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The morphology of the Arrival City - A global categorization based on literature surveys and remotely sensed data

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ABSTRACT

When we think about living environments of the urban poor, slums might be the most immediate association. These slums evoke a more or less stereotype impression of built environments: complex, high dense alignments of small makeshift or run-down shelters. However, this perceived characteristic morphology is neither globally homogeneous nor is this perception covering morphologic appearances of urban poverty in a comprehensive way. This research provides an empirical baseline study of existing morphologies, their similarities and differences across the globe. To do so, we conceptually approach urban poverty as places which provide relatively cheap living spaces serving as possible access to the city, to its society and to its functions – so called Arrival Cities. Based on a systematic literature survey we select a sample of 44 Arrival Cities across the globe. Using very high resolution optical satellite data in combination with street view images and field work we derive level of detail-1 3D-building models for all study areas. We measure the spatial structure of these settlements by the spatial pattern (by three features – building density, building orientation and heterogeneity of the pattern) and the morphology of individual buildings (by two features – building size and height). We develop a morphologic settlement type index based on all five features allowing categorization of Arrival Cities. We find a large morphologic variety for built environments of the urban poor, from slum and slum-like structures to formal and planned structures. This variability is found on all continents, within countries and even within a single city. At the same time detected categories (such as slums) are found to have very similar physical features across the globe.

1. Introduction

"*We did not see a mountain full of houses, but rather a house the size of a mountain*" (UTT, 2016). This statement captures the overwhelming impression one gets of informal land occupation capitalizing every inch of urban space in cities across the globe. Organic, amorphous, complex, and dense seas of makeshift shelters have significantly different physical appearances than formal, planned parts in cities (e.g. Fig. 1). 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). While a first superficial observation may suggest forms of living at the lower end of urban societies feature great similarities in terms of their physical appearance, (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).

Settlements of the urban poor are by no means a homogeneous physical phenomenon (e.g. Schneider-Sliwa & Bhatt, 2008; Taubenböck & Kraff, 2015). Nevertheless, most studies describing the physical appearance of such areas are of qualitative nature observing e.g. high building densities or organic patterns as characteristic (e.g. Davis, 2007; Glaeser, 2010); however, relatively little systematic quantitative, spatial research exists about their explicit physical appearance (Hofmann, 2001; Kuffer, Pfeffer & Sliuzas, 2016), not to mention a systematic inventory of morphologic types across the globe.

In this paper, we aim at reducing these knowledge gaps about settlements of the urban poor by an empirical baseline study taking stock of physical building types and determining structural patterns across the globe. Avoiding terminological imprecision and related conceptual restrictions of terms such as 'slum' or 'informal settlement', we base this study on the term '*Arrival City*' (introduced by Saunders, 2010). The term conceptually 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 allows a broader perspective on the specific places and their built morphologies.

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Fig. 1. The morphologic appearances of informal versus formal settlements for the example of Kibera, Nairobi; Top: Photography of Kibera: © Johnny Miller/Thomson Reuters Foundation; Bottom: High resolution optical satellite imagery © Google Earth.

Arrival Cities show a large variety of built forms. Earth observation (EO) data are the crucial data source to consistently capture built environments. However, due to conceptual imprecision of the target class, due to challenges for image classifications algorithms in these complex environments and due to unavailability or high costs of appropriate EO-data, spatial data on the level of individual buildings (level of detail-1 (LoD-1)) for the neglected parts of cities are mostly inconsistent, generalized or simply inexistent. The purposeful development of classification algorithms for mapping living environments of the urban poor from EO-data demands for empirical knowledge on the morphologies of the respective target class.

In this paper, we find 44 Arrival Cities by an extensive literature survey. They function as representatives for built environments of urban poor across the globe. For these samples, we produce three-dimensional (3D) building models in LoD-1 using a combination of high resolution satellite data as well as auxiliary data sources (such as geotagged photos or in-situ surveys). Based on these 3D-building models we introduce a method for classification of physical built-up categories of Arrival Cities. Methodologically we extend established approaches on the measurement of patterns of the built environment from EO data (based on Taubenböck & Kraff, 2014). In consequence, this study relies on a data set which has been produced in a consistent and comparable way, allowing a single methodological logic and is thus unbiased from possible inconsistencies that usually occur, if multiple input data across countries are applied. With it, we aim to add to the current body of literature for a better empirical documentation of the settlement morphologies of Arrival Cities.

Specifically, we aim to answer the following research questions: (1) Which physical morphologic settlement categories of Arrival Cities can be distinguished? (2) Which similarities and differences between building morphologies of Arrival Cities exist within a city, a country or a continent?

The remainder of the work is structured as follows: Section 2 briefly presents the relevance of this topic on the political development agenda and reviews the state of the art from an urban remote sensing perspective. Section 3 introduces the 'Arrival City' as conceptual framework for using a physical approach towards classifying and characterizing morphologies of the urban poor. Section 4 presents the methodology of the literature survey, the selection process of representative Arrival Cities, the classification of 3D building models, and finally the analysis of spatial patterns and their categorization. In section 5 the results on the measured spectrum of morphologies in Arrival Cites and the resulting categories are presented. This is followed by a discussion in section 6, where we also try to evaluate which influence determinants such as the topographic situation or pre-existing patterns have on urban morphology. Section 7 concludes with a perspective.

2. Background and state of the art

The intergovernmental agreement on the *Sustainable Development Goals (SDGs)* acts as the post 2015 Development Agenda (successor to the Millennium Development Goals) (UN, 2015). To end poverty, ensure healthy lives, provide access to quality education, water and sanitation, to build sustainable cities and communities, among others are goals directly relating to challenges for the urban poor. 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).

2.1. Approaches towards assessment of the urban poor

A number of statistics underpin the urgent need for more extensive empirical knowledge on the places of the urban poor. 25% of the global urban population (which is almost 1 billion people) live in slums or informal settlements (UN-Habitat, 2015). The builders of informal housing have become the largest builders of housing in the world (Tiwari, 2007), and thus, they are creating the cities of tomorrow. Davis (2007) estimates 200,000 slums globally, not to mention the unknown higher quantity of Arrival Cities. These often neglected parts of the city are of crucial importance due to their arrival functions providing access to the labour markets, education, etc. In Mumbai, for example, 65% of the workforce is employed in the informal sector (Sudjic, 2010) or in Mexico City 60% of construction is informally done (Burdett & Sudjic, 2007).

Although we observe an increasing quantity and variety of publications on this topic of urban poverty, these still lack consistent conceptual understandings across or even within disciplines, agreed methods of measurement or empirical data necessary. This leads to, as Satterthwaite (2003) proclaimed "*there is no lack of nonsense statistics on levels of urban poverty*", or the general statement in the World Migration Report (2015) that we have a massive lack of basic data about urban poverty.

From a spatial point of view, the coverage of data on areas of the urban poor varies significantly across the globe; especially in the Global South large data gaps exist. In consequence, a systematic quantitative spatial documentation of morphologic forms is absent. With the recent massive increasing availability of EO sensors, remote sensing data have become crucial for spatially capturing urban inequality. Freed from any administrative boundaries, the data are consistent and (in theory as e.g. data costs are still a restriction) available globally. Nevertheless, with only 87 key publications identified to date in the field of remote sensing (Kuffer, Pfeffer & Sliuzas, 2016), we are still far away from a global inventory of Arrival Cities or a systematic classification of physical characteristics of these places. However, we must be aware that using the morphologic structures as proxy for identifying the social group of the urban poor is simplifying the spatial and social complexity (e.g. Wurm & Taubenböck, 2018). In consequence, the remote sensing community conceptualizes poverty by features describing the morphologic urban appearance (Sliuzas et al., 2008). In a generic slum ontology indicators are conceptualized allowing a localization of settlements of the urban poor from EO-data (Kohli, Sliuzas, Kerle, & Stein, 2012). However, as slums are a relative concept (Gilbert, 2007), a physical approach to mapping these areas still lacks an internationally agreed concept as well as systematic empirical documentation. As a result studies using remote sensing data still lead to incomparable data sets across studies and study sites due to conceptual differences and the relativity of the target classes.

2.2. Mapping the urban poor with EO-data

From a remote sensing perspective, recent work predominantly focused on the development of methodologies for automatic classification of slum areas. Based on morphologic assumptions defining these areas of the urban poor, considerable methodological development has been achieved to automatically classify locations and extents of slums from optical (e.g. Hofmann, Strobl, Blaschke, & Kux, 2008; Kuffer & Barros, 2011; Kuffer, Pfeffer, Sliuzas, & Baud, 2016; Shekhar, 2012) as well as radar (e.g. Stasolla & Gamba, 2008; Wurm, Taubenböck, Weigand, & Schmitt, 2017) data. The developed approaches rely on physical features characterizing the built environment by indicators such as high heterogeneity in building alignments (e.g. Jain, 2007; Owen & Wong, 2013), irregular street networks (e.g. Gueguen, 2014; Niebergall, Loew, & Mauser, 2008), small building sizes (e.g. Baud, Kuffer, Pfeffer, Sliuzas, & Karuppannan, 2010; Graesser et al., 2012) or high building densities (e.g. Kit, Lüdeke, & Reckien, 2012; Taubenböck & Kraff, 2014) to differentiate these housing areas from formal ones. Studies use spectral, spatial and textural features and combinations of them (e.g. Engstrom et al., 2015; Graesser et al., 2012; Kit & Lüdeke, 2013; Sandborn & Engstrom, 2016; Wurm, Weigand, Schmitt, Geiß, & Taubenböck, 2017) for operationalizing the observed built-up features by image features. In this regard, Kohli, Stein and Sliuzas (2016) present related uncertainties in image interpretation.

