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An ontology of slums for image-based classification

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ABSTRACT

Information about rapidly changing slum areas may support the development of appropriate interventions by concerned authorities. Often, however, traditional data collection methods lack information on the spatial distribution of slum-dwellers. Remote sensing based methods could be used for a rapid inventory of the location and physical composition of slums. (Semi-)automatic detection of slums in image data is challenging, owing to the high variability in appearance and definitions across different contexts. This paper develops an ontological framework to conceptualize slums using input from 50 domain-experts covering 16 different countries. This generic slum ontology (GSO) comprises concepts identified at three levels that refer to the morphology of the built environment: the environs level, the settlement level and the object level. It serves as a comprehensive basis for image-based classification of slums, in particular, using object-oriented image analysis (OOA) techniques. This is demonstrated by with an example of local adaptation of GSO and OOA parameterization for a study area in Kisumu, Kenya. At the object level, building and road characteristics are major components of the ontology. At the settlement level, texture measures can be potentially used to represent the contrast between planned and unplanned settlements. At the environs level, factors which extend beyond the site itself are important indicators, e.g. hazards due to floods plains and marshy conditions. The GSO provides a comprehensive framework that includes all potentially relevant indicators that can be used for image-based slum identification. These characteristics may be different for other study areas, but show the applicability of the developed framework.

1. Introduction

At present about half of the world's population is estimated to live in cities. According to the projection by a recent report of UN-HABITAT (UN-HABITAT, 2010), urban areas will be the epicenter of almost all of the world's population growth in the next 30 years. In addition to this growth, planners and governments in developing countries face the challenge of high growth rates of poverty. Whereas poverty was once seen as being a largely rural problem, today we speak of the urbanization of poverty (Kombe, 2005). Urban poverty is manifested most conspicuously in the proliferation and expansion of slums, which are home to a growing proportion of urban dwellers. Though there have been collective efforts at global and national levels to improve the condition of slum dwellers, the world's slum population is estimated to reach 889 million by 2020 (UN-HABITAT, 2010).

Addressing the problems of slums requires comprehensive information on these highly dynamic areas as a basis for coordinated actions at local, national and international level. As slums are directly related to poverty, consistent information on the nature and extent of slums is useful for planning, implementing and monitoring urban poverty alleviation programs. The systematic quantification of slums requires methods to identify and define them spatially in a consistent manner in support of geographical targeting in slum intervention programmes (EGM, 2008). Further, considering the rapid change in the structures of such settlements as a result of expansion, infill, relocation and extension, automatic techniques could help in slum monitoring. For these reasons, there is a growing interest in developing and exploiting robust approaches for collecting information on slums. These approaches include participatory methods (Hasan, 2006; Joshi, Sen, & Hobson, 2002; Lemma, Sliuzas, & Kuffer, 2006), mapping census data with GIS (Baud, Pfeffer, Sridharan, & Nainan, 2009; Baud, Sridharan, & Pfeffer, 2008) as well as very high resolution (VHR) remote sensing based methods for mapping slums (Mason & Fraser, 1998; Sliuzas, Kerle, & Kuffer, 2008). In particular RS methods could provide updates also for the parts of the world where census data or other data are not readily available (Weeks, Hill, Stow, Getis, & Fugate, 2007).

Traditionally, urban slum and non-slum settlements have been differentiated based on administrative definitions or income-based

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indicators. The official data collection methods in most developing countries are typically head-count based (census) that do not provide detailed spatial information about the concentration or location of slum-dwellers. Furthermore, there can be contradictions between the definition of slums in different countries that often develop their own definitions, making data exchange, comparisons and monitoring of intervention plans difficult.

In this paper, we first provide a brief review of the three major approaches of slum mapping, including the use of very high resolution (VHR) optical images. Recent research in the use of VHR images has been moving from pixel-based methods to object -oriented image analysis approaches, which requires a clear conceptualization of the object of interest. Such a conceptualization forms the basis of image-based mapping, but also needs to address the huge variability in slum characteristics and appearance across different contexts. The purpose is to develop contextual OOA methods that closely resemble the cognitive approach of visual image analysis for slum identification and mapping. We follow an ontological approach to conceptualize slums using indicators related to the morphology of the built environment. The ontological framework provides a comprehensive description of spatial characteristics and their relationships to represent and characterize slums in an image.

2. Ontology

The first use of the term "Ontology" is attributed to Aristotle around 340 BC as representing reality by breaking it down into concepts, relations and rules (Agarwal, 2005). Gruber (1993) defined ontology as a specification of conceptualization, i.e. an abstract and simplified representation of real-world entities. According to Benslimane, Leclercq, Savonnet, Terrasse, and Yétongnon (2000, p. 195), "*Ontology provides a formal representation for the concepts of an application and relationships among them, thus capturing the intended meaning of the terms of the domain of interest*". Ontology thus provides a basic knowledge skeleton around which a knowledge base can be built (Swartout & Tate, 1999). For Chandrasekharan and Josephson (1999) ontology acts as the representation vocabulary for a specific domain, defining the terms that are used. These definitions show slight variations in the terminology to define ontology, depending on the viewpoint of the author (Winter, 2001). We follow the definition of Sowa (2000), who considers the ontology of a specific domain to consist of the domain vocabulary, all its essential concepts, their classification, taxonomy, relations and domain axioms.

