Monitoring and Modelling of Informal Settlements – a Review on Recent Developments and Challenges

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Abstract— The increasing development of informal settlements and slums in the years to come is a humanitarian challenge we are facing worldwide. The reasons for this development are mainly given by an urbanization of poverty and the lack of affordable housing in urban areas. Consequently, the majority of slum dwellers are forced to live in housing conditions which are simply unacceptable. In order to fight urban poverty and develop strategies to reduce the number of slum dwellers it is essential to inventory and monitor slums and to understand the underlying mechanisms of slum genesis. However, systematic spatial knowledge about these mechanisms is still absent. This paper addresses the capabilities of mapping and structural analysis of informal settlements using remote sensing data and modelling their genesis based on agent based approaches.

I. INTRODUCTION

Per UN-Habitat definition, a slum dweller fulfills at least one of five conditions: lack of tenure, lack of access to safe water, lack of access to improved sanitation non-durable housing and overcrowding. The term “informal settlements” is used for urbanization originating outside of municipal planning efforts (if they exist). Thus, informal settlements are not synonymous with “slums”, but most of them fulfill at least one of the UN Habitat’s conditions for slums. Recently, more than 1 billion people are living in slums worldwide [1]. Estimates expect this number to rise up to 1.5 billion in 2020 [2] and to three billion in 2050 [3]. Although informal settlements are a world-wide phenomenon, mainly observable in less developed or developing countries, yet little is known about the mechanisms of their genesis and development. In many cases they are the result of a continued rural-urban migration and a lack of affordable formal housing offers. Often, informal settlements occur on marginal land of urban regions as a result of informal urbanization. The process of informal urbanization ranges from large scale, organized land occupation by undercover developers to small scale, sporadic land occupation by individual families. Consequently the morphology of informal settlements ranges from regular, gridded layouts to irregular, organic layouts. If not removed, the development of informal settlements can have very different outcomes. Respectively, informal settlements can be very different in their dynamic of physical shape, which aggravates their detection for inventory or planning issues.

Thus, adequate methods and tools to detect informal settlements and to estimate their future developments are of importance. At this background we investigate recent methods for monitoring and modelling informal settlements and the methods’ potential to foster the understanding of slum genesis and development in general and at slum-individual level.

II. DETECTING AND MONITORING INFORMAL SETTLEMENTS

In order to detect and monitor informal settlements, different and mutually non-exclusive methodological ways of information gathering can be applied, ranging from volunteered mapping by the settlements inhabitants [4], to the analysis of remote sensing data.

A. Detecting informal settlements in remote sensing data

Due to the lack of a definite definition of slums or a general theory on such locations [5] it is hard to describe general mapping rules for slums. Additionally, some informal settlements can be hardly distinguished from formal settlements just by their physiognomy. For these cases rather in-depth knowledge about the individual history and actual situation is indispensable [6]. This lack of a definition or theory paired with the high variability in appearance across different contexts [7] turns the (semi-) automatic spatial detection and delineation of slums in remote sensing data to a complex problem. In 2001 Hofmann [8] stated that relatively little systematic research exists about the physical appearance of slums. Although this statement has been made more than a decade ago global spatial knowledge on the location, dimension, structure and morphology of informal settlements or slums is still absent. In 2008 an expert group meeting took place [9] which led to the preliminary notion of qualitative and quantitative indicators for slum identification from VHR remote sensing data (Tab. 1). However, since that time, in remote sensing various earth observation data has been tested to increase spatial knowledge on slums. Kohli et al. [7] developed a general ontology of slums with respect to image based classification. In any case, VHR optical data have been widely applied to detect and analyze slums. Few studies even used radar data to detect informal settlements [10]. Conceptually, most studies address the block level aiming to
delineate informal settlements within the urban fabric. In this context, Taubenböck and Kraff [11] exemplarily proved that morphological and structural characteristics of informal settlements can show significant differences to the surrounding formal urban areas. Object-based algorithms [12] (Fig. 1), snakes [13], radial casting algorithms [14] as well as visual classifications [15] have been applied to take advantage of the morphological difference of slum appearance in remote sensing data. Nevertheless, the variety of spatial features possibly classifying informal settlements is large [16]. Other authors use direct spatial features derived from individual buildings such as size, shape or height together with their density and orientation [17], [18]. At the level of individual buildings, approaches are mostly restricted to visual interpretations as the high density of buildings, spatial overlapping of roofs and their heterogeneous composition do not yet allow for an automatic spatial separation of individual structures with sufficient accuracy. Thus, studies on structural analysis at individual building level [19] are still rare (Fig. 2).