Beyond, the combination of remote sensing with other data sources for detecting (and characterizing) areas of the urban poor is an emerging research field. The interplay of EO-data with census information proves correlations of image features with socio-economic parameters of the areas (e.g. Duque, Patino, Ruiz, & Pardo-Pascual, 2015; Sandborn & Engstrom, 2016; Taubenböck et al., 2009). Wurm and Taubenböck (2018) prove that morphologic slums classified from EO-data allow the localization of urban poor with high accuracies; however, spatial differences between morphologic and census slums also reveal shortcomings of the physical approach towards completeness. Applications of EO-based morphologic slum classifications are e.g. the assessment of slum populations (Kit, Lüdeke & Reckien, 2013; Taubenböck & Wurm, 2015) or the combination with geotagged data from social media identifying most areas of urban poor being digital deserts (Klotz, Wurm, Zhu, & Taubenböck, 2017).

At the spatial level of 3D building models, studies documenting the built environment are very scarce. This is due to the complexity of slum morphologies in combination with the low availability of highest resolution (< 1 m) digital surface models. Few studies measure the mentioned physical features of slums in a quantitative sense and compare morphologies within (Taubenböck & Kraff, 2014) and across cities (Taubenböck & Kraff, 2015). Studies also acknowledge that even within one city, physical morphologies, roof appearances as well as types of slums vary significantly (Kuffer, Pfeffer, Sliuzas, Baud, & Maarseveen, 2017).

Summarizing, although remote sensing is a crucial data source for detecting and characterizing areas of the urban poor, significant knowledge gaps exist: 1) remote sensing reduces the social group of the urban poor to slum areas; 2) classification algorithms remain proof of concept for limited test sites failing to provide consistent large area (continental scale) classifications of slums with high accuracies; 3) documentation of the variability of morphologic forms of the urban poor at 3D city model resolutions remain scarce; and 4) an inventory of morphological types as conceptual foundation is inexistent due to data gaps. In this paper, we aim with our comprehensive empirical baseline study at reducing the data gaps regarding physical morphologic categories of Arrival cities across the globe and we aim at providing the knowledge for algorithm development capturing these areas in EO-data.

3. Conceptualization of this study – the Arrival City

The challenge of a global characterization of physical appearances of settlements titled ‘slum’, ‘informal’, ‘squatter’, ‘spontaneous’, ‘ghetto’, ‘illegal’ or ‘irregular’ or described by local names such as ‘favela’, ‘bidonville’, ‘township’ or ‘gecekondu’, among many others, starts with terminology and related conceptualizations. Given the attention in literature, one expects the evolution of a clear and consistent conceptualization and method of measurement; however, these terms do not base on a standard definition, they are conceptually neither distinct nor consistent (Ghani & Ranbur, 2015).

By comparing the often used terms *slum* versus *informal settlement,* the conceptual fuzziness becomes obvious. UN-Habitat (2003) defines slums by using qualitative measures based on the so called “shelter deprivation” indicators such as the lack of durable housing and tenure security, overcrowding, and limited access to clean water and acceptable sanitation. The definition of informal settlements differs (although the term is often applied synonymously; in consequence, this leads to an imprecise usage in literature): Informal settlements refer to those areas that developed through unauthorized occupation of land outside a legal, regulatory, planned and professional framework (e.g. Bähr & Mertins, 2002; Huchzermeyer & Karam, 2006). The consequence is that slums refer to highly precarious living conditions whereas informal settlements, in contrast, are not exclusive to these living conditions as the concept relates to the legal jurisdiction. Thus, informality may also refer to better quality of construction and living conditions. Other associated problems arise e.g. as slums are relative in their conceptual meaning: What is considered to be a slum in one country may be regarded as perfectly acceptable accommodation in another (Gilbert, 2007). In consequence, slums cannot be defined safely (or measured in absolute terms) in any universally acceptable way; in the case of informal settlements, their genesis may have occurred outside formal means, but over time got formalized (e.g. by slum upgrading programmes) making it difficult for unambiguous classification. Ambiguity on these areas relates to the common understanding that informal (and also formal) forms of settlements rarely occur in any pure form; hybrid conditions (e.g. complex compositions of organic building layouts interwoven with structured planned forms) are the norm (Werthmann & Bridger, 2016).

Against these issues on terminology and related conceptual complexity, we base this study on the term and concept of the *‘Arrival City’*. The term has been introduced by Saunders (2010), capturing places with the main function of arrival to the city. Semantically the term 'arrival' refers to the relocation of rural populations to urban environments. However, conceptually the term is not just meant as a sole physical arrival functioning as a mere place for living and working; it is most importantly meant as a place of comparatively cheap living conditions that opens up the possibility to become part of the urban society. In consequence, this concept integrates all places which provide low-cost access to ‘arrival functions’ (living, working, education, cultural, etc.) in cities, which morphologically span from spontaneous, precarious shacks built overnight to squatting of informal or formal land and/or structures, to (once respectable) housing affected by deterioration. The concept of the Arrival City is thus embracing the conceptual differences of the other mentioned terms.

But why is this concept of the Arrival City necessary for this study? The literature survey (cf. section 4.1.; appendix 1) 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, as mentioned above, 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.

With this umbrella concept of the Arrival City we overcome these issues and aim at the following specific aims: 1) with the increasing availability of EO data, this data source recently became essential for classification of these areas. However, with respect to the conceptual ambiguity, the capability to measure inequality in cities from space by a spatial approach needs a systematic catalogue of morphological forms. Thus, we aim to bring clarity to the variability of morphological types of Arrival Cities. 2) The existing different concepts lead to incomparable data across nations or continents. With the morphological catalogue, we aim at a distinct conceptual framework; in terms of remote sensing, this aims at baseline information for algorithm development by morphologically defined target classes.

4. Data and methodology

This section is structured into two parts: The *first part* (4.1.) introduces the strategy of study sites selection aiming at a representative global sample of Arrival Cities. The *second part* (4.2.) introduces the spatial concept for classification of physical appearances of the settlement structures, the quantitative spatial analysis of the morphologic patterns and the categorization strategy.

4.1. Literature survey and selection of study sites

A comprehensive global knowledge repository about Arrival Cities to draw from does not exist. Beyond, an exhaustive compilation of the entire variability of the physical appearances of settlements is, at a resolution of individual buildings, still an utopia. Reasons are that informal settlements are mostly absent in official plans, not all existing physical types of informality have been reported or systematized and more generally, availability of adequate highest resolution geodata

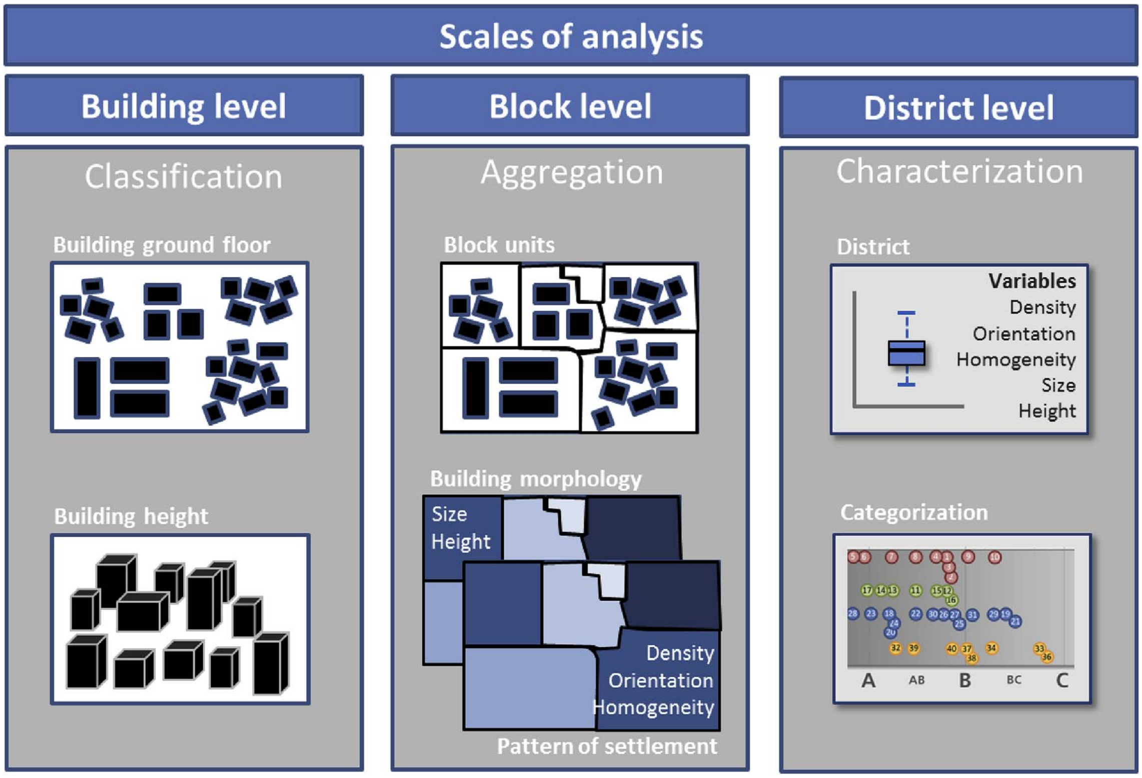

Fig. 2. Hierarchical structure of spatial scales – building, block and district level – for the morphologic settlement analysis and the workflow for calculating the five structural variables and the final categorization of Arrival Cities.

especially in slum-like structures is still scarce. This means a high uncertainty on amount, spatial distribution and types of Arrival Cities exists. In consequence, we conduct a systematic literature survey to compile a large variety of documented Arrival Cities across the globe to provide a representative sample.

