Julius-Maximilians University Würzburg

Department of Geography and Geology

Habilitation Thesis

Remote Sensing for the Analysis of Global Urbanization

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Preface

Since I was a young boy, the city is fascinating to me. In my late teens dense jungles of vibrant urban life had an immense gravity on me. This gravity pulled me from the countryside into cities. Well, this is not special at all; this is happening billion fold across the globe. More and more people migrate to cities transforming our planet in the 21st century into an unprecedented urban one. Personally, this urban gravity made me travel different kinds of cities across the globe chasing my promised land. These travels let me experience, observe, smell, hear, touch, feel cities, their charisma, their energy, their optimism, as well as their misery, their grief and their pessimism: From the cosmopolitan emotion of New York City, the exuberant energy of Mumbai, the infinite will of Sao Paulo's favelas to the unbelievable lonesomeness of China's ghost cities, the toxic air of Jakarta or Cape Town's failing townships. I was mesmerized by the energy, the diversity, the individual characters of cities, and by the specific chaos that seemed to rely on hidden orders that I could not grasp. To that effect, these travels did not quite do the job of explaining and understanding what I have felt and seen; rather more and more questions appeared: Why is this urban gravity so strong on so many people and which spatial compositions make urban places work or fail? This habilitation is an attempt to approach some questions with a different perspective, a scientific one. It is an attempt to map, describe, analyze and compare these crucial urban places using an explicitly spatial view. It is, however, also an attempt to trace explanations for this ongoing global urban gravity. And maybe it helps me fathoming myself.

A habilitation, I guess, is a once in a lifetime thing. In this work I put my love for the city, my love for research, my love for controversial discussions, and, above all, the inspiration I got from people: my mentors, companions, colleagues, friends and family. The long path of compiling these ideas, arguments, perspectives, data, methods and geographic findings would not be possible without you:

My mentor Prof. Dr. Stefan Dech, who is always pushing me to try things that I am scared of, encouraging me to think a little bigger, and who is even keeping a sense of humor when I loose mine. Prof. Dr. Roland Baumhauer and Prof. Dr. Barbara Hahn for accepting the supervision of this habilitation, for the valuable discussions, and for the guidance during these years.

My friends, companions and colleagues Dr. Michael Wurm and Dr. Christian Geiß for their creative inspirations and for contesting any scientific path with invaluable critical humor – being simultaneously ironic as hell and serious as death about our work, a richer story about cities becomes possible. Martin Habermeyer for the fun of scrutinizing just about anything, anytime, anywhere, Dr. Martin Wegmann for strengthening my self-awareness about my urban fascination by continuously advertising flora and fauna, Ines Standfuß for her irrepressible will and for teaching me to ride the emotional rollercoaster with pride, Tobias Leichtle for balancing everything in stoical coolness, Nicolas J. Kraff for his unrivaled motivation week after week after week, Prof. Dr. Xiaoxiang Zhu for pushing this research path in wonderful teamwork, Dr. Thomas Esch and Isabel Georg for the continuous scientific collaboration, Martin Klotz, Andreas Felbier and Michael Wiesner for accompanying a part of the scientific way, Igor Klein for pushing the love for office sports to another level, Prof. Dr. Günter Strunz, Dr. Torsten Riedlinger and Dr. Elisabeth Schöpfer for keeping my back free, and all colleagues in my team and in the department for supporting this winding road, for widening my mind, and making work life very enjoyable. And, I am grateful to DLR for giving me a home at work.

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I am grateful to my wonderful parents for teaching me faith in life and in myself. And I am grateful to my sister Andrea for her encouraging support. And last, but not least: To my lovely girls and sources of energy –Kerstin, Luisa and Alina– for teaching me what really matters and for supporting this crazy ride with so many halcyon days.

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PART I: NEW DIMENSIONS OF URBAN LANDSCAPES

PART II: INTRA-URBAN PATTERNS AND STRUCTURES

List of papers contributing to the habilitation

Part I to Part IV of the habilitation thesis consist of 15 SCI papers and 1 reviewed conference paper. Below they are ordered by their release date. The work is framed by a synthesis.

1. Taubenböck H, Wiesner M, Felbier A, Marconcini M, Esch T & Dech S (2014): *New dimensions of urban landscapes: The spatio-temporal evolution from a polynuclei area to a mega-region based on remote sensing data*. Applied Geography. vol. 47, pp. 137-153.

2. Taubenböck H & Kraff N (2014): *The physical face of slums – A structural comparison of slums in Mumbai, India based on remotely sensed data.* Journal of Housing & the Built Environment. vol. 29, issue 1, pp. 15-38.

3. Taubenböck H & Wiesner M (2015): *The spatial network of megaregions – Types of connectivity between cities based on settlement patterns derived from EO-data.* Computers, Environment & Urban Systems. vol. 54, pp. 165-180.

4. Geiß C, Aravena Pelizari P, Marconcini M, Sengara W, Edwards M, Lakes T & Taubenböck H (2015): Estimation of seismic building structural types using multi-sensor remote sensing and machine learning techniques. ISPRS J of Photogrammetry & Remote Sensing. 104, pp. 175-188.

5. Krehl A, Siedentop S, Taubenböck H & 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), 76; pp. 1-21.

6. Taubenböck H, Standfuß I, Klotz M & Wurm M (2016): *The physical density of the city – Deconstruction of the delusive density measure with evidence from two European megacities.* ISPRS International Journal of Geo-Information, 5(11), pp. 1-24.

7. Georg I, Blaschke T & Taubenböck H (2016): *New spatial dimensions of global cityscapes: From reviewing existing concepts to conceptual spatial approaches.* International Journal of Geographical Sciences. 26(3), pp. 355-380.

8. Georg I, Blaschke T & Taubenböck H (2016): *A global inventory of urban corridors based on perceptions and night-time light imagery.* ISPRS International Journal of Geo-Information. 5(12), pp. 1-19.

9. Taubenböck H, Standfuß I, Wurm M, Krehl A & Siedentop S (2017): *Measuring morphologic polycentricity – A comparative analysis of urban mass concentrations using remote sensing data.* Computers, Environment and Urban Systems, vol. 64, pp 42-56.

10. Klotz M, Wurm M, Zhu X & Taubenböck H (2017): *Digital deserts on the ground and from space – An experimental spatial analysis combining social network and earth observation data in megacity Mumbai.* IEEE-CPS Joint Urban Remote Sensing Event (JURSE), Dubai, VAE.

11. Taubenböck H, Ferstl J & Dech S (2017): *Regions set in stone – Classifying and categorizing regions in Europe by settlement patterns derived from EO-data.* ISPRS International Journal of Geo-Information, 6(2), pp. 1-27.

12. Wurm M & Taubenböck H (2018): *Detecting social groups from space – Remote sensing-based mapping of morphological slums and assessment with income data.* Remote Sensing Letters. vol. 9(1), pp. 41-50.

13. Friesen J, Taubenböck H, Wurm M & Pelz P (2018): *The similar size of slums*. Habitat International, vol. 73, pp. 79-88.

14. Taubenböck H, Kraff N & Wurm M (2018): *The Morphology of the Arrival City – A global categorization based on literature surveys and remotely sensed data*. Applied Geography, vol. 92, pp. 150-167.

15. Taubenböck H, Wurm M, Geiß C, Dech S & Siedentop S (2018): *Urbanization between compactness and dispersion – Designing a spatial model for measuring 2D binary settlement landscape configurations.* International Journal of Digital Earth. DOI: 10.1080/17538947.2018.1474957.

16. Wentz EA, York AM, Alberti M, Conrow L, Fischer H, Inostroza L, Jantz C, Pickett STA, Seto KC, Taubenböck H (2018): *Six fundamental aspects for conceptualizing multidimensional urban form.* Landscape and Urban Planning, vol. 179, pp. 55-62.

Chapter I

Synthesis –

Remote sensing for the analysis of global urbanization

1. Introduction

Humankind is within the largest migration ever: out of rural agricultural life into cities (Saunders, 2010). This migration process is reshaping our world. In 2008 and for the first time ever in human history more people lived in urban areas than in rural environments (UN, 2017). Today, the global number of urban residents exceeds the rural population by far; and, population projections imply that the entire expected future world population growth will be absorbed by urban areas (cf. Fig. 1; UN, 2017). Although urban growth rates vary across continents, with Asia and Africa expected to absorb the largest shares, the trend itself is global. With more and more people concentrating in ever-increasing urban landscapes, our predominant living environments, our "ways of life", and our societies transform us into an unprecedented "urban species".

The spatial expansion and structural transformation of the built environment is the most obvious and visible result of urbanization. Scholars have documented spatial urban growth dynamics and settlements expanding into hinterlands (e.g., Angel *et al.*, 2010; Frolking *et al.*, 2013; Taubenböck *et al.*, 2012) as well as intra-urban structural/morphologic transformations (e.g. Anas, Arnott & Small, 1998; Garreau, 1991; Lefebvre & Corpetti, 2017; Leichtle *et al.*, 2017) for many parts of our world. With the focus on this physical expansion and transformation of cities Hollis (2013, p. 416) raises the question: "[…] *will the megalopolis grow so vast that it loses its center, continue to expand without end, making it impossible to identify the border between city, suburb, exurb or townscape? Will the endless expansion force us to rethink what a city is?*" With the built environment seen as the *theater for life* (Jacobs, 1961), *urban form* has crucial influence on shaping societies. It is a key element for understanding urban systems as it organizes where people live and work and how interaction is spatially structured (Grimm *et al.*, 2016). Jackson (1983) postulated that the arrangement and design of the built environment reveals more about societies than arts or culture. Just like Winston Churchill once said "*we shape our buildings; thereafter they shape us*". As cities grow and transform, we have the opportunity to rethink urban form so that transitions underway contribute to solutions rather than problems for pressing challenges.

On the political agenda these challenges of urbanization and urban transformation are echoed by the intergovernmental agreements on Sustainable Development Goals (SDGs) (UN, 2015). To build sustainable cities (SDG 11), to end poverty (SDG 1), to provide access to clean water and sanitation (SDG 6), decent work and economic growth (SDG 8) are, among others, development goals explicitly referring to urban challenges.

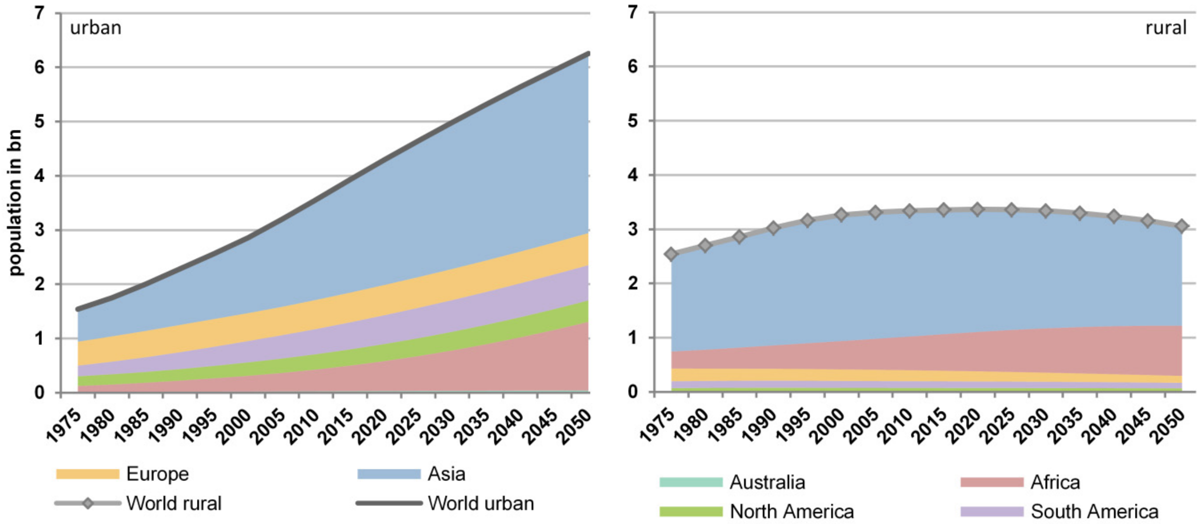

Figure 1 Development and prospects of the global population in urban and rural areas (based on data from the UN, 2017)

However, the demand for '*sustainable data for sustainable development*' or, in other words, improved data availability, quality, consistency, timeliness and disaggregation is often not met (UN, 2015) to address the previously identified effects of urbanization. Although we live in an age where the availability and generation of data is explosively growing, we still have massive lacks of knowledge on urban issues across the globe. As an example, the physical extent of all settlements across the globe is still not exactly known. Mapping products reveal high uncertainties as they range from 0.21% to 2.74% of the land surface covered by settlements (Schneider *et al.*, 2010; Klotz *et al.*, 2016). Another example is stated in the World Migration Report (2015): we still have a massive lack of (spatial) data on urban poverty, and Tacoli, McGranahan & Satterthwaite (2015) even doubt the credibility of existing (geo)-information on urban poverty.

Remote sensing from space is one data source with the capability to reduce this lack of (spatial) data. Earth observation (EO) provides us with spatial perspectives of our planet. The data sets allow for deriving information on the atmosphere, the land surface or the oceans. With the advent of very high resolution satellite data (i.e., a geometric resolution of 1 meter and better) starting with the Ikonos satellite in 1999, remote sensing developed to a crucial data source for mapping, monitoring and analyzing in particular the complex and small-scale built environments of cities. However, most studies within the remote sensing community still foremost focus on the development of methods to transform image data from satellites into reliable geo-information. But, if we want to rethink urban form and the related impact on our societies, a systematic exploration of the ever-increasing multi-scale mapping products from remote sensing is in demand.

No single data source, however, is sufficient to satisfy the information needs required to map, monitor, model, and understand the multi-dimensional complexity of urban systems and their change over time (Blaschke *et al.*, 2011; Batty, 2007). The looming paradigm shift toward data-intensive science (Zhu *et al.*, 2017) sets the path to combine mapping products from remote sensing with other (geo-)data sources to open up new analytical capabilities for documenting, analyzing and ultimately better understanding the processes shaping and characterizing urban landscapes.

Against this background, this habilitation centers on research questions related to urban geography with a special focus on urban form. The focus is also set on the exploration of remote sensing data and derived mapping products for analyzing spatial effects of past and current urbanization processes at very different spatial scales – from settlement patterns at continental scale to building structures in urban neighborhoods. Beyond, the multidisciplinary combination of remote sensing and ancillary data such as census information or social network data is exploited. The framework is set multidisciplinary for new findings in urban geography.

2. Foundation of this work: The city, its urban form and remote sensing

"The city may be looked on as a story, a pattern of relations between human groups, a production and distribution space, a field of physical force, a set of linked decisions, or an arena of conflict. Values are embedded in these metaphors: historic continuity, stable equilibrium, productive efficiency, capable decision and management, maximum interaction, or the progress of political struggle. Certain actors become the decisive elements of transformation in each view: political leaders, families and ethnic groups, major investors, the technicians of transport, the decision elite, the revolutionary classes." (Lynch, 1981). This quotation reveals the plurality of approaches for analyzing 'the city'. Commonly, definitions of 'the city' refer to historic-genetic and legal acts, to statistical approaches using, for instance, population densities, to social and economic functions or to descriptions and measurements of urban form (Paessler, 2008).

In this work, urban form serves as central theme. The forms in which cities take shape are determined by economic arrangements, social relations and divisions, legal constructions, political systems (Tonkiss, 2013) and the history of all these interdependent processes (Kostof, 1991). Urban form is constituted by spatial and social patterns that compose it and that allow to describe networks, built spaces, and empty spaces in shape-related, topological and hierarchical terms in two, three and four dimensions (Salat, 2011). It represents the visible objects of a city as well as how they change over time. Lynch (1981) provided a minimalist definition of urban form as "*the spatial pattern of the large, inert, permanent physical objects*" in a city. Seen as amalgams of objects, urban form is composed of buildings, streets, plots, and open spaces (Kostof, 1991). The "physicalism" is one appropriate way to represent cities in term of their geography, geometry and associated attributes (Batty, 2013). The spatial composition of these objects can take on quite variable forms and varying degrees of complexity. Contrasting complex, irregular, high dense arrangements of shacks in slums of Indian megacities with geometric, regular, low dense arrangements of houses in American suburbs marks two ends of a physical continuum under the terminological category "city".

The spatial compositions of urban form, as Kropf (1996) suggests, can be approached by varying urban tissues which form an organic whole at various levels of resolution. Scholars document urban form from individual objects such as buildings to neighborhoods (e.g. Krizek, 2011), transects (e.g. Luck & Wu, 2002), individual cities (e.g. Griffiths *et al.*, 2010) or large urban constellations such as urban corridors or mega-regions (e.g. Florida, Gulden & Mellander, 2008). Ross (2009) examplifies these varying scales by "*the neighborhood is a critical building block for a city, cities are now the building blocks for mega-regions*". Morphologies of cites are today reflected in a hierarchy of centers, subcenters or clusters across many scales (Batty, 2008). The physical urban form allows studying relationsships between these objects "*from the part to the whole*" (Oliveira, 2016) and vice versa.

Urban form can be considered a key element for understanding urban systems as social-ecological-technological hybrids because it situates and structures where people live and work, and it influences mobility, interactions, processes, and networks (e.g. Grimm *et al.*, 2016). It provides the functional space for urban activities – and either facilitates or limits interaction. Numerous studies approach urban form from differing perspectives: from conceptual and theoretical issues (e.g. Harris & Ullman, 1945; Lynch & Rodwin, 1958) to methods of quantitative measurements of urban form (e.g. Anas, Arnott & Small, 1998) as well as analytical and normative approaches (e.g. Jenks, Burton & Williams, 1996). Research on urban form is of relevance as it has crucial *economic*, *social* or *environmental* implications. Although a strong link between urban form and sustainable development exists (Jenks, Burton & Williams, 1996), it is not simple and straightforward. However, empirical studies demonstrate positive relationships between the density of the built environment and corresponding economic activities: Producing larger labor and consumer markets, lowering transport costs, increasing productivity and wage levels, producing more innovation, fostering the number of skilled people and creativity and making public service provision more cost-effective (e.g. Anderson, Burgess & Lane, 2007; Bettencourt & West, 2010; Carlino, Chaterjee & Hunt, 2007; Duranton & Puga, 2005; Glaeser, 2010; Florida, 2002; Siedentop *et al.*, 2006). Regarding social dimensions scholars link urban form (in particular high density and compaction) to facilitating access to public transport, fostering a greater degree of physical activity, enabling more social interaction, or decreasing social inequalities (e.g. Jacobs, 1961; Bramley & Power, 2009; Dempsey *et al.*, 2011; Ewing *et al.*, 2014; Hinde & Dixon, 2005). In the environmental domain scholars document the relationship of higher built-up densities with less energy consumption, reduced land consumption, and less demand for motorized transport (e.g. Schläpfer, Lee & Bettencourt, 2015; Rode *et al.*, 2014). On the contrary a decline in biodiversity and ecosystem quality or higher air temperatures (e.g. Tratalos *et al.*, 2007) is related to higher built-up densities. Nevertheless, higher density is not necessarily having positive or negative effects. Context is —as Tonkiss (2013) argues— all in this debate. These examples demonstrate the relevance and potential benefits of urban form with respect to the economic, social and environmental development of cities.

In general, however, the research domain on urban form has long been relatively poor in data and for large parts of the developing world this still holds true. This situation is about to change. The technological progress in the first two decades of the 21st century led to a massive increase of multi-modal data. Varying sources such as sensors mounted at satellites, airplanes, drones or on the ground and even to people sensing via mobile devices or reporting about life in social networks collect data (Blaschke, 2015). These new (geo)data open up new potentials for empirical underlining of (urban) theories or answering new research questions. One data source with exponentially increasing data volumes, constantly improving spectral, radiometric and spatial resolution and an improved accessibility are remote sensing data.

Satellite-based EO from space has long been recognized as an independent tool for the provision of area-wide spatial information on the location of settlement features and their spatial distribution from global (e.g., comprising the large-scale description of urban areas) to local scales (e.g., enabling the characterization of individual buildings) (Klotz *et al.*, 2016; Schneider, Friedl & Potere, 2010). Manifold methods for image analysis have been developed to turn multi-source satellite data (e.g. data from active sensors such as radar or Light Detection and Ranging (LIDAR) or passive sensors such as optical sensing systems) into geo-information. These developments from data pre-processing, classification and validation methods are not in the focus of this work. This work starts with the outcomes of these methods: *mapping products*. The habilitation relies predominantly on multi-scale urban land cover classifications derived from multi-sensoral EO data. These data sets serve as fundament for geospatial analyses of urban form in a quantitative way. The analysis of urban form allows for mapping and capturing patterns of settlements, internal structural variations, physical similarities and irreducible differences of cities. It allows to describe, analyze and understand how thousands of buildings are crystallized into a complex, porous form made of interwoven solid masses and empty spaces, to form morphologies, more or less dense, compact, open to the sky and connected (e.g. Salat, 2011; Batty, 2013).

In condensation of these aspects, this habilitation relies on different mapping products derived from various remotely sensed data. The mapping products are introduced based on the structure of the conceptual framework (Part I – Part IV; the conceptual framework of the habilitation thesis will be presented in detail below (cf. section 3)), i.e., in the sequence from low (Part I) to higher spatial and thematic resolutions (Parts II – IV):

In Part I – *New dimensions of urban landscapes* – the "Global Urban Footprint" mapping product derived from TerraSAR-X and TanDEM-X data is the main data source for analyses. It captures binary patterns of settlements versus non-settlements on global scale (Esch *et al.*, 2012; Esch *et al.*, 2013). In addition, multi-temporal developments of settlement patterns have been derived using the Landsat sensors for specific areas of interest (Taubenböck *et al.*, 2012). Beyond, night-time light data from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) (Elvidge *et al.*, 2013) are also applied to distinguish urban from non-urban space. Figure 1 (Part I) illustrates how urban complexity is reduced to two-dimensional abstract representations of settlements and their evolution over time.

In Part II – *Intra-urban patterns and structures* – image classifications with high thematic and geometric resolutions in two (Taubenböck *et al.*, 2010) or three dimensions (Wurm *et al.*, 2011) lay out the fundament for the subsequent analyses. These mapping products subdivide the urban space into thematic categories such as buildings, impervious surfaces, or green spaces and capture the individual elements which compose urban form. Figure 1 (Part II) illustrates a perspective view on a three-dimensional (3D) city model and a classification of different urban structural types aggregated to block units. The figure visualizes the capacity to analyze internal structural variations within cities by remote sensing-based mapping products. Due to the high geometric and fine semantic granularity, these particular mapping products are not globally available and have been produced specifically for selected regions (Taubenböck *et al.*, 2013; Wurm *et al.*, 2014).

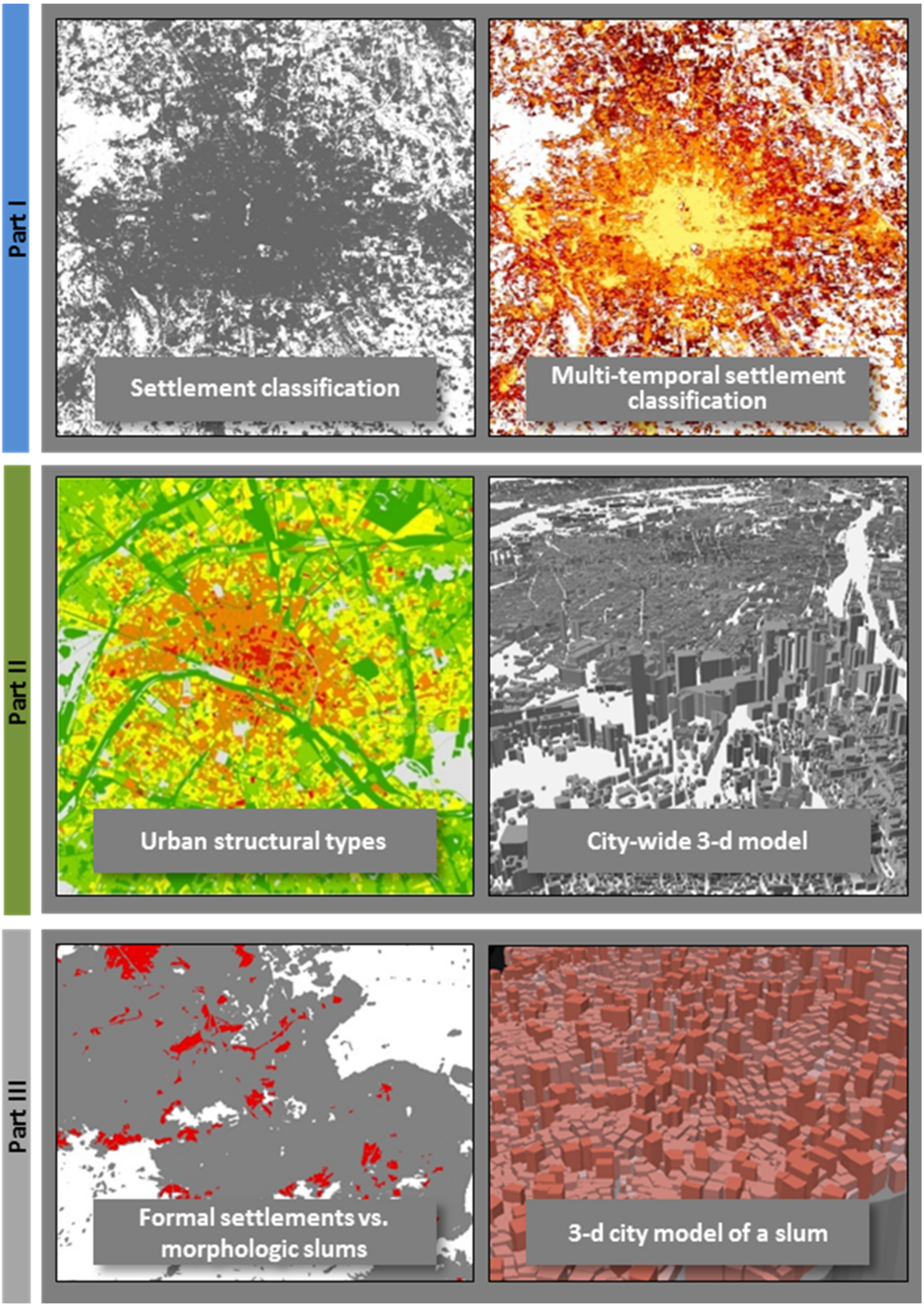

Figure 2 Mapping products with different spatial and thematic resolutions; *Part I*: (Multi-temporal) binary settlement patterns; *Part II*: Structural urban types illustrating intra-urban variability of urban form and city-wide 3D city models; *Part III*: The dichotomic classification of formal settlements versus slum morphologies and a 3D city model specifically for living environments of the urban poor

In Part III – *urban poverty, its physical manifestation and social aspects of it* – data of high detail comparable to Part II are used. The focus here is specifically on the thematic class of buildings. Classifications in two (Schmitt *et al.*, 2018; Wurm *et al.*, 2017) or three dimensions (Taubenböck & Kraff, 2015) are applied for the analyses. Figure 2 (Part III) illustrates a dichotomic classification of formal settlements versus slum morphologies and a 3D city model specifically for living environments of the urban poor.

In Part IV – *aspects of physical urban form* – the fundamental aspects that define urban form are discussed based on the currently available mapping products presented in figure 2.

Since remote sensing is not capable to provide mapping products with the accuracy of cadastral data sets, all mapping products developed and applied in this work have been thoroughly validated (e.g. Taubenböck *et al.*, 2011; Wurm *et al.*, 2014; Klotz *et al.*, 2016; Mück *et al.*, 2017; Wurm *et al.*, 2017). In general, the validation results prove that the reliability of the mapping products is high – predominantly in the dimension of 80 – 90% agreement with reference data.

The availability of new multi-scale and multi-temporal spatial data from remote sensing on cities gives the opportunity to measure, describe, analyze and rethink urban form and the related spatial context. These compilations of data serve as central basis for this work. They provide the geo-information for analyzing spatial aspects of urban form and the urban transformation.

3. Conceptual framework, research structure and scientific goals

The geography of *urban form* is at the center of this habilitation thesis. To approach urban form, Earth observation technologies serve as major data basis. In general, it is hypothesized that combining conceptual ideas, data, methods and results from different starting positions holds immense potential for new scientific findings. Being aware that this combination contains manifold conceptual and methodological challenges, this habilitation aims at developing feasible multidisciplinary approaches allowing new findings in urban geography. The work derives its research foci from on-going debates in urban geography and uses predominantly available mapping products from remote sensing as well as geospatial methods to provide answers to particular research questions.

Mapping products based on remote sensing data provide, first of all, geo-information on the physical objects and their spatial arrangements on the land surface in general (Fig. 2), or, as cities are in the focus of the analyses, on *urban form* in particular. Urbanization processes shape new and larger spatial extents of settlements and transform existing structural patterns and morphologies (Soja & Kanai, 2014). In this work the multi-dimensional phenomenon of urban form is analyzed from a small to a large scale, from simple to highly detailed thematic representations, and in mono- and multi-temporal ways. The thesis is structured in *four main parts*.