Ontologies have acquired considerable importance in knowledge representation in recent years. They are used to represent knowledge in biomedical science (Matei, 2008) and computer science (Guarino, 1995). Ontologies have been applied in landscape-studies (Lepczyk, Lortie, & Anderson, 2008), in crisis management (Fan & Zlatanova, 2010; Li et al., 2008), in GIScience for sharing geographic information in a standardized way (Agarwal, 2005) and in urban studies to facilitate communication between information systems, stakeholders and urban experts (Belmonte, Pérez-de-la-Cruz, & Triguero, 2008; Fonseca, Egenhofer, Davis, & Borges, 2000; Teller, Lee, Roussey, & Laurini, 2007). The common idea behind all these studies has been to develop a common understanding of the domain of interest and facilitate information exchange. Recently, ontologies have been applied in remote sensing studies to address uncertainty in object-reconstruction from an image, based on knowledge of the real world (Agouris, Stefanidis, Bittner, & Winter, 1999).

We expand upon the ontological work of Hofmann, Strobl, Blaschke, and Kux (2008) to develop a generic slum ontology (GSO). We use the "durable housing" indicator of UN-HABITAT (2003a), which defines a slum household as one lacking in any one of five factors: secure tenure, access to safe water, access to sanitation, sufficient living area and durability of housing. Durable housing refers to: permanency of structure – walls, roof and floor; compliance of building codes; well maintained and structurally sound; not be located on a hazardous location (e.g. near toxic waste; on a flood plain; on an unstable slope). VHR images are well suited to quantify the durability of housing, as many of these physical characteristics can be readily observed. In addition, we use knowledge from experts to identify other indicators for slum detection, building upon the study by Ebert, Kerle, and Stein (2009), who used a set of image-derived physical proxy variables to assess urban social vulnerability. We use the physical characteristics of the urban environment apparent from VHR images to characterize slums using the generic slum ontology as a basis.

3. Previous work on slum identification and mapping

In this section, we discuss three different slum mapping approaches, based on (i) census data, (ii) participatory methods and (iii) advanced remote sensing image analysis. Throughout the paper, the terms informal settlements and slums are used interchangeably, since informal settlements are often referred to as slums and vice versa in previous literature (Hofmann, Strobl, Blaschke, & Kux, 2008; UN-HABITAT, 2003b, p. 219). Though by definition, not all slums would be considered as informal settlements, e.g. the inner-city slums which are dilapidated structures with formal rights. However, according to UN-HABITAT's definition informal settlements are always considered to be slums by virtue of the lack of tenure security. Moreover, the great majority of informal areas are occupied by relatively poor residents and will usually have at least one additional form of deprivation (i.e. related to water, sanitation, overcrowding or durable housing).

3.1. Census-based approach

The census-based approach uses data collected through census surveys as a basis of deprivations/poverty mapping. Census data contain details on the inhabitants residing in a country aggregated to small areas to protect individual privacy. They consist of data on social, economic and habitat/infrastructural aspects at the level of an enumeration unit (Baud, Sridharan, & Pfeffer, 2008). Baud et al. (2008) used census data to map concentrations of poverty at the ward level in Delhi, India by developing an index of multiple deprivation. Similar studies were conducted in three other Indian cities using a multi-criteria model within GIS for the identification of multiple deprivation hotspots (Baud, Pfeffer, Sridharan, & Nainan, 2009). Weeks et al. (2007) used census data from Accra, Ghana, to create a slum index based on the UN slum indicators for each Census enumeration area (EA), using it to measure the concentration of slums in each EA. High correlations were found between the slum index, the socio-economic characteristics of neighborhoods and certain land cover metrics derived from VHR satellite imagery (Weeks, Hill, Stow, Getis, & Fugate, 2007).

As census data are routinely collected in many countries, they provide an interesting option for poverty/slum mapping. In addition, they mostly provide information at the household level. Their utility is restricted by the long temporal gap (often a decade, in most countries) between two census surveys (Ebert, Kerle, & Stein, 2009; Hall, Malcolm, & Piwowar, 2001), and time needed to check raw data and collate and release derived statistics to users (Martínez, 2009). Considerable socio-economic and physical changes can occur on the ground, especially in slum areas. Also, the degree of data aggregation can be a problem. For example, census wards in Delhi vary in size between 1500 households to more than 57,000 households.

3.2. Participatory approach

The participatory approach involves mapping the details of informal settlements at individual or household level with the cooperation of slum-dwellers (Joshi, Sen, & Hobson, 2002). Hasan (2006) used this approach to survey and map infrastructure details of informal settlements in Karachi. Karanja (2010) presented a full enumeration of households and slums in Kisumu, Kenya. Earlier, Lemma et al. (2006) employed rapid appraisal techniques that integrate local knowledge with Geographic Information Technology (GIT) in a participatory approach that involved input from stakeholders and visual image interpretation using satellite images and aerial photographs. As community-based slum enumeration is also being actively promoted by international slum networks, such as Slum Dwellers International (see http://www.sdinet.org/ritual/enumerations/), it will likely become a widely used approach and tool.

Participatory approaches can help to generate spatial and non-spatial information in the form of thematic GIS layers that provide a supplement to socio-economic surveys and feed into slum-related policy development and planning. From the perspective of slum communities this is especially important, as the process of enumeration generates much needed data that are useful both for the slum communities themselves, as well as in negotiations with government bodies concerning needs and services. However, the detailed level of information provided by the participatory approach is time consuming to collect. In cities with extensive slum settlements, this information may be difficult to upscale to larger areas. Other methods that can reduce enumeration resources and can systematically generate city wide slum maps from VHR images are thus required. Such maps could be used as an input for urban policy, growth monitoring and various planning processes.