For the systematic search we use general search terms such as 'arrival city', 'informal settlement', 'slum', 'squatter', 'shanty town' and 'ghetto' as well as synonyms in the respective local context such as 'favela', 'gecekondu', among many others. Our search relies on common search engines such as scopus or google scholar (cf. all criterions applied for the systematic search are presented in Table A-2 in the appendix). Yet, not any documented and identified Arrival City in literature is intended to be listed; instead we aim at selecting representative study sites by reason of different attributes:

(a) we select Arrival Cities documented in literature
(b) we select Arrival Cities from different cultural areas and continents for a representative global geographic distribution.

A main challenge arises from the necessity for 3D building models for a structural spatial analysis (cp. spatial concept in 4.2.). The selection process therefore is guided by the limitation that every selected Arrival City needs an extensive classification based on available very high resolution (VHR) EO-data. Based on these considerations we choose Arrival Cities for a quantitative spatial analysis by reason of the following attributes:

c) we select Arrival Cities consisting of a spatial extent formed by a significant group of buildings (> 1000), not by one individual or few buildings.
d) we select a generally even distribution of Arrival Cities in different topographic locations; this allows specific analytic questions whether the physical appearance shows differences due to topography.
e) we select for few examples more than one Arrival City within one city; this allows specific analytical questions whether the physical appearance reveals intra-urban differences.
f) we select Arrival Cities originating from time periods between 2010 and 2016.

In the literature survey many morphologic forms of Arrival Cities are identified which do not fit into our spatial concept; e.g. these are areas with untypical spatial extents that dissent to a significant amount of buildings or there are forms that are less conform to 'settlements' with regard to accommodation. For a more comprehensive picture we additionally provide a qualitative description of these morphologies for a more comprehensive presentative of physical forms of living.

4.2. Classification and characterization of settlement morphologies

What defines the appearance of a settlement? And how can it be measured and characterized? In general, *types and conditions of individual buildings* as well as the *spatial alignment of these buildings* define the urban spatial structure. In consequence, we aim at measuring the appearance of a settlement by the spatial *pattern* buildings create (1) and the (building) *morphology* (2):

(1) For characterizing spatial patterns of settlements we apply three features: *building density* (in 2D), *orientation of buildings* and *heterogeneity index* (relating to the variance of density within the area of interest).
(2) For characterizing the morphology of the individual buildings we use two features: *size* (ground floor) and *height* (number of stories). The condition of the building is disregarded here, as this parameter is difficult to assess using EO-data.

In the workflow we use three spatial *scales of analysis*, from the smallest to the largest: *Building level* (a), *block level* (b), *district level* (c) (Fig. 2).

a) **Building level**: The building level refers to the highest spatial detail – the individual buildings (Fig. 2). We derive the necessary high detailed geoinformation from very high resolution optical satellite data in combination with Google Street view information, georeferenced photos and partially in-situ observations. As structural complexity in Arrival Cities does mostly not allow for fully automatic delineation of individual building footprints with acceptable accuracies from EO-data, we derive the complex settlement structures using the cognitive perception of an experienced image analyst. Employing a standardized digitization protocol a consistent data base is derived at building level: Using EO-data having geometric resolutions of 1 m and better (e.g. QuickBird, WorldView) and a consistent scale of 1:1000 for image analysis, *each building is digitized and represented by a single polygon.* The polygons contain several vertices representing real shapes of ground floors even for more complex buildings than rectangle structures. We are aware that in certain areas the complexity of dense building patterns and respective roof structures is even outdrawing the visual capabilities to distinguish individual buildings in VHR optical EO-data; thus it might lead in certain cases to a generalized derivation of a polygon representing a mixture of houses instead of an individual unambiguous polygon per building. However, as Sliuzas et al., 2008 remark, the visual interpretation still offers the best capability for deriving these complex structures.

From the building classification, the individual *building sizes* and *orientations* are calculated. Beyond this, *building heights* (as number of floors) are attributed to every individual building. To do so, we incorporate in-situ information on building heights from field surveys (done for the samples in Mumbai, Izmir, Istanbul, Sao Paulo, Athens, Bucharest, Berlin, Nairobi and Cape Town), we employ spectral and spatial characteristics in VHR EO-data (we use estimations by the interpreter such as shadows or building patterns allowing an assessment of building height) and analyse georeferenced photos in online platforms such as GoogleEarth or, if available, Google Street view information (where we count the number of floors). In a previous study the building heights assessed using this approach resulted in an accuracy of 91,9% (Taubenböck & Kraff, 2014). Based on the parameters building sizes and heights we achieve 3-D city models in level of detail 1 (LoD1). All variables measuring the appearance of settlements relate to these 3D city models.

b) **Block Level**: The city block is a spatial entity combining the individual elements (buildings) into spatial aggregates aiming to capture spatial patterns of the settlements on a meso scale (Fig. 2). To do so, the close meshed street network is used to define city blocks; or, if in organic (informal) settlement structures streets are absent, visually identifiable pathways or obvious structural changeovers are introduced manually for the sub-division of space. As example, if a dense settlement area turns abruptly into an open space without a street as separating line, we introduce one to provide spatial entities capturing high and low density without mixed areas with blurring effects. In general, the city blocks are spatially subdividing the district level.

At this block level, we calculate five features to spatially measure the built environment of a settlement: we calculate the *building density* as the ratio between the sums of all cumulated building ground floors to the respective block unit area (eq. (1)).

$$B_d = \frac{\sum_{n=1}^{n_{R_u}} \mathrm{BF_n}}{\mathrm{A}_{\mathrm{R_u}}} \tag{1}$$

A = area; $\mathrm{B_d}$ = building density; BF = extent of building footprint; $\mathrm{R_u}$ = reference unit; n = number of buildings;

We derive the *orientation of buildings* as proxy for measuring the complexity of the alignment of buildings. We assume unplanned areas are by nature more irregular than planned. To do so, we calculate the individual orientation of each building h using the longitudinal side. Subsequently, the nearest spatial neighbor of each building is detected and the difference in main orientation ΔO is calculated as difference in angular degree (eq. (2)).

$$\Delta O^{bh} = O^{bh} - O^{N(bh)} | b = 1, \ \ldots, \mathrm{B}; \ \mathrm{h} = 1, \ \ldots, \mathrm{H^b}; \ 0^{\circ} \le |O^{bh}| \le 90^{\circ} \tag{2}$$

where B is the total number of building blocks, H^b is the number of buildings per block b, O^{bh} is the orientation to geographic north and N (bh) describes the one nearest neighbor of each building within the block.

We assume a geometric order of building pairs if orientation differences are close to 0 or 90°. In contrary, we assume complex alignments closer to orientation differences of 45°. We convert this into a continuous index I^{bh} of orientation complexity ranging from 0 (= geometric) to 1 (= highest degree of geometric chaos) for every building pair (eq. (3)).

$$I^{bh} = -\left|\Delta O^{bh} - 45\right| \times \frac{1}{45} + 1 \tag{3}$$

We aggregate all individual index values of building pairs to determine the median alignment index for the respective blocks (eq. (4)).

$$I^b = med\{\mathrm{I^{bh}} | \mathrm{h} = 1, \ldots, \mathrm{H^b}\} | b = 1, \ldots., \mathrm{B} \tag{4}$$

where H^b is the number of buildings in the block b.

As third feature, we measure the morphologic heterogeneity of the pattern over space. The *heterogeneity index* I_h quantifies differences in building densities of a block with all adjacent neighboring blocks. Therefore, absolute building density differences from a center block to all adjacent neighboring blocks are calculated. The individual density differences are added in absolute values (as the subtraction of density values of the center block with the density value of an adjacent block may result either in a positive or a negative value). The respective quantity of norm changes is noted also. This sum of norm differences gets divided by the quantity of neighboring blocks for normalization leading to a nondimensional number. The number of norm changes will be multiplied with the sum of building density differences; if a block has no norm changes, it will always be added to 1. With increasing differences of density values in adjacent blocks, the index indicates a higher heterogeneity of a pattern (eq. (5)) (for more details see also Taubenböck & Kraff, 2014).

$$I_h = \left(\frac{\sum_{i=1}^{k} |\mathrm{bd_c} - \mathrm{bd_i}|}{\mathrm{k}}\right) * NC \tag{5}$$

$\mathrm{I_h}$ = heterogeneity index; k = quantity of adjacent neighboring blocks; $\mathrm{bd_c}$ = built-up density value of the center block; bd = built-up density value of an adjacent block, NC = quantity of norm changes.

As fourth feature, we calculate the *building sizes* as the average of all building ground floors in the respective block unit area (eq. (6)).

$$B_s = \frac{\sum_{n=1}^{n_{R_u}} \mathrm{BF_n}}{\mathrm{n_{R_u}}} \tag{6}$$

$\mathrm{B_s}$ = average building size.

And, as fifth feature, we calculate the *building heights* as the average of all building floors within the respective block unit area (eq. (7)).

$$BA_h = \frac{\sum_{n=1}^{n_{R_u}} \mathrm{B_{h_n}}}{\mathrm{n_{R_u}}} \tag{7}$$

$\mathrm{B_h}$ = building height; $\mathrm{BA_h}$ = average building height.

c) **District level**: As main spatial level of analysis we employ the *district level* (Fig. 2). The district level represents the entire area of one Arrival City (or at least for the parts where geoinformation have been derived). This unit functions as one, consistent spatial level for the aggregated morphologic settlement analysis. Here, the variability of the five features at block level are presented by providing the median (for building heights we apply the mean, as the limited number of classes and the often dominant low building heights do not allow for a precise differentiation using the median) and the data distributions are presented in box plots.