(1) ***Part I*** addresses ***new dimensions of urban landscapes*** with the research focus on evolving urban entities way beyond the size of individual, large cities. Conceptualized as mega-regions or urban corridors these large urban constellations consist of many coalescent or connected large urban entities. For the (multi-temporal) spatial analysis of urban patterns of such large areas binary classifications of 'settlements' and 'non-settlements' from multi-source EO-data are used. Thus, to focus specifically on this aspect, the physical complexity of urban systems is reduced to two-dimensional representations.

In order to approach these large evolving urban entities, terms, concepts and spatial features defining such areas are systematized by a comprehensive literature review. Based on the findings of this review a schematic spatial juxtaposition of concepts for these large urban constellations is complied. With this conceptual spatial frame the complexity and multidimensionality of the partly overlapping theoretical concepts is reduced to a spatially delimitable form. Characteristic physical features defining the settlement pattern of these large urban constellations are deduced from this spatial juxtaposition that are applicable to mapping products from remote sensing (Chapter II).

Taking the specific concept of the 'mega-region' from the schematic spatial juxtaposition an approach is developed to turn its descriptive stage into a quantitative spatial definition. Spatial methods are developed to identify main urban hubs defining a mega-region, to measure spatial connectedness between these hubs, to evaluate the development of settlement patterns over time, and to approximate and delimit these areas. The aim is an empirical definition of spatial attributes characterizing a mega-region (Chapter III).

These spatial mega-region attributes, however, are derived from the specific mega-region in the Pearl River Delta in China. A subsequent analysis evaluates whether settlement patterns of different mega-regions, defined as such in literature, from across the globe feature similar spatial attributes. As settlement patterns differ, it is evaluated which settlement patterns qualify the respective area spatially as mega-region or whether these attributes are not in line with derived empirical definitions. Beyond, in a multi-temporal analysis using data since 1975 it is assessed at which time in the past the evolving settlement pattern qualified as mega-region (Chapter IV).

When the subject of research is not on pre-defined spatial entities such as mega-regions, the methodological approach can be extended and applied to a new setting: the settlement pattern of an entire continent (in this case Europe is used). Based on the idea that similar characteristics of the landscape, i.e., here similar characteristics of settlement size and density constitute regions, geographically linked areas independent from administrative boundaries can be mapped. With it, regional settlement phenomena for entire Europe are uncovered and large urban constellations are identified and categorized based on physical attributes such as number of urban centers, spatial extent or connectivity (Chapter V).

One specific urban concept part of the schematic spatial juxtaposition and mapped in Europe is denominated 'urban corridor'. However, a comprehensive global inventory of urban corridors is inexistent. Based on a combination of methods (literature review, questionnaires and spatial analysis based on satellite data) urban corridors are compiled, systemized, categorized and spatially characterized for the entire globe (Chapter VI).

Figure 3 illustrates in a general overview the structure of *Part I*, the used multi-source data, the methodological approaches and the main results.

	Structure	Data	Approach	Results
Part I New dimensions of urban landscapes	Chapter II	Scientific platforms such as **web of science**	**Literature survey**	**Consistent spatial concept** for large urban constellations
	Chapter III	**EO-data** (Landsat & TerraSAR-X) **Census data** on population	Classification of settlement pattern and definition of **spatial features** characterizing mega-regions	**Delimitation of a mega-region** based on settlement pattern characteristics
	Chapter IV	**EO-data** (Landsat & TerraSAR-X) **Census data** on population	Application of **spatial features** on settlement pattern for **classification of mega-regions** across the globe	**Comparison & characterization** of multi-temporal settlement patterns in **mega-regions**
	Chapter V	**EO-data** (TerraSAR-X) **Adminstrative data** (Eurostat) **Census data** on population	**Measuring connectivity** between urban nodes and **spatial delimitation** of regions	**Mapping regions in Europe** based on the settlement pattern
	Chapter VI	**EO-data** (night-time lights from the DMSP-OLS) **OpenStreetMap** data	**Literature survey, questionaire** and **spatial delimitation/ characterization** of urban corridors	**Global map/inventory** and spatial characteristics of **urban corridors**

Figure 3 Structure of Part I – New dimensions of urban landscapes.

(2) ***Part II*** addresses ***intra-urban patterns and structures*** of cities, i.e., the research focus is on the internal spatial composition of cities at geometrically and thematically finer granularity than in Part I. Cities feature different arrangements of its elements: centers, building types, gradients of density, or the like. The subject of research is the measurement and characterization of these intra-urban structures, the evaluation and comparison of

spatial configurations within and across cities. Beyond, approaches are developed that relate certain intra-urban physical structures to thematic applications. The relationships between physical structures and economic activity or the vulnerability of building types in case of an earthquake impact are investigated. For the spatial analyses two-dimensional classifications of urban footprints as well as three-dimensional city models in level of detail-1 (LoD-1) derived from multi-source EO-data are used.

Starting at a city-wide perspective, the measurement of spatial patterns of settlements with respect to compactness versus dispersion is at focus. A spatial model capable of evaluating grades of spatial dispersion in an unambiguous way is developed. By the example of real-world settlement patterns of selected cities their spatial configurations are compared based on the model. The analysis evaluates spatial urban configurations at city level for two-dimensional map representations of settlements (Chapter VII).

Cities, however, consist of a complex arrangement of structures at intra-urban scale. At this scale the subject of research is on centers and sub-centers within the settlements of city regions. In contrast to customarily used employment or population data for center localization, here the built dimension and the derived concentration of urban masses are applied. Thus a physical approach towards the localization of (sub-)centers and their related spatial arrangements is investigated. With it, a set of tools is developed for the measurement of polycentricity for comparative urban research (Chapter VIII).

The concentration of urban masses for center identification is a measure of density. Density, in general, is a popular (proxy) measure in urban research as it seems to be self-explanatory. However, as there is a lack of clarity about how to measure and how to use density within the scientific debate, in a subsequent analysis the conceptual and empirical delusiveness of the density measure is systematically uncovered. By considering multiple aspects of the density concept, a framework is set that systemizes the variables to be considered when applying density measures (Chapter IX).

Based on this foundation, morphological density measures such as the urban mass concentrations are mirrored by socio-economic data. The main subject of research is the analysis to which degree centers identified by physical density measures are correlated with economic activity. Thus, it is investigated whether a morphologic approach can serve as a feasible proxy (Chapter X).

Beyond, the capability to measure parameters of urban form and their intra-urban variations by remotely sensed data is tested in a different thematic domain. It is investigated how urban structural types can be conceptualized for the assessment of seismic building stability in case of an earthquake event. An indirect relationship between the proxy 'urban structural type' and the empirical measurement of building vulnerability under seismic load is established and verified (Chapter XI).

The structure, the used multi-source remotely sensed as well as ancillary data, the fundamental methodological approaches and the main results of *Part II* are illustrated in Figure 4.

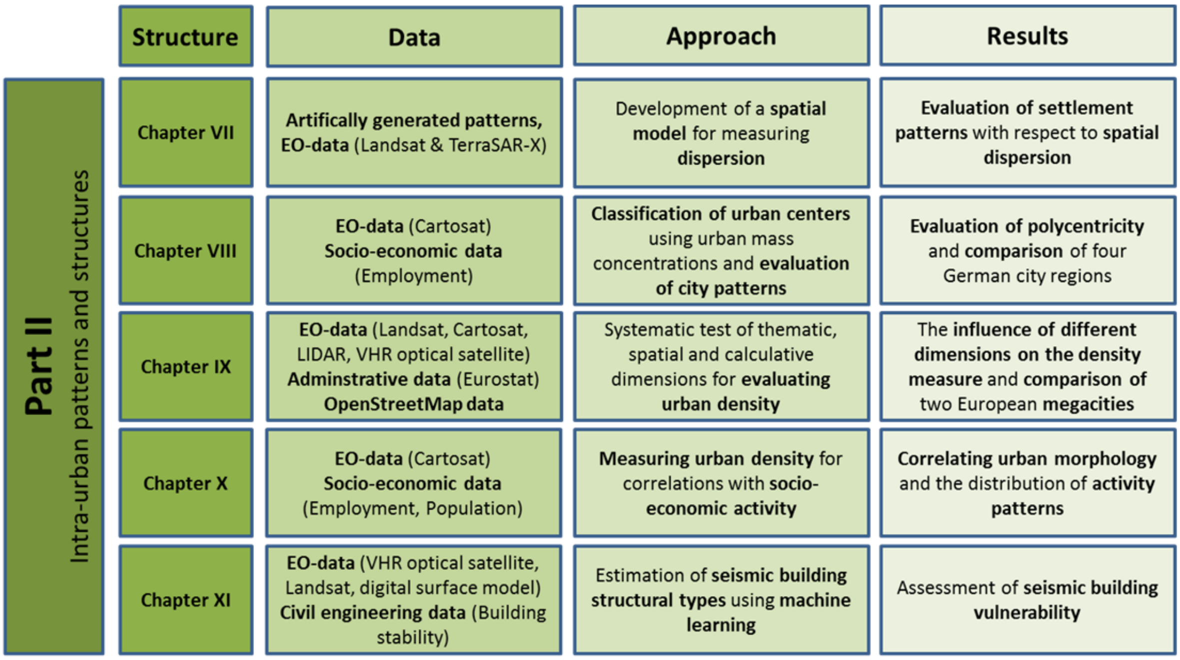

Figure 4 Structure of Part II – Intra-urban patterns and structures of cities.

(3) ***Part III*** addresses ***urban poverty, its physical manifestation and social aspects of it***. The focus is on the most visible characteristic for urban poverty – morphologic forms of slum structures. The measurement and characterization of living environments of the urban poor and whether these physical attributes provide a feasible proxy to spatially approach poverty in cities are investigated. For the spatial analyses, two-dimensional classifications as well as three-dimensional city models in LoD-1 of morphologic slum structures are predominantly used in combination with census or in-situ data.

Initially, evidence that slums show significant morphologic differences to formal settlements is provided. Based on this, physical attributes which are characteristic for slums are defined. It is also investigated whether slum morphologies, which are often described as similar, are de facto structurally homogeneous or heterogeneous (Chapter XII).

In literature it is frequently assumed that physical attributes which are characteristic for slums are a valuable proxy for the spatial localization of the urban poor using derived EO data. In a multidisciplinary spatial combination of city-wide morphologic slum classifications with household income information from census data, evidence is found that these locations are as a matter of fact predominantly inhabited by the social group of urban poor. With it, it is verified that the built environment can be used as proxy to detect a specific social group (Chapter XIII).

Building up on this evidence it is legitimate to use this proxy for applied research. As example, the issue is addressed whether the economic disadvantage of this social group is reflected in their online behavior. Therefore the potential of a novel data source — location-based social networks— in conjunction with EO-based slum maps is explored. In an experimental setting it is found that residents of slums indeed have less online activity than the city average (Chapter XIV).

The disadvantage of the urban poor is also reflected in the fact that many informal parts in cities do not feature a sufficient supply of resources such as water. For the integration of this social group into the urban supply chains an optimized way needs to be found. For the development of supply chains fundamental knowledge on slum sizes is in demand and whether slums tend to have characteristic, universalizable spatial extents. In a cross-city study it is found that independent from the city, the country or the continent slums do feature typical spatial extents (Chapter XV).

However, the social group of the urban poor is not only represented by slums or slum-like structures. Thus, it is investigated which morphological forms for the urban poor can be distinguished across the globe. Using the concept of the Arrival City and based on a literature survey, a large sample is selected across the globe and the built morphologies of these places are classified in LoD-1. A global morphologic categorization of forms of living environments representing urban poverty is developed (Chapter XVI).

Figure 5 gives a general overview on the structure of Part III, the used data, the methodological approaches and the main results

	Structure	Data	Approach	Results
Part III Urban poverty and physical manifestations	Chapter XII	EO-data (VHR optical satellite)	Development of spatial indicators allowing to measure urban morphologies	Spatio-quantitative diffentiation of slum structures vs. formal settlements
	Chapter XIII	EO-data (TerraSAR-X, VHR optical satellite) Socio-economic data (Income)	Spatial correlation of morphologic slums and census information	Confirmation that morphologic slums capture a social class of urban poor
	Chapter XIV	EO-data (VHR optical satellite) Social media data (Twitter) Demographic data (census)	Analyzing quantities of geolocated tweet in morphologic slums vs. formal settlements	Revealing morphologic slums as digital deserts
	Chapter XV	EO-data (VHR optical satellite)	Applying rank-size distributions onto morphologic slums	Documenting characteristic sizes of slums independent from city locations
	Chapter XVI	EO-data (VHR optical satellite) Other data (in-situ information, photos)	Literature survey and applying spatial indicators to measure urban morphologies	Documenting physical appearances of urban poverty across the globe

Figure 5 Structure of Part III – Urban poverty and its physical manifestations

(4) *Part IV* conceptualizes ***aspects of physical urban form***, i.e., a résumé is provided on the fundamental aspects that define urban form in past and current literature. In Part I, II and III the analytical work on urban issues predominantly focuses on the built aspects of the urban landscapes. Here, the conceptual approach towards urban form is widened by a systematization of six fundamental physical aspects for a more comprehensive documentation and analysis of urban form (Chapter XVII). The concept shall allow producing generalizable results in future studies (Fig. 6).

	Structure	Data	Approach	Results
Part IV	Chapter XVII	Scientific platforms such as web of science	Literature survey for developing a concept for measuring urban form	Systematic concept for measuring urban form

Figure 6 Structure of Part IV – Aspects of physical urban form

4. New dimensions of urban landscapes (papers related to Part I)

Megacities are usually defined as cities with more than 10 million inhabitants (UN, 2006). They are often associated as the largest urban agglomerations on our planet. However, the concept of megacities still derives from a concentric, medieval city model with a defined, dense center surrounded by a more or less complex halo of lower dense settlements and suburbs ultimately turning into rural environments. Today this concept does not represent the largest category of urban landscapes anymore as current global urbanization processes are leading to new urban forms of massive, multi-nuclei urban constellations.

In a thorough literature survey (**Chapter II**) it becomes obvious that there is an abundance of terms describing such massive large urban constellations (e.g. Taylor & Lang, 2004). *Mega-region* (e.g. Florida, Gulden & Mellander, 2008), *megalopolis* (e.g. Gottmann, 1957), *megapolitan* (e.g. Lang & Dhavale, 2003), *network city* (Castells, 1989, 2002), *world city region* (e.g. Scott, 2000), *megacity-region* (e.g. Hall & Pain, 2006), *urban corridor* (e.g. Whebell, 1989), *urban field* (e.g. Friedmann & Miller, 1965), *metroplex* (e.g. Lang & Nelson, 2007) or *conurbation* (e.g. Geddes, 1915) are examples describing concepts which are in parts very similar and show considerable overlap; as Brenner (2013) puts it provocative, "*definitional contours have become unmanageably slippery*". Many concepts are abstract or unspecific, and when approaching these concepts with a spatial perspective the physical parameters —if they exist— are neither properly defined nor used in standardized ways. The limiting factor when delineating large urban areas seems to be a commonly agreed ontology. While understandably concepts originate from various disciplines, for a consistent empirical and spatial approach there is a need for more precise definitions and use of parameters. In a thorough literature review a set of qualitative and quantitative spatial parameters are collected and systematized. The over-arching goal is to find a basis for a consistent spatial analysis to parameterize such massive urban constellations using mapping products from EO data.

Compiling information from scientific literature on indicators such as population numbers, spatial extents, typical shapes, or number of urban hubs allows for systemizing descriptions and definitions of these urban concepts by spatial attributes. The spatial relationships of the reviewed concepts provided in the definitions in literature are implemented in a common spatial juxtaposition. The resulting spatial impression of the concepts in relation to each other is illustrated in figure 7.

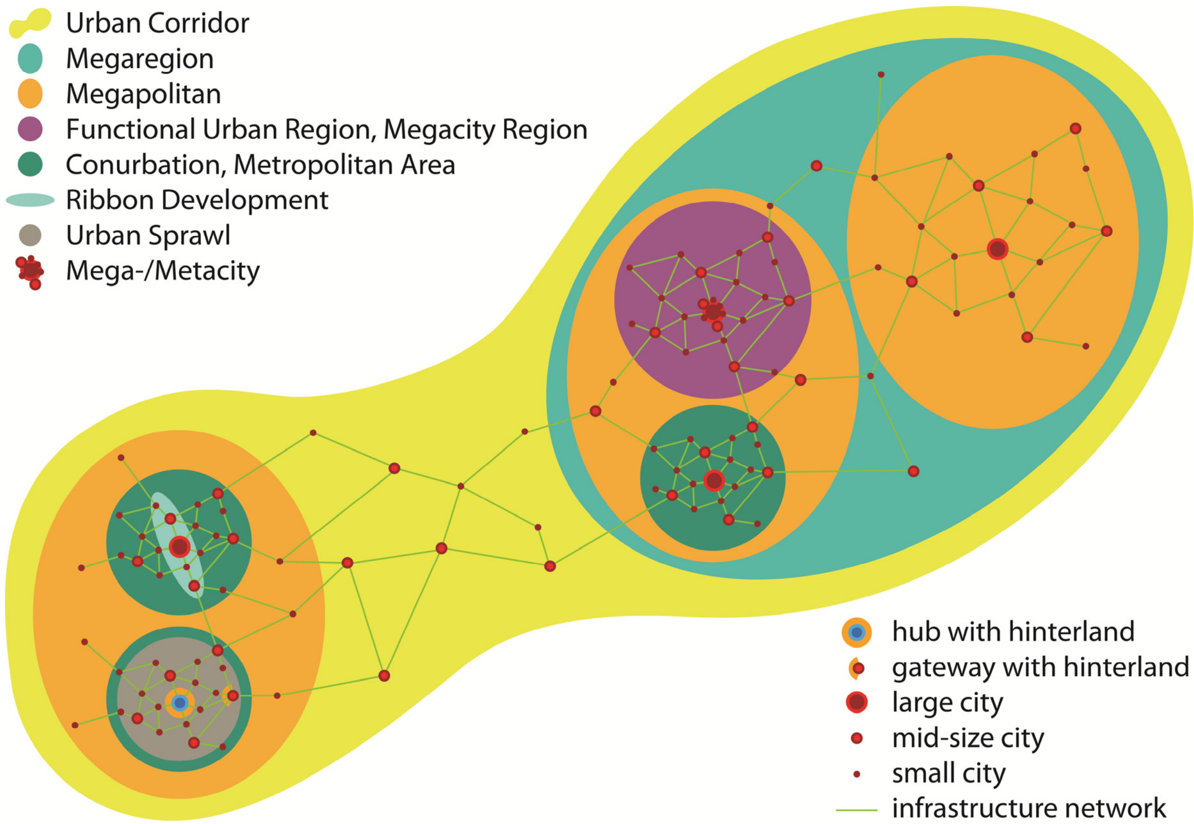

Figure 7 Juxtaposition of different concepts for large urban areas in spatial agreement

Based on existing definitions, individual small, medium, and/or large cities spatially constitute the bricks (or urban hubs) for larger urban constellations. They form on higher level functional urban regions, megacity regions, conurbations or metropolitan areas which have considerable interrelations with surrounding cities and hinterlands. On the next level the megapolitan conceptually unites conurbations or metropolitan areas by their joint transport infrastructure or coalescent settlement patterns in relative spatial proximity. This is followed by the mega-region which constitutes the second largest constellation found in literature merging all these previous elements at the various levels together. Finally, the largest constellations by far are formed by urban corridors. Their dimension exceeds that of all other large urban concepts and strings together individual bricks of urban concepts along a linear line up to hundreds of even thousands of kilometers.

The spatial juxtaposition can only be an approximation of the scale and extent of large urban constellations, but the results show the physical parallels between different concepts. The systematization, however, intends to provide a consistent, spatial hierarchy of these concepts. The result serves as a guideline for delineating large urban areas using spatial parameters in empirical studies.

Although figure 7 provides an approximation towards the spatial configurations of large urban areas, the transformation from its theoretical configuration to real-world settlement patterns is neither obvious nor trivial. The conceptual fuzziness and complexity for constructing regions leads to a challenge to arrange them into consistent territorial maps (Harrison & Growe, 2014). While there is consensus that the term 'region' refers to space, the construction of space itself can rely on different indicators and logics, and intrinsically features several connotations or meanings: territorial space; political space; space of social interaction; economic space; functional space; institutional space (Keating, 1998).

In this work the basic data sets used are classifications of settlement patterns derived from EO data. In consequence, the focus of the developed approaches for constructing space is on territorial thinking (however, not in a political sense of territories, but on territories defined by similar spatial characteristics of the landscape). Regions are understood as unfixed, fuzzy territorial entities, boundaries are malleable based on the criteria used or the thresholds defined (e.g. Ross, 2011; Haughton *et al.*, 2010; Georg, Blaschke & Taubenböck, 2018).

The construction of space for one specific concept of a large urban constellation —the *mega-region* (e.g. Florida, Gulden & Mellander, 2008; UN-Habitat, 2008)— is at focus in **Chapter III**. The aim is to turn the general guidelines of the developed spatial concept from a qualitative and descriptive stage into a quantitative, empirical spatial definition.

Mega-regions are described as territorial and functional areas bound by economic, political, socio-cultural, and ecological attributes that result from the growth, convergence (e.g. shared infrastructure systems) and spatial spread of geographically linked metropolitan areas and other agglomerations (Atlanta Regional Commission, 2008; Florida, Gulden & Mellander, 2008; UN-Habitat, 2008). They are polycentric urban clusters surrounded by low density hinterlands, and they grow considerably faster than the overall population of the nations in which they are located (Florida, Gulden & Mellander, 2008).

Using the EO-based large area binary settlement patterns available over time (cf. Fig. 2, Part I) allows tuning the conceptual approach of mega-regions into a quantitative spatial approach. The main idea of the developed approach relies on two spatial indicators: *First*, large urban centers function as main urban nodes defining the network of cities possibly constructing such areas. The urban nodes are identified as center points of large cities either measured by population or measured spatially by areas of large and continuous high settlement density. *Second*, the physical connectedness between two urban nodes is evaluated. The classification of connectedness relies on the highest possible settlement density with the shortest possible distance between identified urban nodes.

In this work, the Pearl River Delta mega-region (consisting of many coalescing large cities such as Hong Kong, Shenzhen or Guangzhou, among others) in Southern China (Yang, Son & Lin, 2012; Oizumi, 2011) is used as exemplary prototype for the analysis. The urban nodes are defined by the largest cities in the region as measured by population. The settlement patterns are classified from multi-source satellite data (Landsat and TerraSAR-X) for the epochs 1975, 1990, 2000 and 2011. The settlement density is derived from the urban footprint classifications by the total settlement area per 1x1 km grid cell. The resulting gridded settlement density serves as one, consistent spatial input data set for evaluating the spatial connectivity between nodes.

Evaluating the results, the Pearl River Delta mega-region shows a very large and complex settlement pattern. The urban landscape stretches far beyond individual city limits to a more or less coalescent polynuclei pattern spanning roughly an area of 250 km x 220 km (Fig. 8). The area measured with spatial connectivity by high settlement density has more than 50 million inhabitants and a coalescent settlement pattern – these are the new dimensions of urban landscape on our planet today.

However, this was not always the case. The multi-temporal classification of spatial connectivity reveals that in the 1970s individual cities with significant distances to the next larger city shaped the landscape. Back then only two cities were classified connected: Foshan and Guangzhou (Fig. 8). Thus, in the 1970s most cities can be considered spatially as a center in their own right. In the following decades the highly dynamic process of spatial urban expansion transformed the area from individual cities separated by low dense rural areas into an almost totally merged settlement pattern of a mega-region.

An empirical spatial definition constituting the pattern of a mega-region relies on a set of spatial statistics: The settlement pattern strechtes from the city of Jiangmen to Foshan, via Guangzhou to Dongguan, Huizhou, Shenzhen and finally to Hong Kong and is continuously classified as highly connected – a distance of 625 km (Fig. 8). These cities form the spatially highly connected main network of urban nodes over hundreds of kilometers around the Perl River Delta. Beyond, the entire mega-region grows spatially with higher pace than mega-cities in China. It grew 13.1 times regarding its spatial extent since 1975, while highly dynamic mega-cities such as Beijing or Shanghai only grew by 6 to 7 times (cp. Taubenböck *et al.*, 2012). This insight confirms the statement that mega-regions grow considerably faster than other parts of the nation (Florida, Gulden &

Mellander, 2008). Furthermore, it is noteworthy, that the hinterland of the mega-region shows the highest increase of spatial settlement growth. Thus, it is obviously characteristic for a mega-region that urban expansion between and beyond the main city centers outdraws the core city growth. This proofs a coalescent process to a multi-nuclei mega-region. In conclusion, the measured spatial features of the settlement pattern in the Pearl River Delta are found to match the descriptive concept of a mega-region.

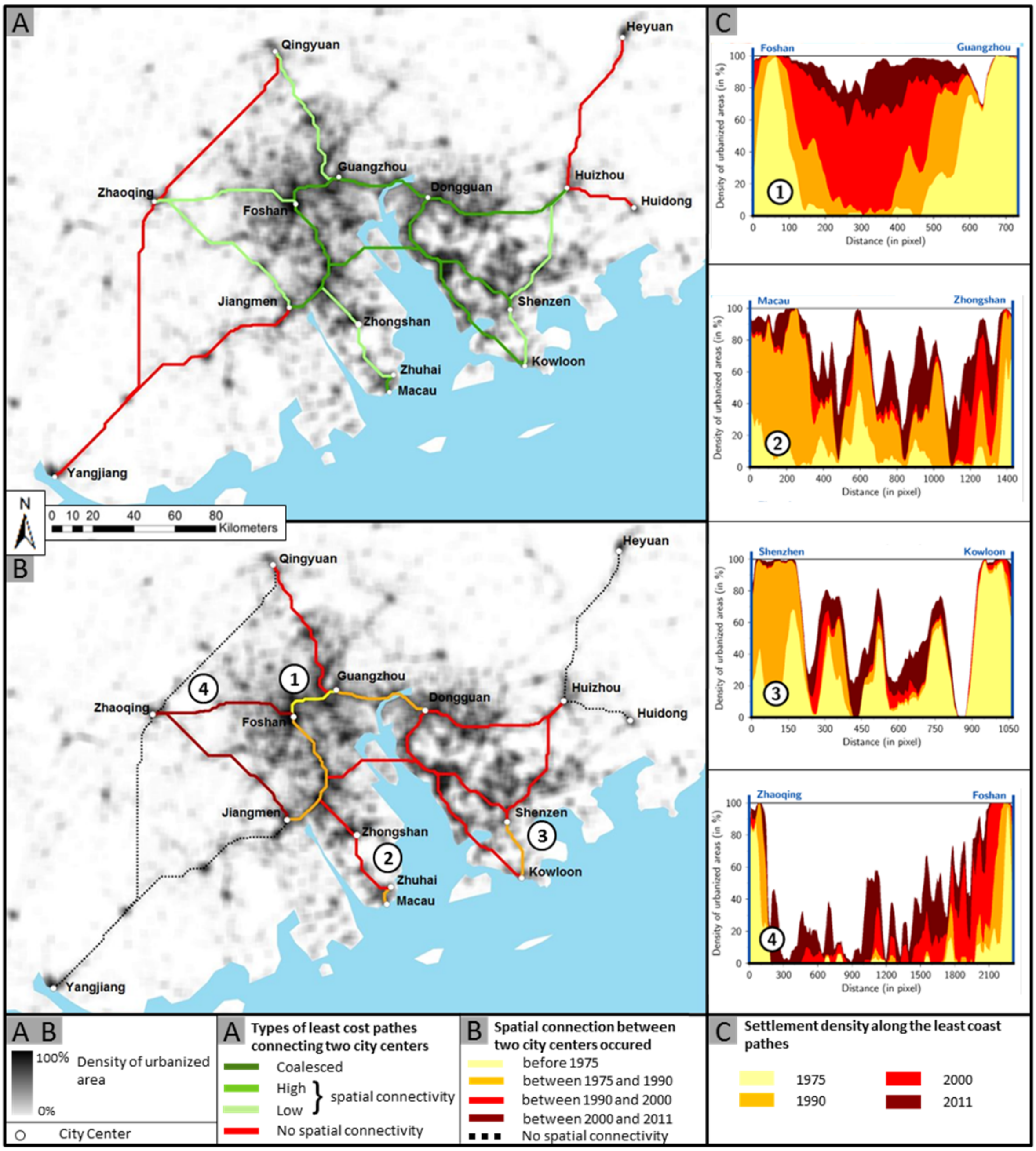

Figure 8 Settlement density, classification connectivity between major cities (A), classification of connectivity between major cities and their timely occurrence (B), and development of density values at interurban connection lines over time (C) in the Pearl River Delta mega-region.

