaufen sich in den eher monozentrischen Metropolregionen mit einer dominanten Kernstadt (Berlin, Hamburg, München) auf 0,730, 0,677 und 0,687, womit 73,0 %, 67,7 % bzw. 68,7 % der Beschäftigung umverteilt werden müsste, um eine „flächenproportionale“ Beschäftigungsverteilung in den Untersuchungsräumen zu erlangen (vgl. Tab. **4**).

3) Seite 65, erster Satz sowie vierter Satz nach Tabelle 5: In diesem Absatz fehlen Verweise auf eine Abbildung. Die korrekten Fassungen der Absätze lauten (Korrekturen sind in Fettdruck hervorgehoben):

Satz 1: Deutlich wird bei der Betrachtung der **Abbildung 3** (oberer Teil), dass sich in dem Metropolregionskern ein zusammenhängender Standortraum, bestehend aus Gemeinden mit hoher Beschäftigungsdichte, herausgebildet hat.

Satz 4: Gemessen an der Gesamtzahl der jeweils regionszugehörigen Gemeinden fallen die Verschiebungen der relativen Positionen der einzelnen Gemeinden aber moderat aus, denn es handelt sich um einen Zeitraum von fast 40 Jahren (vgl. **Abb. 3**, unterer Teil).

Die bauliche Dichte der Stadtregion – Erzeugung kleinräumiger Dichtedaten mit fernerkundlichen Mitteln

Stefan Siedentop, Angelika Krehl, Hannes Taubenböck, Michael Wurm

Zusammenfassung

Die unbestrittene Bedeutung der baulichen Dichte als normative und deskriptive Größe in der Raumplanung sowie den Raumwissenschaften und benachbarten Disziplinen steht in bemerkenswertem Kontrast zur mangelnden Verfügbarkeit qualifizierter Daten. So war es bislang nicht möglich, gebräuchliche Dichteindikatoren wie die Geschossflächendichte für größere Gebietskulissen verlässlich zu ermitteln. Das sich ständig weiterentwickelnde Datenangebot der Fernerkundung kann jedoch dazu beitragen, diese Leerstelle in der laufenden Beobachtung der Stadt- und Regionalentwicklung zu schließen. In diesem Beitrag wird ein methodischer Ansatz präsentiert, mit dem aus fernerkundlich erzeugten Gebäudemodellen Dichteinformationen abgleitet werden. Der für vier Regionen erprobte Ansatz ermöglicht es, Ver- und Entdichtungsprozesse in Stadtregionen zukünftig einem systematischen Monitoring zu unterziehen.

1 Einführung

In der Raumplanung fungiert die bauliche Dichte als eines der wichtigsten Maße zur Steuerung der städtebaulichen Entwicklung. In qualifizierten Bebauungsplänen finden sich regelmäßig verbindliche Regelungen zum Umfang der überbaubaren Grundstücksfläche (Grundflächenzahl, GRZ) sowie zum maximalen oder minimalen Umfang der realisierbaren Geschossfläche (Geschossflächenzahl, GFZ) eines Grundstücks. Mit diesbezüglichen städtebaulichen Festsetzungen lassen sich wichtige Rahmenbedingungen für eine nachhaltige Stadt- und Quartiersentwicklung treffen, da sowohl flächenextensive Bodennutzungsformen als auch eine „Überverdichtung“ unterbunden werden können (Bott, Siedentop 2013, 98 ff.). Dichtebezogenen Planungsaussagen kommt zudem erhebliche Bedeutung für den Wert von Grundstücken zu. Vor diesem Hintergrund kann es nicht verwundern, dass die planungsrechtliche Regulierung der Dichte nicht selten Gegenstand rechtlicher Auseinandersetzungen sowie kontroverser öffentlicher Diskussion ist. Dabei zeigt sich, dass die Wahrnehmung und Bewertung von Dichte in hohem Maß kulturellen und sozialen Prägungen unterliegt (Acioly, Davidson 1996, 6). Ein objektiver Maßstab, mit dem bauliche oder nutzungsbezogene Dichten als „hoch“ oder „gering“ zu bewerten sind, existiert nicht.