4.3. Categorization of settlement morphologies

For the categorization of the measured settlement morphologies we quantify deviations from measured spatial features against an expected (model) value. The expected (model) value represents the measured maxima per feature across all Arrival Cities. For every one of the five spatial features we state a hypothesis. We let ourselves guide from the common usages in literature for a subtype of Arrival Cities – morphologic slums – which we assume to have patterns of highest morphologic complexity:

1) We expect high building densities 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.
2) We expect non-geometric, irregular orientations of buildings as planning regulations are absent, regular street pattern not given, individual decision form random lay-outs, and –in certain cases– adjustments to complex topographic situations may lead to non-regular lay-outs.
3) We expect high structural homogeneity of the building patterns as full utilization of space is targeted as space is limited.
4) We expect shelters of small sizes as available land is limited and precious, population pressure is high and financial capabilities of the dwellers are low.
5) We expect low building heights as financial capabilities of the dwellers are low and building materials are limited.

The virtual combination of measured maxima per feature generates a *theoretical ideal type morphologic slum.* This virtual combination is, of course, not existent in reality as the maxima per feature result from different Arrival Cities; however, it marks the virtual end of measured real-world structures for calibration in the analysis.

We categorize a *morphologic settlement type index value* I_m as deviation from the theoretical ideal type morphologic slum. To do so, we find maximum and minimum values per feature of the calculated medians (mean for building heights). By minimum-maximum normalization [0, 1] (eq. (8)), we adjust heterogeneous values measured to a notionally common scale per variable.

$$x' := (x - x_{\min})/(x_{\max} - x_{\min}) \tag{8}$$

$x_{\min}$ is the minimal median value per feature; $x_{\max}$ is the maximum median value per feature.

The I_m results from the cumulative deviation from the *theoretical ideal type morphologic slum* (eq. (9)).

$$\mathrm{I_m} = x'(\mathrm{d}) + x'(\mathrm{o}) + (1 - x'(\mathrm{h_i})) + (1 - x'(\mathrm{s})) + (1 - x'(\mathrm{h})) \tag{9}$$

$\mathrm{I_m}$ is the morphologic index, d = density; o = orientation; $\mathrm{h_i}$ = heterogeneity index; s = building size; h = building height.

With it, the measured physical appearances of Arrival Cities can be classified along a continuous scale for categorization. However, as auxiliary means for semantic description we apply discrete categories using equal distances among groups.

Beyond, we classify additional categories by descriptive analysis for the Arrival Cities identified in the literature survey, but not fulfilling the spatial concept of analysis.

5. Results

This section is organized as follows: *First,* the selected Arrival Cities used for the spatial analysis of settlements are presented and related background information from the literature survey is provided (5.1.). *Second*, the physical characteristics of the selected Arrival Cities are presented (5.2.). *Third*, we introduce the categorization of the Arrival Cities (5.3.). In this part we relate the categories to different location based observations, i.e. whether categories have obvious similarities within one city or country. *Fourth*, we present other types of Arrival Cities which do not fit into the spatial concept of analysis but are relevant forms (5.4.).

5.1. Global representatives for Arrival Cities

Based on the literature survey we select 44 Arrival Cities across the globe. With *10 Arrival Cities from Africa*, *9 from America*, *15 from Asia* and *10 from Europe*, a global distribution is realized. Within the continents a spatial distribution is carried out (e.g. for Asia we chose Arrival Cities from western (e.g. Turkey), central (e.g. Iran, India), and eastern parts (Mongolia, China, The Philippines)). Beyond, the sample also contains different Arrival Cities within the same country (e.g. for Brazil, China, France, Turkey and USA) as well as different Arrival Cities within sample cities (e.g. Cairo, Cape Town, Mumbai and Dhaka). Fig. 3 illustrates the spatial distribution of the selected samples and visualizes spatial appearances of selected settlement structures in very high resolution optical EO-data. It becomes obvious that building morphologies being the home of the urban poor feature a large variability.

In the appendix (Table A-1) comprehensive background information on all 44 selected Arrival Cities are introduced: locations, names, sizes of the areas of interest, the number of buildings classified from Earth observation data. Furthermore, the table gives systematic background information on the topographic situation, descriptive information on housing types and materials, access to infrastructure, legal status, if possible, and the estimated population. The reference from literature which defines the selected sample as Arrival City complements the table.

5.2. Physical characteristics of Arrival Cities

Under the conceptual umbrella of the *Arrival City* we unite terms such as slums, informal settlements and the like. These terms implicitly carry the idea of a uniform urban type including morphologic similarity. The reported physical appearances of these settlements are mostly of qualitative nature and do not allow for an objective, quantitative generalization. Other studies using EO-data take conceptually a certain morphologic similarity as a given basis.

In general, the classifications of Arrival Cities from EO-data presented in ground figure plans (Fig. 4) illustrate that morphologic similarity cannot be taken for granted. The visualized building ground floors and their patterns feature variabilities, but also similarities. We find that, as many descriptive studies suggested, high building densities, complex, organic patterns and small building sizes are features applying to many of the Arrival Cities. However, a closer inspection reveals that it is not as simple as that: We also find significant lower building densities, large building sizes, lay-outs with a geometric organization, in all kinds of combinations. As examples, we find in highly dense areas both, complex (e.g. number 06 in Fig. 4) and ordered (e.g. 13) alignments of buildings; we find large (e.g. 37) vs. small buildings (e.g. 31). We also find highest building densities (e.g. 05) vs. comparatively low densities (e.g. 44).

The visual inspection of the ground figure plans does not allow for a quantitative, resilient analysis of the building patterns and

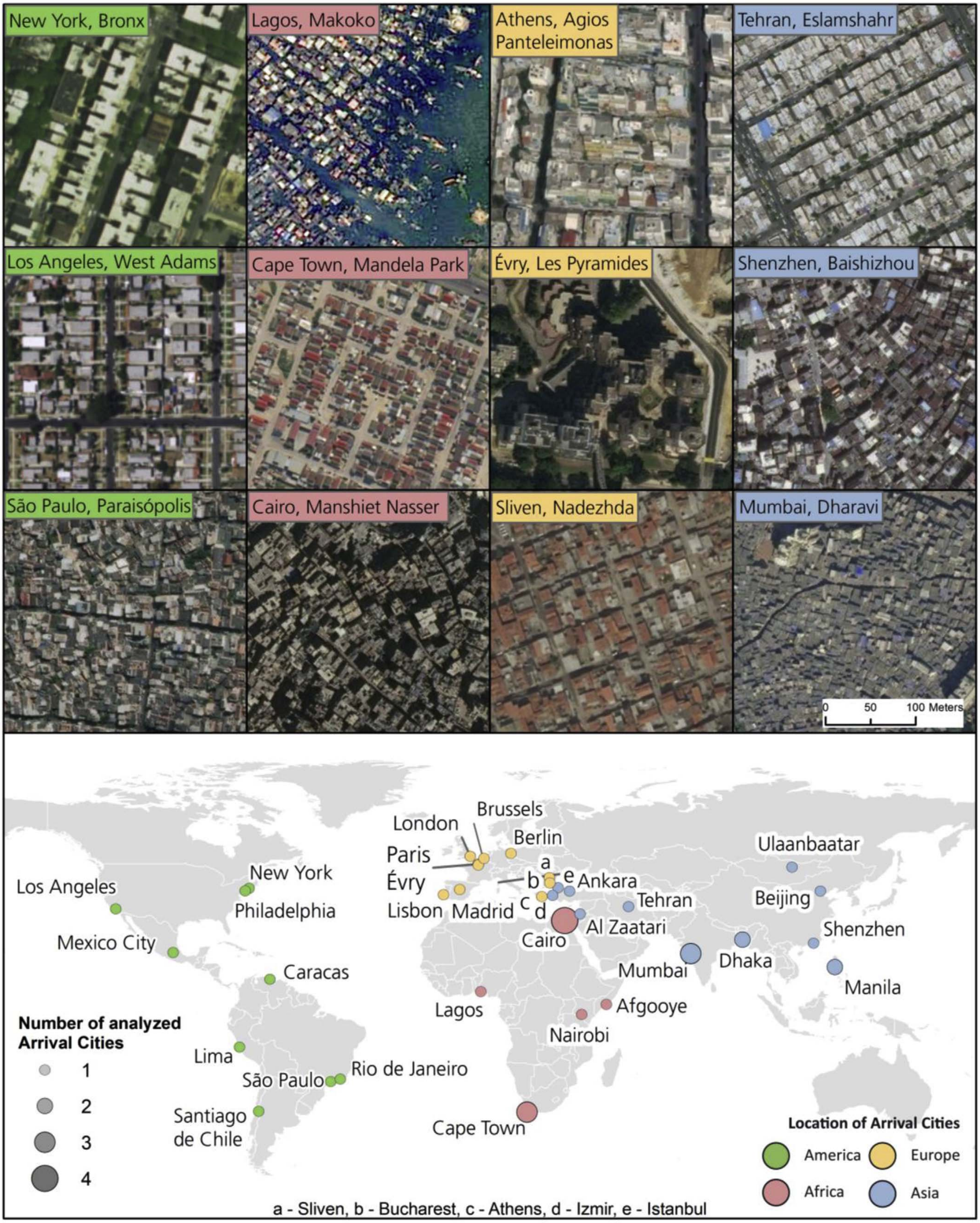

Fig. 3. Selected Arrival Cities across the globe from the literature survey and illustration of the appearance of different morphologic forms of the built environment in EO-data.