### TABLE I. INDICATORS FOR DETECTING INFORMAL SETTLEMENTS IN VHR REMOTE SENSING DATA (SOURCE: [9] p. 6-7)

<table>
<thead>
<tr>
<th>Qualitative indicator</th>
<th>Quantitative indicators</th>
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<tbody>
<tr>
<td>Haphazard, high density building pattern</td>
<td>Proportions of land cover (% area covered by structures, % area of open spaces, % of vegetation)</td>
</tr>
<tr>
<td>Durability of housing/material for roofing (corrugated tin, plastic sheeting/tarps, cloth/grass)</td>
<td>Spatial metrics (lactanarity, textural contrast, variability of building size &amp; orientation)</td>
</tr>
<tr>
<td>Proximity to natural and technological hazards</td>
<td>Morphology of building heights (derived from shadows or lidar)</td>
</tr>
<tr>
<td>Structure, size and condition of road network</td>
<td>Characteristic scale (relative size of housing units, relative size of road networks, plot ratio, floor area ratio)</td>
</tr>
<tr>
<td>Proximity to public services (health, education, open space, public transport)</td>
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Fig. 1: Segmentation and classification results for an IKONOS scene in Cape Town (top) and a QuickBird scene in Rio de Janeiro (bottom). Left: top segmentation level with respective classes. Right: base segmentation level with respective classes. Blue rectangular in the left images indicates the location of the right images (Source: [18]).

**Fig. 2:** 3-D city model derived from QuickBird data and field work from Bharat Nagar in Mumbai, India for differentiation of formal and informal settlement structures (Source: [19]).

### B. Monitoring informal settlements in remote sensing data

Although many studies demonstrate successful identification of informal settlement structures and slums, only few studies have addressed the multi-temporal evolution of slums [20], [21], [22], [23], all of them more or less mapping the general change of land use and land cover but not explicitly the areas covered by informal settlement structures. Recently, Kit and Lüdeke [24] used multi-temporal VHR data in order to automatically detect the change of slum areas in Hyderabad. Gruebner et al. [25] used visual interpretation of VHR data to map spatial extents and evolution of slum areas in Dhaka from 2006 to 2010. With it they allow monitoring demolition and new developments of informal areas.

### III. MODELLING AND SIMULATING INFORMAL SETTLEMENTS

While detecting and monitoring informal settlements aims at describing and delineating their physiognomy, location and extent (over a past period of time), the modelling and simulation of informal settlements is rather explanatory and predictive. Several methods for spatial modelling and simulating are available. All of them are based on mathematical models formalizing the underlying development hypothesis of slum and informal settlement development.

#### A. Available methods

Simulation and modelling is very popular in landscape ecology, in social and economic sciences, in political sciences or in urban studies. The mathematical methods used for process description are manifold, ranging from Genetic Algorithms (GA) [26], via Markov-Random-Fields (MRF) [27], Regression Models (RM) [28], Multi Criteria Evaluation (MCE) [29], Artificial Neural Networks (ANN) [30] to Cellular Automata (CA) [31], Agent-Based Modelling (ABM) [32] and Multiple Point Statistics (MPS) [33]. Combinations of these methods are possible. For modelling and simulating informal settlements, recently ABM and CA are very widespread. Since both methods are close relatives, CA and ABM are very often used and described synonymously. In
contrast, some authors [34] clearly distinguish between CA and ABM. CA are organized as regular 2D grids wherein each grid cell follows pre-defined rules of state transition. Thus, spatially each cell of a CA is static, but during simulation it changes its state depending on the underlying transition rules. Eventually, the agglomerate of all CA in a simulation produces space-temporal patterns which are more or less similar with those observable in the real world. In ABM agents are not necessarily bound to a specific position [34]. By definition [35] each agent is capable to sense the environment it is acting in - including other agents - and intends to achieve its pre-defined goals. All agents are autonomous in their decisions how to achieve their goals. Thus, they can behave proactive and collaborative and can have different roles within the ABM. Individual agents can emerge to higher level aggregates which can behave dynamic, too [36]. However, CA and ABM are not necessarily mutually exclusive. Systems such as VecGCA [37] or hybrid models [34] allow polygons in GIS to behave like CA and thus to change their shape, that is, acting like dynamic patches [38]. Hofmann et al. [39] made a first attempt to conceptually marry image segments with the ABM paradigm.