Das Maß der Verdichtung einer Stadt ist aber nicht nur ein planungspraktisch und lebensweltlich relevantes Thema, auch die Stadt- und Regionalforschung hat sich immer wieder – sowohl aus theoretischer wie aus empirischer Perspektive – mit dem Phänomen „Dichte“ beschäftigt (einen Überblick gibt Westphal 2008). Die bauliche Dichte und mit dieser korrespondierende Nutzungsdichten (z. B. die Bevölkerungs- und Arbeitsplatzdichte) gelten beispielsweise als Schlüsselfaktoren bei der Erklärung von standörtlichen Unterschieden des Verkehrs- und Bewegungsverhaltens der Bevölkerung (Ewing, Cervero 2010; Kelly-Schwartz et al. 2004; Newman, Kenworthy 1989), der Wirtschaftlichkeit technischer Infrastrukturen (siehe z. B. Siedentop et al. 2006, 6 ff.) oder lokalen und regionalen Umweltbedingungen wie lufthygienischen oder mikroklimatischen Belastungen (Koppe et al. 2004).

Die unbestrittene Bedeutung von „Dichte“ als normative und deskriptive Größe in der Raumplanung sowie den Raumwissenschaften steht im bemerkenswerten Kontrast zur mangelnden Verfügbarkeit qualifizierter Daten zur baulichen Verdichtung besiedelter Flächen. Vor diesem Hintergrund stellt dieser Beitrag einen neuen methodischen Ansatz zur Ermittlung der baulichen Dichte städtischer Siedlungsgebiete vor. Dieser basiert im Wesentlichen auf fernerkundlichen Daten und ermöglicht die Erzeugung großflächiger dreidimensionaler Gebäudemodelle, welche die Grundlage für Dichteberechnungen darstellen. Im Folgenden wird die methodische Vorgehensweise vorgestellt und für vier Stadtregionen in knapper Form diskutiert.

2 Methodischer Ansatz

2.1 Konzeptioneller Rahmen

Unter den Dichteindikatoren lassen sich bauliche Dichten und Nutzungsdichten unterscheiden. Erstere beziehen sich allein auf die Menge von Baumassen in einer Gebietseinheit, während Nutzungsdichten auch die Intensität der menschlichen Nutzung der betreffenden Flächen berücksichtigen. Der verbreitetste bauliche Dichteindikator ist die Geschossflächenzahl (GFZ) bzw. die Geschossflächendichte (GFD), welcher sich auf das Verhältnis von Gebäudegeschossfläche zur Grundstücksfläche bezieht. Bekannt sind ferner Volumengrößen wie die Baumassenzahl, die das Verhältnis des Gebäudevolumens und der Grundstücksfläche angibt. Neben den grundstücksbezogenen Dichtemaßen existieren Messgrößen für Gebietsausschnitte auf verschiedenen Skalenebenen (Quartier, Gesamtstadt, Region).

Der wissenschaftliche Anspruch einer objektiven Ermittlung von Geschossflächendichten und Baumassenvolumina war bislang mit datentechnischen Problemen konfrontiert. So war es bis vor wenigen Jahren kaum möglich, die GFD für größere Regionen in verlässlicher Form zu ermitteln. Nur wenige Städte waren in der Lage, aufwändige terrestrische Erhebungen durchzuführen, die zudem nur mit hohem Aufwand regelmäßig aktualisiert werden können.

Abhilfe versprechen fernerkundliche Daten, die Höheninformation für sehr große räumliche Gebiete verfügbar machen. In den vergangenen beiden Jahrzehnten wurden vermehrt Höhenmessungen aus berührungslosen Instrumenten zum Einsatz gebracht, wozu vor allem Aufnahmen aus flugzeuggetragenen Laserverfahren zählen. Mit diesen Daten lassen sich modellhafte Darstellungen von Gebäuden sowohl in ihrer flächenhaften Form als auch in ihrer Höhe erzeugen, die wiederum Grundlage für verschiedenartige Dichteberechnungen sein können. Diese Art der Datenerhebung hat den Vorteil, dass sehr präzise Messungen mit einer Höhengenauigkeit von einigen Zentimetern und einer Lagegenauigkeit im Dezimeterbereich möglich sind. Der entscheidende Nachteil kommt im Zusammenhang mit sehr großflächiger Datenerhebung durch die Anbringung des Messinstrumentes auf einem Flugzeug zum Tragen, wodurch die Gebiete von Interesse beflogen werden müssen. In diesem Zusammenhang ermöglicht die satellitengestützte Erhebung von räumlichen Daten auf der Erdoberfläche, dass von nahezu jedem Punkt auf der Erde berührungslos Daten aufgenommen werden können.