3.3. Remote sensing-based approach

The remote sensing (RS)-based approach uses image processing techniques to map slums from satellite imagery. RS can provide spatially disaggregated data with high temporal consistency, which can facilitate rapid monitoring and effective intervention of slums by local authorities. Mason and Fraser (1998) demonstrated automated shack extraction from a VHR aerial imagery. Visual interpretation from VHR images has been used to extract concentrations of urban poverty (Angeles et al., 2009; Sliuzas & Kuffer, 2008). Baud, Kuffer, Pfeffer, Sliuzas, and Karuppannan (2010) used VHR images to identify precise patterns within deprived areas using physical variables such as built-up density, building size and site suitability. Visual interpretation methods, however, require extensive local expert knowledge to produce reliable results. Moreover, automating the interpretations can lead to more objective and faster results. Jain, Sokhi, and Sur (2005) suggested and later demonstrated (Jain, 2007) that studying informal development through image classification could explain the patterns over time and space. Weeks et al. (2007) used Ridd's vegetation, impervious surface, bare soil (V-I-S) model (Ridd, 1995) to classify slum neighborhoods in Accra, Ghana. However, pixel-based classification, as used in these studies, is unable to represent the heterogeneity of an urban environment (Myint, Gober, Brazel, Grossman-Clarke, & Weng, 2011).

With VHR images, OOA techniques for classification have proven to be accurate in urban applications (Ebert, Kerle, & Stein, 2009; Sliuzas, Kerle, & Kuffer, 2008). Such a multi-scale approach may capture the heterogeneity of urban areas by following a hierarchy for object-classification that includes contextual information for objects and non-physical features (Ebert, Kerle, & Stein, 2009), specifically for informal settlements (Hofmann, 2001). These opportunities are coupled with higher levels of complexity in terms of deriving real-world knowledge through remote sensing. Therefore, it is important to understand and integrate epistemological and ontological aspects of real-world objects for wider OOA applicability (Blaschke, 2010). Hofmann et al. (2008) extended earlier work (Hofmann, 2001) by introducing the concept of ontology to first define informal settlements as a basis for object-based classification. Their ontological framework was able to represent conceptual knowledge but the indicators and the absolute thresholds for the variables remained data/scene specific. The work described in this paper builds on this ontological approach, but instead of focusing on a particular study area, we develop a generic ontological framework for slums as a basis for object-based classification across different contexts.

4. Ontological framework for slums

The GSO consists of characteristics at three spatial levels: object level, slum settlement level and the slum environment. We follow this multi-scale approach considering the variable nature of slums across different contexts, by considering a set of indicators at different scales for a slum as a vague phenomenon. The ontology development process is based on the one suggested by Fernández López, Gómez-Pérez, Sierra, and Sierra (1999) named "*Methontology*", comprising three phases: specification, conceptualization and implementation.

4.1. Specification

Specification refers to determining the domain, its scope and the set of terms to be represented in an ontology (Fernández López, Gómez-Pérez, Sierra, & Sierra, 1999). It creates a clear vision of the ontology's coverage, its intended use and the types of questions the information in the ontology should provide answers to. On the basis of image-based identification and classification of slums, we focus on those characteristics that are observable from VHR images. To collate information on the main concepts and relationships associated with slums, first a literature review was carried out to form an initial list of potential indicators. To refine this list and to include any missing indicators, we carried out semi-structured surveys and interviews with 50 domain experts (urban planners, remote sensing experts, academics and local administrators) with knowledge in remote sensing and field experience of slums. The experts were from Asia, Sub-Saharan Africa (SSA), Europe, Latin America, North America and Australia. They were asked to fill the questionnaire considering the slums they were most familiar with. All experts referred only to slums from countries in Asia, SSA or Latin America. Table 1 shows the names and numbers of the countries in Asia, SSA or Latin America mentioned by respondents. As is evident from the table, the majority of responses referred to SSA and Asia. The low representation of Latin America and the absence of several other regions where slums are known to exist is a limitation of the study.

4.2. Knowledge acquisition

Methontology identifies knowledge acquisition as an important and independent step for ontology development (Fernández López et al., 1999). We used literature review, interviews and semi-structured survey for knowledge acquisition. The survey consisted of questions on how domain experts defined slums (open-ended question), specific characteristics of slums in their respective context (Table 2) and a section for delineating slums (Fig. 1). Their

Table 1
List of countries referred to by respondents in the expert survey grouped by region.

Region	Countries	Number of responses
Asia	Bangladesh, India, Indonesia, Nepal, Philippines	15
Sub-Saharan Africa	Ghana, Namibia, Malawi, Mozambique, Rwanda, South Africa, Tanzania, Uganda	32
Latin America	Argentina, Venezuela, Jamaica	3

Table 2
Characteristics of slums for each general indicator that were specified by domain experts.

General indicators	Specific characteristics
Building characteristics	Building types, number of floors, footprint in m^2,building height, roof, wall and floor materials
Access network	Type of roads, percentage paved, width, layout
Density	Percentage of roof coverage, open spaces and vegetation
Settlement shape	Shape of slum
Location	Site condition of slum
Neighborhood characteristics	Relationship with surrounding areas of slum

responses were used to understand how experts perceive a slum. They also helped to comprehend the decision-making steps employed by experts to identify slums in an image. The responses provided insight into the variability and similarities of slums in various contexts. Based on this, we finalized the list of indicators to form the generic slum ontology as a comprehensive set to capture main slum features.