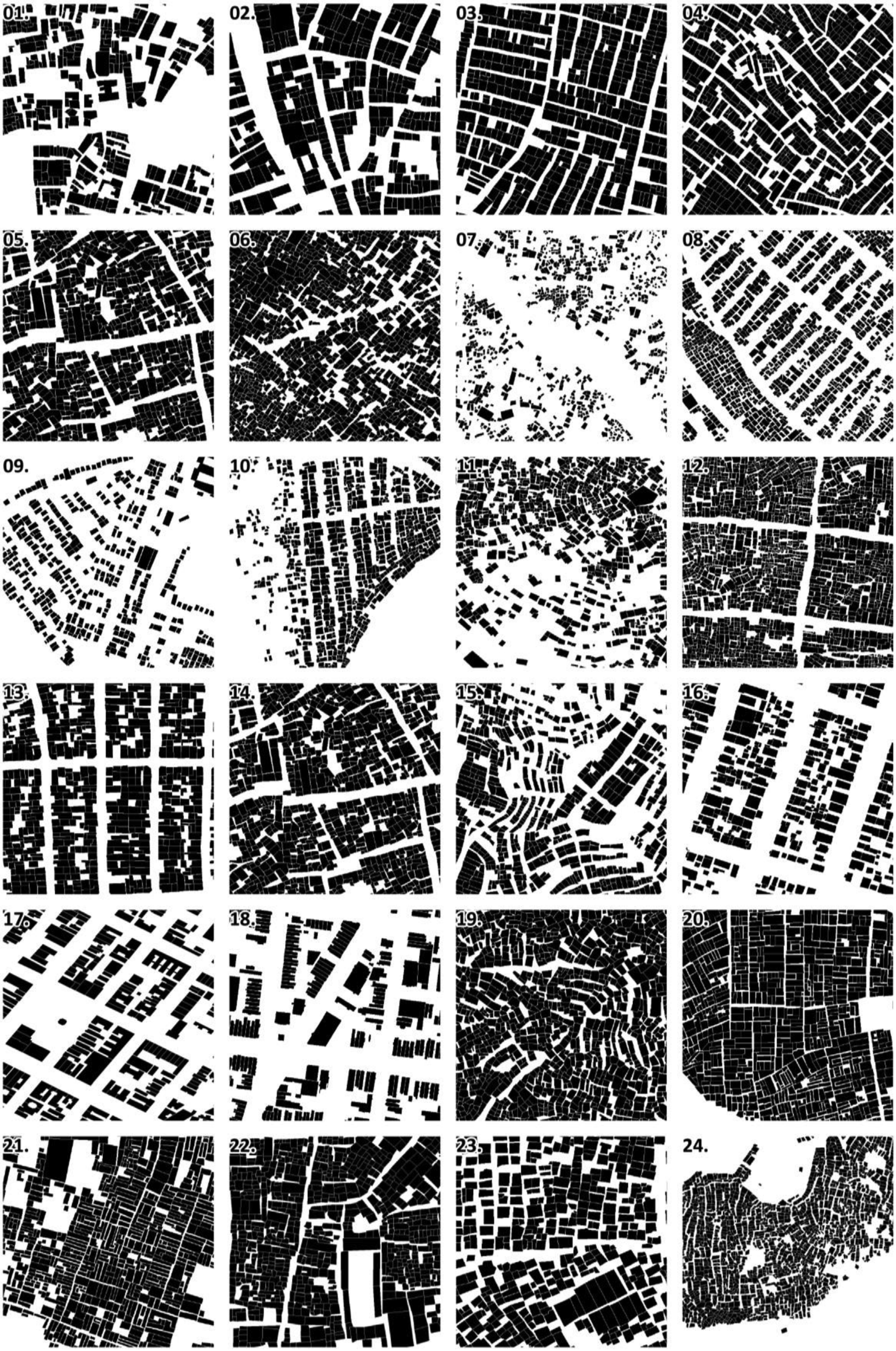

Fig. 4. Ground figure plans of the 44 selected Arrival Cities.

Regions in alphabetical order by continents, countries, cities and areas

Africa

01. Eldarb el-Ahmar, Cairo, Egypt
02. Ezbet el-Haggana, Cairo, Egypt
03. Imbaba, Cairo, Egypt
04. Manshiet Nasser, Cairo, Egypt
05. Kibera, Nairobi, Kenya
06. Makoko, Lagos, Nigeria
07. Lafoole Refugee Camps, Afgooye, Somalia
08. Griffiths Mxenge/Silver T., Khayelitsha, Cape Town, South Africa
09. Mandela Park, Khayelitsha, Cape Town, South Africa
10. Victoria Merge, Khayelitsha, Cape Town, South Africa

America

11. Turano, Rio de Janeiro, Brazil
12. Paraisópolis, São Paulo, Brazil
13. Lo Prado, Santiago de Chile, Chile
14. Magdalena Contreras, Mexico City, Mexico
15. Comas/Independencia, Lima, Peru
16. West Adams, Los Angeles, USA
17. Bronx, New York City, USA
18. North Philadelphia, Philadelphia, USA
19. Petare, Caracas, Venezuela

Asia

20. Islambag, Dhaka, Bangladesh
21. Kadamtali/Chunkutia, Dhaka, Bangladesh
22. Dashilanr/Chunshu/Liuxue Road Community, Beijing, China
23. Baishizhou, Shenzhen, China
24. Bharat Nagar, Mumbai, India
25. Dharavi, Mumbai, India
26. Santosh Nagar, Mumbai, India
27. Eslamshahr, Tehran, Iran
28. Refugee Camp, Al-Zataari, Jordan
29. Khoroo 9, Ulaanbaatar, Mongolia
30. North Cemetery, Manila, The Philippines
31. Tondo/San Nicolas, Manila, The Philippines
32. Karaağaç/Altıağaç, Ankara, Turkey
33. Gülsuyu-Gülensu, Istanbul, Turkey
34. Kadifekale, Izmir, Turkey

Europe

35. Molenbeek, Brussels, Belgium
36. Nadezhda, Sliven, Bulgaria
37. Tower Hamlets, London, England/UK
38. Belleville/Combat/La Banane, Paris, France
39. Le Pyramide, Évry, France
40. Kreuzberg, Berlin, Germany
41. Agios Panteleimonas, Athens, Greece
42. Cova da Moura, Lisbon, Portugal
43. Tei Toboc, Bucharest, Romania
44. Cañada Real Galiana, Madrid, Spain

Fig. 4. (*continued*)

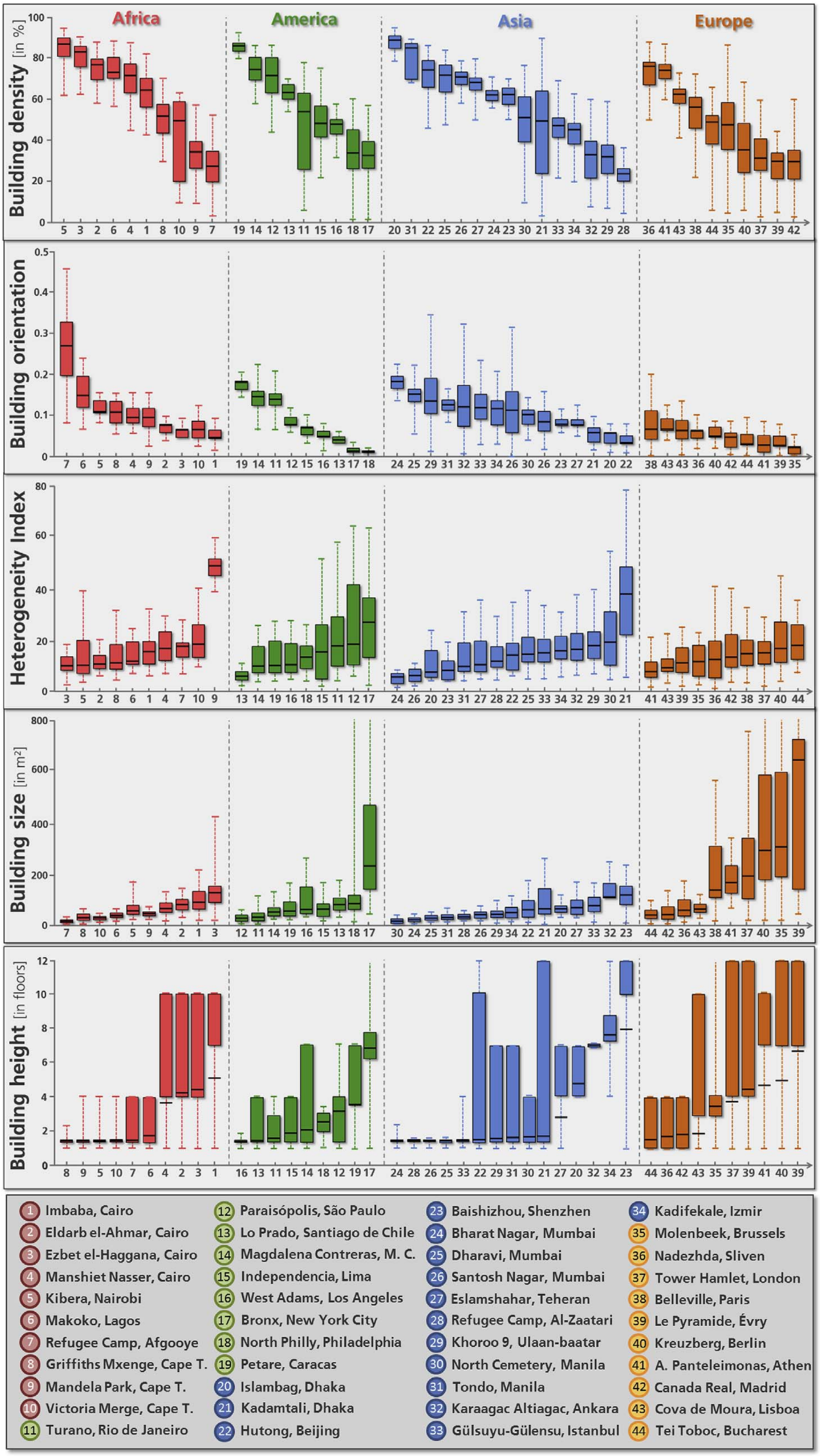

Fig. 5. Boxplots illustrating five variables defining urban morphologies for all 44 selected Arrival Cities.