2.2 Methodische Vorgehensweise

2.2.1 Datengrundlagen

Für die Berechnung der Gebäudehöhen werden Höhendaten aus digitalen Oberflächenmodellen (DOM) verwendet, welche aus stereoskopischen Satellitenaufnahmen gewonnen werden. Der Satellit Cartosat-1 wurde insbesondere für großflächige Stereoaufnahmen konstruiert und stellt Aufnahmen mit einer Pixelauflösung von 2,5 m in einer Schwadbreite von 27 km zur Verfügung. Die Stereoaufnahmen können für die Herstellung von digitalen Oberflächenmodellen mit einer Rasterweite von 5 m (d'Angelo et al. 2008) und in weiterer Folge für die Ableitung von digitalen Gebäudemodellen verwendet werden (z. B. Wurm et al. 2014; Sirmacek et al. 2012; Crespi et al. 2006).

Für die Untersuchungsgebiete in der vorliegenden Studie wurden insgesamt 56 Cartosat-Aufnahmen verwendet und zu digitalen Oberflächenmodellen umgewandelt. Da die Rasterweite der Oberflächenmodelle von 5 m allerdings nicht für eine automatisierte Abgrenzung der individuellen Gebäudegrundrisse ausreicht, werden für die Erstellung der 3D-Gebäudemodelle zusätzliche Gebäudegrundflächen aus topographischen Karten im Maßstab 1:25 000 verwendet. Die Karten wurden in einer Auflösung von 254 dpi gescannt und beinhalten alle schwarzen Kartenelemente. Karteninformationen werden für die Herstellung der 3D-Gebäudemodelle verwendet, um die Gebäudegrundflächen daraus zu extrahieren und mit der Höheninformation aus den Oberflächenmodellen zu vereinigen.

Für die Berechnung der GFD werden noch zusätzliche Informationen über die Siedlungsstruktur benötigt. Vor diesem Hintergrund werden Daten aus dem European Urban Atlas integriert. Die Daten beschreiben eine thematische Klassifikation der urbanen Struktur für alle europäischen Großstadtregionen mit mindestens 100 000 Einwohnern. Als räumliche Bezugsebene für die Berechnung der Dichten wurde im Rahmen der Untersuchung das Europäische Gitter INSPIRE bestehend aus überlappungsfreien, quadratischen Zellen mit einer Kantenlänge von 1 000 m verwendet.

2.2.2 Berechnung der Baumassenkonzentrationen

Aus der Fusion der Gebäudegrundflächen aus den topographischen Karten und den Höheninformationen aus dem DOM werden in der Folge 3D-Gebäudemodelle hergestellt. Sie repräsentieren die urbanen Elemente als generalisiertes Klötzchenmodell mit einem Level-of-Detail 1. Das bedeutet, dass jeder Grundfläche ein Höhenwert zugeschrieben wird (Abb. 1). Mit diesem einfachen Gebäudemodell können für beliebige Raumeinheiten Dichteindikatoren berechnet werden. In diesem Beitrag werden neben dem angesprochenen INSPIRE–Grid Baublöcke aus dem European Urban Atlas als Bezugsgeometrien eingesetzt.

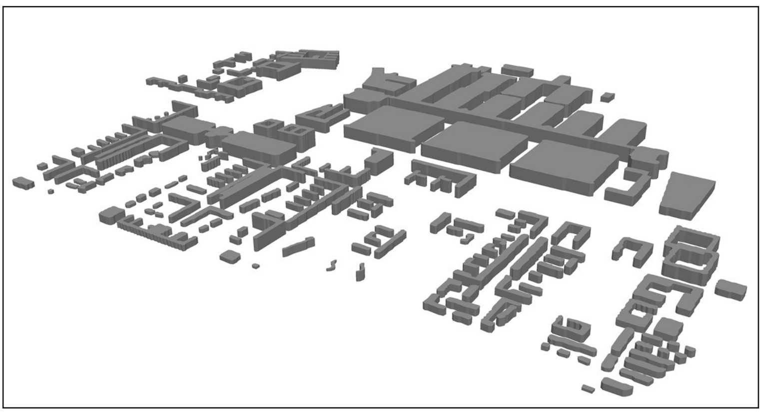

Abb. 1: 3D-Klötzchenmodell aus Gebäudegrundflächen und Höheninformation aus Cartosat-1 (Quelle: eigene Darstellung, Gebäudegrundflächen: © GeoBasis-DE/BKG 2010)