The developed conceptual approach and the related spatial metrics allow the delineation and characterization of the settlement pattern of the mega-region in the Pearl River Delta. This spatial characterization of a region concordantly denominated a mega-region in literature is empirical. However, it remains an open question whether this specific pattern is spatially characteristic for mega-regions across the globe. Or do other areas conceptualized as mega-region feature different spatial characteristics? To answer these questions four additional areas classified in the literature as mega-region are selected (**Chapter IV**): the mega-regions *Southern California* in the USA (SC) (e.g. Ross *et al.*, 2009), *São Paulo – Rio de Janeiro* in Brazil (SP-RdJ) (e.g. UN-Habitat, 2008), *Nile delta* in Egypt (CA) (e.g. UN-Habitat, 2008), and *Ruhr-Randstad* across the European countries of The Netherlands, Belgium, France and Germany (RR) (e.g. Soja & Kanai, 2007).

Applying the same methodological approach of analyzing multi-temporal settlement patterns for the years 1975, 1990, 2000 and 2011 for all regions, a spatial comparison in a consistent manner is made possible (Fig. 9). In comparison to the settlement pattern of the *Pearl River Delta* mega-region, the analysis reveals that the mega-region in Europe is spatially also connected between the main city centers. However, compared to the *Pearl River Delta* mega-region there is no core area, which is contiuously highly connected. It becomes evident, that the *Ruhr-Randstad* mega-region is subdivded into three separated areas which are highly connected or even coalesced: *The Hague, Amsterdam, Utrecht and Rotterdam* are one core, the *Ruhr-Cologne* area – *Duisburg, Essen, Dortmund, Wuppertal, Düsseldorf, Cologne and Bonn* form another core and the third core is *Antwerp, Ghent, Bruges, Lille and Brussels*. As these three highly connected core areas are bound together based on the settlement patterns with low connectivity, the entire region is *evaluated a mega-region*.

The *SC* region also shows basically two core areas of high connectivity. The first area streches along the coastline from *Santa Barbara* to *L.A., Long Beach, Irvine,* with a detour to inland *San Bernadino*. The second core area is the cross-border region of *Tijuana* to *National City* to *San Diego* and to *Oceanside*. As both core areas are, similarily to Europe, spatially associated with low connectivity, the entire strech along the coastline spatially *qualifies as mega-region*.

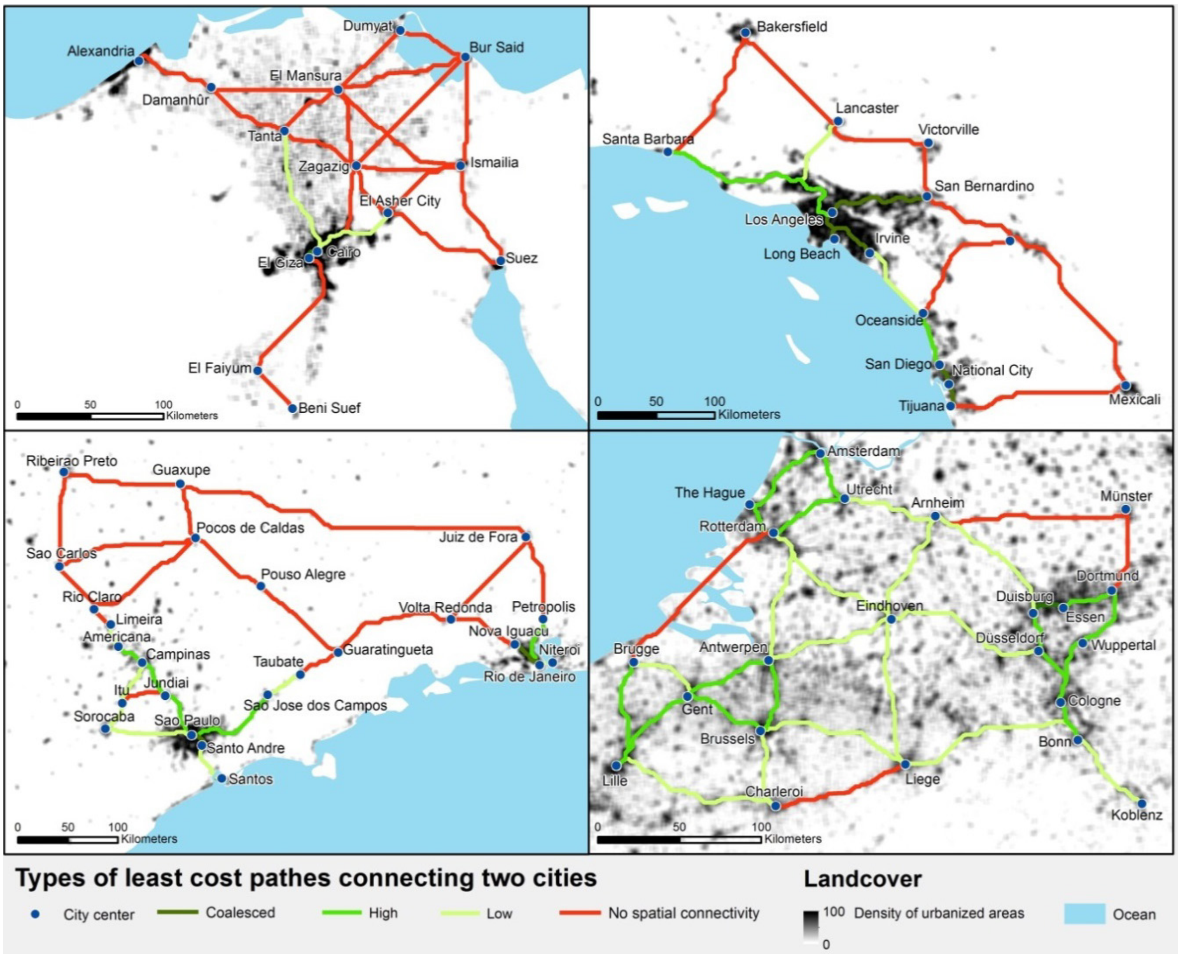

Figure 9 Classification of connectivity between major cities based on settlement density in the Nile Delta, the Southern California region, the Sao Paulo – Rio de Janiero region and the Ruhr-Randstad area (clockwise).

In comparison, the *SP-RdJ* region in Brazil features core connected areas; however, with a difference to the other regions analyzed: the two core areas are spatially not yet measured as connected. The area of *São Paulo, Santo Andre, São Jose dos Campos, Jundiai, Campinas* and *Americana* forms one core. The second core is located around *Rio de Janeiro* with connections to *Nova Iguacu* and *Petropolis* and with low connectivity to *Niteroi.* Both areas act as economic hubs, with the highway BR-161 being one major transportation connection. However, spatial connectivity based on high settlement density between both cores is not yet observed. In consequence, both areas are more characterized as megacities dominating a larger metropolitan area and thus, *do spatially not qualify as mega-region*.

Results for the Nile delta reveal a very different magnitude of spatial connectivity. Connectivity between the main city centers of the region is not measured except between the cities of *Cairo* and *El Giza*, and with low connectivity to *Tanta* as well as to *El Asher*

City. All other connections are classified as spatially not connected. This region is very much dominated by the megacity of Cairo. Although the Nile delta is one of the most densly populated areas across the globe, the settlement patterns are still highly fragmented. Thus, in a global comparison of settlement characteristics the Nile delta region does spatially *not yet qualify as mega-region*.

In general, it is found that mega-regions titled as such in scientific literature feature varying settlement patterns: From the five mega-regions under investigation only three fulfill the criterias of a spatially coalesced and polycentric settlement pattern at an interregional scale beyond limits of individual cities. The other two regions are measured with still fragmented settlement patterns, where dominating large cities are not sufficiently connected spatially with other large cities.

The spatial characterization of mega-regions is based on areas suggested in literature. However, the developed methodology is independent from pre-defined regions. Without any spatial limitation the approach allows uncovering hidden spatial settlement patterns on continental or global scale. The typical maps of Europe, as example, are either a topographic reconstruction of the continent or they visualize the administrative boundaries of nation-states. The transfer of the developed methods —using settlement density and distribution of settlements as indicators for identifying urban nodes and delimiting regions around them— allows tackling regional phenomena (**Chapter V**). Understanding regions in the sense that similar physical characteristics may construct alternative spatial entities which may sub-divide or cross-over the administrative boundaries of nation-states allows overcoming common map projections.

The work is based on the Global Urban Footprint derived from TerraSAR-X data featuring European-wide consistent spatial information on settlement patterns (Esch *et al.*, 2012). In the previous approaches urban nodes have been identified by center points of large cities measured by population. However, population statistics do suffer from inconsistencies due to varying acquisition dates or differing census techniques, among others. As example, the population grid from Eurostat (2016a) is not available in consistent manner outside EU member states. In contrast, the settlement classification based on EO-data features consistent accuracies across Europe (Klotz *et al.*, 2016) and is thus a feasible data set for comparison. In this approach the method is extended to become a meaningful alternative completely independent from population data.

It is assumed that an urban node of relevance features a comparatively large area of high settlement density. With respect to those two variables —high settlement density and comparatively large areas featuring high settlement density— urban nodes are localized. For the evaluation of connectivity between two identified urban nodes the density of the settlement pattern in between is used again. In addition to the connection between two nodes, in this approach territorial entities around the identified urban nodes are also mapped using settlement densities around the nodes. Finally, the identified regions are categorized based on four physical attributes: extent of the identified region, number of urban nodes, connectivity between nodes and average path length of connected cities within a region. By combination of these attributes an index is generated: higher values indicate regions with more nodes, more clustered arrangements, higher connectivity and larger extents. Based on a statistical method for clustering, five groups (Category A – E) are identified.

As a major outcome of this study uneven settlement pattern development across Europe is revealed. Figure 10 illustrates that the dominating core of spatially connected nodes by high settlement density streches from central England to northern Italy via The Netherlands, Belgium, Luxembourg, France, Germany and Switzerland. This settlement pattern basically reflects the form of the Blue Banana (RECLUS, 1989), which has been titled the backbone of European economic development originating along century-old trade routes and from an industrial past, sometimes terminologically called an *urban corridor* (Heidenreich, 1998; Hospers, 2003). However, using the settlement pattern as proxy allows to identify an expansion beyond the indicated former shape. Paris and its surrounding city regions (in the RECLUS (1989) study evaluated as not connected to the Blue Banana) are now classified as connected to the large network; in England the network today expands further to the north to Newcastle; the network also expands to central/northern Germany to Hamburg and Hannover, and to the southeast towards Munich along new development axes. This spatially streched area is still characterized by the Blue Banana as backbone, but today shows many detours from its main body indicating newly developing axes. It's dominating character in quantitative manners is shown as 51.7% of all identified nodes across Europe are spatially connected to this network.

Beyond, the Yellow Banana —from Paris to Warzaw— is developing in bricks which are not yet measured as fully connected by nodes, but confirming the expected rise of this development direction (Hospers 2003). Also for the Sunbelt Banana —from Milan to Valencia (Hospers 2003)— these connected bricks are detected; overall, these spatial entites of connected nodes are spatially very well reconstructing, but also extending the European 'blue star' map introduced by IAURIF (1991) or the 'red octopus' (Van der Meer, 1998). The method also visualizes how e.g. nodes of relevance such as the national captials Madrid, Stockholm or Bucharest are spatially isolated to other nodes.

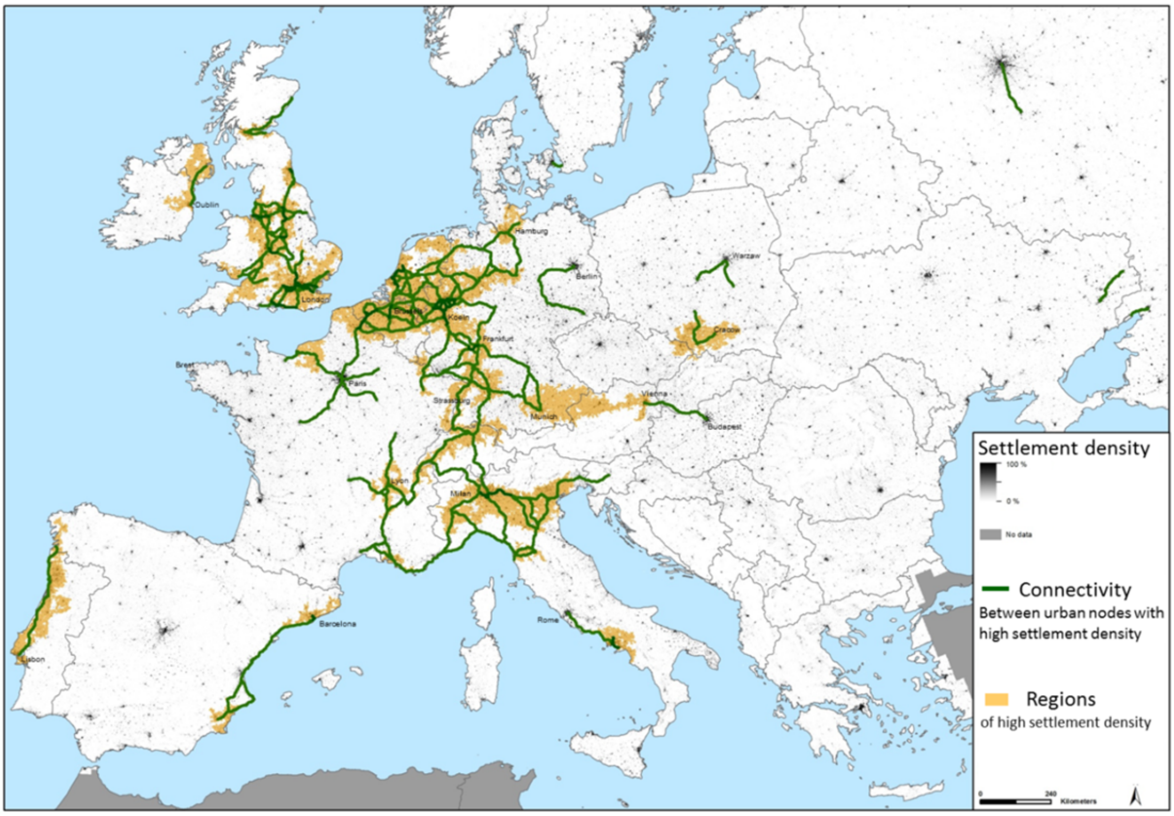

Figure 10 Identified regions of high settlement density around the identified urban nodes classified as connected by high settlement density

Applying the methodology for categorization, 22 regions (Cat. A – D) and 39 monocentric city regions (Cat. E) are detected across Europe. The delimited regions themselves feature very different constitutions: one transnational, very large mega-region (Cat. A) with highest measures of the four variables across Europe is identified; the transnational Ruhr-Randstad mega-region is Europe's most dominating region (*Category A*). This large mega-region houses more than 51 million inhabitants, 10% of the entire population of Europe. The three *Category B* mega-regions are significantly smaller entities; however, these regions still consist of a large number of nodes constructing large ploycentric patterns far beyond conceptions of individual cities: the London dominated region, the area strechting from Cardiff via Birmingham to Liverpool and Leeds as well as the region in northern Italy. Their significance is also shown by their populations which are between 21 and 24 million inhabitants. The three *Category C* regions consist of areas of 3-6 nodes and significant smaller populations (between 5 to 13 million inhabitants), and the *Category D* group of regions feature only two to three nodes (ranging between 1.2 and 9 million inhabitants).

The developed approach relying solely on a mapping product based on remote sensing data proves high plausibility. One example allowing the plausibilization of results relies on a comparison with an independent other data set (the Urban Audit Cities (UAC)). The UAC are classified based on certain criteria such as population numbers, among others (Eurostat, 2016b). It is assumed that the approach for urban node identification using the physical proxy of settlement density is feasible if the data sets do not differ significantly. Within a search radius of 5km from the detected nodes using the EO-approach, in 89% of all cases the center of an Urban Audit City is found. If the search radius is extended to 25km, 100% confirmation is revealed. Those numbers confirm the capability of the proxy 'settlement pattern' to identify urban nodes of relevance.

However, although this study uncovers spatial settlement patterns across Europe it is also shown that there is neither only one regional logic, nor is there just a single dimension defining regional phenomena, nor is a constructed territorial or relational space 'correct' or 'incorrect' in absolute measures. As Dicken (2014) discusses, regional phenomena are not a single, unified phenomena, but a syndrome of processes and activities. There is not one single 'driver', but a supercomplex series of multicentric, multiscalar, multitemporal, multiform and multicausal processes. Thus, we understand that it is increasingly different combinations of these elements that construct today's multitudes of 'new regional worlds' (Harrison, 2013), forming spaces that complement, compete, or even contradict each other. The proxy 'settlement pattern' derived from EO-data, however, is found to provide one additional perspective to capture regions. Geographically the study illustrates that regional disparities in Europe are still enormous and are conflicting the idea of a balanced economic growth and territorial equilibrium. While it was prefigured that advances in technology and communication would induce an era of global deconcentration and a diminishing role of cities in globalization (Harrison & Growe, 2014), there is still a convergence of cities in ever-more large and complex polycentric concentrations of settlements found.

The identified stretch from central England to northern Italy via The Netherlands, Belgium, Luxembourg, France, Germany and Switzerland represents the conceptual idea of an urban corridor – the largest constellation introduced above. On global-scale *urban corridors* are described as a number of large, linear urban areas linked through a well-developed transport network (e.g. Trip, 2003; Li & Cao, 2005; Chapman *et al.*, 2003). The term has been applied to quite some extent in scientific literature. However, the concept and understanding of the term is complex and, comparable to the concept of mega-regions, a universal acceptance of indicators for a classification and delimitation is not given. This serves as further example to underline the different perceptions and insufficient definition of a relatively unexplored conceptual approach. A number of qualitative case studies exist but there are no systematic, transferable approaches to capture, quantify, characterize and delineate urban corridors on a global scale. The United Nations Human Settlements Programme (UN-Habitat) (UN-Habitat, 2008) provides a global map of urban corridors, mega-regions and city-regions, but the methodology for localization is not specified. This map is furthermore not based on a clear definition of the term and shows inconsistencies in the interpretation of different types of large urban areas.

The work in **Chapter VI** seeks to update this map with a comprehensive and consistent approach using a combination of methods: *First*, a systematic literature review delivers definitions and a list of areas categorized as urban corridors. *Second*, the perception of urban corridors on a global scale in the geo-scientific community is investigated. A questionnaire was handed out to 40 scientists. Additionally a printed poster illustrating the global night-time lights distribution acquired by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) (Elvidge *et al.*, 2001) was used for drawing corridor outlines. *Third*, the potential urban corridors identified in the literature review and questionnaires are measured using remote sensing imagery, road data and image analysis software.

The literature review sets the conceptual foundation: the term *urban corridor* should in general be applied for *linear, massive urban constructs* (e.g. Whebell, 1969). Among the constituent features of a global urban corridor are *several major cities*, a more or less *linear structure* (i.e., generally linear but with curves and branches to the side), and a *connecting transport infrastructure*. To be more precise, urban corridors consist of a number of cities of significant size, expand over several hundred kilometers and have a well-developed *surface transport infrastructure* (rail, road). Urban corridors have a high length-to-width ratio and are more or less continuously populated if the physical land surface allows. Administrative and international boundaries can be crossed (e.g. Trip, 2003; Li & Cao, 2005; Chapman *et al.*, 2003; Florida, Gulden & Mellander, 2008).

The perception of urban corridors by the geo-scientific community sets a second basis for spatially capturing features of urban corridors. 40 scientists answered a structured questionnaire and visually mapped corridors on DMSP-OLS data. However, neither the literature review nor the perception of scientists on urban corridors provides an unambiguous localization or delimitation of these. 63 corridors are derived from the literature review, plus a further 17 from the surveys that have not previously been identified in the literature. These 80 areas are subjective and not independently proven but serve as a first guideline for further investigation.

An analysis using the night-time light imagery aims at measuring spatial attributes of all suggested corridors to find common denominators of suggested urban corridors. Since the understanding of an urban corridor is extremely varied, the approach developed here is based on a "master" corridor which serves as a template for the analysis of identified corridor candidates. This "master" is the Boswash region in the USA.

The general approach is that the master corridor from Boston to Washington must be spatially connected based on the night-time light imagery. Using image analysis techniques, an empirical threshold is defined that forms a cohesive region from Boston to Washington without interruption. This threshold is subsequently applied globally to form large patches of "light" (urban) and "dark" (non-urban) areas.

In general, the identified urban patches represent a single city or several connected cities but do not form fully joined corridors, i.e., most presumed urban corridors consist of a number of smaller patches which are not merged into one single, large patch like the Boswash master corridor. Thus, the patches of potential corridors (identified through literature and questionnaires) are linked by their main road connection (using OpenStreetMap data), taking into account the fact that cities within urban corridors are aligned along high-speed transportation routes: a road network is one of the defining features of an urban corridor. This road connection is defined through the start and end nodes of an urban corridor. Usually, the literature provided information of the main cities along an urban corridor, often located at either end. In the Boswash example, this means the fastest road trip from Boston to Washington.

From the resulting connected patches —i.e., from the global inventory of potential urban corridors— the following spatial attributes properties are obtained: Total urban area (calculated from the total area of all night-lit patches of a corridor classified as "urban"), length and width, length-to-width ratio and number of gaps along the route. This method allows that the same dataset is globally applied, independent of administrative units. Figure 11 provides an overview of all identified urban corridors.

Overall it is found the urban corridors on global scale are typically between 400 and 1200 km long, 70 to 200 km wide and with a length-to-width ratio between four and ten. The urbanized area is between 10,000 and 50,000 km^2.

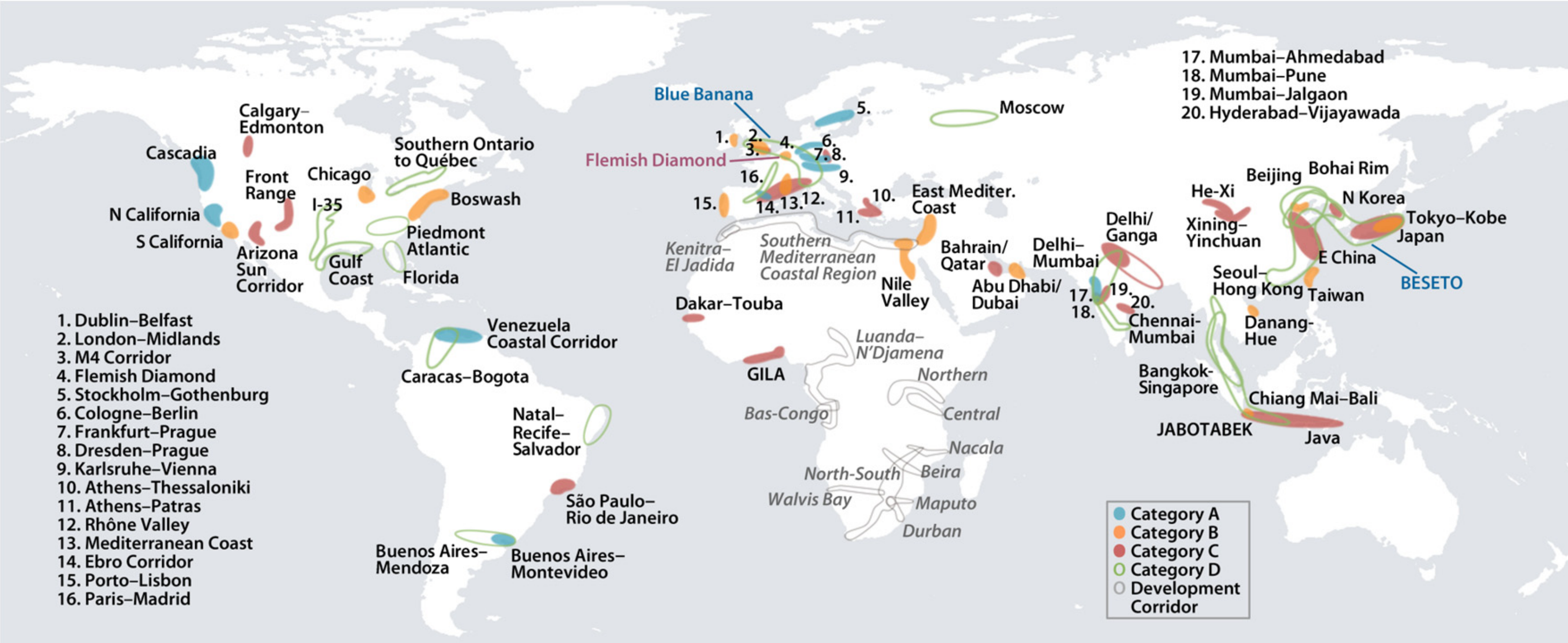

Figure 11 Global inventory of urban corridors based on a literature survey, questionnaires and spatial analysis of night-time imagery. The categories of corridors are indicated by color.

Based on the spatial attributes length, width, length-to-width ratio, urbanized area, number of gaps between urban patches a categorization is provided. *Category A* includes the most "typical" (but not necessarily "best") corridors from the analysis. *Category B* contains the least fragmented corridors, *category C* those with a typical number of gaps and *category D* the most fragmented ones. All urban corridors suggested are mapped in figure 11. Using the same consistent method based on objectively measurable criteria, a comprehensive global inventory of urban corridors is generated. This inventory shows the (rough) spatial extent of all corridors in addition to a categorization according to the derived spatial criteria. However, the results are a rough approximation of the extent of urban corridors since no proper outlines were provided in the literature. List and map are thus intended as an empirical typification of possible urban corridors.

In general a large share of urban corridors is found to be located in Asia, including the three longest ones (Chiang Mai–Bali, Seoul–Hong Kong and Beijing-Seoul-Tokyo). With the exception of the Blue Banana in Europe, no corridor outside of Asia exceeds much above 1500 km. However, also in Europe and North America many urban corridors are localized.

In conclusion, **Part I** documents and reveals evolving **new dimensions of urban landscapes** across the globe. It is shown that (large) cities merge into spatially clustered networks of massive urban forms home to 50 million inhabitants and more. Remote sensing in combination with other data and methods is capable to identify, systemize and characterize these evolving new massive urban forms. The proxy 'settlement pattern' derived from multi-source EO-data is one feasible and necessary empirical foundation to spatially delimit and charaterize conceptual approaches such as mega-regions or urban corridors. With the physicalism of settlement patterns the intensification of every-increasing urban centers is spatially uncovered and reveals uneven development across the globe.

5. Intra-urban patterns and structures (papers related to Part II)

In Part I the focus was on urban form with respect to spatial patterns beyond the size of individual large cities. As documented, today's large urban corridors and mega-regions consist of complex and often expanding spatial patterns of the built environment now coalescing once individual cities. Thus, urban form has been addressed at scales of continents or large (trans-)national regions based on binary classifications of 'settlements' and 'non-settlements'. In the current **Part II** the focus is on internal spatial compositions of cities. Today's metropolitan regions consist of complex spatial arrangements, from compact to dispersed, from dense to scattered, or from monocentric to polycentric urban forms. Intra-urban structural variabilities that subdivide the urban space into its basic physical elements (such as buildings, impervious surfaces, green spaces or the like) serve as cornerstones in the following approaches. In the analyses the physical elements are used either directly for findings on structural city compositions or as proxy information in domains such as economic activities or vulnerability of building structures under seismic load.

The question whether the spatial layout of a cities' settlement pattern can be considered compact or disperse seems to allow for a simple intuitive answer. An objective measurement of spatial patterns or their comparison across space, however, is not trivial. In the urban research domain, a multitude of elements constitute morphological patterns. With respect to scale, individual objects such as buildings, but also aggregated thematic patches of land use at city levels shape these patterns. It is not explicitly agreed upon which spatial dimensions (scale, units of measurement) and which thematic features allow for a suitable characterization and representation of urban spatial patterns. As a consequence, the debate on the shape of spatial urbanization includes a confusing variety of theories, conceptual approaches, data sources and techniques for measurement applied to varying (land use-related) objects across different spatial scales of observation (e.g., Tsai, 2005; Jabareen, 2006; Galster *et al.* 2001; Batty, 2008). Critics claim that much of the work in the past can be contested due to a data-driven approach and a rather arbitrary use of metrics, scales of observation, spatial reference systems and geographical boundaries (e.g. Lechner *et al.*, 2013; Riiters *et al.*, 1995).

In **Chapter VII** a model-based conceptualization of spatial patterns is developed. The idea is to allow for an unambiguous, transparent and reproducible evaluation of settlement patterns between 'compactness' and 'dispersion'. Dispersed landscape configurations are typically characterized by increasing levels of urban expansion at large distances from the city center and, thus, a less concentrated, spatially clustered or clumped location of urban functions. In the respective literature, related terms such as “scattered” or “sprawled” land use patterns can often be found (e.g. Poelmans & Van Rompaey 2009; Garcia-López & Muñiz 2010). Against this background, a given land use pattern is conceptualized as more dispersed if the number of urban patches is higher and the size of the largest (central) patch is lower. In contrast, compact urban forms are characterized by a large urban core as a continuously urbanized area and a relatively low number of urban patches.