morphologies. Fig. 5 presents and contrasts the five features defining these urban morphologies at block level– *building density*, *building orientation* and *heterogeneity index* representing the patterns and *building size* and *height* representing the building morphologies –in form of boxplots. The 44 Arrival Cities are grouped based on their continental location. Beyond, each variable is ordered in decreasing or respectively

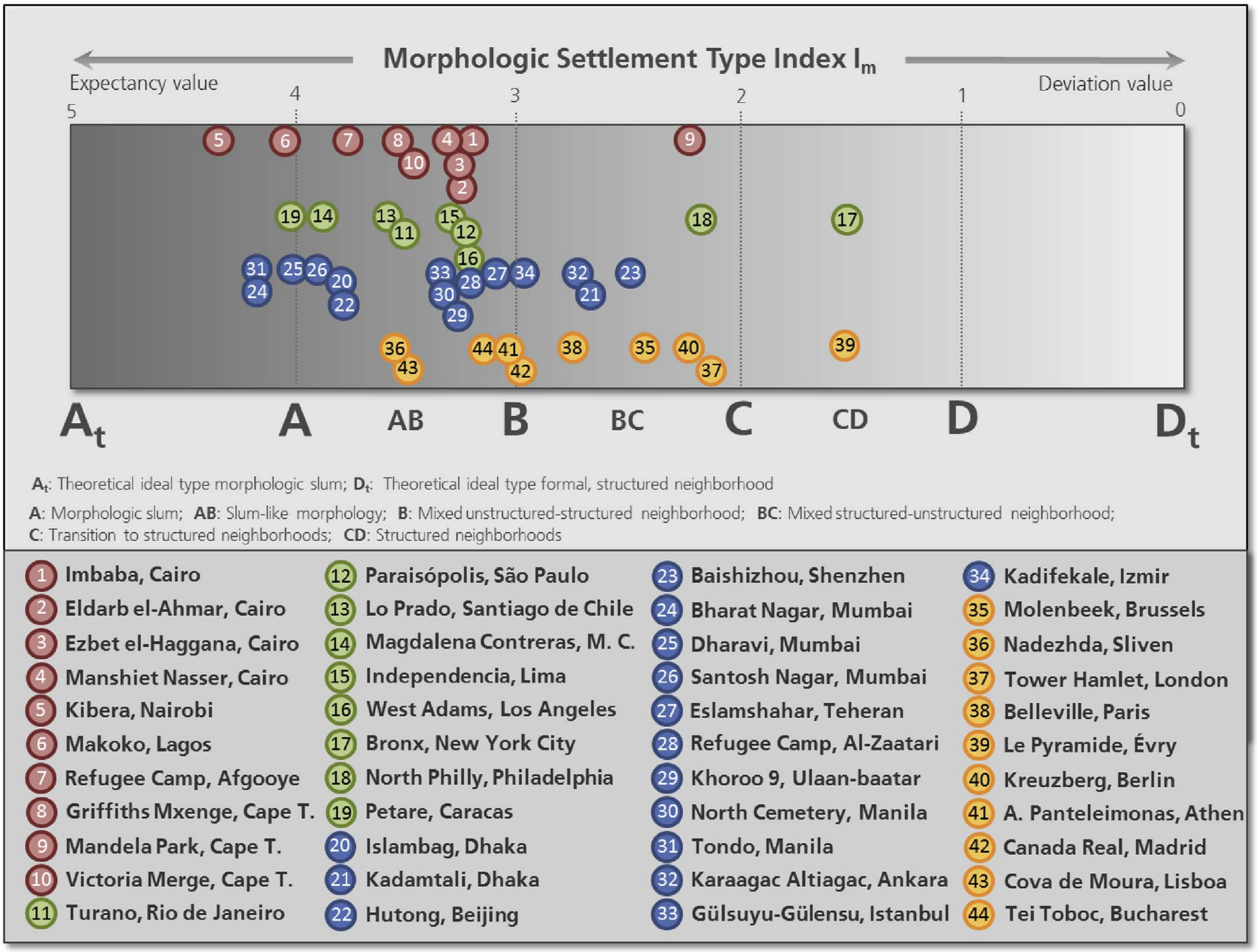

Fig. 6. Categorization based on the developed morphologic settlement type index value I_m for all 44 Arrival Cities.

increasing manner of the median (mean for building heights) for the particular feature.

In general, we find that a simplistic approach towards the morphology of the living areas of urban poor obscures reality. *On the one hand*, 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. *First*, we detect that a large variance within continents appears (e.g. we find on every continent Arrival Cities with building densities of 70% and more to below 40%). *Second*, we find large varieties of morphologic forms within one country (e.g. with building heights of 1.57 stores on average for Gülsuyu-Gülensu, Istanbul vs. 4.59 stores in Kadifekale, Izmir). *Third*, we find large varieties of morphologic forms within one city (e.g. building sizes of Eldarb el-Ahmar in Cairo are in median with 131 m^2 more than twice as large as the ones in Manshiet Nasser with 60.5 m^2). *On the other hand*, the boxplots also reveal that although these morphologically hybrid forms are identified, the stated hypothesis on typical morphologic features (cf. section 4.3) can be confirmed to a certain degree: *First*, we measure that 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%). This remarkable intense utilization of space can be benchmarked when we relate these values to other parts in cities. As examples, the medians of building densities are significantly lower in central areas of mega cities (e.g. in a circle of a 10 km radius around the center of London, UK the density is 30% or in Paris, France it is 34%). They are also significantly lower for planned cities (Chandigarh, India 35%; Lingang, China 24%), large housing estates (e.g. Neuperlach, Munich 18%; Gropiusstadt, Berlin 16%) or residential suburbs (e.g. Sun City, USA 24%, garden city Letchworth, UK 15%). Within our (incomplete) sample for comparison of building densities to Arrival Cities, historical European city centers reveal densities closest to Arrival Cities (Hamburg, Germany 46%; Dortmund, Germany 46%; Munich, Germany 52%). *Second*, we measure that the hypotheses for the heterogeneity index (29 Arrival Cities below the value of 15, which is comparatively homogeneous), the building sizes (half of the study sites have ground floors below 60 m^2) and heights (24 Arrival Cities are not higher than 2 floors in average) can largely be confirmed. In contrast, for the building orientation a clear trend towards complex alignments is not existent (12 Arrival Cities are below 0.2, what indicates a relatively regular orientation; 16 Arrival Cities feature values between 0.2 and 0.4, and 16 Arrival Cities are above the value 0.4).

5.3. Morphologic categorization of Arrival Cities

For the morphologic categorization of Arrival Cities we transfer the features into a common scale by the minimum-maximum normalization. The cumulative combination of all normalized variables results in the *morphologic settlement type index*. The index allows classification of the different Arrival Cities into morphologic categories.

As we base our categorization on relative deviation from the

Table 1
Morphologic categories of Arrival Cities.

Cat.	Terminology	Description	Samples & morphologic index
A_t	Theoretical ideal type morphologic slum	This theoretical morphology reflects the combination of the extrema per physical feature measured from the 44 samples across the globe.	Density: Islambagh, Dhaka (90.2%); orientation: Afgooye (0.27); heterogeneity index: Bharat Nagar, Mumbai (5.2); size: north cemetery, Manila (7.7 m^2); height, West Adams, L.A. (1.5 floors); (**morphologic index** = **5.0**).
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 in literature. Small makeshift shelters are huddled together in most complex alignments.	Kibera, Nairobi (**4.36**); Bharat Nagar, Mumbai (**4.19**); Tondo, Manila (**4.19**); Makoko, Lagos (**4.08**); Petare, Caracas (**4.03**); Dharavi, Mumbai (**4.01**); Santosh Nagar, Mumbai (**3.95**); Magdalena Contreras, Mexico City (**3.93**); Islambagh, Dhaka (**3.82**); Hutong, Beijing (**3.81**); Afgooye (**3.78**);
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.	Lo Prado, Santiago de Chile (**3.62**); Griffiths Mxenge, Cape Town (**3.60**); Nadezhda, Sliven (**3.58**); Turano, Rio de Janeiro (**3.56**); Cova de Moura, Lisboa (**3.50**); Victoria Merge, Cape Town (**3.50**); Gülsuyu-Gülensu, Istanbul (**3.43**); North Cemetery, Manila (**3.41**); Manshiet Nasser, Cairo (**3.39**); Independencia, Lima (**3.36**); Paraisópolis, Sao Paulo (**3.30**); Imbaba, Cairo (**3.30**); Khoroo 9, Ulan Bator (**3.30**); Refugee Camp, Al-Zataari (**3.30**); Ezbet el-Hagana, Cairo (**3.29**); West Adams, L. A. (**3.29**); Eldarb el Ahmar, Cairo (**3.25**);
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.	Tei Toboc, Bucharest (**3.25**); Eslamsahar, Teheran (**3.17**); Agios Panteleimonas, Athen (**3.07**); Canada Real, Madrid (**2.99**); Kadifekale, Izmir (**2.97**); Belleville, Paris (**2.80**); Karaagac-Altigagac, Ankara (**2.78**);
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	Kadamtali, Dhaka (**2.73**); Baishizhou, Shenzhen (**2.57**); Molenbeek, Brussels (**2,43**); Mandela Park, Cape Town (**2.32**); Kreuzberg, Berlin (**2.26**);
C	Transition to structured character of neighborhoods	The morphology combines typical features of planned, structured neighborhoods such as regular alignments or lower densities with few slum-like features.	North Philadelphia, Philadelphia (**2,17**); Tower Hamlets, London (**2.16**);
CD	Formal, structured neighborhoods	The morphology provides typical features of planned, formal, structured neighborhoods: low densities, geometric alignments, large and high buildings.	Le Pyramide, Évry (**1.53**). Bronx, New York City (**1.52**);
D_t	Theoretical ideal type formal, structured neighborhood	This theoretical morphology reflects the combination of the minima per physical feature measured from the 44 samples across the globe.	Density: Al-Zataari (24.3%); orientation: North Philadelphia, Philadelphia (0.00); heterogeneity index: Victoria Merge, Cape Town (50.8); size: Le Pyramide, Évry (685.9m^2); height: Baishizhou, Shenzhen (7.7 floors); (**morphologic index** = **1.0**).