Da die Berechnung der Geschossflächendichte die Kenntnis der Anzahl der Geschosse eines Gebäudes voraussetzt, diese Informationen aber im Gebäudemodell nicht enthalten sind, kommt ein Schätzverfahren zum Einsatz (Wurm et al. 2011). Die Geschossflächendichte wird darauf basierend aus der Summe aller Geschossflächen für jede INSPIRE-Gridzelle abgeleitet (Abb. 2). Bei der Berechnung der GFD werden allerdings nur jene Flächen innerhalb jeder Gitterzelle verwendet, welche baulich überprägt sind. Diese Flächen wurden aus der räumlichen Überlagerung mit den Daten des European Urban Atlas gewonnen. Mit diesem Verfahren werden die realen Dichten vermutlich leicht unterschätzt, weil die Bezugsflächen aus dem Urban Atlas auch Nutzungen enthalten, die bei der Berechnung einer GFD üblicherweise nicht enthalten sind, beispielsweise städtische Grünflächen.

Abb. 2: Geschossflächendichte für 1 km x 1 km INSPIRE-Gridzellen. In Schwarz sind die Gebäudegrundflächen dargestellt, in Rot sehr hohe Dichten, in Orange hohe, in Gelb mittlere und in Weiß niedrige Dichten (Quelle: eigene Darstellung, Gebäudegrundflächen: © GeoBasis-DE/BKG 2010)

3 Ergebnisse

Mit dem vorgestellten methodischen Ansatz ist erstmals eine regionsweite Ermittlung von baulichen Dichten möglich. Damit lassen sich auch intra- und inter-regionale Vergleiche der Verdichtungssituation durchführen. Abbildung 3 zeigt die Geschossflächendichten in den vier Regionen Köln, Frankfurt am Main, Stuttgart und München in der Abgrenzung des Urban Atlas. Deutlich zu erkennen sind die unterschiedlichen siedlungsstrukturellen Grundmuster der Regionen. So tritt die axiale Struktur der Region Stuttgart in deutlichen Kontrast zur monozentrisch geprägten Region München. Sichtbar wird auch, dass, mit Ausnahme der Region Köln, außerhalb der Kernstädte und weniger zentraler Orte im Umland kaum höhere bauliche Dichten angetroffen werden. Bereits die Ränder der Kernstädte werden von gering verdichteten Siedlungsgebieten dominiert, deren Geschossflächendichten meistens unter einem Durchschnittswert von 0,5 rangieren.

Ursächlich dafür sind die Beharrungskräfte des Siedlungssystems, die darin zum Ausdruck kommen, dass die in Zeiten noch geringer oder moderater Bodenpreise – in der Gründer- oder der Nachkriegszeit – entstandenen suburbanen Siedlungen kaum einer nachträglichen Verdichtung unterlagen. So finden sich in zentrumsnahen Lagen oder in räumlicher Nähe zu den Haltepunkten des schienengebundenen Nahverkehrs häufig geringe Baudichten und damit auch geringe Einwohner-Arbeitsplatzdichten. Die planerisch durchaus gewünschte Verdichtung solcher Bereiche unterliegt den planungsrechtlichen Restriktionen des Bestandsschutzes und wird auch aus Gründen geringer sozialer Akzeptanz nur selten konsequent angestrebt. An dieser Stelle sei nochmals darauf verwiesen, dass der hier zum Tragen kommende methodische Ansatz zu einer leichten systematischen Unterschätzung der realen Dichten neigt. Eine genauere Quantifizierung dieser Abweichungen ist indes nicht möglich, da keine regionalen oder gemeindlichen Referenzdaten aus anderen Quellen vorliegen.