To capture the basic understanding of slums in different contexts, we analyzed the definitions provided by the experts. Content analysis was used to categorize answers from respondents by studying all responses to develop a set of general deprivation issues that frequently occurred in their responses (Table 3). Subsequently, we counted the number of responses that referred to each issue. The issue *basic services* include those responses that mentioned any one or a combination of: access to water, sanitation, drainage and electricity. The issue *socio-economic conditions*

Table 3
Number and percentage of experts who referred to a general deprivation issue while defining slums.

Responses	General deprivation issues			
	Basic services	Socio-economic conditions	Physical infrastructure	Others (tenure, overcrowding)
Number of respondents	35	30	43	38
Percentage	70	60	86	76

include responses referring to low income, poor/sub-standard living conditions, schools and health facilities. Finally, the responses related to the physical conditions were allocated in the *physical infrastructure* issue including responses related to the physical condition of houses, absence of or irregular roads, high building density, hazardous location, poor environmental condition, durability (remote sensing derivable). The category *others* refer to responses mentioning tenure or overcrowding in their definitions. As is evident from the table, 86% of the respondents referred to physical infrastructure while defining slums. This substantiates the potential of using remote sensing for slum identification and mapping.

We also asked the domain experts to identify and delineate slums in satellite images of four cities acquired from Google Earth (Fig. 1). Additionally, the experts were asked to list the factors they used for identification and delineation. Finally, they were also asked to mention the reasons, if any, for not being able to identify a slum.

The results of the survey show that experts use eleven basic slum indicators to delineate slums from imagery: building size, roof material, absence of roads, irregular roads, lack of vegetation and open spaces, density (compactness), irregular shape of settlement, association with neighboring areas, texture and locality. The combination of indicators, however, varied from place to place. This information was used in conceptualizing the basic knowledge about slums and finalizing the set of indicators.

4.3. Conceptualization

Conceptualization refers to organizing and structuring the knowledge acquired during the specification phase in a semi

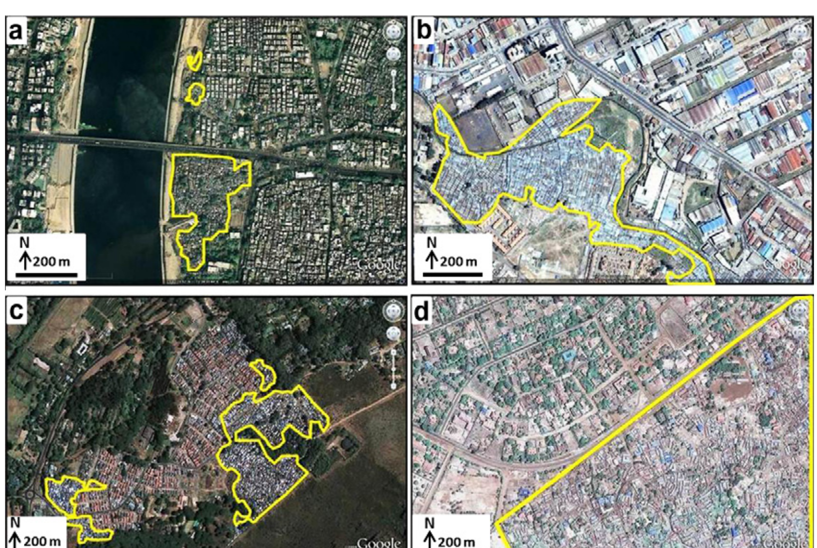

Fig. 1. An example of slum delineation in different contexts by an Indian expert. City names: (a) Ahmedabad (India), (b) Nairobi (Kenya), (c) Cape Town (South Africa) and (d) Kisumu (Kenya). *Source*: Google Earth.

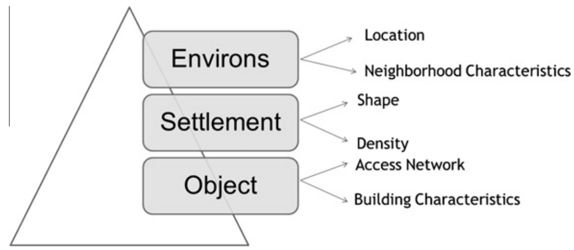

Fig. 2. The six general indicators categorized to form a hierarchy to represent concepts at three spatial levels.

-formal way, using a set of immediate representations that both the domain experts and ontologists can understand (Fernández López et al., 1999). Fig. 2 shows the classification (taxonomy) starting from object level to a higher level, referred to as environs (Gasevic, Djuric, & Devedzic, 2009). It shows the concepts at three spatial levels, their hierarchy and the indicators associated with each level. Axioms, such as *closeto, has, is in, is of*, are used to specify relation between indicators and their attributes. The description of concepts is as follows:

• Environs	Surroundings of the settlement, i.e. its location with respect to neighboring land uses, or areas with specific environmental conditions, such as hazardous areas
• Settlement level	Overall form/shape/density of the settlement
• Object level	Components of the settlement, such as characteristics of buildings and roads

4.3.1. Building characteristics

A building is a structure with roof and walls. Buildings in a slum settlement tend to have characteristics that are different from those in non-slum areas. Some authors have explicitly described features of buildings while discussing slums in different contexts (see Davis, 2007; Neuwirth, 2005). 76% of the domain experts referred to building characteristics while defining slums. All attributes related to a building are represented in Fig. 3; however, not all of them are detectable from satellite images. A combination of attributes such as roof type, footprint, shape and orientation can be used to identify slum buildings using remote sensing. There may be regional similarities in slum characteristics. All the experts referring to SSA mentioned the roof material to be either tin or iron sheets in addition to others. The materials from Asian context include mud, plastic or straw thatch etc. with color being a distinguishing feature (Fig. 1). Sixty three percent of the responses from the SSA context said that the type of building is detached, whereas 73% from Asian context mentioned the type as attached. Generally, the footprints of dwellings in a slum are smaller than in planned settlements, and their shape and orientation do not generally comply with planning standards.