assumptions we 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 (class A_t in Fig. 6). The maxima are Islambagh, Dhaka for building density (Median = 90.2%), the refugee camp Afgooye for building orientation (0.27), Bharat Nagar, Mumbai for the heterogeneity index (5.2), the north cemetery, Manila for building size (7.7 m^2) and West Adams, Los Angeles for building height (1.5 floors). The large range of morphologic categories becomes tangible when we compare these values with the ones measured with maximum deviation (class D_t in Fig. 6). This is the virtual combination of the refugee camp Al-Zataari for building density (Median = 24.3%), North Philadelphia, Philadelphia for building orientation (0.0), Khayelitsha (Victoria Merge), Cape Town for the heterogeneity index (50.8), Les Pyramide, Évry for building size (685.9 m^2) and Baishizhou, Shenzhen for building height (7.7 floors). They mark the unexpected virtual end of morphologic categories (cf. Table 1).

In general, we find 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. Referring to the first specific research questions stated in the introduction, we classify *three main categories* and *three respective transitional forms*. They stretch from *slum* (Cat. A; threshold > 3.75) and *slum-like* (Cat. AB; range 3.75–3.25) morphologies to *mixed unstructured-structured* neighborhoods (Cat. B; range 3.25–2.75) and *mixed structured-unstructured* neighborhoods (Cat. BC; range 2.75–2.25) even to *structured* (Cat. C; range 2.25–1.75) and *formally planned* (Cat. CD; range 1.75–1.25) areas. In general, the applied continuous scale allows an unambiguous assessment of the morphologic conditions. However, for a more general description and nomenclature we use the mentioned thresholds of equal-distance. Table 1 introduces the categories, describes the measured physical features and lists samples and the resulting morphologic settlement type index values.

Regarding the second specific research question stated in the introduction we find similarities and differences between building morphologies of Arrival Cities: Within *a single city* we find that places of urban poor do not necessarily reflect similar morphologies. In Cape Town the morphologic differences reach from the (informal) slum-like structures of Griffiths Mxenge (Cat. AB; I_m of 3.60) to the planned township of Mandela Park (Cat. C; I_m of 2.32); in Dhaka they reach from mature downtown slums where continuously re-densification processes occurred over time (Islambagh, Cat. A; I_m of 3.82) to more recent, more peripheral informal developments where full utilization of space still lies ahead (Kadamtali; Cat. BC; I_m of 2.73). However, we also observe at the same time that structures of the same category are reproduced in very similar manner within one city (e.g. in Cape Town the areas of Griffiths Mxenge and Victoria Merge are both Cat. AB with I_m of 3.60 and 3.50; or in Cairo all four Arrival Cities are classified as Cat. AB).

Logically, also within *a single country* places of urban poor do not necessarily reflect similar morphologies. In China the traditional Hutongs feature with slum morphologies (Cat. A; I_m of 3.81) significant morphologic differences to urban villages (Cat. BC; I_m of 2.57). In the USA we find significant morphologic differences between the low-rise infill housing in West Adams, L.A. (Cat. B, I_m of 3.29) vs. high rise ordered structures in the Bronx, New York City (Cat. CD; I_m of 1.52). However, we also observe that morphologies are reproduced in similar manner within one country (e.g. Turkey with Gülsuyu-Gülensu in Istanbul (Cat. AB; I_m of 3.43), Kadifekale in Izmir (Cat. B; I_m of 2.97) or Karaagac-Altigagac, Ankara (Cat. B; I_m of 2.78) or in Brazil with Turano in Rio de Janeiro (Cat. AB; I_m of 3.56) and Paraisópolis in Sao Paulo (Cat. B; I_m of 3.30)).

At *the continental level* Arrival Cities obviously feature a large variety of morphologies and we basically identify almost all categories at every continent. The category morphologic slums (Cat. A) is found typical for cities of the Global South: America (e.g. Petare, Caracas; I_m of 4.03), Africa (Kibera, Nairobi; I_m of 4.36) and Asia (e.g. Tondo, Manila; I_m of 4.19). Categories AB, B, BC generally are found to exist at every continent.

Fig. 7 exemplifies LoD-1 building models for different categories based on the developed morphologic index. From the high dense, low rise slum-like structures in Kibera Nairobi (Cat. A) to the structured high rise pattern in Évry (Cat. CD) the visualization aims to illustrate this morphological transition.

5.4. Forms of Arrival Cities not fulfilling the spatial concept of analysis

Beyond the identified three main and three transitional categories of building categories in Arrival Cities, we identified other physical appearances of Arrival Cities (or types of living conditions) 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 we present these forms in a descriptive way. Table 2 introduces *four further categories* (E-H) and lists examples.

6. Discussion and interpretation

When you walk through the city, one immediately senses the neighborhood. The physical appearance of the built environment plays a decisive role for its atmosphere – rich, poor, safe, unsafe, busy or sleepy. One particular part in cities – the so called Arrival City – fulfills a specific function: cheap living spaces for the poor to get access to urban functions. The common perception of these areas is very much connected to slums. While slums might be the most prominent example suggesting a globally uniform morphologic type, this study reveals and documents the large morphological variety of Arrival Cities (or places of the urban poor) which existed or exist across the globe. We acknowledge that the variability of physical manifestations of Arrival Cities is inexhaustible, and that their morphology is often highly dynamic, which is not captured comprehensively in this study either. Although we entered an age of a massive increase of (geo-)data, the highly resolved geoinformation (LoD1) necessary for the morphologic analysis of these places is still widely absent. A morphologic catalogue, an inventory, or even global maps of these places are inexistent and only very few examples have been documented in explicit, quantitative spatial manner at this geometric level (Kuffer, Pfeffer & Sliuzas, 2016). In consequence, taking stock of morphologic appearances conceptualized as Arrival City with 44 test sites across the globe in LoD1 functions as empirical baseline to reduce these knowledge gaps and approximate existing categories across the globe. However, as we refer to the selection of 44 Arrival Cities it is likely that our categorization of morphologic types using maxima and minima is biased by our samples and the analysis might need an adjustment if other Arrival Cities may feature more unexpected morphologic appearances.

6.1. Capabilities for mapping of Arrival Cities

Remote sensing functions here as crucial data source – as it is, compared to e.g. census data consistent, up-to-date and available across the globe – and it has the capability to spatially capture certain locations of the urban poor based on the assumption of morphologic correlation. This study enlarges empirical knowledge on the morphological characteristics of Arrival Cities and presents a catalogue of measured structural categories. We acknowledge that measurement of spatial structures and patterns is complex and calculation methods, spatial units of analysis or thematic dimensions have significant influence (Taubenböck, Standfuß, Klotz, & Wurm, 2016). However, we rely on the block units suggested in literature for capturing the features of individual building structures. Beyond, we are in line with the structural features from the ontologies presented by Kohli et al. (2012) and Sliuzas et al. (2008). In consequence, we assume the physical appearance is measured in a transparent and reproducible way. Using these features we detect three main morphological categories and three respective transitional forms as well as four categories not fitting into the presented spatial concept. This result of seven main categories and three transitional classes reveals the morphologic complexity and variety of such places.

In a way, this also reflects current challenges regarding conceptual complexity and inconsistent usages of various terms in literature (slum, informal settlement, ghettos, etc.) aiming at urban poor. This leads to imprecise target classes and varying measurement methods. And, it consequently is intrinsically leading to incomparable data and biased conclusions. The morphological perspective taken here is, naturally, only one part of a comprehensive understanding of such areas; however, with the adopted umbrella concept of the Arrival City a distinct catalogue of morphological categories allows systematic documentation of such places. With this approach, we are not targeting a pre-defined class which is conceptually fuzzy, internationally not agreed, or ambiguously defined; rather, this allows finding distinct morphological types without restrictions by conceptual ambiguity, legal status, or such.