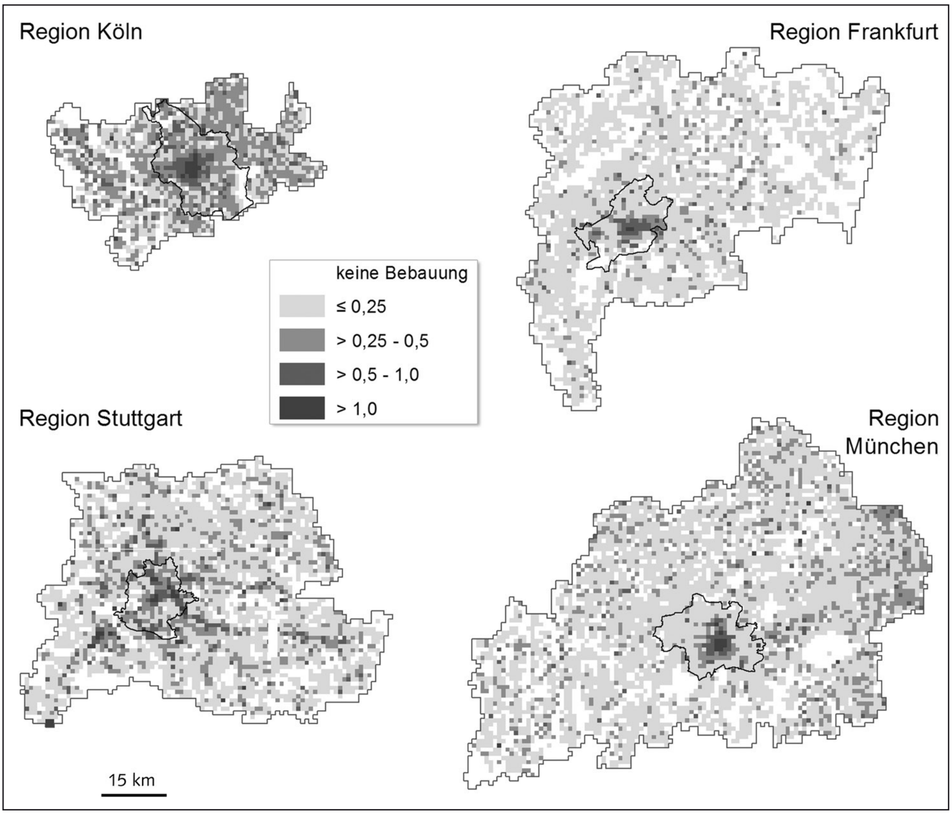

Abb. 3: Geschossflächendichte [m² pro m²] gemäß European Urban Atlas baulich überprägter Fläche in vier Fallstudienregionen bezogen auf das INSPIRE-Grid mit 1 000 m Kantenlänge (Quelle: eigene Darstellung)

Die Abbildungen 3 und 4 lassen darüber hinaus erhebliche interregionale Unterschiede des Verdichtungsniveaus erkennen. So erreicht die Geschossflächendichte in der Region Köln deutlich höhere Werte als in den drei übrigen Regionen. Ein Grund hierfür ist zum einen in der früher und flächenhaft erfolgten Industrialisierung der Region Köln zu vermuten, die zu deutlich höheren Siedlungsdichten geführt hat. Zum anderen könnten die wirtschaftsstrukturellen Gegebenheiten und Entwicklungen in den Regionen Dichteunterschiede erklären. Unterschiedliche Ausmaße altindustrieller Bausubstanz oder auch abweichende Branchenstrukturen im produzierenden Gewerbe und im Handel lassen sich als plausible Faktoren vermuten.

Abbildung 4 verdeutlicht die durchschnittlichen Geschossflächendichten für drei kreisförmige Zonen um die Kernstädte der vier Regionen: eine innere Zone mit einer maximalen Distanz von zwei Kilometern zum Zentrum der Kernstadt, eine Randzone mit einem Radius von zwei bis fünf Kilometern zum Zentrum sowie eine äußere Zone mit einer radialen Distanz von 5 bis 10 Kilometern zum Zentrum. Hier zeigt sich, dass die Stadt Köln die stärkste Verdichtung des zentralen Siedlungsbereichs aufweist: Die mittlere Geschossflächendichte nimmt einen Wert von nahezu 1,5 an. Aber bereits die Randlagen um die Innenstadt herum (2- bis 5-km Zone) sind in allen Regionen ähnlich gering verdichtet, in drei von vier Fällen mit Geschossflächendichtewerten von durchschnittlich weniger als 0,5. In der äußeren (suburbanen) Zone werden erwartungsgemäß geringe Dichten angetroffen. Dies ist in besonderem Maße in den Städten Frankfurt und München ausgeprägt.