The approach is developed for two-dimensional patterns constituted by two thematic classes: ‘settlement’ and ‘non-settlement’. The model is constructed by two spatial metrics: the *largest patch* (LP) is used as a proxy to evaluate whether this largest patch is dominating an urban landscape or not. This proxy is related to monocentric city models, i.e., the basic idea that a dense core city is surrounded by a less dense surrounding area (e.g., Anas & Kim, 1996). The *number of patches (NP)* and especially a higher number of patches around the dominating largest patch are conceptualized as indicator for a more fragmented, less compact and thus, more disperse landscape pattern. These two landscape features (LP, NP) span a two-dimensional space allowing a ranking of any pattern in relative, but also absolute terms between compact and dispersed layouts. ‘Compactness’ and ‘dispersion’ are considered as directions on the two ends of a continuum rather than fixed categories (Ewing & Hamidi, 2015; Johnston, 2001).

The model spanned by both parameters ranks patterns with maximum values for the LP (100%) in the upper left corner (Fig. 12; perfectly compact). In contrast, if the LP is minimal and the complete class area is represented by the maximum possible number of non-coalescent individual patches, the pattern is ranked in the lower right corner (Fig. 12; perfectly dispersed). All possible pattern configurations between the perfectly compact and the perfectly dispersed patterns are in the intermediate zone. When projected on the connecting line between both extremes, every settlement pattern can be linked to a value indicating the landscape configuration by the *dispersion index*. The schematic illustration of the dispersion model in figure 12 demonstrates that all parameter-combinations feature an unambiguous location within the model.

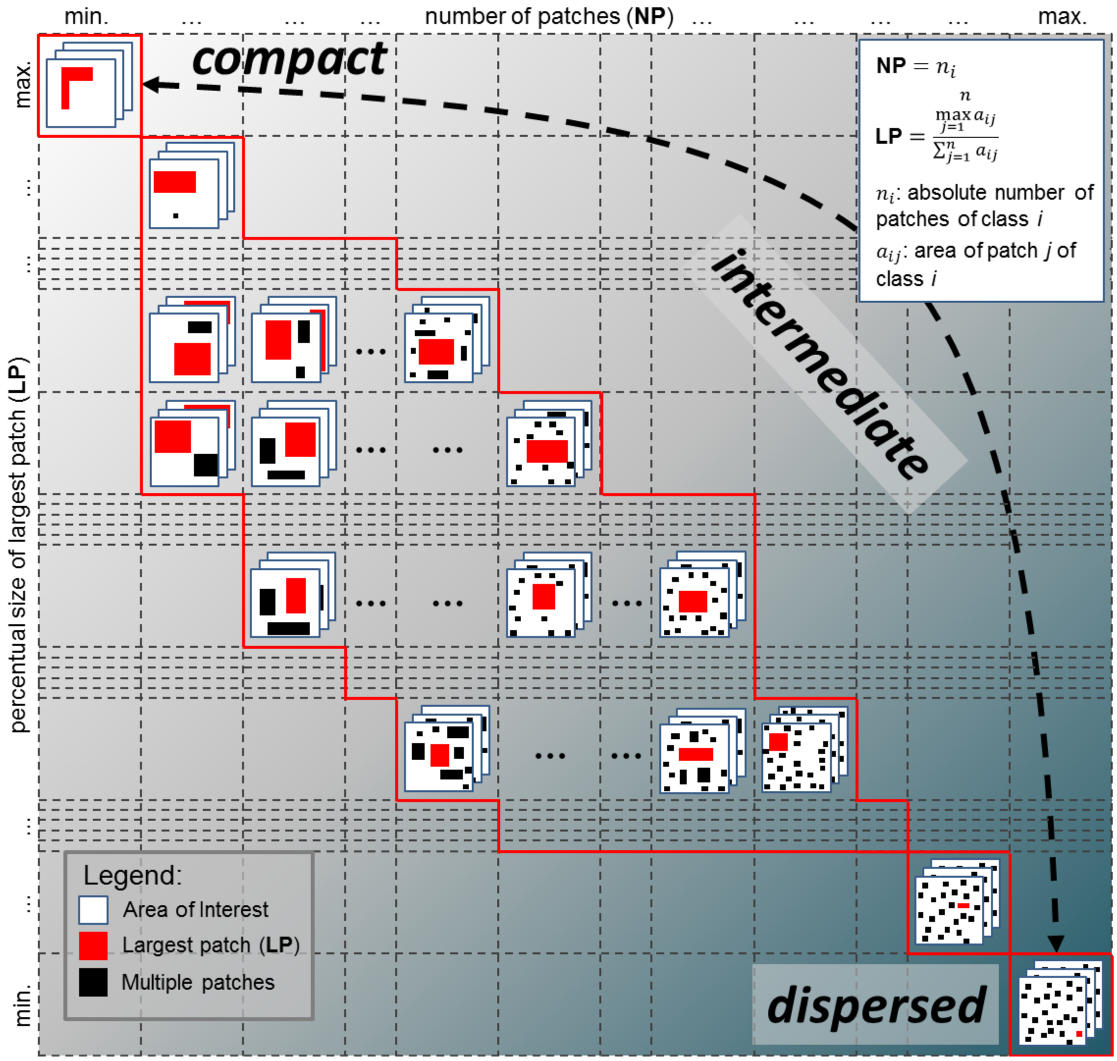

Figure 12 Schematic illustration of the model design for ranking binary patterns with respect to their spatial dispersion. Each arbitrary binary and two-dimensional pattern can be unambiguously located within the feature space of the model, which is defined only by two parameters, the NP on the x-axis and the LP on the y-axis.

Naturally, spatial resolutions of input data as well as selected areas of interest influence measurement results. In the work, dependencies within the model are systematically tested based on 300,000 generated landscape configurations which are representative for all possible patterns. It is found that as long as the input data characteristics are held constant, the relative ranking in the dispersion index remains also constant. However, the absolute evaluation of the landscape dispersion varies.

Based on this model parametrization, the dispersion index is applied to real world settlement patterns derived from EO data for the time steps 1975, 1990, 2000 and 2010. Five metropolitan regions serve as example: Two highly dynamic Chinese cities (Shenzhen and Dongguan), two regions with comparatively less spatial change in Germany (Cologne and Frankfurt/Main) and one region with a change in dynamics over time (Warsaw in Poland). The urban land cover patterns and their temporal evolution are exemplified for two cities in figure 13.

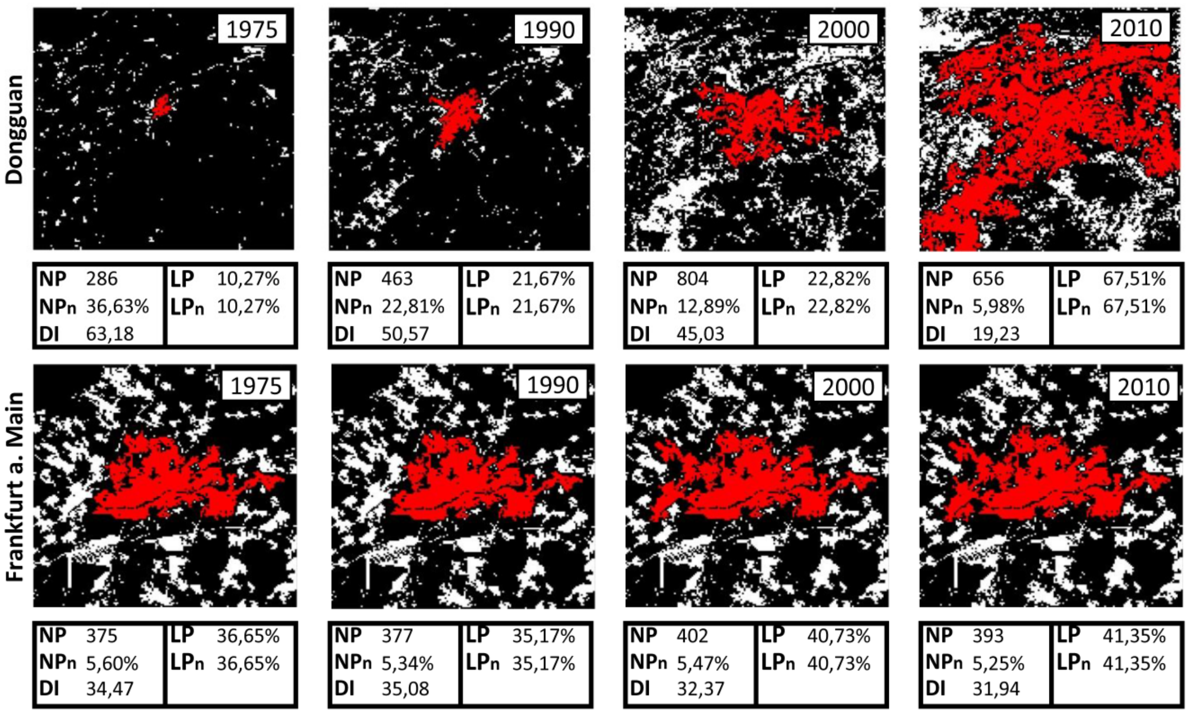

Figure 13 Binary settlement patterns for the cities Dongguan in China, and Frankfurt/Main in Germany at four different time steps (1975, 1990, 2000, 2010). Areas covered by settlements are displayed in white/red. The largest patch (LP) is visualized in red. The dimension of each frame is 30x30km around a defined city center; the geometric resolution of each raster is 200 meters.

In general, the ongoing process of urbanization physically manifests itself in the emergence of more complex, irregular spatial patterns. The once clear core-periphery divide in the illustrated Chinese city has diminished in favor of a spatially extended, scattered urban field without a visible urban core. In contrast, the displayed German city was already large in the 1970s, and the settlement pattern is relatively stable over time. When transferring these patterns into the developed dispersion model, this qualitative description is supported by quantitative evidence: In Dongguan the highly dynamic transition of a small city with a small largest patch and a disperse, agricultural settlement pattern in 1975 (DI value of 63.18) to a very large and compact agglomeration dominated by a very large patch in 2010 (DI of 19.23) is manifested in the model (Fig. 14). Essentially, the same development is measured for another sample city in China: Shenzhen. In contrast, the urban region of Frankfurt am Main features a basically constant dispersion index (e.g., Frankfurt in 1975 with DI of 34.47 was 31.94 in 2010). The change is marginal. Basically the same development is measured for another German example of

Cologne. In another example, the city of Warsaw pictures a relative constant pattern until the year 2000 and experiences compaction until 2010. Beyond the relative comparison, the model allows additionally to classify the respective patterns with respect to the entire spectrum of possible landscape configurations.

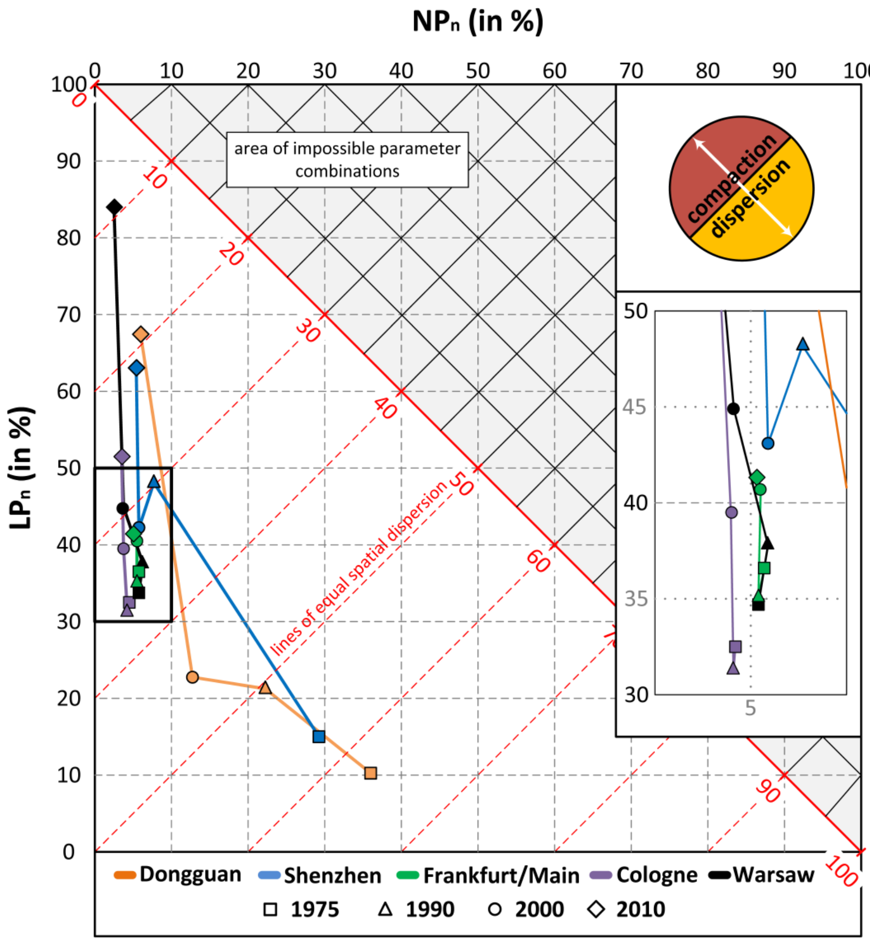

Figure 14 Shifts in dispersion for the five sample cities within the two-dimensional feature space spanned by the parameters NPn and LPn.

The characterization and understanding of (urban) spatial patterns is of central concern in the spatial sciences (Klippel *et al.*, 2011). As every single spatial pattern configuration is unique across the globe and none of these spatial configurations are likely to be identical, it is crucial to provide methods to systematically measure convergent and divergent development trends.

However, as introduced above, a multitude of elements can constitute morphological patterns, i.e., intra-urban structural variabilities of urban form need also to be addressed at geometrically and thematically higher resolutions. Within settlement patterns, metropolitan regions consist of complex spatial arrangements of centers and subcenters. Thus, urban form can be approached with classifications that thematically subdivide the urban space into categories such as buildings, impervious surfaces, green spaces or the like at geometric resolutions of individual objects (or aggregates) in two or three dimensions.

Numerous studies have documented that internal spatial composition of cities vary across space and time. In times of dynamic processes of urbanization the transformation of formerly monocentric metropolitan regions into polycentric or even dispersed spatial configurations that are characterized by a diminishing regional primacy of the core center has been documented (e.g. Anas *et al.*, 1998; Batty *et al.*, 2004; Garreau, 1991; Siedentop, 2015; Zhong *et al.*, 2015). Accordingly, many scholars point out that standard monocentric models of constantly decreasing densities with increasing distances to the center are not reflecting metro regions' today's urban spatial form (e.g. Adolphson, 2009; Garreau, 1991; Anas *et al.*, 1998; Roca Cladera *et al.*, 2008; Siedentop *et al.*, 2003).

If these restructuring processes are limited to issues of urban form and spatial configurations, they are often referred to the term *polycentricity,* which implies that more than one center exists within a conurbation (e.g. Kloosterman & Musterd, 2001; Riguelle, Thomas & Verhetsel, 2007; Burger & Meijers, 2011). A morphological view of polycentricity refers to the distribution of objects within a given area. Generally speaking, a *center* is distinguished from a subcenter or any other kind of spatial densification by its primacy (cf. Champion, 2001; Davoudi, 2003). A major challenge for any empirical investigation of polycentricity is the definition of a *center* and *subcenter(s)* (Duranton & Puga, 2015). Taking a closer look at the variables considered when addressing hierarchies in urban systems reveals a striking focus: the majority of studies consider economic variables such as firms or employees whereas multi-dimensional analyses are scarce (exceptions are e.g. Barr & Cohen, 2014; Sarzynski *et al.*, 2005). However, urban centers and subcenters are usually not mono-functional spatial entities consisting of only businesses and jobs. They usually contain further functions and can take quite different physical shapes. Previous research has often undervalued the variegated nature of urban and suburban subcenters in terms of physical outcomes.

Using remote sensing data and its implicit physical access to city configurations allows contributing to the notion of polycentricity by addressing the built dimension of urban form (**Chapter VII**). Only few studies so far have approached polycentric spatial configurations by analyzing the built dimension. This scarcity originates in an elusive conceptual delimitation of built densities on the one hand and in deficiencies of the high spatial detail of data necessary on the other hand.

In this work a (sub-)center is operationalized by a *high urban mass concentration* (hUMC) instead of commonly used employment or residential densifications. Urban masses (UM) correspond to accumulated built-up volume (m^3) per reference unit (m^2). hUMCs are considered valid centers as high built densities have proven fairly well to resemble the spatial distribution of employees (cf. Krehl, 2015) and they explain the perception of a center to a certain degree (Taubenböck & Wurm, 2015).

Four German metro regions are selected as sites under investigation: two definitional inter-urban polycentric regions (Frankfurt/Main and Cologne) with four and two core cities respectively, and two definitional monocentric regions (Munich and Stuttgart) with one core city each.

One family of methods —threshold approaches— which are often used for (sub-)center identification are applied onto LoD-1 3D building models. It is found that a combination of two thresholding techniques —a region-specific approach and a distance-based approach— allows capturing both, the hUMCs in city centers as well as in peripheral areas. The thresholds are derived by calculating region-specific means and standard deviations. Thus, the thresholds are comparable across sites. In addition, a set of measures are combined to evaluate the *degree of polycentricity* based on the identified centers and subcenters: *non-spatial* (quantity of hUMCs; rank-size distributions of hUMCs) and *spatial* (characterizing locations of hUMCs) *metrics*. Whereas the non-spatial metrics refer to the existence of disparities, the spatial metrics shed light on the actual localization of those disparities.

Applying the developed methodology allows to evaluate polycentricity of the four German regions. In general, spatial hierarchies of centers and subcenters are found in all metro regions under consideration (Fig. 15). This finding reveals that traditional urban centers still dominate in German metro regions. Especially the Munich region features a large, dominating core area. When considering the developed spatial indicators, this region scores the highest numbers for almost all indicators (cf. Table 1). Noteworthy is especially the share of the largest hUMC patch in extent and volume (LPIarea and LPIvol in table 1) which reveal with 56.2% and 72.5% their dominating character in Munich. These figures indicate a low degree of polycentricity for Munich. A markedly lower dominance of the traditional urban center is measured in all other regions, indicating more polycentric spatial patterns. In contrast, the Stuttgart region features a small and less distinct hUMC in the downtown area in relation to its other spatial densifications. The latter case, in particular, indicates in combination with smallest mean sizes and volumes of hUMCs, lowest total area and volume of hUMCs a pattern with a high degree of polycentricity, maybe even directing to dispersion. In the Frankfurt region a polycentric spatial pattern is inherent due to its four core cities (Frankfurt, Wiesbaden, Mainz, and Darmstadt). Beyond, large hUMCs are detected e.g. for the city of Hanau, the airport or production sites such as in Rüsselsheim, Hoechst and Ingelheim, among others which overall form a polycentric spatial pattern. The figures suggest Frankfurt as well as Cologne between both extremes regarding the degree of polycentricity (cf. Table 1).

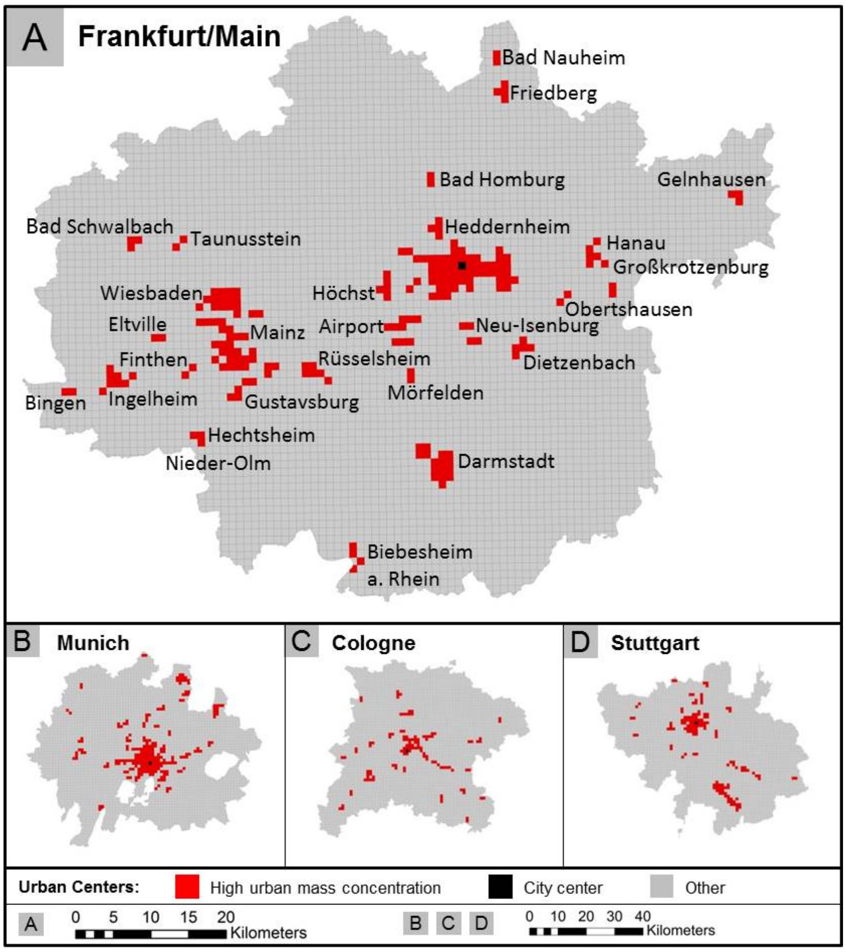

Figure 15 High urban mass concentrations and their spatial patterns in four German city regions; the algorithm relies on the following conditions: threshold >1.3 standard deviation; no consideration of grids with less than 1000 m³ built-up volume; a center covers an area ≥ 2km²; merge of neighboring classified hUMC grids

Table 1: Spatial indicators comparing the four metro regions using the combined approach

Spatial Indicators	Cologne	Frankfurt	Munich	Stuttgart
Share of hUMC area UMC (%)	5.3	4.3	7.1	4.0
LPIarea (%)	35.8	27.4	56.2	30.1
Share of hUMC volume UMC (%)	33.6	35.8	52.4	28.8
LPIvol (%)	45.9	35.5	72.5	38.8

The plausibility of this developed physical approach towards the configuration of urban form is evidenced by the calculation of shares of employees within the areas of detected hUMCs. They range between 18.8% (Stuttgart region) and 52.9% (Munich region). The corresponding shares of areas covered by the detected hUMCs are markedly lower and score between 4.0% (Stuttgart) and 7.1% (Cologne; Tab. 2). From a content-oriented perspective, further support is provided for the Munich region being fairly concentrated as the identified centers capture about seven times more the share of employees than the share of area (Tab. 2). A visual check proves in addition all identified hUMCs to either be industrial/commercial sites or downtown areas.

Table 2 Shares of employees and shares of hUMC areas per region

	Cologne	Frankfurt	Munich	Stuttgart
Share of hUMC area covered (%)	4.9	4.2	7.1	4.0
Share of employees (%)	24.7	23.9	52.9	18.7
Ratio of shares	5.1	5.7	7.4	4.7

Source: Own calculations based on the georeferenced Integrated Employment Biographies as of 30 June 2009, which are provided by the Research Data Centre of the Federal Employment Agency at the Institute for Employment Research (for both the data and data manipulation details, see Krehl, 2015b)

The work shows that the localization of (sub-)centers defined as densifications of urban masses can be carried out with meaningful results based on using EO-data. With the finding that these centers represent a reasonable proxy for hubs of intra-regional economic activity, a new analytical view on the issue of polycentricity becomes possible. In consequence, the use of built-up volumes instead of employees facilitates —in future— cost-efficient, comparable analyses of metro regions all over the world since the used remote sensing data are available for any region of interest. Moreover, these data are not subject to national policies, definitions, or interpretations, but consistent across regions.

Nevertheless, the question regarding the characterization of spatial urban structures in metropolitan regions is still challenging due to conceptual and analytical fuzziness. The mentioned analytical fuzziness in polycentricity research can be traced back to the measurement of density. The concentration of urban masses is one measure of density. Density, in general, is among the most important descriptive as well as normative measures in urban research (Roskamm, 2011). 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 (Ewing & Hamidi, 2015; OECD, 2012; Churchman, 1999; Roberts, 2007; Acioly & Davidson, 1996). While its basic concept is generally understandable, approaches towards the density measure are manifold, diverse and of multidimensional complexity (McFarlane, 2015). This evolves from differing thematic, spatial and calculative specifications. Consequently, applied density measures are often used in a subjective, non-transparent, unspecific and thus non-comparable manner. The density measure is thus delusive; there is a lack of clarity about how to measure and how to use density within the scientific debate (Fina *et al.*, 2014).

In **Chapter VIII** the measure 'density' is deconstructed in a systematic quantitative way to shed light to the various conceptual and empirical aspects.

With respect to the physical urban form, density measures are for instance the street network density (e.g., Masucci, Stanilov & Batty, 2013), density of impervious surfaces (e.g., Weng, 2012), building density (e.g., Anas, Arnott & Small, 1998) or related parameters such as the floor space density —as a measure for 3D building density (e.g., Wurm *et al.*, 2014). Analytical approaches on the physical density of cities use, e.g. gradient analysis (e.g., Luck & Wu, 2002; Guerois & Pumain, 2008; McMillen, 2006), exploratory approaches (e.g., Krehl, 2015; Poumadere *et al.*, 2005) or spatial metrics (e.g., Angel *et al.*, 2010). In these studies, the density measure is used as a descriptive, empirical variable for physical urban form as well as an explanatory variable for issues such as energy consumption, commuting times, work patterns, etc. However, an agreed definition on how to address physical urban morphology or urban form is inexistent (Oliviera, 2016).

For a better understanding of the density measure, in this work different *thematic* (buildings, impervious surfaces, etc.) and *spatial* dimensions (administrative boundaries, districts, blocks, etc.) as well as different *aggregation* functions (gross vs. net densities, etc.) are systematically analyzed.

The multitude of *thematic density dimensions* is inexhaustible; to reduce complexity the focus chosen here is on a mere physical perspective, i.e., variables that describe the physical arrangement of the built environment: the quantitative measures *building density*, *degree of soil sealing*, *floor space density* and, more specifically, the density of generic structural classes such as *open spaces* and *highest built-up density* areas are applied. This family of variables and the respective analyses (using various spatial dimensions and calculation techniques) are seen as a blueprint to deconstruct the delusiveness of the measure and, by this, allows highlighting the fragility of the concept.

The *spatial dimension of the density measure* is addressed at two scales: a general *city scale* and a *site-specific (zonal)* scale which aims at the analysis of intra-urban variations of urban form. A ring zone model of concentric rings around the respective center is used. However, these two spatial scales do not take the variability of density within the respective reference units into account. To do so, three types of reference units commonly used in the literature are systematically tested: (1) *administrative units*; artificial jurisdictional units defined through a political process over time; (2) *block units;* in contrast to the administrative units, the block units derived from the European Urban Atlas are small spatial entities delineated through the close meshed street network; and (3) *grid units;* a standard grid geometry allows to evaluate the influence of varying grid sizes with respect to the density measure.

The *calculation of the density measure* relies on the relation between a certain type of class (or object) to the respective reference unit. Here the differentiation between *net* and *gross density* is systematically tested. Net density refers to densities where the reference units applied exclude certain areas. In this study, net density refers only to reference units which contain "buildings". Beyond, for the zonal model two different strategies are tested: The calculation of density measures per individual ring and for a cumulative reference; the latter means density measures for the reference unit of the first ring, then for the first and second rings combined, and accordingly are calculated.

The evaluation of the density measures relies on *quantitative*, *thematic*, *spatial* and intrinsically *geographic* approaches. Figure 16 illustrates measured variabilities of the density measures by the example of building density for the cities of Paris and London. In general, both cities show maximum building densities in their respective geographic centers. However, the cities also reveal differences in density patterns: The extent of highest building densities is significantly larger for Paris.

The comparison of map appearances for the parameter building density in dependence of the reference units (block units (Fig. 16a and b) vs. administrative unit (Fig. 16c) vs. grid level (Fig. 16d) illustrates their significant influence. Both, block level and the grid level capture the change of complex, small-scale urban form. In contrast, administrative units blur the real physical configuration of the city. While the general decrease in building density from the city center to peripheral areas is preserved, the true urban form configuration is hidden due to the large size of spatial units and their inappropriateness to represent the true intra-urban morphology.