4.3.2. Access network

A slum settlement generally has an irregular access network with variable street types, surfaces and widths (Fig. 1). The Oxford dictionary (2011) defines a street as "*a public road in a city, town, or village, typically with houses and buildings on one or both sides*". Fig. 4 gives an overview of attributes related to street layout and connectivity. According to our field experience and previous literature (Hofmann et al., 2008; Nobrega, O'Hara, & Quintanilha, 2008; Sliuzas et al., 2008), road characteristics are an important indicator for slum identification, as most slums lack proper road networks and existing roads are often poorly connected to surrounding areas. The expert survey confirms this. Terms referring to access/roads appeared in 50% of the respondent's definitions of slums, and 96% of the respondents said that the road layout in a slum is irregular, while only 14% said that it is likely to be well connected with neighboring areas. Slums may also only have footpaths or access streets that are un-paved.

4.3.3. Shape

Slums tend to follow the shape of features such as roads, railways or drainage channels, due to comparatively easy availability of public land (Davis, 2007, pp. 121–150; Neuwirth, 2005). Slums may also be adjacent to planned areas or major ring roads. The terms elongated or linear were used by 59% of the experts to specify the shape of slum in their respective context, while 50% also mentioned irregular. This indicator can be used to find probable location of slums based on distance from such features.

4.3.4. Building density

Building density is a key variable for identifying slums. Slums generally have high roof coverage with no open spaces or vegetation

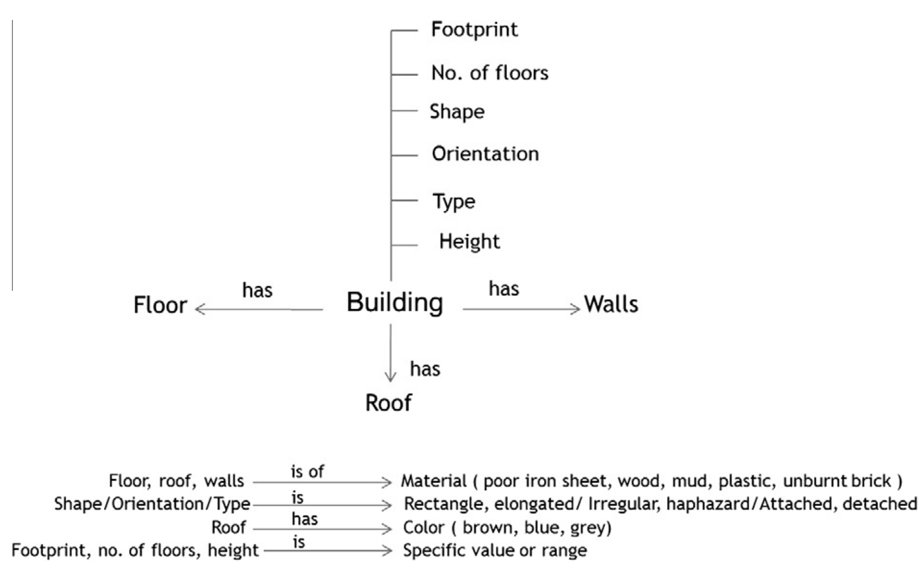

Fig. 3. Diagram of building attributes with the corresponding values derived from the expert survey.

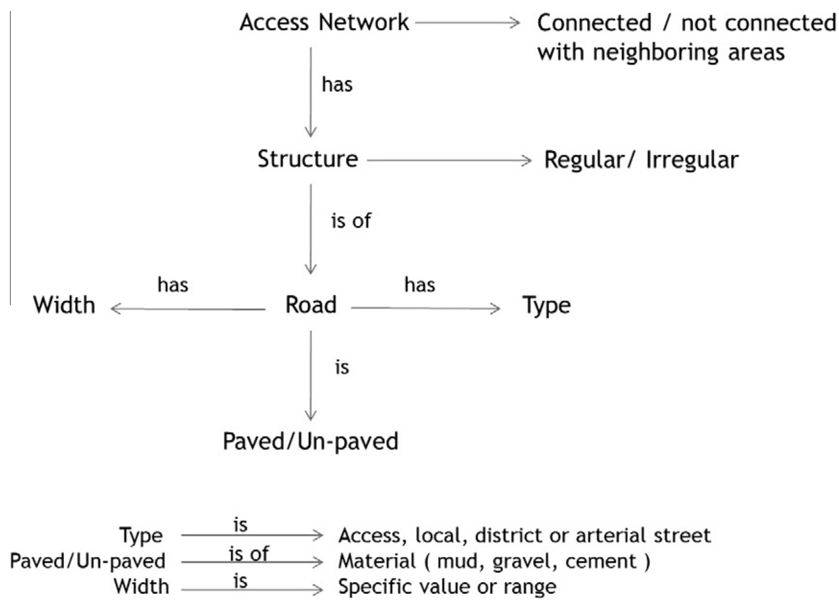

Fig. 4. Diagram of access network characteristics observable via VHR images with the corresponding values derived from the expert survey.