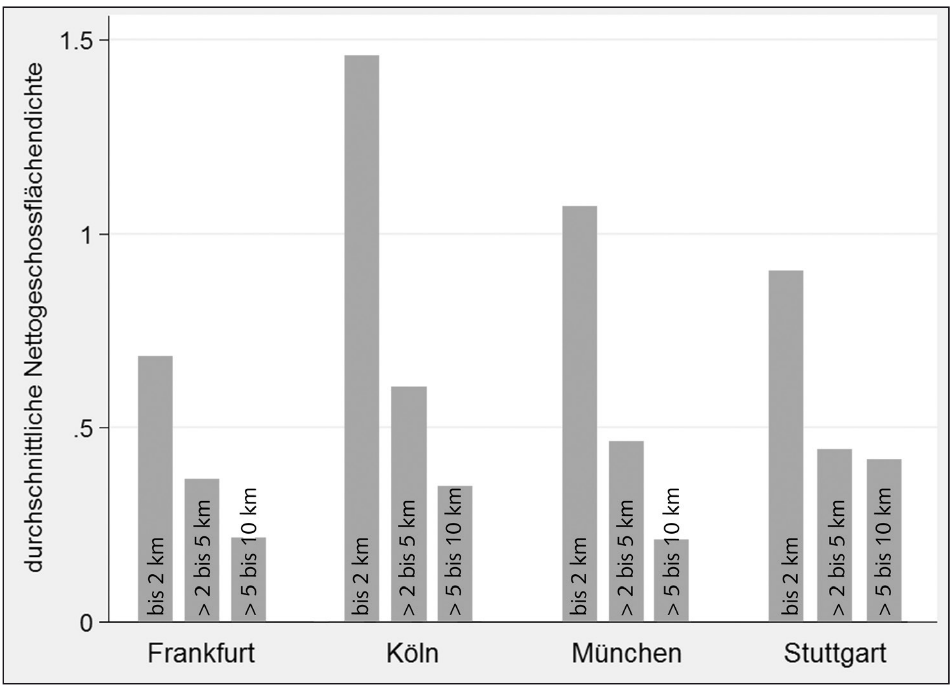

Abb. 4: Durchschnittliche Geschossflächendichte in vier Fallstudienregionen nach Ringzonen (Quelle: eigene Berechnung)

4 Fazit

Der vorliegende Beitrag zeigt, dass es mithilfe von Fernerkundungsdaten möglich ist, Gebäudemodelle für Großstadtregionen zu erzeugen und daraus Dichteinformationen abzuleiten. Damit wird eine erhebliche Lücke in der laufenden Beobachtung von Prozessen der Stadt- und Regionalentwicklung geschlossen. Zukünftig wird es möglich sein, Ver- und Entdichtungsprozesse in Stadtregionen einem systematischen Monitoring zu unterziehen.

Sowohl aus planungspraktischer als auch aus raumwissenschaftlicher Perspektive eröffnen sich mit der Verfügbarkeit kleinräumiger Dichtedaten vielfältige Nutzungsoptionen. Beispielhafte Anwendungsbezüge bieten sich in der Stadtklimatologie und in Vulnerabilitätsstudien an. Auch die Planung des Stadtumbaus könnte von Gebäude- und Dichtedaten profitieren, indem u. a. Rückbauoptionen auf ihre infrastrukturellen Implikationen vertiefend untersucht werden. Ähnliches gilt für die Bewertung von Nachverdichtungsmaßnahmen mit ihren positiven und negativen Auswirkungen (z. B. Verbesserung der Infrastruktureffizienz, Verringerung der Freiraumversorgung). So könnte beispielsweise ermittelt werden, welche potenziellen Nachverdichtungsmöglichkeiten im Umfeld von U- oder S-Bahnhöfen bestehen.

Fina et al. (2014) weisen ferner darauf hin, dass die Ergänzung konventioneller Raumbeobachtungssysteme Chancen für ein multidimensionales Monitoring der Stadt- und Regionalentwicklung bietet, indem Dichteindikatoren integriert und mit anderen Indikatoren kombiniert werden können. Die damit erleichterte Verfügbarkeit untergemeindlicher Daten ermöglicht interregional vergleichende Analysen siedlungsstruktureller Zustände und Entwicklungen, die für die Bundesrepublik Deutschland so bisher nicht möglich waren.

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