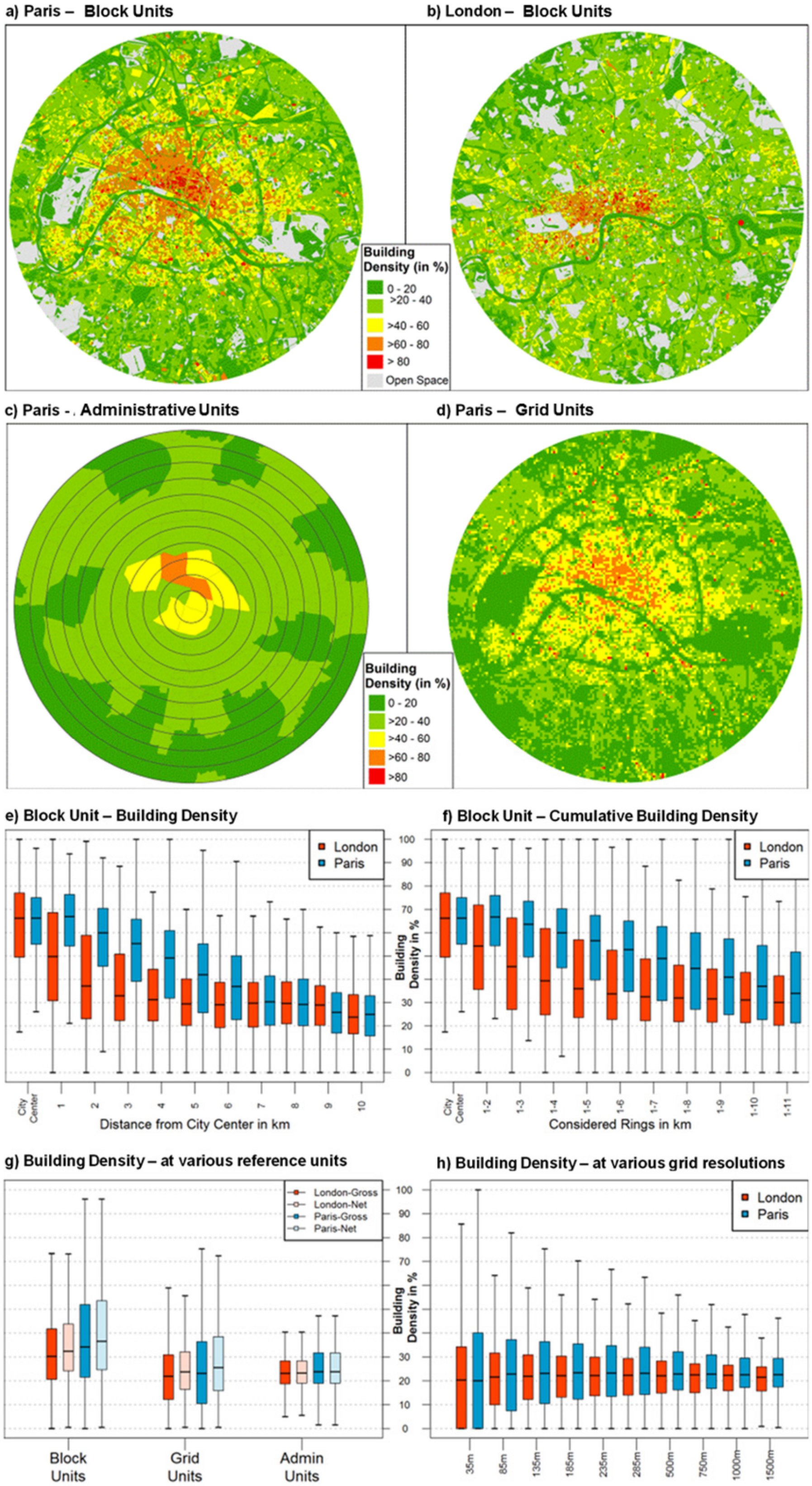

Figure 16 Building density maps for a) Paris and b) London at block level and maps related to c) administrative and d) grid units; e) gradient analysis of building density illustrated by site-specific boxplots and f) cumulative gradient analysis at block units; g) the influence of the reference units calculated for gross and net densities at city scale; h) the influence of varying grid sizes on density measures calculated for gross densities for London and Paris.

Figure 16e illustrates the site-specific gradient analysis in boxplots. They reflect the intra-urban spatial density distributions from the city center to peripheral areas. The basic assumption —high dense center and decreasing densities with rising distances— for the physical configuration of a city is confirmed. The calculation method using individual rings vs. the cumulative gradient analysis confirms this typical imagination of the city's urban physical form. However, it is interesting to note that for the cumulative gradient analysis, the decrease of density is not as distinct, and naturally the absolute density values are higher. This can be naturally related to the alternative reference units constantly integrating the center; however, with significantly higher values in the outer areas, this calculation method reveals the sensitivity of the measure and its interpretation.

When comparing *building density* at city scale for three reference units (administrative, grid and block units) as well as for two calculation methods (gross and net density) the fragility of the measure is also revealed. It is found that, naturally, net densities are consistently higher than gross densities (Fig. 16g). Consequently, the application of either of the measures has influence on the absolute values of density measured. The differences vary between 0% and 4%. Thus, whenever used for cross-city comparisons the specification of the measurement of density is imperative. Beyond, the administrative units result in the comparably lowest density values. In contrast, the block units reveal the highest values. The assumption suggests that this is due to the larger sizes of administrative units.

In the previous analyses a fixed standard grid size has been used. Addressing the modifiable areal unit problem (MAUP) problem (Openshaw, 1983), the effects of varying grid sizes on density measures are evaluated. Figure 16h illustrates the variation of density values at city level in dependence of varying grid sizes. The analysis reveals a natural trend of decreasing density variances with increasing grid sizes. Larger grid sizes obviously are more likely to contain a mixture of structural types leveling local variations of density throughout urban morphology.

In general this analysis reveals that density as term and as measure is complex, fuzzy and delusive. This analysis quantitatively reveals that when using density measures a careful and clearly defined application is necessary:

First, the thematic dimension applied needs an unambiguous definition. Even as here the understanding of density is reduced to a mere physical perspective on the city, the thematic variables used —building density, soil sealing, floor space density and the two generic structural types— must be seen as an incomplete proxy for the multidimensionality of the measure. Thus, in every analysis the thematic dimension must be understood as fragmentary for the density of the entire (physical) city system. Furthermore, the thematic definition of density is crucial as even related dimensions such as building density and floor space density are not linearly correlating (r^2 of 0.66 in linear regression; $r^2 = 0.42$ for soil sealing and building density; $r^2 = 0.28$ for soil sealing and floor space density).

Second, the spatial dimension needs an unambiguous definition. This issue is approached by: (a) applying a monocentric city model conceptualized by one defined center point; (b) applying a spatial concept using city scale and zonal scale as spatial baseline to account for city-wide and site-specific statements; and (c) using various reference units —block, grid and administrative units— to measure median and variance of density. For a valid cross-city comparison, a consistent level for all spatial dimensions needs to be determined. Furthermore, the spatial dimensions of applied reference units inherit significant impact on the results: Block and grid units show minor deviations regarding the relative distribution of density values. Administrative units disqualify as reference unit, as their inherent delineation issues results in non-comparable numbers.

Third, the aggregation function has significant influence on the absolute measured density values and requires an unambiguous definition.

Geographically the two areas of investigation —Paris and London— clearly reveal that the physical built-up configuration of Paris is significantly denser than in London. While this result is based on a systematic and clearly defined multidimensional analysis, less systematic approaches may lead to contradicting results. If building density for both cities at a grid size of 35 m would have been calculated, London would be measured denser than Paris by medians. The conclusion that London is denser then Paris would be reasonable as the result relies on the same parameter constellation for both cities and thus, it basis on an ostensibly comparable way. The systematic deconstruction of the measure density, however, reveals that this conclusion would be at least questionable due to its random selection of parameters. This example reveals how delusive density measures can be when based on unsystematic conceptions without sensitivity analyses. In contrast, for this specific case, all other grid sizes calculated confirm the original statement that Paris is denser than London.

As a *concluding remark*, this study reveals, whenever density is used as indicator, it is advisable to scrutinize the definition and calculation of density —with respect to the thematic and spatial dimensions as well as the calculus, and thus to verify the related interpretation.

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 **Chapter IX** the interrelations between built and activity densities are investigated. The work supports a more encompassing and robust understanding of the urban density concept and its variegated applications in urban research and planning practice.

A general distinction between built densities and activity densities is the relation between rather static built structures, since they only change very slowly over time and constantly changing activity densities as they are underpinned by dynamic, often discontinuous, demographic and socioeconomic processes.

Four German city regions —Stuttgart, Cologne, Munich and Frankfurt/Main (cf. Chapter VII)— are selected as test sites. Four physical density measures, the floor area ratio, the built-up volume, the average floor space per building and the number of buildings per grid cell are calculated for the city regions. For an analysis of the relationship between urban morphology and the distribution of socioeconomic activity Spearman's rank correlation coefficients between these density measures and the number of employees and residents per grid cell are calculated. The a priori expectation is that the five variables should be highly and positively correlated. The results confirm this expectation. All rank correlations are statistically significant below the 0.1% significance level and are positive (Tab. 3).

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)

The relationships reveal if the share of built-up volume within a grid cell is relatively high, socioeconomic activity tends to be high in this area (Figure 17 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. The analyses again reveal 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 floor area ratio, the built-up volume or the density of socioeconomic use. Correlations between the individual variables are certainly sometimes high, but this does not apply in all cases. Thus, urban density cannot be solely considered either by built or by activity densities.

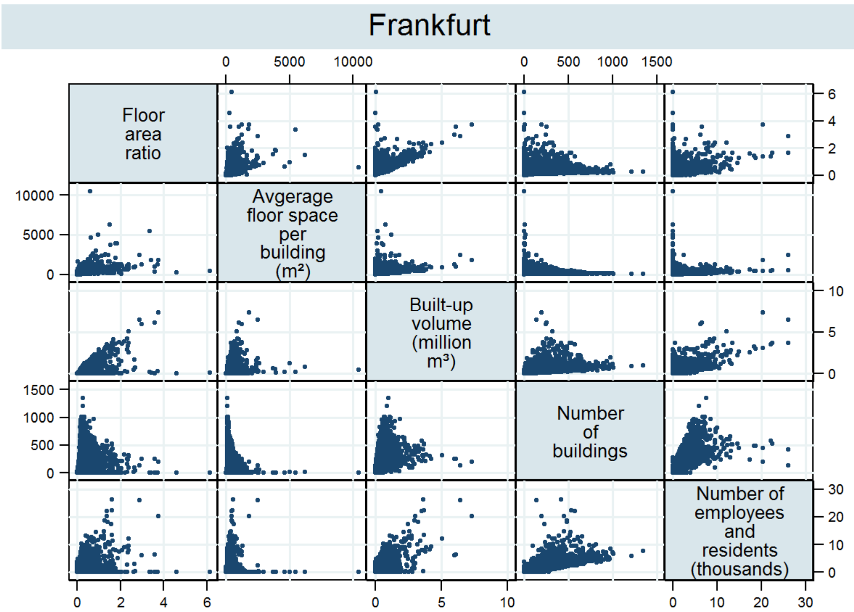

Figure 17 Scatterplot matrices showing the relationship between built and activity densities. (Employment data are taken from georeferenced Integrated Employment Biographies (georeferenced IEB) as of 30 June 2009, which are provided by the Research Data Centre (FDZ) of the Federal Employment Agency (BA) at the Institute for Employment Research (IAB) (for details and documentation, see Scholz *et al.*, 2012)).

Most available mapping products of today, such as the European Urban Atlas, provide data regarding density for two dimensions to a limited extent. Analyses of urban morphology and form, however, as we have seen need to be related to the built-up volume and, thus, to the third dimension. The work shows that remote sensing is 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 capability of modelling urban form at the spatial and thematic level of individual buildings in two and three dimensions by remotely sensed data opens up possibilities for applications which feature relations to the physical appearance of cities. Examples are proven relations to socioeconomic activity as introduced above, or population density (e.g. Aubrecht *et al.*, 2012; Taubenböck & Wurm, 2015b), among others. One thematic relation can be linked with approaches in civil engineering.

Civil engineering techniques allow the modelling of the vulnerability of building structures under seismic load using knowledge on the construction type or the material of buildings. However, due to the highly dynamic process of urbanization in numerous earthquake prone city regions, conventional civil engineering approaches such as detailed *in situ* building-by-building analysis by structural engineers is decreasingly able to cope with this situation. The capability of remote sensing to physically model urban form triggered approaches for multidisciplinary combination of both disciplines for pre-event vulnerability analysis of built-up structures (Borfecchia *et al.*, 2010; Geiß & Taubenböck, 2013). In **Chapter X** it is explored whether remotely sensed data and methods allow for describing urban form (seismic building structural types (SBSTs)) to a degree that a reliable area-wide estimation of building vulnerability for an effective earthquake loss modeling becomes possible.

The developed experimental set-up follows a sequential procedure of advanced machine learning techniques which rely on two input data sets: scarce *in situ* ground truth data describing building vulnerability, and complementary multi-sensor remote sensing data capturing physical characteristics of the city-wide built environment.

At the earthquake prone city of Padang in Indonesia almost 600 buildings were surveyed, and assigned to a specific structural building system based on characteristics such as wall type, roofing type, number of storeys, building usage, or the degree of damage suffered from an earthquake event (based on Sengara *et al.*, 2010). To derive fragility curves, the surveyed buildings are categorized according to SBSTs, which reflect similar behavior under seismic load. In particular, the following classes were considered: “Confined masonry” (*CM*), “Reinforced concrete high” (*RC high*), “Reinforced concrete low” (*RC low*), “Steel frame” (*SF*), “Timber frame residential” (*TF res*), “Timber frame non-residential” (*TF non-res*), and “Unreinforced masonry” (*URM*).

For the city-wide assessment of building vulnerability a sequential procedure to estimate SBSTs is developed using remote sensing data in combination with the punctual *in situ* data. A set of features is derived from the remote sensing data at two different spatial levels, building and block level. Overall, each building object is represented by a 145-dimensional feature vector, whereby 79 features are calculated based on the individual building footprints, and 66 are calculated based on the building blocks. In this manner, a perceptual coherence of physical appearance (Steiniger *et al.*, 2008), spatial composition and context, and temporal development of the urban morphology and the main load-bearing structure of buildings is assumed.

A hierarchical supervised classification approach is developed which identifies outliers in the *in situ* data and the building inventory. Therefore, a subset based feature selection technique is used to create a suitable group of features for building robust one-class classification models based on the *in situ* data. The models are built by means of a one-class support vector machine approach and are applied on both, the *in situ* data and the building inventory. Subsequent to outlier identification, multiclass classification models are built in three consecutive steps. The remaining *in situ* samples are used to identify useful groups of features for building robust models by applying subset and ranker based feature selection techniques. To tackle scarcity of the *in situ* data and learn efficient discriminative classifiers, synthetic training samples are generated by means of an oversampling technique. Based on the generated feature groups and oversampled training data, multiclass classification models are learned by using Support Vector Machines (Vapnik, 1998; Schölkopf & Smola, 2002) and Random Forests (RF) (Breiman, 2001) as they have the capability of effectively handling complex remote sensing classification problems (Camps-Valls & Bruzzone, 2009; Gislason, 2006). Finally, the most accurate model is applied on the building inventory in Padang to estimate SBSTs in their spatial distribution. Since spatially distributed estimation of SBSTs represents a critical input for earthquake loss estimation models, the applicability of the presented approach is presented for varying scenario-based loss estimations.

For illustration of the applicability of the approach for Earthquake Loss Estimation (ELE) modeling, scenario-based loss estimations for Padang are presented. The spatially distributed estimation of SBSTs is illustrated in Figure 18a. Analogous to the shares of the different SBSTs of the *in situ* data, the building inventory of Padang is dominated by *CM* and *RC low* buildings. The spatially distributed building damage assessment is based on a *violent* Modified Mercalli Intensity of 9 (Fig. 18b). It reveals intra-urban variabilities of expected damage and thus, spatially varying risk zones. Fragility functions in the form of cumulative log-normal distributions have been derived from data collected after the 30th September 2009 event (Fig. 18c, Sengara *et al.*, 2010) for different SBSTs. They relate the Modified Mercalli Intensity (MMI) to a damage index *DI*. The latter represents an economic measure for damage and is constituted by the ratio of repair cost and total building reconstruction cost. For the presented scenarios, it is assumed that site effects do not play a significant role in the intensity distribution. Figure 18d reveals calculated building inventory loss for several MMIs for the presented study area.

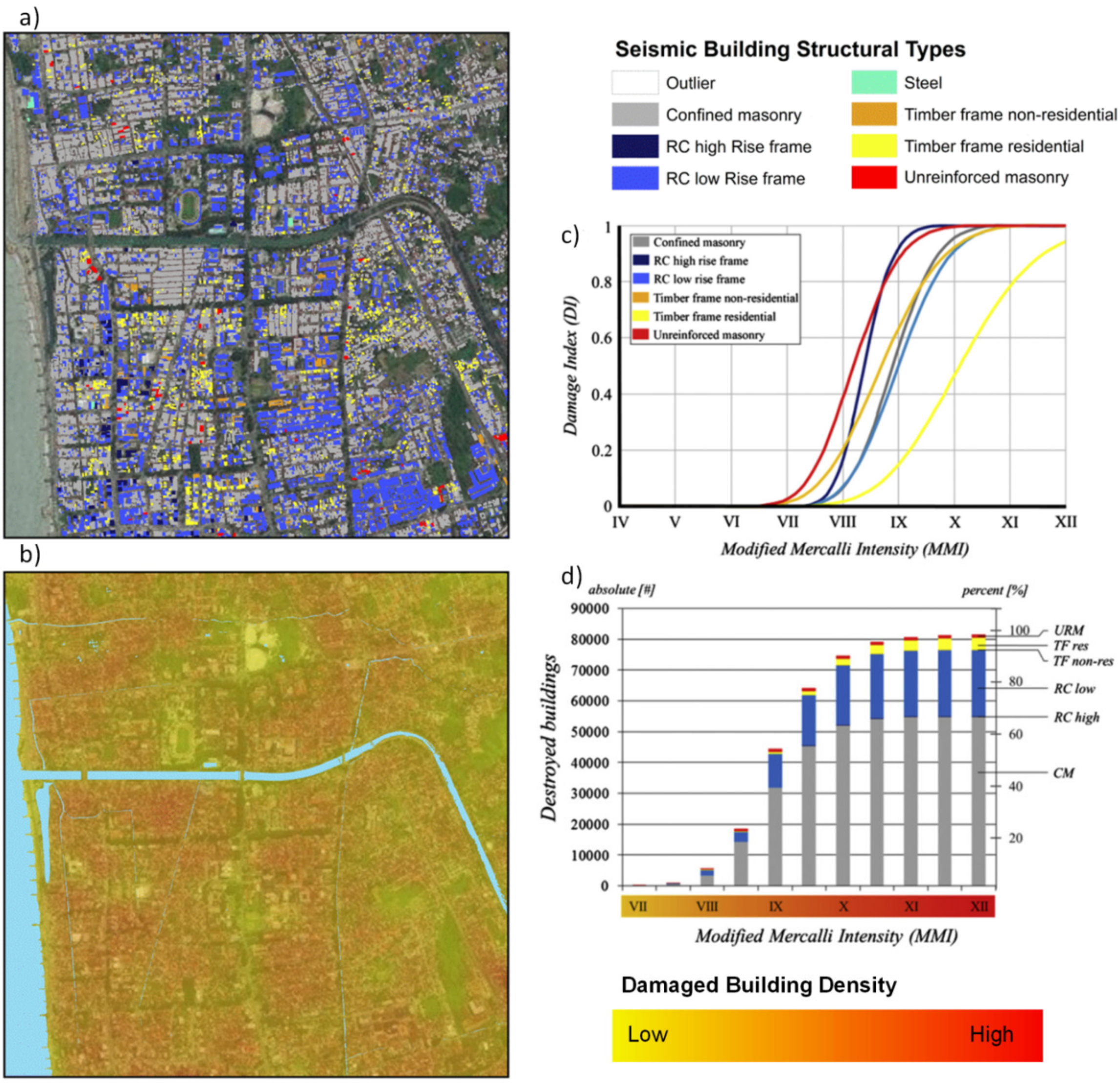

Figure 18 a) Spatially distributed estimation of SBSTs by application of learned classification models; b) spatially distributed building damage for a MMI of 9; c) Fragility functions for different SBSTs. They were derived empirically by Sengara *et al.* (2010) for the buildings of Padang after the 30th September 2009 earthquake; c) building inventory loss for several Modified Mercalli Intensities.

The presented approach allows to quantify building damage in a detailed and accurate way and make damage estimations spatially explicit by e.g., localizing hot spots within a city. These are key features for significant earthquake loss modeling and predictions. In consequence, it is evident that remote sensing based approaches on urban form allow the estimation of seismic building structural types. In combination with the capability to quantify exposed people the estimation of human casualties within the aforementioned model setting becomes possible.

From a technical point of view, the most exigent challenge regarding amplification of this capability is the systematic and comprehensive collection of accurate georeferenced *in situ* data for both SBSTs and experienced earthquake damage by structural engineers. Only this way the remote sensing community can fully demonstrate the usability of EO-data for SBSTs estimation and ELE modeling. Again, remote sensing can provide valuable proxy information. However, only a close interdisciplinary collaboration will enable systematic and valid large-area estimations of SBSTs and earthquake loss of dynamic earthquake prone urban areas around the globe.

In conclusion, **Part II** documents and reveals the capabilities of remote sensing to spatially reconstruct urban form (or morphology) in two and three dimensions at geometric levels of individual buildings and the related intra-urban variabilities for geographic comparisons and/or applications.

It is found that the on-going dynamic process of urban transformation can be approached with a new analytical view using the built environment as an indicator for itself. In this manner, the transformation from monocentric into polycentric or even dispersed spatial configurations that are characterized by a diminishing regional primacy of the core center has been documented. Beyond, it is also proven that the built environment can be a feasible proxy for socioeconomic activity or the vulnerability assessment of building structures. The studies reveal if the share of built-up volume is relatively high, socioeconomic activity tends to be high, too. This sets the stage for several prospective research questions regarding comparative urban research. The use of EO-data as proxy information enables cost-efficient, comparable analyses of metro regions all over the world as the used data are available for any region of interest. Moreover, these EO-data are not subject to national policies, definitions, or interpretations, but consistent across regions.

6. Urban poverty and its physical manifestation (papers related to Part III)

Currently we are living in a world where the place of birth and the place of living have significant impact on wealth (Milanovic, 2016). Even if Branko Milanovic addressed with this statement the geographic differences and their influence from a global perspective, the same applies at the scale of individual cities: "*Every city, however small, is, in fact, divided into two, one city of the poor, the other of the rich; […]*" (Hollis, 2013, after Plato). In **Part III** the focus is on the city of the poor. Specifically, research concentrates on the relations between urban form and the social group of the urban poor.

In statistics, poverty is commonly defined by economic indicators such as for households having less than half of the median income of all households of a certain area (OECD, 2017). However, for the 'city of the poor' most countries lack the necessary data on income at household level; especially in very poor areas of the Global South, data are mostly not available, outdated or not existent at all. In consequence, the poorest people often remain invisible in statistics (World Migration Report, 2015). In addition, if data are available, scholars doubt the credibility of these data (Tacoli, MacGranahan & Satterthwaite, 2015). Although we live in an era where more (geo)data are available than ever before in human history, the World Migration Report (2015) states "*we face a massive lack of basic data about urban poverty*".

A number of statistics underpin the urgent need for more extensive empirical knowledge on the places of the urban poor. The formation and proliferation of slums in cities is one of the most visible manifestations of urban poverty (Arimah, 2010). Almost 1 billion people, or 25% of the world's urban population, live in such areas (UN-Habitat, 2015). In the developing world, even 43% of the urban population lives in slums. And estimates expect that this number is rising to 1.5 billion people by 2020. In consequence, new data sources, approaches or proxies for the localization, quantification or assessment of poverty are in demand.

However, the problem with measuring slums starts with the lack of an agreed definition (UN-Habitat, 2003). The term ‚slum' today is part of general linguistic usage. While the meaning of the term seems to be obvious, objective definitions are vague. The many synonyms used for the term 'slum' such as 'informal settlements', 'squatter', 'shanty town' or 'ghetto' also testify imprecise connotations. UN-Habitat (2006) defines slums as areas of people lacking one or more of the following indicators: durable housing of permanent nature, sufficient living space, easy access to safe water, access to adequate sanitation and security of tenure. Arimah (2010) adds to these indicators deplorable environmental conditions characterized by dilapidated habitation, hazardous location as well as economic and social deprivation. Beyond this, the UN-Habitat Expert Group Meeting (EGM) on slum indicators states that a slum is a contiguous settlement where the inhabitants are characterized as having inadequate housing and basic services (Sliuzas, Mboup & de Sherbinin, 2008).

In consequence, urban form can be understood as one appropriate proxy to approach slums or urban poverty. Organic, amorphous, complex, and dense seas of small makeshift shelters are a physical expression of poverty (Kuffer, Pfeffer & Sliuzas, 2016). The building types and patterns have significantly different physical appearances than formal, planned parts in cities. With it, the built environment can be an expression of inequality in cities, and socio-economic disparities even become visible from space (e.g. Davis, 2007; Sliuzas, Mboup & de Sherbinin, 2008).

However, most studies describing urban forms of the urban poor within the complex morphology of cities are of qualitative nature observing e.g. high building densities or complex, organic patterns as characteristic (e.g. Davis, 2007; Glaeser, 2010); but relatively little systematic quantitative, spatial research exists about their explicit physical appearance (Hofmann, 2001; Kuffer, Pfeffer & Sliuzas, 2016).

As a basis, the assumed differences in urban form between slum areas and formal settlements are contrasted in quantitative manner (**Chapter XI**). For the spatial analysis three quarters in mega city Mumbai, India which contain slum areas are investigated. The sites have been indicated as slums in literature (Indiastat, 2011; Fuchs, 2006). The analysis relies on a 3D city model at individual building level derived from very high resolution optical satellite data. The 3D city model represents the referenced slums and the surrounding urban settlement structures in the respective quarter.

The spatial indicators *building density*, *average building size*, and *average building height* are applied to measure urban form. A two-class unsupervised clustering process approximates thresholds for a morphological differentiation. The clustering results in the following characteristic thresholds separating the two thematic classes ‘slum’ and ‘formal settlement’: for slums the built-up density is larger than 50%, the average building sizes are smaller than $60m^2$ and the average building heights are not higher than 2.3 floors. The resulting clustering process in slum-like urban forms and formal urban forms is illustrated by a three dimensional perspective view on the quarter of Dharavi in the megacity of Mumbai (Fig. 19). This area features a spatial mix of formal and non-formal settlements differentiated by the developed approach.

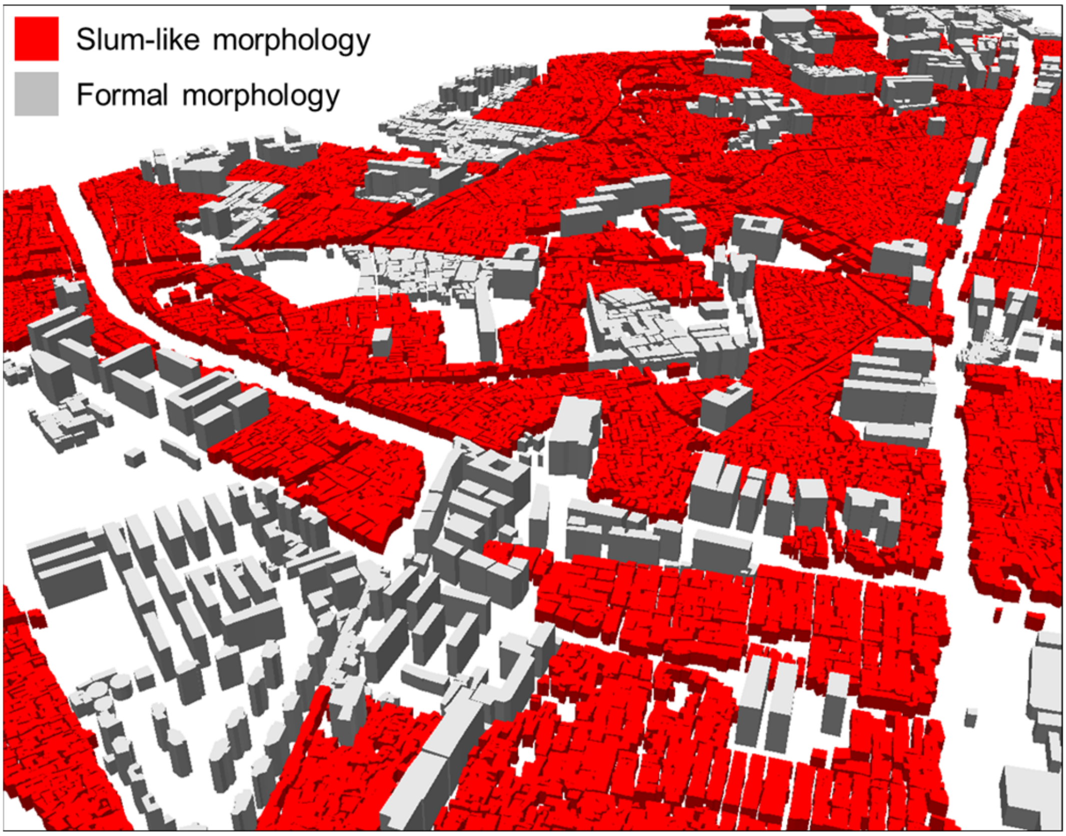

Figure 19 Contrasting slum-like and formal urban forms in Dharavi, Mumbai (India) based on the derived thresholds from the two-class unsupervised clustering process

When characterizing the identified slum-like urban forms and formal settlements, the hypotheses that physical appearances show considerable differences are confirmed. Taking one sample spatial indicator —building density— slum structures show significantly higher densities than formal settlements, confirming the hypothesis. The within group variability is lower among slums than in formal settlements. The 'slum' as structural type is thus measured with comparatively high homogeneity. Figure 20 reveals slums in Mumbai with median densities between 60% and 76%. Formal settlements feature with median densities between 23% and 38% different urban forms with significant less utilization of space.