(Davis, 2007; Neuwirth, 2005). For the Asian context, 14 (93%) out of 15 of the experts specified roof coverage as 80% or above. By comparison, in the SSA context only 12 (60%) out of 20 experts who responded to this question specified such high densities. Thus, density differs locally, and it also depends upon the age of the settlement. The association with surrounding areas (planned) plays an important role in using this indicator for identifying slums. Building density plays a central role in a typical slum definition but both dense formal neighborhoods, and low density slums are sufficiently common worldwide to ensure ambiguity. Therefore, density cannot be used as the sole variable for slum identification.

4.3.5. Location

Slums frequently develop on hazardous sites where other development is not possible. A site is defined as a plot or area of land that has been or is intended to be constructed or used for some purpose. Table 4 shows the number and respective percentages of respondents who said that a slum is likely to have a specific site condition. Slums may be found, for example, in flood zones, marshy areas, along railways and on steep slopes (Fig. 5) (see Davis, 2007, pp. 121–150). In Latin American cities, for example, slums may be located on high and unstable slopes, whereas in India the majority of slums are located next to linear features such as roads and canals. These indicators are context dependent, as also became evident from the expert survey. However, the percentage of responses for proximity to railway lines and roads is relatively high in both Asia and SSA. By proximity or closeness we mean the spatial distance that could have a detrimental effect on the living conditions of the people living in a slum. The expression is context-dependent and the implications of distance will vary from place to place. RS can be used to locate probable slum settlements based on hazard zones, height information and GIS layers of the area.

4.3.6. Neighborhood characteristics

The location of a slum settlement depends on socio-economic factors (Fig. 6). Slums are often formed close to opportunities for unskilled or low skilled jobs. The opportunities can be in higher socio-economic status neighborhoods, which lead to the development of informal houses in their vicinity. Industries and central business districts (CBD), in most developing countries, also attract slum development due to employment possibilities such locations offer (Davis, 2007; Neuwirth, 2005). This is evident from the expert survey also. Ninety three percentage of respondents from the Asian context and 72% of the experts referring to SSA said that it is likely that a slum is located close to sites of employment opportunities. Slums further tend to develop in existing low socio-economic areas due to affordable living expenses (Table 4).

Table 4
Number and percentage of experts identifying a site or neighborhood condition as being a likely characteristic of an Asian or SSA slum.

Site or neighborhood condition	Asia (15 valid responses)		SSA (29 valid responses)	
	Number	Percentage	Number	Percentage
Flood zone	6	40	14	48
Steep slopes	3	20	10	34
Close to railway lines, highways, major roads	13	87	22	76
Close to high-voltage power lines	5	33	17	59
Close to hazardous industries	8	53	9	31
Connected to infrastructure in neighboring areas	4	27	9	31
Close to/inside neighborhood of low socio-economic status	11	73	16	55
Close to/inside neighborhood of middle/high socio-economic status	4	27	19	66
Close to employment	14	93	21	72

4.4. Implementation – local adaptation of GSO

Implementation involves the transformation of conceptual model into an implemented model (Fernández López et al., 1999). To illustrate this, we provide one example of local adaptation of GSO to one of the cities used in the expert survey. We emphasize the need for local adaptation of the concepts mentioned in the generic ontology, as not all indicators would apply to all areas.

Kisumu (Fig. 7) is the third largest city in Kenya, with a population in 2004 estimated at 500,000. It is one of the poorest cities in Kenya with more than 60% of population living in slums (UN-HAB-

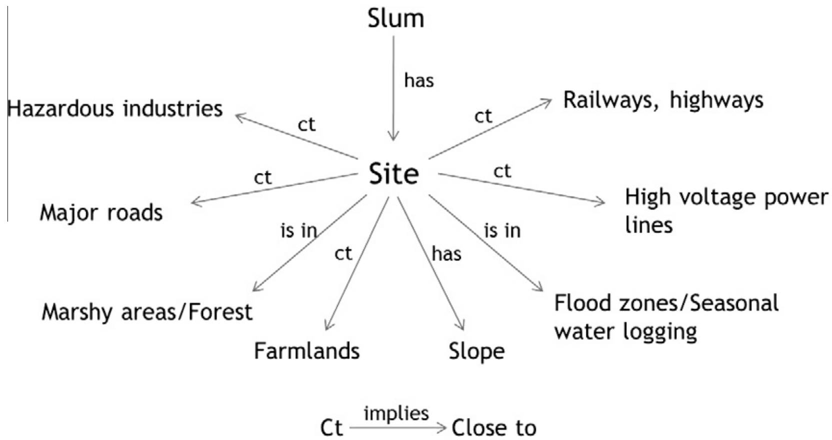

Fig. 5. Diagram showing possible site conditions of a slum derived from expert survey.

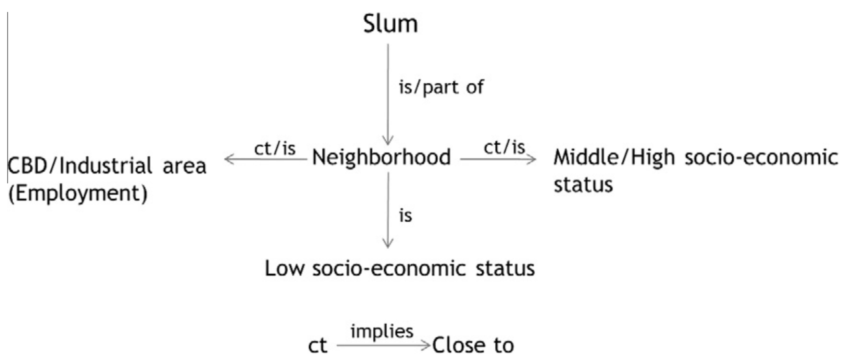

Fig. 6. Diagram of socio-economic factors that are possible driving forces for development of slums according to domain expert survey.