The measured large morphological variety reveals that we have to accept that solely remote sensing as single discipline is not capable for a global classification of Arrival Cities and related urban poverty in a complete and unambiguous way. Some forms of the measured morphology do not differ sufficiently to other physical appearances within the urban built landscape (e.g. Categories C and CD). In consequence, it is legitimate to reduce EO-based applications to capturing urban poverty to the categories 'morphologic slums' (Cat. A) and 'slum-like morphologies' (Cat. AB), as these are morphologically the most significant categories found anywhere across the globe. This is confirmed as it has been shown that these reflect the social group of urban poor with high correlations (e.g. Sandborn & Engstrom, 2016; Wurm & Taubenböck, 2018). However, the categories B and BC, although containing characteristic morphologic features of Arrival Cities, reflect hybrid forms. This means they contain significant deviations from the stated morphologic assumptions and, in addition, their relative morphological differences to other, surrounding morphological appearances often become more and more marginal. Naturally, the social groups residing there are also mixed. In consequence, a comprehensive detection of Arrival Cities, especially for the latter cases, needs

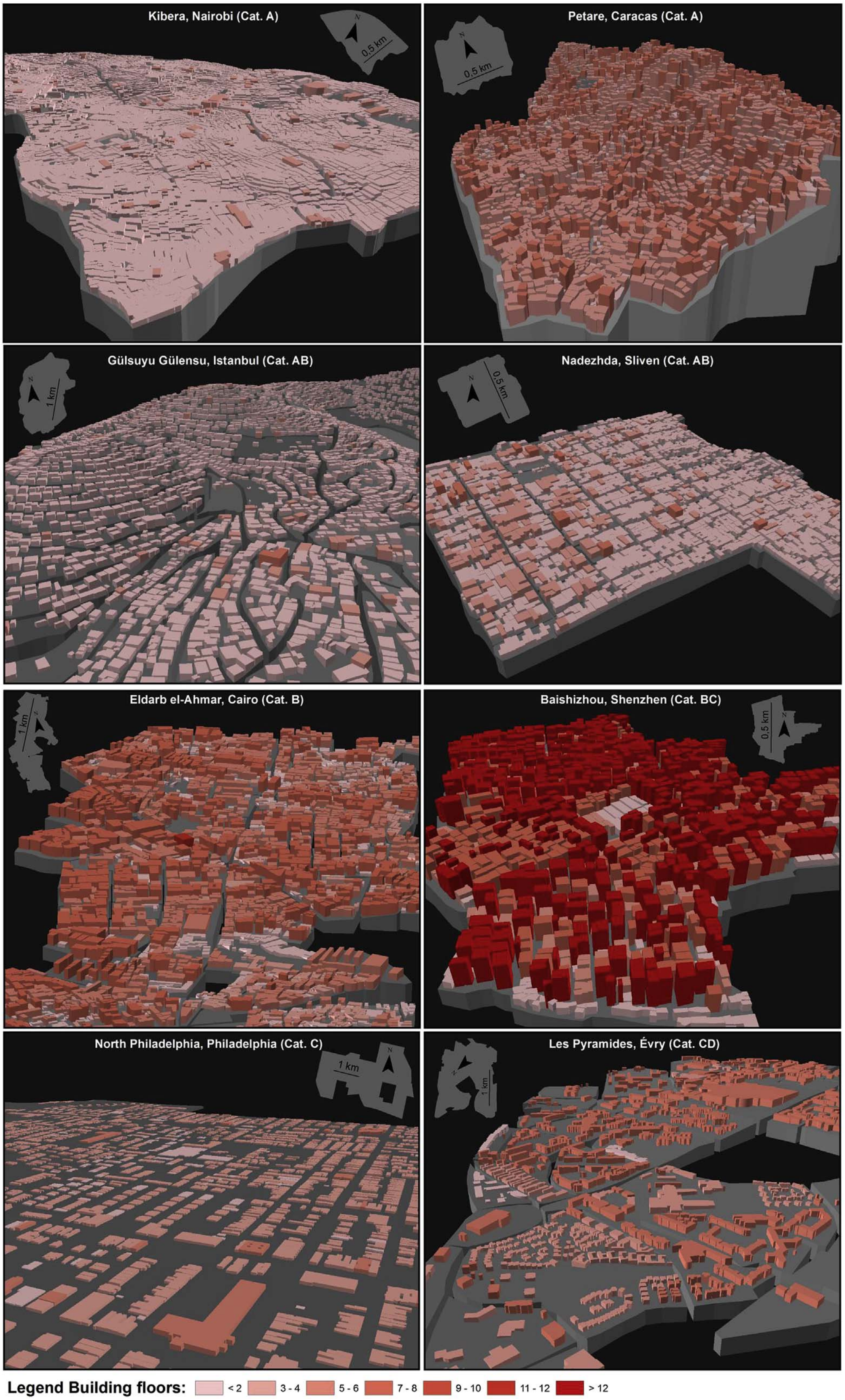

Fig. 7. Selected examples of 3-D building models of the defined categories A, AB, B, BC, C and CD.

Table 2
Categories of physical appearances of Arrival Cities not being selected for the morphologic analysis.

Cat.	Terminology	Description	Samples & literature
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)	e.g. the Curvy, Berlin, Germany (Wehner, 2015); Terras do Lelo Martins Lissabon, Portugal (Campos Costa et al., 2013); laneway alleys in Hamilton or Toronto, Canada (Cubitt, 2008).
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.	Roof top dwellers, e.g. Hong-Kong, China; Singapore, Singapore Pomeroy (2012); basement suites, e.g. Calgary, Canada (Tanasescu, Wing-tak, & Smart, 2010); e.g. Torre de Davide in Caracas, Venezuela (Davis, 2007); e.g. converting cubicles verandas, staircases into living environments in Hong Kong (Schmitt, 2007).
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	e.g. Dale Farm, Basildon, England; Hayes road, Sully, Wales (Porter & Taylor, 2010); or, 0.4.% of Australians are counted 'caravan park residents' (Greenhalgh, 2002); boat people in Hong Kong (Schmitt, 2007) or Australia (O'Doherty & Lecouteur, 2007)
H	Houseless/Homeless/Roofless population	e.g. pavement dwellers includes people sleeping on streets without any or inadequate shelter	e.g. pavement dwellers; e.g. in Indian cities such as Calcutta, Mumbai, or in Dhaka, Bangladesh (Padgett & Priyam, 2017) or in Australia where 0.5 of the population is reported to be without shelter (ABS, 2012); for more detailed classifications see (European Federation of National Organizations Working with the Homeless, 2017)

additional data sources (such as data on income, education, among others). This shows that EO data and classification algorithms are feasible to contribute significantly to a global catalogue or inventory of Arrival Cities (categories A and AB), but the morphologic catalogue also reveals that a comprehensive global inventory needs multi-disciplinary data and methods.

6.2. Determinants of morphologic appearances: theory and evidence

What remains in this discussion is the question what might determine the seemingly idiosyncratic physical appearances that evolved. The most widely acknowledged causality is the *natural landscape*; against the general acceptance, we found that when classifying the 44 test sites into generally flat and generally hilly terrains (using a digital terrain model; cf. Table A-1 appendix), the structural features in each group do not significantly differ (e.g. median building densities show 57.4% for hilly vs. 54.9% for flat terrains). If we base this comparative analysis only on slums (Cat. A) and slum-like (Cat. AB) structures ($I_m > 3.25$), we find building densities in hilly terrain with 66.1% slightly denser than in flat terrain with 64.8%. Admittedly, although there are no major differences, we find that in our sample steep terrains cause higher utilization of space.

Another defining issue of idiosyncratic appearances is *pre-urban land division* (Kostof, 1991), which can be influenced by topographical issues but goes further involving patterns of ownership (e.g. pre-existing rural properties or current informal land developers) or the disposition of previous usages (e.g. farming practices). Here we find that areas with clear pre-existing geometric street patterns for the categories A, AB, and B (we selected unambiguous examples of Imbaba, Paraisópolis, West Adams, Eslamsahar, Nadezhda and Lo Prado) feature a median building density of 66.8%. This is significantly lower compared to areas of no obvious pre-existing geometric order (we selected unambiguous examples of Makkoko, Kibera, Petare, Tondo, Dharavi, Bharat Nagar and Santosh Nagar) featuring 75.6%. The remaining Arrival Cities are a mixture of both classes and are thus not considered. This result lets us assume that in areas of no pre-existing order space is utilized to a higher degree. Pre-existing patterns also lead to a more clear geometric order: For slums (Cat. A) and slum-like (Cat. AB) structures ($I_m > 3.25$) we see building orientations for these areas with 0.065 more geometric than without (0.108).

In general, we find the two most prominent theories – topography and pre-existing patterns – tested here do influence urban patterns. But, we find there is nothing completely instinctive or predestined regarding evolving urban patterns – either planned or unplanned. Landscape features may sometimes be embraced, but others may also be rejected. So, it is the complexity of local determinants within globalized processes that form these structures.

7. Conclusion and outlook

This study documents that there is not one global morphologic settlement type solely characteristic for Arrival Cities. And we show that remote sensing is a crucial data source for detecting and characterizing built environments of the urban poor as they are still widely neglected in official maps. This empirical baseline study can now function as initial point to develop EO-based classification algorithms beyond proof of concept for morphologic slum and slum-like areas. Beyond, matching the spatial knowledge for morphologically insignificant areas with location-based information of urban geography may allow a more systematic, consistent approach of localizing patterns, quantities and forms of poor urban living on global scale. With it we add a step towards a comprehensive morphological catalogue or even an inventory as foundation for urban geography and studies about urban poverty. Or, with a development agenda perspective, this study may provide additional knowledge for a more comprehensive registration of the dimension and distribution of urban poverty.

"We shape our buildings; thereafter they shape us". This famous quote of Winston Churchill reveals how built environments shape societies. In times of the largest migration ever – from rural areas into cities (UN, 2014) with cities extensively sprawling into their hinterlands (Taubenböck et al., 2012), informal developers have become the largest builders of housing in the world. They shape a large share of living environments in Arrival Cities. In consequence, the responsibility for shaping societies by the built environment is widely left to them. This is not necessarily negative, as many of the former European downtown slums have turned into beloved spots of today (Glaeser, 2010). It is of course not the built environment alone that defines whether Arrival Cities become an integral part of the urban landscape and society, but it is argued to play a relevant role. In light of this it is alarming that although we are aware of this issue as well as of the dramatic global process of migration into cities, systematic spatial knowledge on the physical appearance of Arrival Cities is still underrepresented.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2018.02.002.

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