B. ABM and CA to simulate informal settlements

Roy et al. [40] recently compiled a review on contemporary slum simulation models. All of them are either agent-based or based on CA but follow particularly different intentions. The review roughly analyzes six slum simulation systems (ISGM [41], Peripherization [42], ISGPM [43], MSGM [44], Slumulation [45] and Economic disparity [46]) comparing their socio-economic and environmental aspects, their spatial and temporal resolution, their level of abstraction and the procedures to evaluate and calibrate them. MSGM intends to simulate the inner physical settlement structure while Economic disparity and ISGM focus on slum boundaries and the socio-economic structure. Slumulation is rather focusing on the location of potential slums within Hyderabad. Aside the reviewed models, Crooks et al. [32] developed an ABM to investigate segregation patterns of informal settlements under varying environmental conditions and under varying behavior rules. Interestingly, none of the models takes into account information gathered from remote sensing data or considers the 3rd dimension.

IV. CHALLENGES FOR MONITORING AND MODELLING INFORMAL SETTLEMENTS

Whatever instruments and actions are applied to improve the housing situations of slum dwellers, appropriate situation awareness of the acting protagonists is necessary, which includes appropriate geo-information. Since slums and informal settlements are unplanned and dynamic by nature, only methods allowing an in-situ and sometimes even an in-vivo (e.g. volunteered mapping) information retrieval are appropriate. For estimating future developments CA and ABM are certainly appropriate and state-of-the-art. However, the creation of plausible scenarios of informal settlement and slum development is only feasible if the models are fed with profound knowledge about the genesis steering mechanisms. Recently, we can just hypothesize these mechanisms and create appropriate simulation models, which we than compare with the observable reality. Therefore, the better the surveyed information the better the models can be evaluated and calibrated, which in turn improves our understanding of the mechanisms. In this context, detection and modelling must be capable to operate in 3D and intrinsically consider time to enlarge information and knowledge on environmental indicators such as their location and evolution in the larger urban context. Within the slums, indicators such as the building density, the buildings appearance and orientation in 2D and 3D, the layout of street networks and the terrain situation must be detected and considered. Accordingly, the spatial and temporal resolution of data and models must be appropriate. Methods for information extraction from remote sensing data must allow analyzing VHR remote sensing data together with accurate elevation data (Fig. 2) at multiple dates and scales. Although highly desirable, identifying general rules of genesis for informal settlements is recently unfeasible. However, international comparative studies of informal settlements and their histories could potentially uncover mechanisms yet unknown. But comparing informal settlements and slums means to identify and develop comparable features and provide standardized methods of comparison.

V. CONCLUSIONS

Recent methods of detecting slums and informal settlements are mainly focusing on detecting the status quo. Methods based on remote sensing data predominantly intend to delineate informal settlement structures from other urban fabric. For this purpose expert knowledge in image analysis and about principle mechanisms of the settlement-forming mechanisms is necessary. Multi-temporal remote sensing data recently is just used to document changes of land cover in urban areas but it has no impact on the modelling in terms of calibrating the models. 3D information is neither used for object detection within slums nor for modelling and simulation. However, in order to gain a deeper understanding of the mechanisms of informal settlement genesis, it is necessary to monitor individual informal settlements and their structures in-situ and ex-post and in all spatial dimensions. With this knowledge at hand, models simulating the development of informal settlements can be developed and improved, which in turn can improve the methods for detecting and delineating informal settlements from remote sensing data and foster our understanding of their genesis. Thus, from our point of view future developments should allow to more closely link methods of remote sensing data analysis with those of modeling and simulation and consider time and space in all their facets.

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