ITAT, 2005). Urbanization and lack of planning over the past decades have led to uncontrolled slum formation, with slum settlements encircling the entire inner planned area of the city. This is evident from the clear contrast between the planned areas and the slums in the image (Fig. 7). We used a subset of Kisumu for slum delineations by respondents in the expert survey. The experts were provided snapshots of Google Earth images in kml format that could be reopened with the same extents (Fig. 1). Fig. 8 shows an example of slum outlines by five experts for Kisumu. The slum boundaries have deviations as three respondents in this example

Fig. 7. A snapshot of Kisumu, Kenya. The Nyalenda slum area is clearly visible below the major road running diagonally from bottom left to top right.

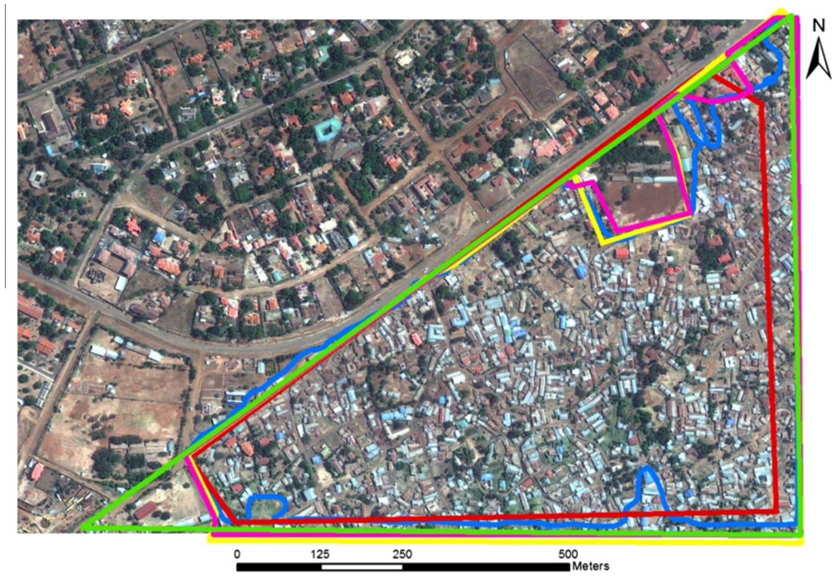

Fig. 8. Delineations of slums from a snapshot of Kisumu, Kenya produced by five randomly selected domain experts.

excluded patches of open areas. One respondent included one open area while the remaining expert (green[1] colored) outlined the area including both open areas. The difference in boundaries could also be due to shift in the image extent while digitizing in Google Earth. Nonetheless, there is considerable overlap between the delineations and the indicators used in the decision-making process. The following indicators recurred while reading through the respondent's factors for slum delineations in this context: Color, shape, size and orientation of buildings, chaotic street pattern, irregular layout, high density, less vegetation, contrast with planned area and haphazard development.

Table 5 summarizes the observations of visual image interpretation integrated with the knowledge of slums from local experts. These observations helped to understand the characteristics of slums in Kisumu. Four main indicators comprising spectral range, geometry, texture and association were chosen to translate the slum knowledge into specific OOA parameters.

Table 6 shows the analysis of physical characteristics adopted from the generic ontology that can be used as the basis for identification and classification of slums in this particular context. In Kisumu, the haphazard orientation of individual buildings, irregular and unpaved roads, high density of settlements, and location in flood-prone and marshy areas were the most important observations for slum identification by experts with local knowledge and visual interpretation. These observations were further categorized and analyzed based on the ontological framework by assigning potential parameters for each relevant attribute. It is to be noted that a set of relevant attributes or their thresholds will differ for different contexts. Nonetheless, the GSO provides the basic set of indicators relevant to represent slums in an image.

The detailed analysis of translation of ontological concepts from object to environs level is shown in Table 6. At object level, the layer mean values and brightness can be used as the main spectral features to represent roof color and its material. Main direction, angle of buildings and shadows are important parameters to classify slums, considering the haphazard nature of buildings in Kisumu slums. The shape features chosen to characterize buildings include rectangular fit, elliptic fit and area. Number of nodes is an important parameter for roads, as irregular roads tend to have

Table 5
Translation of visual observation and expert knowledge to image-based indicators.

Image observation	Knowledge of slums from local experts	Indicators
Buildings range from bright grey to a dark brown color; a few are bright blue and red.	Majority of roofs constructed from galvanized iron sheets, tin, few painted with blue and red color	Spectral
Same building with varying colors	Single building made up of mixture of old and new iron sheets	
Rectangular and elongated shape of buildings, varying building size	Row houses for rental purpose – many units in a single building	Shape/ Geometry
Irregular orientation of buildings	Buildings built haphazardly due to lack of planning	
Unpaved and irregular roads	Access through unplanned mud roads	
Irregular shape of slum settlements	Slums form a belt around the planned area and are along the major roads	
Settlements surrounded by farmlands	Traditional houses/villages being engulfed by uncontrolled slum development	Association
Settlements in swamps, black soil	Some slums located in marshy and flood –prone areas	
Clear shadow in the west of the building	Single story buildings mostly	
Variable densities	Density of buildings higher than planned areas	Texture

higher number of nodes compared to planned roads. Length and width can also be used to classify roads as there is a high concentration of access paths within the slum areas unlike planned settlements, where there are regulations for the length, width and area of roads. Unpaved roads can be classified using spectral signatures. The belt-like shape of slums in Kisumu, which border the planned areas, can be characterized by using a buffer around the major road. At settlement level, texture measures can be potentially used to represent the contrast between planned and unplanned settle-

[1] For interpretation of color in Figs. 1, 7 and 8, the reader is referred to the web version of this article.