In general, this study reveals considerable differences of slums to formal settlements with respect to urban form. However, the slums are by no means physically homogeneous. Although analogies across slum areas in Mumbai are obvious with respect to building densities, sizes, and heights, differences —as measured for example for the spatial indicator building density with 16% difference in medians between areas— reveal that first impressions of similar morphologies might be delusive. As a first quantitative approach it can be concluded that urban forms of slums differ physically from other parts of cities.

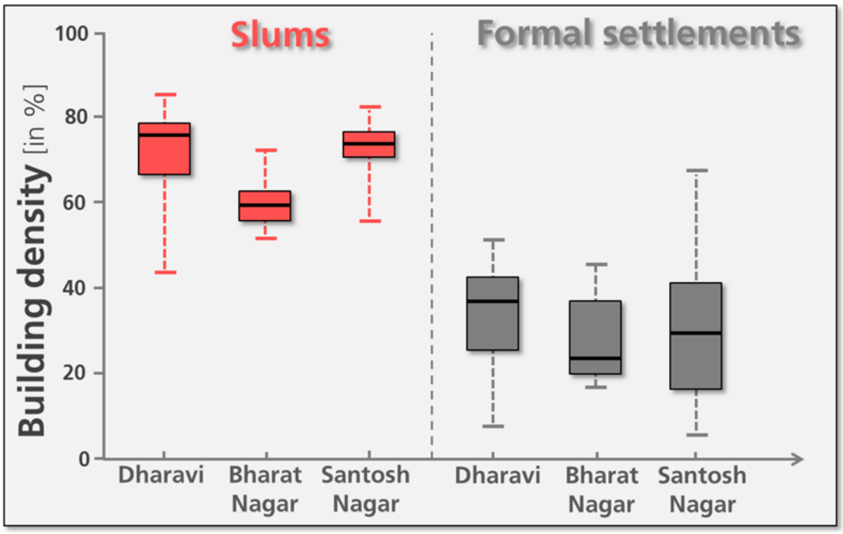

Figure 20 Boxplots contrasting building densities of slum and formal settlements for three districts in Mumbai, India

This evidence raises the following question: can these places with a specific urban form de facto be considered the home of a specific social group, i.e., of the 'urban poor'? In **Chapter XII** a '*socioeconomy-morphology relationship*' is established between identified morphologic slum areas and their household income to answer this research question.

For the '*socioeconomy-morphology relationship*' two different data sets are applied: 1) a *city-wide morphologic slum classification* based on very high resolution optical satellite data (Fig. 21). Relying on the physical features found characteristic for the morphologic appearances of slums (building density and size, arrangement of buildings, etc., cf. Chapter XI and Chapter XIV), a mapping protocol is applied to classify these areas at the spatial level of blocks. 2) The *Brazilian census* (IBGE, 2010). Census variables provide detailed information on the household income per census sector. For the subsequent analyses, the variable 'Nominal average monthly income of persons responsible for permanent private households (with and without income)' for modelling the socioeconomic status is used.

In the spatial analysis based on both input data sets, the distribution of household income for morphological slums and formal urban development is evaluated using box plots (Fig. 21). Data reveal a median household income of 673 Brazilian real (R$) and an interquartile range (IR; 25th quantile-75th quantile) between 585–787 R$ for morphological slums. In general, the median value indicates a very low income level in these areas. But, more significantly, the low spread of IR also reveals a very homogeneous distribution of household income in morphological slums. In contrary, the median income for households in formal settlements is 1615 R$ with an IR between 1055–3269 R$. This reveals a significantly higher income for households in formal neighborhoods. It also illustrates a large income spread marked by the large IR. Comparing both groups by the household income, it becomes obvious that the population living in morphological slums is much more homogenous in terms of their socioeconomic characteristics than the entire population residing in all kinds of formal urban neighborhoods.

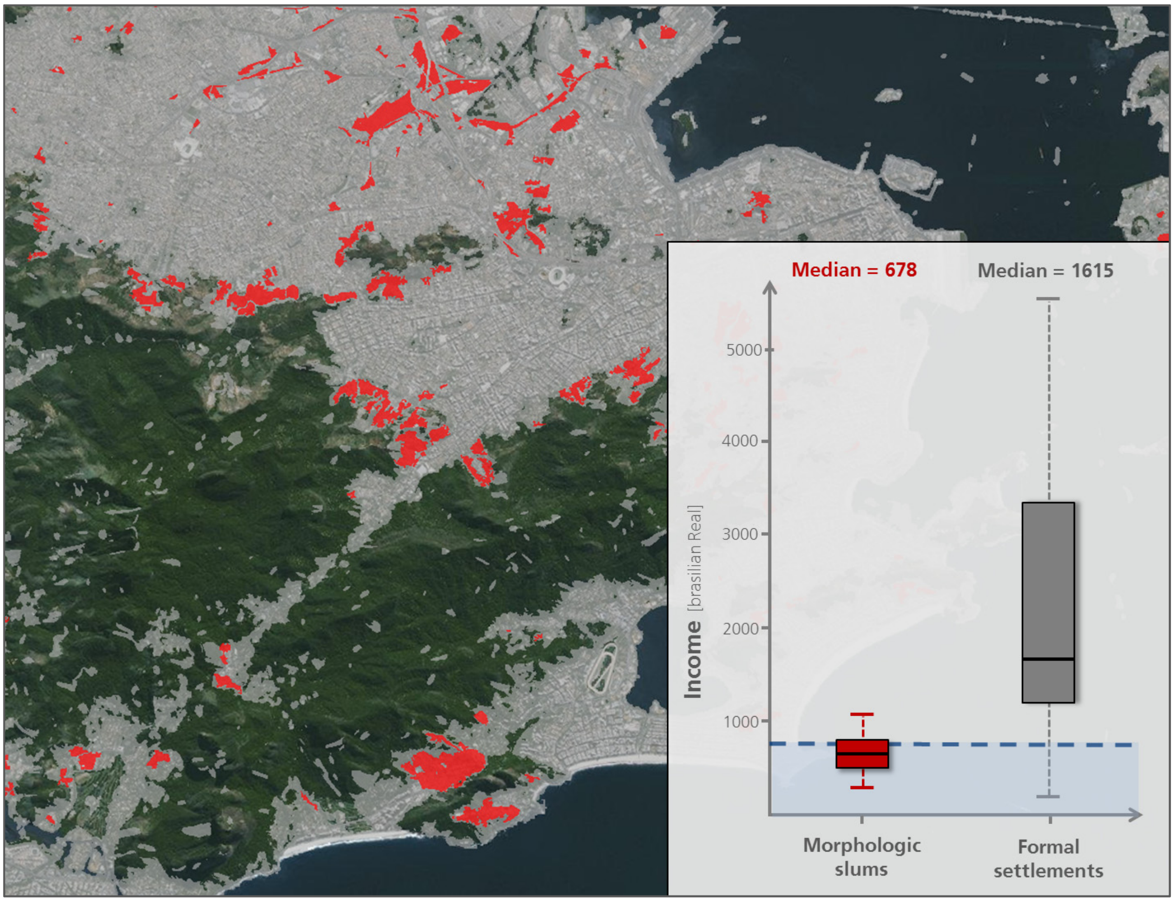

Figure 21 Dichotomic thematic classification of settlements into 'morphologic slums' (in red) and formal settlements (in grey) and boxplots revealing the income distribution per thematic class; the dotted indicates the poverty line.

Considering the definition of the poverty line, as defined by the Organization for Economic Co-operation and Development (OECD), as being the value of half the median household income of the total population (OECD, 2017), a city-specific poverty line for Rio de Janeiro derived from the census data of 639 R$ is deployed. This value agrees widely with the identified median household income for morphological slums. Census-based income data proof that while almost 45% of all mapped slum blocks are characterized by incomes below the poverty line, this holds true for only about 6% of the formal urban neighborhoods.

Overall, these observed correlations between urban form and socioeconomic status indicate that remote sensing data represent one key data source to map urban poverty at global scale. However, understanding of the mutual interweaving complexity of morphologic variations and socioeconomic hybridity across local settings is a prerequisite for remote sensing to fulfil its promises.

The physical appearances of morphologic slums differ from the surrounding built morphologies in cities. As it has been shown, this spatial approach allows the localization of a social group to a certain degree. In consequence it is legitimate to use the morphological proxy for continuative studies using these classifications.

As example, research questions can be followed up on the widely discussed disadvantages of these areas and people at the fringes of society. In the advent of 'Big Data' (Batty, 2013), novel data sources that are extensive in space and time allow to address new phenomena. In this work it is addressed whether the economic disadvantage of the urban poor is also reflected in their online behavior. Therefore the potential of location-based social network data (LBSN) from the twitter platform are explored in conjunction with EO-based maps of morphological slums (**Chapter XIV**). In spite of the inherent biases of such data from social media (the twitter users cannot be taken as representative of the entire population or the users being online. The proxy contains a highly non-uniform sample of the entire population with inherent biases (e.g. Goodchild, 2013; Morstatter *et al.*, 2013)), several previous studies have shown that LBSN activity can act as an indicator for the socioeconomic divide across space, population groups and thus, neighborhoods (Li, Goodchild & Xu, 2013).

In general it is hypothesized that LBSN activity reflects socioeconomic differences between social groups and in our case the inhabitants of morphologic slums and formal settlements. By adopting the 'Digital Neighborhoods' approach from (Anselin & Williams, 2016), hot and cold spots of LBSN activity are detected using spatial clustering techniques. The analysis relies on a ten week sample of approximately 70,000 geolocated tweets from the popular social network short message service 'Twitter'. In addition a classification of urban structural types (including morphologic slums) derived from VHR optical satellite data is applied. The morphological categorization of the urban structural types based on built-up density and building height classes serves to obtain a measure of the spatial population distribution. Therefore census information is spatially disaggregated using a dasymetric mapping approach that takes the recorded structural characteristics into account (for details see Taubenböck & Wurm, 2015b).

The experimental design is based on the quantification of the intensity of LBSN activity on the level of building blocks to detect spatial clusters, i.e., neighborhoods that are more or less digitally oriented. The approach relies on a ‘location quotient’ highlighting concentrations of LBSN activity relative to population. Spatial measures are applied relative to the surrounding urban environment aiming to detect regional highs and lows (clusters) of LBSN activity. The spatial combination with the EO-based morphologic slums allows analyzing whether urban poor are de facto less digitally oriented.

The results of the experiment show that a low LBSN activity is not exclusively limited to slums (Fig. 22). However, it is evident that the majority of morphologically defined slum areas are in fact digital deserts. Slums are found to feature, compared to formal settlements the highest share of digital deserts. With it, this study shows that the combination of EO and social media data allows to paints a broader picture of the socioeconomic urban divide between formal and informal settlements.

The rapid urbanization and growth of cities is observed especially in developing countries, leading to a massive strain on the infrastructure of these cities and, e.g., to underdeveloped water or energy supply systems (van der Bruggen, Borghgraef & Vinchier, 2010). As in most of the explosively growing cities, a big amount of poor inhabitants live in areas outside of municipal planning efforts, they have to live outside the supply systems. The Millennium Development Goal Report (2015) states that most countries lack adequate data to monitor poverty and as a result, the poorest people often remain invisible. In consequence these parts of cities remain neglected when it comes to social, economic, political, technical, or infrastructural integration into the urban landscape. If the political will to develop (optimal) supply systems is (or would be) existent, knowledge on the topologies of slums and their spatial patterns is crucial for planning. To create holistic strategies to improve the unfavorable living conditions of the poor (Martinez *et al.*, 2008), it is important to understand the spatiality of the urban poor, and the patterns of slums (Friesen, Rausch & Pelz, 2017; Hachmann, Arsanjani & Vaz, 2017).

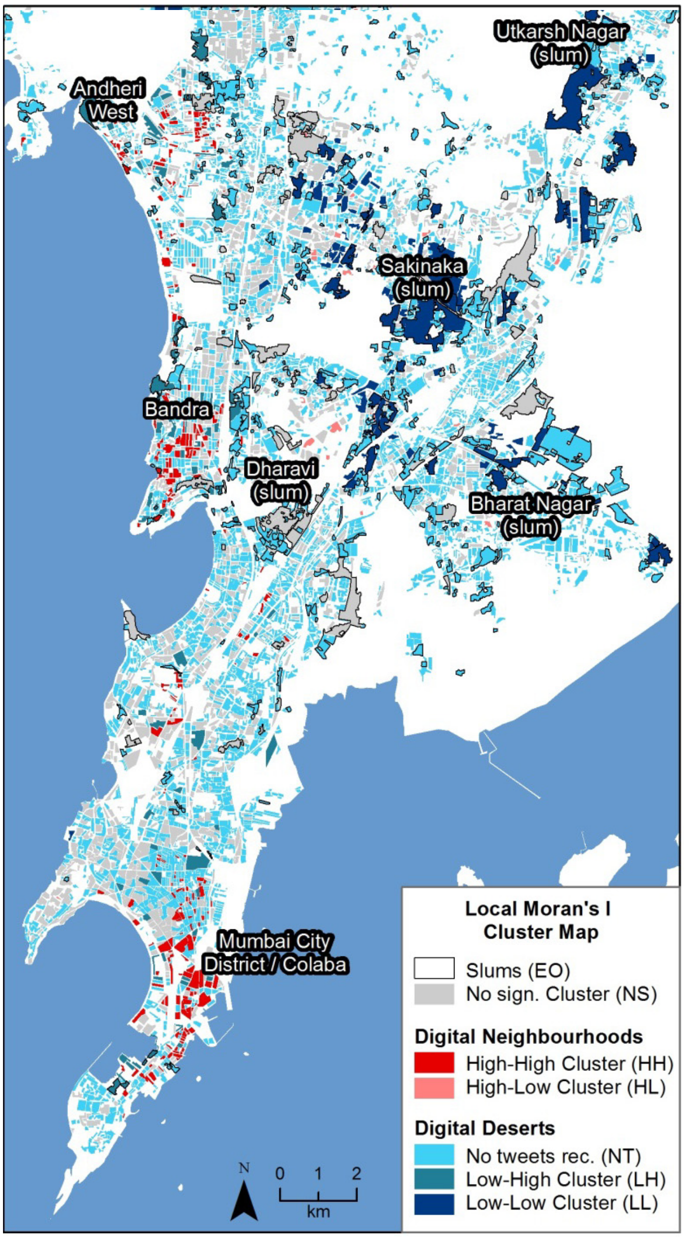

Figure 22 Local Moran's I Cluster Map of digital neighborhoods and digital deserts for megacity Mumbai

Urban landscapes in these explosively growing cities are often characterized by a typical polar structure (Hoerning, 2016), i.e., a complex arrangement of slum areas forms a complex pattern within the formal city. The research goal in **Chapter XIII** is to identify whether size distributions of morphological slums in different cities show similarities.

A common used tool to describe spatial configurations is rank size distributions (Zipf, 1941). In this method, the different elements of a system are ordered by size and the emerged distribution is analyzed. Here, the rank size distributions are applied to the measured extents of the morphological slums derived from EO-data. The elements are ordered by size and analyzed in a log-log plot. A log-normal distribution is used to fit the data. In consequence, the relative frequency distribution is analyzed and the results using histograms with logarithmic bin sizes next to the fitted log-normal distribution are presented.

The cities investigated here are Metro Manila (Philippines), Mumbai (India), Rio de Janeiro (Brazil) and Cape Town (South Africa). These cities are selected due to their different geographical location in different continents, the different cultural and economic influences of their countries and the different geographical topologies. Beyond, all four cities feature a documented and significant share of slums within their urban landscapes. For all study cities, the rank size distributions for morphological slums (as they have been classified across the cities based on the developed consistent mapping protocol using remote sensing data) are analyzed. However, to account for the variations in measurement methods, in two cases additional geo-information are used: *First*, in Cape Town, rank size distributions of morphological slums combined with townships are additionally considered. The townships derived from official data feature a more formal structure (and thus, cannot be unambiguously classified using the EO-approach); however, they are considered slum-like areas for the urban poor. *Secondly*, in Rio de Janeiro, the rank size distributions of census slums are additionally analyzed. With it differences of measurement methods between the census and the EO-approach can be identified. These census data were collected in the census 2010 (IBGE, 2017).

In general it is found that for all size distributions of morphologic slums across all cities a geometric mean of nearly 10^{-2} km^2 exists (Fig. 23). 91.5 % of all considered slums have a size between 10^{-3} km^2 and 10^{-1} km^2. While typical sizes of cities in different countries differ from another (e.g. Auerbach, 1913; Nitsch, 2005), here the major finding is that slum sizes appear globally uniform in extent. The typical size of morphologic slums in different urban systems is stable near 10^{-2} km^2 and independent from country, continent or culture. Both distributions are very similar to the log-normal distribution. In turn, supply systems can be developed which are designed specifically for this spatial expansion.

As a matter of principle, one must be aware that the method of slum measurement does have influence on size distributions and, thus on the conclusions. It is found that the geometric mean in Rio de Janeiro differs between the mapped morphologic slums from remote sensing data and the slums by census data. While the Census data from 2010 provide a geometric mean value of 0.0374 km^2, the remote sensing approach from 2015 provides results of 0.0198 km^2. This effect can be related to the administrative units for slums used in the census; the artificial administrative units do not always correspond with the urban morphology but integrate a larger variety of morphological structures. In the case of Cape Town the typical size of morphologic slums and morphologic slums combined with townships is nearly identical in both distributions. However, the size distribution when considering the townships loses its stochastic character, it looks more regular and corresponds visually rather to a log-normal distribution (Fig. 23).

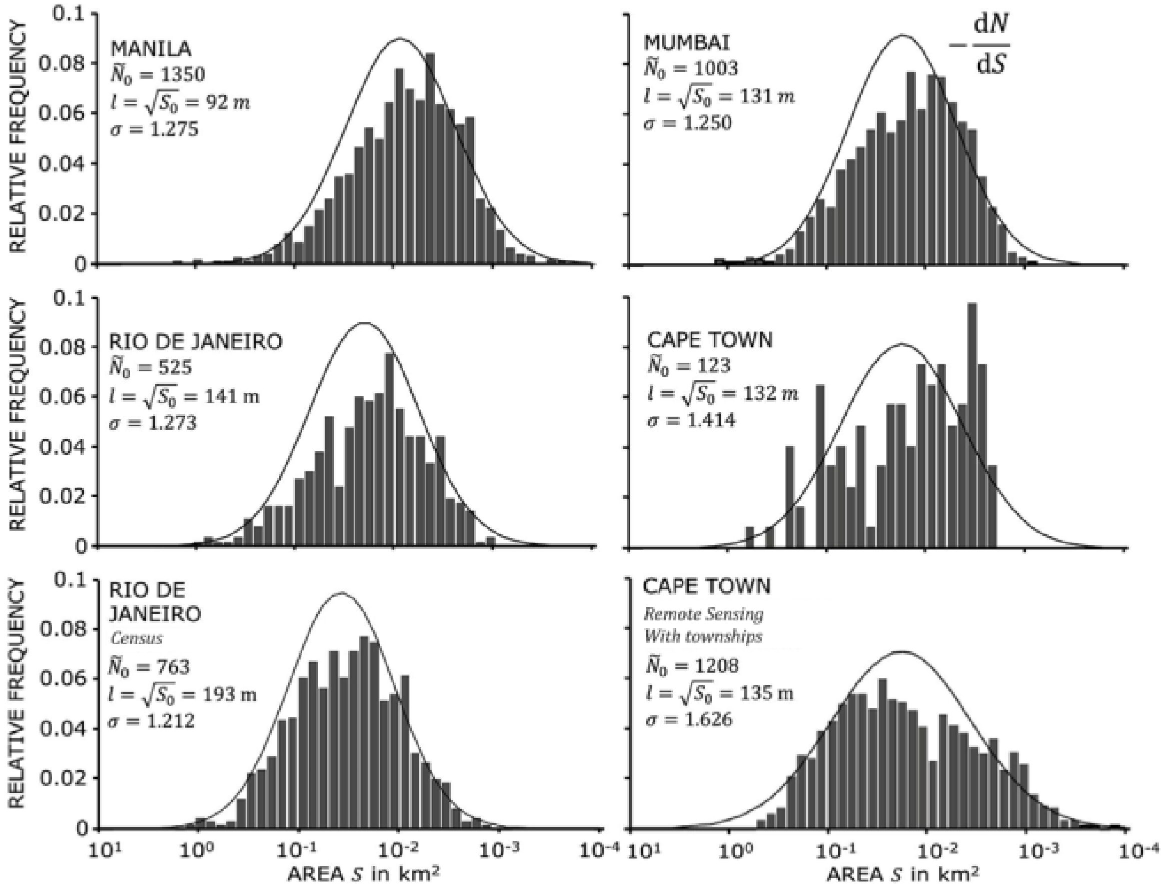

Figure 23 Histograms and log-normal distribution of morphological slums in Manila, Mumbai, Rio de Janeiro, and Cape Town (first and second row). Beyond, histograms and log-normal distribution are presented for census slums in Rio de Janeiro (bottom left) and for morphological slums combined with townships in Cape Town (bottom right).

The question arises as to what effects the findings made here have on the planning of the basic infrastructure (water, sanitary facilities, electrical energy, etc.). The study empirically reveals that the typical slum size corresponds approximately to the size of a football field. This finding shows that large slums, which are often at focus in studies, are not the dominating form, but the exceptional case. For the frequently occurring relatively small units, it may be advantageous to use decentralized supply structures (e.g. Rausch *et al.*, 2018). In the case of water supply, for example, these could be smaller filling stations supplied by trucks or, in the case of energy supply, concepts such as solar kiosks for charging mobile phones. It seems to be necessary that research and planning is not just focused on the well-known large slum areas, but on the much more frequent occurrence of small slums.

Until now, an approach for localizing the urban poor by using physical features of their living environments has been followed. Conceptualizing urban poverty by the proxy of morphologic slums proves being a legitimate approach. However, settlements of the urban poor are by no means a homogeneous physical phenomenon (e.g. Schneider-Sliwa & Bhatt, 2008; Taubenböck & Kraff, 2015). A superficial observation may suggest forms of living at the lower end of urban societies feature great similarities in terms of their physical appearance. However, (informal) processes such as illegal land occupation do not always shape such distinct and demarcating building morphologies and patterns for this social group (Saunders, 2010; Vaz & Berenstein 2004). Against this background, a systematic global inventory of morphologic types for the urban poor is in demand.

In **Chapter XIV** knowledge gaps about settlements of the urban poor are reduced by an extensive empirical baseline study taking stock of physical building types and determining structural patterns across the globe. Based on an extensive literature survey, representative locations across the globe are identified as living environments of the urban poor. As stated in Davis (2007), measuring urban poverty by the slum definition of the United Nations is considered very conservative. In consequence, the terminological and conceptual umbrella is widened. In this work the term '*Arrival City*' (introduced by Saunders, 2010) is adopted. Conceptually the term integrates all places which provide comparably cheap living spaces serving as possible access to the city, to its society and to its functions for rural-urban migrants as well as for the existing urban poor; this conceptual umbrella is necessary as the literature survey reveals that an unambiguous conclusion on the status of a study site regarding informality, security of tenure, access to sanitation, etc. is not always possible; furthermore, as hybrid forms are the norm a discrete classification can obscure reality. A conclusion on the functioning as Arrival City is, in turn, more straight-forward and unambiguous. Another issue is that various popular terms such as 'slum' or 'informality' are very inconsistently applied in different studies (e.g. Kuffer, Pfeffer & Sliuzas, 2016); a comparison of morphological patterns is at least at risk to be conceptually illegitimate. The lack of terminological consistency especially in literature dealing with physical appearances (mostly using remote sensing data) results in ontologies and classifications which remain conceptually vague, inconsistent and incomparable.

From the results in the literature survey, 44 Arrival cities are selected to specifically address the research question, which physical morphologic settlement categories of Arrival Cities can be distinguished across the globe. A set of spatial indicators has been developed to measure the appearance of a settlement: The spatial *pattern* buildings create is measured by three features: *building density* (in 2D), *orientation of buildings* and *heterogeneity index* (relating to the variance of density within the area of interest). For characterization of the (building) *morphology* two features are used: *size* (ground floor) and *height* (number of stories). The condition of the building is disregarded, as this parameter is difficult to assess using EO-data.

Based on LoD-1 building models, the spatial indicators are derived in a multi-scale analysis strategy at building, block and district level. The individual objects (buildings) are aggregated to the block level to provide measures such as density, mean size or mean height. The *district level* serves as main spatial level of analysis. The district represents the entire area of an Arrival City. This unit functions as one, consistent level for the aggregated morphologic settlement analysis. Here, the variability of the five features at block level is presented by providing the median and the data distributions are presented in box plots.

Using these spatial, quantitative descriptions of the built environments of Arrival Cities a new methodology is introduced to classify morphologic categories: deviations from measured spatial features against an expected (model) value are applied, i.e., for each individual of the five spatial features a hypothesis is presented that is related to morphologic slum structures. Deviations to this subtype of an Arrival Cities are used for categorization. In remote sensing studies specific feature of urban form (small buildings, high densities, etc.) are commonly used to localize these places (Sliuzas, Mboup & de Sherbinin, 2008; cf. Chapter XI). In accordance to this, hypotheses are formulated for every spatial indicator. As example, for slums very high building densities are expected, as open space in cities is limited and precious, population pressure is high and planning regulations are absent, which leads to a minimization of open public space. The categorization is subsequently based on relative deviations from the measured maxima relating to these assumptions stated per variable. The morphologic type fulfilling the expectations of all variables with 100% is a virtual combination of maxima measured for all 44 Arrival Cities.

In general, we find that a simplistic approach towards the morphology of the living areas of urban poor obscures reality. Figure 24 illustrates ground figure plans of eight sample

Arrival Cities. They visually reveal that the building morphologies and patterns are not uniform for places of the urban poor. The boxplots for almost all features and study sites reveal that we are dealing with hybrid forms of building patterns and morphologies, as they feature more or less variance within and across Arrival Cities.

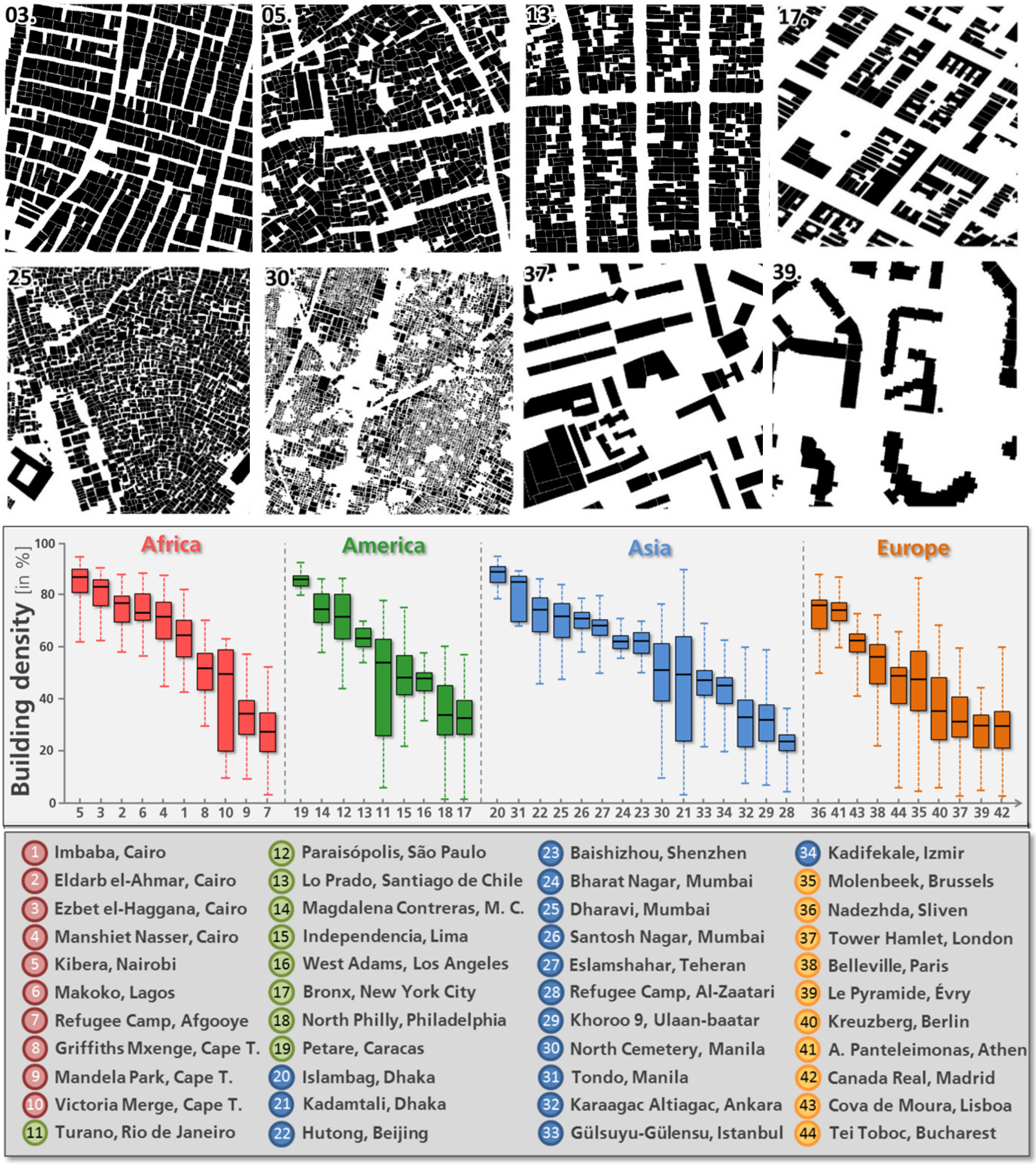

Figure 24 Ground figure plans of eight selected Arrival Cities and boxplots illustrating one sample spatial variable —building density— defining urban morphologies for all 44 selected Arrival Cities

First, it is detected that a large variance within continents appears (e.g. on every continent Arrival Cities with building densities of 70% and more to below 40% are found) (cf. Fig.

24). *Second*, large varieties of morphologic forms within one country, and *third*, within one city are measured. However, the boxplots also reveal that although these morphologically hybrid forms are identified, the stated hypothesis on typical morphologic features can be confirmed to a certain degree: high building densities are a characteristic feature of Arrival Cities. Although building densities fluctuate across the globe, 21 out of the 44 Arrival Cities feature densities higher than 60% (26 with densities higher than 50%) (Fig. 24). The hypotheses that these areas feature homogenous intra-urban forms (29 Arrival Cities below the value of 15, which is comparatively homogeneous) is also met, the building sizes are small (half of the study sites have ground floors below 60 m²) and low heights (24 Arrival Cities are not higher than 2 floors in average) can largely be confirmed.

Beyond the empirical description, a spatio-quantitative morphologic categorization of Arrival Cities is performed. To do so, all normalized variables are combined to a *morphologic settlement type index*. In general, it is found that there is no homogeneous morphological global everywhere of Arrival Cities. The social group of urban poor trying to get access to urban societies and functions live in very different structural patterns and building morphologies (Fig. 25).

Three main categories and *three respective transitional forms* of morphologic appearances are classified. These morphologies of the built environments stretch from *slum* (Category A) and *slum-like* morphologies (Cat. AB) to *mixed unstructured-structured* (Cat. B) neighbourhoods and *mixed structured-unstructured* (Cat. BC) neighborhoods even to *structured* (Cat. C) and *formally planned* (Cat. CD) areas. Figure 25 exemplifies LoD-1 building models for selected categories based on the morphologic index in a perspective view. From the high dense, low rise slum-like structures in Petare, Caracas (Cat. A) to the structured and geometric low rise pattern in North Philadelphia, Philadelphia (Cat. C) the visualization aims to illustrate morphological appearances.

Table 4 introduces the identified categories (Category A – D), describes the measured physical features and lists samples and the resulting morphologic settlement type index values. Beyond the identified three main and three transitional categories of building categories in Arrival Cities, other physical appearances of Arrival Cities (or types of living conditions) are identified in the literature survey. They are not part of our morphologic analysis of settlements patterns due to their incongruity with the applied spatial concept, as they consist e.g. of just one building, a very small amount of shelters, or they have no shelters at all. However, for a more comprehensive perspective on the physical appearances of Arrival Cities and respective living conditions these forms are also presented in a descriptive way (Category E – H).

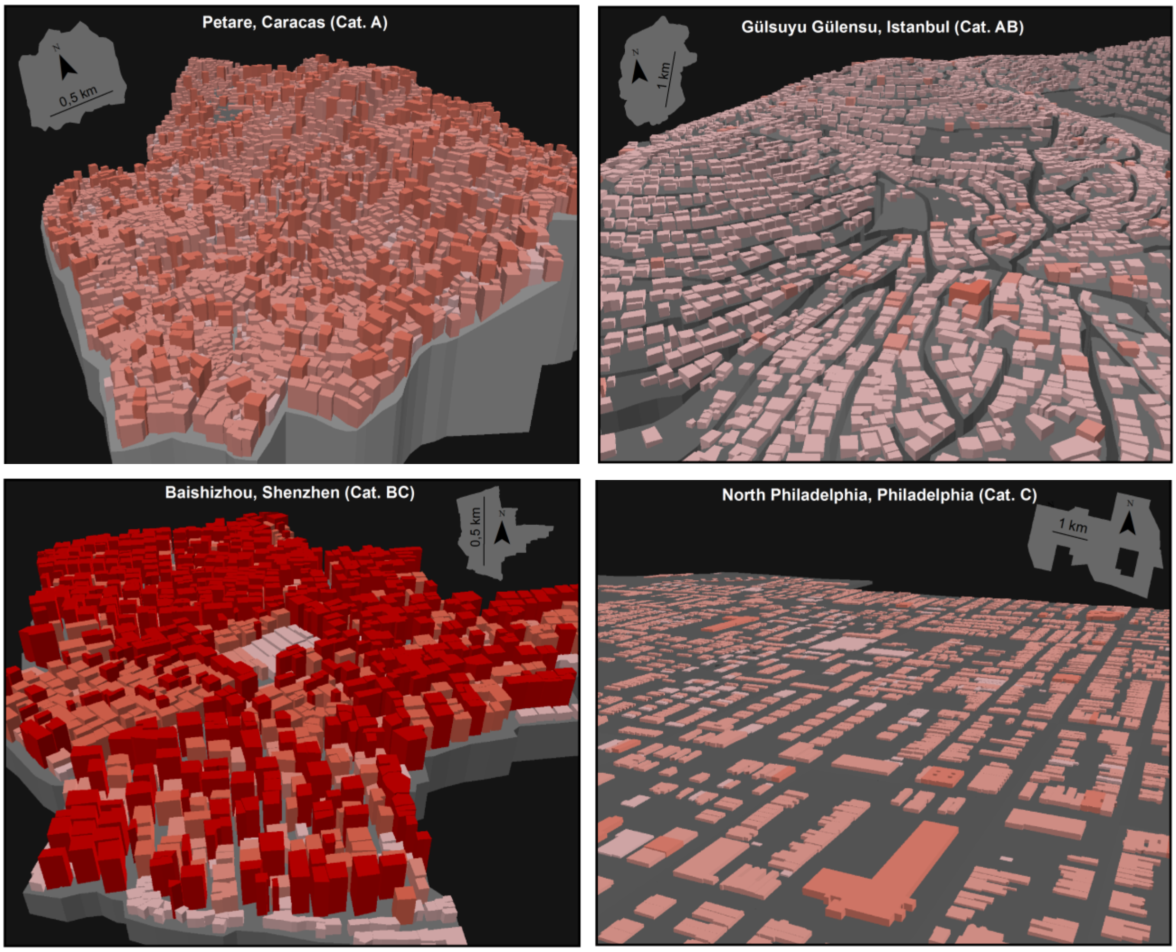

Figure 25 Perspective views on four selected examples of LoD-1 building models of the categories A (Caracas), B (Istanbul), BC (Shenzhen) and C (Philadelphia).

This study documents that there is not one global morphologic settlement type solely characteristic for Arrival Cities. With it a step towards a comprehensive morphological catalogue or even an inventory as foundation for studies about urban form and urban poverty is presented. Or, with a development agenda perspective, this study may provide additional knowledge for a more comprehensive registration of the dimensions and distributions of urban poverty.

Table 4 Morphologic categories of Arrival Cities

Cat.	Terminology	Description
A	Morphologic slum	The morphology measured in one real Arrival City corresponds to the greatest possible extent with the physical assumptions in our spatial concept as well as with the suggested ontologies and qualitative descriptions. Small makeshift shelters are huddled together in most complex alignments.
AB	Slum-like morphology	The morphology features deviations from the measured extrema or the common assumptions in at least one of the five physical features. However, the dominant physical appearance is a very dense, complex pattern of deprived building types.
B	Mixed unstructured-structured neighborhoods	The morphology features significant deviations from the measured extrema or the common assumptions of slum morphology in more than one of the five physical features; it contains mixed forms still by trend closer to slum morphology than to structured, formal neighbourhoods: Forms include further developed once slum-like morphologies (e.g. increase in building heights), run-down, deprived (and once higher quality) building blocks, infiltration of shelters into existing residential structures, or converting of shelter usages for urban poor.
BC	Mixed structured-unstructured neighborhoods	The morphology features significant deviations from the measured morphologic slums and slum-like morphologies as well as from the related common assumptions. The morphology combines typical features of structured (e.g. geometric alignments, frequent spatial transition of buildings and open spaces) und unstructured neighbourhoods. The morphology is by trend closer to structured, formal neighbourhoods
C	Transition to structured character of neighborhoods	The morphology combines typical features of planned, structured neighborhoods with few slum-like features.
CD	Formal, structured neighborhoods	The morphology provides typical features of planned, formal, structured neighborhoods: low densities, geometric alignments, large and high buildings.

Categories not part of our morphologic analysis of settlements patterns due to their incongruity with the applied spatial concept, as they consist e.g. of just one building, a very small amount of shelters, or they have no shelters at all.

Cat.	Terminology	Description
E	Small Infill occupation	Informal occupation of small urban empty spaces (e.g. by tents or makeshift shelters; or so called 'laneway alleys' are an often informal way (and sometimes tolerated by city officials) for urban density increase by housing infill)
F	Illegal squatting in and at existing structures	Roof top dwellers (informal top up urban densification virtueing and replenishing space; basement suites (Informal occupation or illegal squatting of basements); formally planned structures (informal occupation of formal structures, e.g. when unfinished due to construction stops); other forms of illegal squatting include converting cubicles, verandas, staircases into living environments.
G	Trailer homes/ Traveller camps/ Mobile homes/ Boat people	A group with a nomadic life for example in caravan pitches or boats; e.g. in Great Britain for about 25%, legal caravan pitches are inexistent and lead to informal parking; or in Hong Kong boat people finding homes in cargo boats, houseboats, small fishing crafts ashore close to the city
H	Houseless/ Homeless/ Roofless population	e.g. pavement dwellers includes people sleeping on streets without any or inadequate shelter

In conclusion, **Part III** documents and reveals the capabilities of remote sensing to approach the social group of the urban poor by the built environment classified from remotely sensed data.

It is shown that the physical appearances of morphological slums differ from the surrounding morphologies of cities. In conclusion, the localization of a relatively homogeneous social group of the urban poor is feasible. It is legitimate to use the morphological proxy for continuative studies using these classifications.

In one example of a continuative study it is shown that this spatial knowledge allows the finding that slum extents are globally uniform in extent. The typical size of morphologic slums in different urban systems is stable near 10^{-2} km^2 and independent from country, continent or culture. This finding differs from typical sizes at city level, where in different countries sizes differ from another. This generated knowledge is crucial for example for planning of the basic infrastructure such as water supply systems.

However, in general it is found that although it is legitimate to approach urban poverty by the physical proxy of the built environment, that there is no homogeneous morphological global everywhere of living environments of the urban poor, here conceptualized by the term Arrival City. The social group of urban poor trying to get access to urban societies and functions live in very different structural patterns and building morphologies from slum typologies to structured and planned urban forms.

7. Aspects of the physical approach towards cities (paper related to Part IV)

The urban form of cities features different dimensions, different configurations of their patterns, structures and morphological constitutions. In this work urban form has been analyzed at very different scales and spatial, thematic and temporal resolutions (Part I, II and III): approaches reducing urban complexity into a two dimensional urban/non-urban binary classification system allow analyzing rates and types of change over time, capturing large area spatial patterns of settlements and city-to-city comparisons become possible and straightforward (Part I). What is not addressed by this approach, however, is any capacity to analyze within-urban patterns or dynamics, crucial to understanding the complexity and nuance of urban conditions. This challenge has been addressed in this habilitation by three dimensional city models representing individual urban objects such as buildings and, where required, with more thematic detail. With it, urban form is analyzed with more specificity of the spatial composition and configuration allowing intra-urban analysis (Part II and III).

In general the focus of this work has consistently been on the built environment. This perspective, however, separates landscapes that are dominated by human construction within cities from biologically, geophysical or hydrological ones (e.g. Cadenasso, Pickett & Schwarz, 2007; McPhearson *et al.*, 2016). Biologically active areas in urban systems, for instance, provide relevant services to the human population, such as shading, aesthetics, food production, or stormwater mitigation, and they fundamentally affect the dynamics of the urban system. This disproportional focus on the built environment limits insights on the inherent complexity between urban (i.e., impervious surfaces) and non-urban categories (e.g. water), challenging the ability to consider the multiple functions of urban areas for movement and flows (Gómez-Baggethun & Barton, 2016; Boone *et al.*, 2014). While the built environment enables manifold approaches towards urban form, it admittedly bases on a relatively narrow defined classification system. This limits the ability to understand urban complexity and dynamics in a holistic sense.

In a concluding discussion the conceptual umbrella towards a more holistic analysis of urban form is posited in **Chapter XVI**. A framework of six aspects of urban form provides the foundation for integrating existing and new forms of EO-data and analysis in future studies.

The *six aspects of urban form* are systemized within three overarching components: *materials*, *configuration*, and *time*:

Materials, or the physical elements of the urban landscape, consist of three aspects: *human constructed elements* (*Aspect 1*); these include any and all land surfaces containing buildings, roads, above ground utilities, and altered topography; the *soil-plant continuum* (*Aspect 2*) of urban form includes land surfaces with biological activity including microbial activity, living plants, dead organic matter, and soil processes; and *water elements* (*Aspect 3*). The surface water of urban form includes land surfaces that are predominantly water such as streams, ponds, lakes, canals, reservoirs, swimming pools, and large fountains but excluding subsurface water such as groundwater and sewer systems. The materials are separated into three aspects because all three are required to comprehensively characterize these key dimensions of the built environment. Traditionally, constructs of urban form focus exclusively on the human constructed elements, limiting understanding of the within-urban dynamics of plant and water features.

The second component is *configuration*, which includes the *two- and three-dimensional space* (*Aspect 4*); it refers to how the material elements of urban areas are spatially arranged within a 2D flat surface perspective and a 3D perspective that includes height; this includes the underlying topography as well as the dimensionality of the structures in the built environment; and *spatial pattern of urban areas* (*Aspect 5*). Spatial pattern refers to how the patches of material elements of urban areas are arranged in space, both in 2D and 3D. The representation of urban materials in 3D and the quantification of spatially explicit arrangement of materials will enable a richer approach to analyzing urban form. This shift will create opportunities to understand how cities function in a completely new way reflecting the reality of lived experience in cities and the ecological processes within them. While challenging, this presents an opportunity for avenues of research to develop new theories, methods, and techniques to conceptualize and analyze urban form.

Lastly, because of the dynamics of human activities and biophysical processes, an important final component is the change of urban form over *time* (*Aspect 6*). Time explicitly emphasizes that the materials and their configurations are dynamic assemblages changing over different spans of time. Indeed, time itself is complex, and can be conceptually refined to deal with the onset, end, and duration of events as well as the existence of temporal lags and legacies. While the time dimension is often recognized in the widely documented expansion of urban areas, cities are also being abandoned or adapted through processes such as gentrification or repurposing of commercial zones. Time is an essential aspect of urban form because activities such as newly constructed buildings and roadways, diurnal and seasonal changes to vegetation and surface water, and demolition results in alterations to the 2D/3D structure and the arrangement of urban materials.

Recognizing that these *six aspects of urban form* do not exist in isolation, a framework on urban form is constructed that integrates into a broader discussion of urbanization. Most urban change studies to date permit only one urban class, so detecting changes to the soil-plant continuum, surface waters, or repurposed land use is limiting. Similarly limiting is the emphasis on 2D representation of urban form, which minimizes any analysis and understanding of the 3D urban density, urban texture, and urban profiles.

The time aspect, in conjunction with the three material aspects and the two configuration aspects, provides a broader and more complete representation of urban form, but the value of these six aspects are best realized when they are embedded in the analysis of the more inclusive, complex, and dynamic social and biophysical urban system. There are few studies analyzing urban form from a more holistic perspective and the level of impact across domains remains unclear to date (Biljecki, Ledoux & Stoter, 2014). The intent of identifying and defining six aspects of urban form within this component framework is to create an approach that can be consistently applied across all spatial resolutions and scales and allows for intra- and interurban comparisons.

These last considerations (**Part IV**) conceptually integrate the path taken within the habilitation into a wider research framework for future studies. The habilitation in its entirety predominantly focused on parts of Aspect 1, i.e., on the human constructed elements building and roads. The focus was also on Aspects 4 and 5, i.e., the configuration of cities in two and three dimension and related spatial pattern of urban areas at various scales. And, the focus was on Aspect 6, i.e., the change of urban form over *time* at decadal intervals. The here developed conceptual framework reveals that a broader discussion of urbanization is in demand. Aspect 2 and 3, i.e., the soil-plant continuum and water elements have basically been not considered in the presented studies, and consequently these aspects have also not been addressed for aspects 4 and 5. The time aspect addressed here is limited to decadal intervals at comparatively low resolutions to analyze urban growth rates and their patterns in two dimensional urban forms. The time aspect, however, needs to be addressed at intra-urban structures at higher temporal scales in all thematic dimensions. This framework of *six aspects* shall lay the foundation for more holistic approaches in the domains of remote sensing and urban form.

8. Conclusion

"*It's a town full of losers, and we are pulling out of here to win*". This quote of Bruce Springsteen's song 'Thunder Road' envisioned the hopes and promises of life —the American dream— outside of some failing American cities of the 1970s. In the decades since then, however, the destiny of the Thunder Road did not lead into a romantic rural existence of humankind. In the USA and foremost globally, since this song has been written, the Thunder Road pushed and pulled most people into ever-increasing cities aiming *to win*: getting a job, aiming at rising incomes, better education, etc. We have been and probably are within the largest migration ever in human history – out of rural agricultural life into cities (Saunders, 2010). However, as cities grow and transform they do not necessarily become places *to win*.

This process of urbanization is global; the spatial dimensions of urban expansion and transformations, or the evolving urban networks are beyond the scope of individual cities not to mention the reality of life's of individuals. Urban form, however, is still determining locally how and where we live and work. Documenting and analyzing urban form has been at the focus of this habilitation to contribute to a better understanding of transitions underway.

The scientific discipline of (urban) remote sensing has been undergoing big changes in the last two decades: From experimental methodological preparatory studies for small areas towards the unique capability to produce consistent, large area and even global geodata sets with temporal, thematic and geometric resolutions that allow the documentation and analysis of physical processes of urbanization. These multi-scale and multi-temporal remotely sensed data are nowadays one crucial basis for the analysis of urban form, its oscillation between the whole and the parts, between the continuity of the structure and the sequential perception of fragments. This capability is especially relevant as for many parts of the world still massive data lacks exist.

The intrinsic capability of remote sensing to approach cities with a physical perspective allows documenting and analyzing the patterns and structures at global to local scales in multi-temporal manner. This physical approach unfolds immense potential also in other domains as the built environment proves a feasible proxy indirectly reflecting demographic, social, or economic effects and impacts. If further and different kinds of data are available, the capability to complement the physical approach to the city with e.g. census or social media data proves the large capability that lies in multidisciplinary research to document and uncover processes of urbanization with a more comprehensive perspective.

As today's urban landscapes turn into larger urban constellations, conceptually captured by terms such as mega-region or urban corridor, remote sensing data and techniques reveal the evolving new massive spatial dimensions, their settlement patterns and their temporal dynamics; remote sensing mapping products let us grasp these developments and spatial methods allow for a documentation and systematization of the differing regions across the globe. More and more of these clusters of cities with inhabitants beyond 50 million are developing.

At the same time, the intra-urban configurations of these urban landscapes are transforming. The capability to systematically capture the basic elements defining the intra-urban structural compositions of cities by remotely sensed data opens up a large research field. Analyzing structural urban transformations such as developments towards more dispersed settlement layouts, more fragmented patterns of centers and subcenters, or gradients of urban densities allows for systematic comparative urban research. The built environment, however, can in addition serve as a valid proxy, where other data are inconsistent, outdated or unavailable: on the one hand it proves to be a proxy for population distributions, income levels or economic activity and on the other hand for assessing the vulnerability of structures under seismic load. In consequence, urban form can serve as an integrating basis for manifold thematic research directions.

One specific thematic research direction is related to a certain social group. The built environment is a feasible proxy for approaching the urban poor. With informal living environments featuring considerable morphologic difference to formal settlements, remote sensing techniques prove the capability to contribute geo-information on urban poverty, a field where globally massive data lacks exist. In physical approaches the shares of morphologic slums complement unreliable population assessments or underlying spatial characteristics of slum sizes are revealed. Multidisciplinary analyses of heterogeneous data sets from different sources, such as from remote sensing and social media, allow for discovering disadvantages of this social group. The share of people participating in modern online communication platforms is found significantly lower in slums. However, it needs to be emphasized that the used morphological proxy to approach the urban poor can only capture parts of this social group. Their living environments are not a morphologically homogeneous group across the globe, but feature a large variety of physical appearances.

All approaches towards the city use indicators/spatial metrics capturing urban form, at different scales or with thematic differences. In a systematization of these varying factors, six fundamental aspects are identified to approach urban form. In combination with the new availability of EO-data this framework shall lay the foundation to reconstruct and understand urban form in a more comprehensive view in future studies.

"*Cities are perhaps one of humanity's most complex creations, never finished, never definitive. They are like a journey that never ends*" (UN-Habitat, 2008). The current transformation of urban landscapes at various scales on our planet is challenging for the global society. This habilitation elaborated applied research directions based on remote sensing and other geodata sources in urban geography. It shows that remote sensing data are crucial to document the physical developments and outcomes of this transformation in ever-increasing speed. It also reveals that this spatial approach towards urban form allows uncovering underlying demographic, social, economic, political or environmental patterns. This makes clear that remote sensing must play a crucial role for a more comprehensive documentation and understanding of these (physical) processes and related urban forms across the globe. These uncovered capabilities of remote sensing data, however, contain a commitment for this discipline and its communities that on-going transitions on our planet need to be documented, observed and analyzed in a more systematic way to really gain societal impact.

This habilitation concludes with the plea towards the urban remote sensing community to no longer neglect research driven by urban geographic questions instead of limiting the research discipline to methodological classification challenges. Future studies need to consequentially follow the path of multidisciplinary frameworks combining urban concepts, theories and research questions with data-intensive approaches relying on EO and ancillary geodata to develop a clearer, more comprehensive picture of urban form and its role in global urbanization processes. This knowledge is in demand as cities and their populations continue to grow and transform. It is especially necessary as urban form is known to have crucial influence on shaping the societies of today and tomorrow. We must develop new geo-information and techniques to better understand urban form, its effects on organizing where people live and work and how interaction is spatially structured. Evidence-based knowledge must support rethinking urban form in a way that these areas can be developed as places providing perspectives for people *to win*.

References

Acioly, C., Davidson, F. (1996): Density in urban development. *Build. Issues*, vol. 8, 3–25.

Adolphson, M. (2009): Estimating a Polycentric Urban Structure. Case Study: Urban Changes in the Stockholm Region 1991–2004. *Journal of Urban Planning and Development*, vol. 135(1), pp. 19–30.

Anas, A., Arnott, R. & Small, K. A. (1989): Urban spatial structure. Journal of Economic Literature 36 (3), S. 1426-1464.

Anderson, F., Burgess, S. & Lane, J, (2007): Cities, matching and the productivity gains of agglomeration. *Journal of Urban Economics*, vol 61(1), pp. 112 – 128.

Angel, S., Parent, J., Civco, D. L. & Blei, A. (2010): *The Persistent Decline in Urban Densities: Global and Historical Evidence of "Sprawl"*. Available online: https://www.lincolninst.edu/pubs/dl/1834_1085_Angel%20Final%201.pdf (accessed on 16 November 2015).

Anselin, L. & Williams, S. (2016): Digital neighborhoods. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, vol. 9, pp. 305–328.

Arimah, B.C. (2010): *The Face of Urban Poverty.* UNU-WIDER, United Nations University (Working paper No. 2010/30). https://www.wider.unu.edu/sites/default/files/wp2010-30.pdf

Atlanta Regional Commission (ARC) (2008): *Megaregions.* http://www.atlantafiftyforward.com/megaregions.html http://www.atlantafiftyforward.com/documents/ARCFFmegaregions_web.pdf

Aubrecht, C., Ö'zceylan, D., Steinnocher, K. & Freire, S. (2012): Multi-level geospatial modeling of human exposure patterns and vulnerability indicators. *Natural Hazards*, vol. 68(1), 147-163.

Auerbach, F. (1913): Das Gesetz der Bevölkerungskonzentration, *Petermanns Geographische Mitteilungen*, vol. 59, pp. 74–76.

Barr, J. & Cohen, J. P. (2014): The floor area ratio gradient: New York City, 1890–2009. *Reg. Sci. Urban Econom.* vol. 48, pp. 110–119.

Batty, M., Besussi, E., Maat, K., & Harts, J. J. (2004): Representing Multifunctional Cities: Density and Diversity in Space and Time. *Built Environment*, vol. 30(4), pp. 324–337.

Batty, M. (2007): *The New Science of Cities.* The MIT Press, Cambridge, Massachusetts, USA. 496 p.

Batty, M. (2008): The size, scale, and shape of cities. *Science*, vol. 319, pp. 769–771.

Batty, M. (2013): *The New Science of Cities*. The MIT Press. 520p.

Bettencourt, L. M. A. & West, G. B. (2010): A unified theory of urban living. *Nature*, vol. 467, pp. 912–913.

Biljecki, F., Ledoux, H., & Stoter, J. (2014): Error propagation in the computation of volumes in 3D city models with the Monte Carlo method. ISPRS annals photogrammetry, remote sensing and spatial information sciences, vol. II(2), pp. 31–39.

Blaschke, T., Hay, G. J., Weng, Q. & Resch, B. (2011): Collective sensing: Integrating geospatial technologies to understand urban systems: An overview. *Remote Sensing*, vol. 3(8), pp. 1743–1776.

Blaschke, T. (2015): *Collective sensing: Fernerkundung, Sensorik in den Straßen, soziale Netzwerke und "die Crowd".* In: Taubenböck, H. et al., *Globale Urbanisierung – Perspektive aus dem All.* SpringerSpektrum, pp. 267-269.

Boone, C. G., Redman, C. L., Blanco, H., Haase, D., Koch, J., Lwasa, S., Nagendra, H., Pauleit, S., Pickett, S. T. A., Seto, K. C. & Yokohari, M. (2014): *Reconceptualizing land for sustainable urbanity.* In: K. C. Seto & A. Reenberg, editors. *Rethinking urban land use in a global era.* MIT Press, Cambridge. pp 313–391.

Borfecchia, F., Pollino, M., De Cecco, L., Lugari, A., Martini, S., La Porta, L., Ristoratore, E., Pascale, C. (2010): Active and passive remote sensing for supporting the evaluation of the urban seismic vulnerability. *Italian J Remote Sens*, vol. 42(3), pp. 129–141.

Bramley, G. & Power, S. (2009): Urban form and social sustainability: The role of density and housing type. *Environment and Planning B*, vol. 36(1), pp. 30-48.

Breiman, L. (2001): Random Forests. *Mach. Learn.*, vol. 45, pp. 5–32.

Brenner, N. (2013): Theses on urbanization. *Public Culture*, vol. 25(1), pp. 85–114.

Burger, M. & Meijers, E. (2011): Form follows function? Linking morphological and functional polycentricity. *Urban Studies*, 49(5), pp. 1127-1149.