Table 6
Adaptation of ontological concepts from generic slum ontology to the case study and its respective OOA parameterization.

Level	Indicators	Interpretation element	Observation (Kisumu)	OOA parameterization
Environs	Location	Slope, pattern, secondary data	On flood zones, marshy areas, close to farmlands, and along highways	Association – distance to features
	Neighborhood characteristics	Pattern, secondary data	Surrounding the planned areas, close to sites of employment opportunities	Association – distance to planned settlement
Settlement level	Shape	Pattern	Encircling the major ring road	Geometry – buffer
	Density	Texture	Denser compared to planned	Texture – entropy, contrast, variance, mean
			Low vegetation and open spaces	Geometry – area of vegetation, open space
Object level	Building	Shape	Rectangular	Geometry – rectangular/ elliptical fit
		Size	Range of values – 10 to 40 m^2	Geometry – area
		Material	Roofs-corrugated iron sheets, tin	Spectral – layer mean values
		Color	Range-grey, brown, red and blue	Spectral – maximum difference, brightness
		Orientation	Haphazard arrangement	Geometry – angle of buildings and shadows, main direction
	Access network	Shape	Irregular	Geometry – number of nodes, length
		Type	Unpaved access paths	
		Width	Range – 1–3 m	Spectral – length/width ratio, layer mean value

ments. In addition, areas of vegetation and open spaces are relatively rare in slums due to the high density of buildings. At the environs level, most of the slums in Kisumu qualify for hazardous location, i.e. floods plains and marshy land. The slums have typically developed on former farmlands, resulting in dense, haphazard settlements. The context-related features, in terms of association to certain land use and additional GIS layers, can be used to classify slums in this respect. Further, detailed analysis of all the indicators can help to study intra and inter slum variability, e.g. based on different roof colors, densities, presence/absence of roads, development stage (Sliuzas, 2004).

5. Discussion

The absence of a unique and consistent definition of a slum hinders the development of objective, universally applicable slum detection methods using remote sensing and OOA, which require a clear conceptualization of the object of interest. Our conceptualization of slums is based on information obtained from 50 international domain experts on how they identify and delineate slums from VHR images. The resulting framework is robust enough for global application, though it does still require adaptation to local conditions.

In the expert survey, most respondents referred to countries in Asia and SSA. Thus, it was not possible to integrate knowledge from other regions (e.g. Europe, North America, North Africa, Middle East), and there was also insufficient representation (Table 1) for Latin America. The characteristics of slums could be different in these regions (Dubovyk, Sliuzas, & Flacke, 2011; Neuwirth, 2005). Nonetheless, the study does include two world regions with high rates of poverty and slum proliferation (UN-HABITAT, 2010). To fully verify the validity and value of the GSO, a larger, more representative survey of experts covering all world regions is required. However, even without such a survey, the usefulness of the current GSO can be tested through its application in different contexts.

The description of general indicators, their attributes and values provides insight into the variability and similarities of slums across the SSA and Asian region. For example, the great majority of respondents from the SSA context specified the roof material in slums to be tin or iron sheets, providing a clear regional characteristic. Irregularity of roads is common for almost all the slums in both regions. Other similarities are the relatively high percentages for a slum site to be close to linear features, an aspect that also explains the elongated shape of slums mentioned by a considerable number of experts. Proximity to employment may also be an important driving force for slum development as evident from the responses.

There are also some slight, but noticeable differences between the two regions. A high proportion of respondents specified building type as detached in SSA, whereas the majority of responses from Asia specified the building type as attached, an indication of the higher densities that are generally found in Asian slums. The low percentage of slums located close to hazardous industries in SSA is perhaps more a reflection of the lower rate of industrialization in SSA cities than the importance of this factor. The relatively low percentage of slums close to or inside low socio-economic status neighborhood could be due to the relative lack of formal low income housing; in many SSA cities the slums are the sole source of shelter for low-income groups. Due to the lack of such housing, slums develop and expand informally close to middle or high socio-economic status neighborhoods (see Kisumu example), where services and informal sector employment may be found. Further work is needed to confirm the validity of such observations.

6. Conclusion

The generic slum ontology (GSO) provides a set of well-defined attributes that can be used as a starting point for a systematic approach to identify and classify slums. It is useful for the understanding of the relation between image and actual slum characteristics, as it provides the opportunity to integrate local knowledge through the selection of relevant attributes and by adjusting the parameters for each selected attribute to local conditions, as was demonstrated in the Kisumu example. These parameters may be used for practical application in an OOA environment to translate ontology into an operational system of image classification. The GSO can, therefore, be used as a conceptual classification schema as a basis for information extraction from VHR images. In subsequent work, we will adapt and apply the generic ontology to other contexts using an OOA. We expect that such an approach will help to remove the ambiguities in slum definition and also guide the classification process in an objective way. The comprehensive knowledge base that can be generated is important for addressing problems related to monitoring slum growth but perhaps more importantly in supporting slum upgrading and improvement.

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