Cadenasso, M.L., Pickett S.T.A. & Schwarz K (2007): Spatial heterogeneity in urban ecosystems: reconceptualizing land cover and a framework for classification. *Frontiers in Ecology and the Environment*, vol. 5(2), pp. 80-88.
Camps-Valls, G. & Bruzzone, L. (2009): Kernel Methods for Remote Sensing Data Analysis, John Wiley & Sons, New York. 434 p.
Carlino, G., Chaterjee, S. & Hunt, R. (2007): Urban density and the rate of invention. *Journal of Urban Economics*. Vol. 61(3), pp. 389-419.
Castells, M. (2002): Local and global: cities in the network society. *Tijdschrift voor economische en sociale geografie*, vol. 93(5), pp. 548-558.
Castells, M. (1989): The Informational City. Information, Technology, Economic Restructuring and the Urban-Regional Process. Oxford: Wiley. 408 p.
Champion, A. G. (2001): A Changing Demographic Regime and Evolving Polycentric Urban Regions: Consequences for the Size, Composition and Distribution of City Populations. *Urban Studies*, vol. 38(4), pp. 657–677.
Chapman, D., Pratt, D., Larkham, P. & Dickins, I. (2003): Concepts and definitions of corridors: evidence from England's Midlands. *Journal of Transport Geography*, vol. 11(3), pp. 179–191.
Churchman, A. (1999): Disentangling the concept of density. *J. Plan. Lit.* vol. 13, pp. 389–411.
Davis, M. (2007): *Planet of Slums*. Verso: London.
Davoudi, S. (2003): European Briefing: Polycentricity in European spatial planning: from an analytical tool to a normative agenda. *European Planning Studies.* vol. 11(8), pp. 979–999.
Dempsey, N., Bramley, G., Power, S. & Brown, C. (2011): The social dimension of sustainable development: Defining urban social sustainability. *Sustainable Development*, vol. 19(5), pp. 289-300.
Dicken, P. (2014): *Global Shift: Mapping and Changing contuors of the world economy.* Sage Publications Ltd. London, 2014.
Duranton, G. & Puga, D. (2005): From sectoral to functional urban specialisation. *J. Urban Econ.*, *vol. 57*, pp. 343–370.
Elvidge, C. D., Imhoff, M. L., Baugh, K. E., Hobson, V. R., Nelson, I., Safran, J., Dietz, J. B. & Tuttle, B. T. (2001): Nighttime lights of the world: 1994–95. *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 56, pp. 81–99.
Elvidge, C. D., Baugh, K. E., Zhizhin, M. & Hsu, F. C. (2013): Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proceedings of the Asia-Pacific Advanced Network*, vol. 35, pp. 62-69.
Esch, T., Taubenböck, H., Roth, A., Heldens, W., Felbier, A., Thiel, M., Schmidt, M., Müller, A. & Dech, S. (2012): TanDEM-X mission: New perspectives for the inventory and monitoring of global settlement patterns. *Journal of Selected Topics in Applied Earth Observation and Remote Sensing*. vol 6. p.22.
Esch, T., Marconcini, M., Felbier, A., Roth, A., Heldens, W., Huber, M., Schwinger, M., Taubenböck, H., Müller, A. & Dech, S. (2013): Urban footprint processor – Fully automated processing chain generating settlement masks from global data of the TanDEM-X mission. *IEEE Geoscience & Remote Sensing Letters*, vol. 10(6), pp. 1617-1621.
Eurostat (2016a): *Population distribution*. http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat%20-%20geostat11
Eurostat (2016b): *Urban Audit Cities* http://ec.europa.eu/eurostat/documents/4422005/6840613/RYB-2015-Annex2-Cities-CandK.pdf
Ewing, R., Meakins, G., Hamidi, S. & Nelson, A. C. (2014): Relationship between urban sprawl and physical activity, obesity, and morbidity—Update and refinement. *Health Place*, vol. 26, pp. 118–126.
Ewing, R. & Hamidi, S. (2015): Compactness *versus* sprawl: A review of recent evidence from the United States. *J. Plan. Lit.* vol. 30, pp. 413–432.
Fina, S., Krehl, A., Siedentop, S., Taubenböck, H. & Wurm, M. (2014): Dichter dran! Neue Möglichkeiten der räumlichen Analyse und Visualisierung von Stadtstrukturen mit Dichteoberflächen und –profilen basierend aus Erdbeobachtungsdaten. *Raumforschung & Raumordnung*, vol. 72(3), pp. 179-194.
Florida, R., Gulden, T. & Mellander, C. (2008): The rise of the mega-region. *Cambridge Journal of Regions, Economy and Society*, vol. 1(3), pp. 459-476.
Florida, R. (2002): *The rise of the creative class: and how it's transforming work, leisure, community, and everyday life.* Basic Books, 464p.
Friedmann, J. & Miller, J. (1965): The urban field. *Journal of the American Institute of Planners*, vol. 31(4),

pp. 312–320.

Friesen, J., Rausch, L. & Pelz, P. F. (2017): Providing water for the poor-towards optimal water supply infrastructures for informal settlements by using remote sensing data, *IEEE Joint Urban Remote Sensing Event (JURSE)*, pp. 1–4.

Frolking, S., Milliman, T., Seto, K. & Friedl, M. A. (2013): A global fingerprint of macro-scale changes in urban structure from 1999 to 2009. *Environmental Research Letters.* vol. 8, 10 pp.

Fuchs, M. (2006): *Slum als Projekt: Dharavi und die Falle der Marginalisierung.* Ahuja R & Brosius C (Ed.), *Mumbai - Delhi – Kolkata. Annäherungen an die Megastädte Indiens.* Heidelberg: Draupadi. pp. 47-63.

Garreau, J. (1991): *Edge City: Life on the New Frontier.* Anchor Books, 548p.

Geddes, P. (1915): *Cities in Evolution. An Introduction to the Town Planning Movement and to the Study of Civics.* London: Williams & Norgate.

Geiß, C. & Taubenböck, H. (2013): Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap. *Nat. Hazards,* vol. 68, pp. 7-48.

Georg, I., Blaschke, T. & Taubenböck, H. (2018): Are we in Boswash yet? A multi-source geodata approach to spatially delimit urban corridors. *ISPRS Internatl. Journal of Geo-Information*, 7(1), pp. 1-15.

Gislason, P. O., Benediktsson, J. A., Sveinsson, J. R. (2006): Random Forests for land cover classification. *Pattern Recogn. Lett*. vol. 27, pp. 294–300.

Glaeser, E. (2010): *Triumph of the City*; Penguin Press HC: London, UK.

Goodchild, M.F. (2013): The quality of big (geo)data. *Dialogues in Human Geography*, vol. 3, pp. 280–284.

Gómez-Baggethun E. & Barton, D.N. (2013): Classifying and valuing ecosystem services for urban planning. *Ecological Economics*. vol. 86, pp. 235-245.

Gottmann, J. (1957): Megalopolis or the Urbanization of the Northeastern Seaboard. *Economic Geography*, 189-200.

Griffiths, P., Hostert, P., Gruebner, O. & van der Linden, S. (2010): Mapping megacity growth with multi-sensor data. *Remote Sensing of Environment,* vol. 114, pp. 426-439.

Grimm, N. B., Cook, E .M., Hale, R. L. & Iwaniec, D. M. (2016): *A broader framing of ecosystem services in cities: Benefits and challenges of built, natural, or hybrid system function.* In: K. C. Seto, W. D. Solecki & C. A. Griffith, editors. *The Routledge Handbook of Urbanization and Global Environmental Change*. Routledge, New York. pp. 203– 212.

Guerois, M. & Pumain, D. (2008): Built-up encroachment and the urban field: a comparison of forty European cities. *Environ. Plan. A*, vol. 40, pp. 2186–2203.

Hachmann, S., Jokar Arsanjani, J. & Vaz, E. (2018): Spatial data for slum upgrading: Volunteered Geographic Information and the role of citizen science, *Habitat International,* vol. 72(2), pp. 18-26.

Hall, P. & Pain, K. (2006): *From metropolis to polyopolis*. In: Hall P, Pain K (eds.). *The Polycentric Metropolis: Learning from Mega-city Regions in Europe*. London & Sterling, VA: Earthscan, pp. 3–16.

Harris, C. D. & Ullman, E. L. (1945): The nature of cities. American Academy of Political and Social Science 242, S. 7-17.

Harrison, J. (2013): Configuring the new ‘regional world’: On being caught between territory and networks. *Regional Studies*, vol. 47(1), pp. 56-74.

Harrison, J. & Growe, A. (2014): From places to flows? Planning for the new ‘regional world’ in Germany. *European Urban and Regional Studies*, vol. 21(1), pp. 22-41.

Haughton, G., Allmendinger, P., Counsell, D. & Vigar, G. (2010): *The new spatial planning: Territorial management with soft spaces and fuzzy boundaries.* Routledge: London, 289 p.

Heidenreich, M. (1998): The Changing System of European Cities and Regions. *European Planning Studies*, vol. 6(3), pp. 315-332.

Hinde, S. & Dixon, J. (2005): Changing the obesogenic environment: Insights from a cultural economy of car reliance. *Transp. Res. Part D: Transp. Environ.*, vol. 10, pp. 31–53.

Hoerning, J. (2016): *”Megastädte” zwischen Begriff und Wirklichkeit - über Raum, Planung und Alltag in großen Städten,* 1st Edition, transcript Verlag, Bielefeld.

Hofmann, P. (2001): Detecting informal settlements from IKONOS image data using methods of object oriented image analysis—An example from Cape Town (South Africa). *Proceedings of the 2nd international symposium remote sensing of urban areas,* Regensburg, Germany, June 22–23. pp. 107–118.

Hollis, L. (2013): *Cities are are good for you: The genius of the metropolis.* Bloomsbury Press; ISBN-10: 1620402068, pp. 416.

Hospers, G.-J. (2003): Beyond the blue banana? Structural change in Europe's geo-economy. *ERSA Conference Papers*, European Regional Science Association.

IAURIF (Institut D'Amenagement Et D'Urbanisme de la Region D'Ile-De-Frane (1991): *La Charte de L'Ille-de-France.* Paris: IAURIF.

IBGE (Instituto Brasileiro de Geografia e Estatistica) (2010): *Base de Informacões do Censo Demográfico: Resultados do Universo por setor censitário*. IBGE: Rio de Janeiro.

IBGE - I. B. de Geografia e Estatstica, Urbanized Areas (2017):http://www.ibge.gov.br/english/geociencias/geografia/geografia_urbana/areas_urbanizadas/default.shtm?c=8

Indiastat (2011): *Revealing India statistically.* http://www.indiastat.com/urbanareas

Jackson, K. T. (1985): *Crabgrass Frontier – The suburbanization of the United States.* Oxford University Press, 396 p.

Jacobs, J. (1961): *The Death and Life of Great American Cities;* Random House: New York, NY, USA.

Jenks, M. Burton, E. & Williams, K. (1996): *The compact city – A sustainable urban form?* Spon Press.

Keating, M. (1998): *The new regionalism in western Europe: Teritorial restructuring and political change.* Aldershot: Edward Elgar.

Kloosterman, R. C. & Musterd, S. (2001): The polycentric urban region: towards a research agenda. *Urban Studies*, vol. 38(4), pp. 623-633.

Klotz, M., Kemper, T., Geiß, C., Esch, T. & Taubenböck, H. (2016): *How good is the map? A multi-scale cross-comparison framework for global settlement layers: evidence from Central Europe.* Remote Sensing of Environment, 178, pp. 191-212.

Kostof, S. (1991): *The city shaped. Urban Patterns and Meanings Through History*. Thames & Hudson, 352 p.

Krehl, A. (2015): Urban Spatial Structure: An Interaction between Employment and Built-up Volumes. *Regional Studies, Regional Science*, vol. 2(1), pp. 289–307.

Krizek, K. J. (2011): Residential Relocation and Changes in Urban Travel: Does Neighborhood-Scale Urban Form Matter? *Journal of the American Planning Association.* vol. 69(3), pp. 265-281.

Kropf, K. (1996): Urban tissue and the character of towns. *Urban Design International*, vol. 1(3), pp. 247-263.

Kuffer, M., Pfeffer, K. & Sliuzas, R. (2016): Slums from space—15 years of slum mapping using remote sensing. *Remote Sensing,* vol. 8(6), pp. 455–464.

Lang, R. E. & Dhavale, D. (2005): *Beyond Megalopolis: exploring America's new megapolitan geography.* Metropolitan Institute Census Report Series, 05:01, Alexandria, VA: The Metropolitan Institute at Virginia Tech.

Lang, R. E. & Nelson, A. C. (2007): *Beyond the Metroplex: Examining Commuter Patterns at the "Megapolitan" Scale.* Working Paper. Lincoln Institute of Land Policy, Cambridge, MA.

Lang, R. E., & LeFurgy, J. B. (2003): Edgeless cities: Examining the Noncentered metropolis. *Housing Policy Debate*, vol. 14(3), pp. 427–460.

Li, L., Goodchild, M.F. & Xu, B. (2013):. Spatial, temporal, and socioeconomic patterns in the use of Twitter and Flickr. *Cartography and Geographic Information Science*, vol. 40, pp. 61–77.

Luck, M., Wu, J (2002): A gradient analysis of urban landscape pattern: A case study from the Phoenix metropolitan region, Arizona, USA. *Landsc. Ecol.*, vol. 17, pp. 327–339.

Lynch, K. & Rodwin, L. (1958): A Theory of Urban Form. *Journal of the American Institute of Planners*, vol. 24(4), pp. 201-214.

Lynch, K. (1981): *A theory of good city form*, Cambridge, MA: MIT Press.

Lefebvre, A. & Corpetti, T. (2017): Monitoring the morphological transformation of Beijing old city using remote sensing texture analysis. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 10(2), pp. 539-548.

Leichtle, T., Geiß, C., Wurm, M., Lakes, T. & Taubenböck, H. (2017): Unsupervised change detection in VHR remote sensing imagery – an object-based clustering approach in an urban environment. International Journal of Applied Earth Observation & Geoinformation, 54, pp. 15-27.

Martinez, J., Mboup, G., Sliuzas, R. & Stein, A. (2008): Trends in urban and slum indicators across developing world cities, 1990-2003, *Habitat International.* vol. 32(1), pp. 86–108.

Masucci, A. P., Stanilov, K. & Batty, M. (2013): Limited urban growth: London's street network dynamics since the 18th century. *PLOS One*, doi:10.1371/journal.pone.0069469.

McFarlane, C. (2015): The geographies of urban density: Topology, politics and the city. *Prog. Hum. Geogr*, vol. 40, pp. 629-648.

McPhearson, T., Haase, D., Kabisch, N., Gren, Å. (2016): Advancing understanding of the complex nature of urban systems. *Ecological Indicators*, vol. 70, pp. 566–573.

McMillen, D. P. (2006): *Testing for monocentricity.* Arnott, R. J., McMillen, D. P. (eds.) *A Companion to Urban Economics*; Blackwell Publishing: Malden, MA, USA, 2006; pp. 128-140.

Milanovic, B. (2016): *Die Ungleichheit der Welt – Migration, das Eine Prozent und die Zukunft der Mittelschicht.* Suhrkamp, 312 p.

Morstatter, F., Pfeffer, J., Liu, H. & Carley, K. M. (2013): *Is the Sample Good Enough? Comparing Data from Twitter's Streaming API with Twitter's Firehose.* The International AAAI Conference on Web and Social Media. Boston, USA.

Mück, M., Klotz, M. & Taubenböck, H. (2017): Validation of the DLR Global Urban Footprint in rural areas: A case study for Burkina Faso. *IEEE-CPS Joint Urban Remote Sensing Event (JURSE)*, Dubai, VAE.

Nitsch, V. (2005): Zipf zipped, *Journal of Urban Economics,* vol. 57(1), pp. 86–100.

OECD (Organization for Economic Co-operation and Development) (2017): *Poverty rate (indicator).* https://data.oecd.org/inequality/poverty-rate.htm

OECD (Organization for Economic Co-operation and Development) (2012): *Compact City Policies: A Comparative Assessment*; OECD: Paris, France.

Oizumi, K. (2011): The Emergence of the Pearl River Delta Economic Zone. *RIM: Pacific business and industries*, vol. 11(41), pp. 2-20.

Oliviera, V. (2016): *Urban Morphology—An Introduction to the Study of the Physical Form of Cities*; Springer: Berlin, Germany.

Openshaw, S. (1983): *The Modifiable Areal Unit Problem. Norwick: Geo Books*; GeoBooks, Norwhich, England,UK.

Paessler, R. (2008): *Stadtgeographie.* Wissenschaftliche Buchgesellschaft Darmstadt. 136p.

Poumadere, M., Mays, C., Le Mer, S. & Blong, R. (2005) : The 2003 heat wave in France: Dangerous climate change here and now. *Risk Anal.*, vol. 25, pp. 1483–1494.

Rausch, L., Friesen, J., Altherr, L., Meck, M. & Pelz, P. (2018): A Holistic Concept to Design Optimal Water Supply Infrastructures for Informal Settlements Using Remote Sensing Data, *Remote Sensing* vol. 10(2).

RECLUS (1989): *Les Villes Europeennes. Report DATAR.* Paris: La Documentation Francaise.

Riguelle, F., Thomas, I. & Verhetsel, A. (2007): Measuring urban polycentricity: a European case study and its implications. *Journal of Economic Geography.* vol. 7(2), pp. 193-215.

Rode, P., Keim, C., Robazza, G., Viejo, P. & Schofield, J. (2014): Cities and energy: Urban morphology and residential heat-energy demand. *Environ. Plan. B Plan. Des.*, vol. 41, pp. 138–162.

Roca Cladera, J., Marmolejo Duarte, C. R. & Moix, M. (2009): Urban Structure and Polycentrism: Towards a Redefinition of the Sub-centre Concept. *Urban Studies*, vol. 46(13), pp. 2841–2868.

Roberts, B. H. (2007): Changes in urban density: Its implications on the sustainable development of Australian cities. In: *Proceedings of the State of Australian Cities National Conference*, Adelaide, Australia.

Roskamm, N. (2011): *Dichte: Eine transdisziplinäre Dekonstruktion. Diskurse zu Stadt und Raum. Reihe: Urban Studies.* Transcript: Bielefeld, Germany.

Ross, C. L., Barringer, J., Yang, J., Woo, M., Danner, A., West, H., Amekudzi, A., & Meyer, M. (2009): *Megaregions: Delineating Existing and Emerging Megaregions.* Center for Quality Growth and Regional Development (CQGRD) of Georgia Insitute of Technology. Federal Highway Administration: Prepared for the U.S. Department of Transportation.

Ross, C. L. (2011): *Literature Review of Organizational Structures and Finance of Multi-jurisdictional Initiatives and the Implications for Megaregion Transportation Planning in the U.S. 2011.* http://www.fhwa.dot.gov/planning/publications/megaregions_report_2012/megaregions2012.pdf .

Salat, S. (2011): *Cities and Forms – On sustainable urbanism*. CSTB, 544p.

Saunders, D. (2010): *Arrival Cities*. Blessing, London, UK.

Sarzynski, A., Hanson, R., Wolman, H. & McGuire, M. (2005): *All centers are not equal: an exploration of the polycentric metropolis*. Working Paper Number 015. Washington, DC: George Washington Institute of Public Policy.

Schläpfer, M., Lee, J. & Bettencourt, L. M. A. (2015): *Urban Skylines: Building Heights and Shapes As Measures of City Size.* SFI Working Paper 2015-12-045.

Schmitt, A., Sieg, T., Wurm, M. & Taubenböck, H. (2018): Automated slum detection using TerraSAR-X – A super-vised multi-scale and non-pararmetric classification approach based on the evaluation of local histograms. *International Journal of Applied Earth Observation & Geoinformation*, 64, pp. 181-198.

Schneider-Sliwa, R. & Bhatt, M. (Eds.), (2008): *Recovering of Slums. Determinants of poverty and upward social mobility in urban slums. Case studies from India.* Basel: Schwabe/Basel Development Studies.

Schneider, A., Friedl, M. A. & Potere, D. (2010): Mapping global urban areas using MODIS 500-m data: New methods and datasets based on 'urban ecoregions'. *Remote Sensing of Environment*, vol. 114(8), pp. 1733-1746.

Schölkopf, B. & Smola, A. (2002): *Learning with Kernels*. MIT Press, Cambridge (MA).

Scholz, T., Rauscher, C., Reiher, J. (2012): Bachteler, T. *Geocoding of German Administrative Data: The Case of the Institute for Employment Research*; Bundesagentur für Arbeit: Nürnberg, Germany.

Scott, A. J. (2000): *Global city-regions and the new world system.* Unpublished Paper, Department of Policy Studies and Department of Geography, University of California, Los Angeles.

Sengara, W. I., Suarjana, M., Beetham, D., Corby, N., Edwards, M., Griffith, M., Wehner, M. & Weller, R. (2010): The 30th September 2009 West Sumatra Earthquake: Padang region damage survey, *Geoscience Australia*, Record 2010/44, 201p.

Siedentop, S., Kausch, S., Einig, K. & Gössel, J. (2003): *Siedlungsstrukturelle Veränderungen im Umland von Agglomerationsräumen* (Forschungen No. 114). Bonn.

Siedentop, S., Schiller, G., Gutsche, J. M., Koziol, M. & Walther, J. (2006): *Siedlungsentwicklung und Infrastrukturfolgekosten. Bilanzierung und Strategieentwicklung.* Bonn; BBR-Online-Publikationen 3/2006.

Siedentop, S. (2015): *Ursachen, Ausprägungen und Wirkungen der globalen Urbanisierung – ein Überblick.* In: H. Taubenböck, M. Wurm, T. Esch, & S. Dech (Eds.), *Globale Urbanisierung – Perspektive aus dem All,* Berlin Heidelberg: SpringerSpektrum. pp. 11–21.

Sliuzas, R., Mboup, G. & de Sherbinin, A. (2008): *Report of the Expert Group Meeting on Slum Identification and Mapping.* Report by CIESIN, UN-HABITAT, ITC.

Steiniger, S., Lange, T., Burghardt, D. & Weibel, R. (2008): An approach for the classification of urban building structures based on discriminant analysis techniques. *Transactions in GIS,* vol. 12 (1), pp. 31–59.

Soja, E. & Kanai, E. (2007): *The Urbanization of the World.* In: Burdett, R. (Ed.). *The Endless City*. Phaidon Press Limited, pp. 54-69.

Soja, E. & Kanai, E. (2014): *The Urbanization of the World*. In: Brenner, N. (ed.) Implosions/Explosions: *Towards a Study of Planetary Urbanization*. Berlin: Jovis, pp. 142-159

Tacoli, C., MacGranahan, G & Satterthwaite, D (2015): Urbanisation, rural-urban migration and urban poverty. IIED Working Paper, IIED, London.

Taubenböck, H., Esch, T., Felbier, A, Wiesner, M., Roth, A. & Dech, S. (2012): Monitoring of mega cities from space. *Remote Sensing of Environment*, vol. 117, pp. 162-176.

Taubenböck, H. & Wurm, M. (2015): *Ich weiß, dass ich nichts weiß – Bevölkerungsschätzung in der Megacity Mumbai.* In: Taubenböck, H., Wurm, M., Esch, T., Dech, S. (Eds.), *Globale Urbanisierung – Perspektive aus dem All.* SpringerSpektrum, Berlin/Heidelberg, pp. 171–178.

Taubenböck, H. & Kraff, N. J. (2015): *Das globale Gesicht urbaner Armut? Siedlungsstrukturen in Slums.* SpringerSpektrum, Berlin/Heidelberg. pp.. 107-119.

Taubenböck, H. & Wurm, M. (2015): Wo beginnt die Stadt? Urbane Fernerkundung für stadtgeographische Forschung. *DisP Plan. Rev.*, vol. 3, pp. 74–85. (in German)

Taubenböck, H. & Wurm, M. (2015b): *Ich weiß, dass ich nichts weiß – Bevölkerungsschätzung in einer Megacity*. SpringerSpektrum. S. 171-178.

Taubenböck, H., Esch, T., Wurm, M., Roth, A. & Dech, S. (2010): Object-based feature extraction using high spatial resolution satellite data of urban areas. *Journal of Spatial Science*, vol. 55, no. 1, pp. 117-133.

Taubenböck, H., Esch, T., Felbier, A., Roth, A. & Dech, S. (2011): Pattern-based accuracy assessment of an urban footprint classification using TerraSAR-X data. *IEEE Geoscience and Remote Sensing Letters*. vol. 8(2), pp. 278-282.

Taubenböck, H. & Kraff, N. (2014): The physical face of slums: a structural comparison of slums in Mumbai, India, based on remotely sensed data. *Journal of Housing and the Built Environment.* vol. 29(1), pp. 15–38.

Taylor, P. J. & Lang, R. E. (2004): The shock of the new: 100 concepts describing recent urban change. *Environment and Planning A*, vol. 36(6), pp. 951–958.

Tonkiss, F. (2013): *Cities by design: the social life of urban form.* Polity, Cambridge, UK..

Tratalos, J., Fuller, R., Warren, P., Davies, R. & Gaston, K. (2007): Urban form, biodiversity potential and ecosystem services. *Landscape and Urban Planning*, vol. 83(4), pp. 308-317.

Trip, J. J. (2003): *The corridor as a transport network*. In: Zonneveld, W. & Trip, J. J. (Eds.). *Megacorridors in North West Europe. Investigating a new transnational planning concept*. Housing and Urban Policy Studies, 27. Delft: Delft University Press, pp. 17-23.

United Nations (2017): *The 2017 revision*. Population Division. Department of Economic and SocialAffairs. United Nations publications.

United Nations (2015): *The Millennium Development Goals Report.* United Nations, New York.

United Nations (2006): *The 2005 revision*. Population Division. Department of Economic and SocialAffairs. United Nations publications

UN-Habitat (2008): *State of the World's Cities 2010/2011: Bridging the Urban Divide*. London & Sterling, VA: Earthscan.

UN-Habitat (2015): *A Practical Guide to Designing, Planning, and Executing Citywide Slum Upgrading Programmes*. Nairobi: UN-Habitat.

UN-Habitat (2003): *The Challenge of Slums: Global Report on Human Settlements 2003*; Earthscan Publications Ltd.: London, UK; Sterling, VA, USA.

van der Bruggen, B., Borghgraef, K. & Vinckier, C. (2010): Causes of Water Supply Problems in Urbanised Regions in Developing Countries, *Water Resources Management*. vol. 24(9), pp. 1885–1902.

van der Meer, L. (1998): *Red octopus.* In: Blass, W. (eds) *A new perspective for European spatial development policies*, Aldershot, Avebury, pp. 9-19.

Vapnik, V. N. (1998): *Statistical learning theory*. New York, Wiley.

Vaz, L. F. & Berenstein, J. P. (2004): *Morphological diversity in the squatter settlements of Rio de Janeiro*, (Eds) K. Stanilov & B. C. Scheer: *Suburban Form: An International Perspective.* Routledge, New York, pp. 61–72.

Weng, Q. (2012): Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends. *Remote Sens. Environ.*, vol. 117, pp. 34–49.

Whebell, C.F. (1969): Corridors: A theory of urban systems. *Annals of the Association of American Geographers*, vol. 59(1), pp. 1-26.

World Migration Report (2015): *Migrants and Cities.* International Organization for Migration. Geneva, Switzerland.

Wurm, M., Taubenböck, H. & Dech, S. (2010): Quantification of urban structures on building block level utilizing multisensoral remote sensing data. *SPIE Europe,* Toulouse, France. pp. 13.

Wurm, M., Taubenböck, H., Schardt, M., Esch, T. & Dech, S. (2011): Object-based image information fusion using multisensor earth observation data over urban areas. *International Journal of Image and Data Fusion*, vol. 2(2), pp. 121-147.

Wurm, M., d'Angelo, P., Reinartz, P. & Taubenböck, H. (2014): Investigating the applicability of Cartosat-1 DEMs and topographic maps to localize large-area urban mass concentrations. *JSTARS*, vol. 7, pp. 4138–4152.

Wurm, M., Taubenböck, H., Weigand, M. & Schmitt, A. (2017): Slum mapping in polarimetric SAR data using spatial features. *Remote Sensing of Environment,* vol. 194, pp. 190-204.

Yang, J., Son, G. & Lin, J. (2014): Measuring spatial structure of China's megaregions. *Journal of Urban Planning and Development*. 141(2). 04014021.

Zhong, C., Schläpfer, M., Müller-Arisona, S., Batty, M., Ratti, C. & Schmitt, G. (2015):Revealing centrality in the spatial structure of cities from human activity patterns. *Urban Stud.*, vol. 54, pp. 437-455.

Zhu, X. X, Tuia, D., Mou, L., Xia, G.-S., Zhang, L., Xu, F. & Fraundorfer F. (2017): Deep Learning in Remote Sensing: A comprehensive review and list of resources. *IEEE Geoscience and Remote Sensing*. vol. 5(4), pp. 8-36.

Zipf, G. K. (1941): *National Unity and Disunity - The Nation As a Bio-Social Organism*, Bloomington, Indiana.