Developing an urban sustainability toolbox using earth observation data and GIS for monitoring rapid urbanisation in developing countries

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1. Introduction

Urban planners require data to monitor sustainable urban development. Accordingly this study is a synthesis of a studies by Musakwa (2013) and Musakwa and Van Niekerk (2013) who evaluated the potential of earth observation (EO) for monitoring and modeling sustainable land use in urban centers using Stellenbosch, South Africa as a case study. The unavailability, unreliability, outdatedness and unstandardised nature of urban land use planning data in developing countries was the motivation for the investigation. Many local authorities are inadequately equipped to plan for sustainable development in hyperchanging environments. Because sustainable land use, like sustainable development, are elusive concepts to put into practice in routine decision-making, an emerging structured framework, decision consequence analysis (DCA) was proposed to aid decision making for sustainable urban land use planning. DCA breaks complex problems, such as sustainable urban development, into increasingly smaller units until the particular component can be accurately analysed and understood within the context of the overall problem. Therefore, sustainable urban land use was divided into three themes, namely land use change and land use mix, urban sprawl and the urban built-up area. Sustainable urban land use indicators for each theme in the toolbox was identified from literature (Table 1)

2. Urban sustainability toolbox

An overview of the toolbox is summarised in Table 2. For the exploration of the socio-economic impacts relating to social and spatial integration, health and safety, the Global Land Use Mix Index (GLUM) and Local Land Use Mix Index (LLUM) indexes and Land Use Frequency (LUF) can be used. Similarly, land use change, impervious surface concentration and the urban extent highlights environmental impacts and are useful for determining the rate of land transformation, human-nature interaction and growth of the urban footprint. LUC informs decisions pertaining to the preparation of local and zoning plans and spatial development frameworks (SDFs). SDFs and local plans illustrate projected land patterns and developments.

Table 1: Selected sustainable land use indicators

Theme	Indicators	Unit of measurement	Analysis scale	Significance and thresholds	Sources
Land use change and land use mix	Land use mix index (global or local)	0 to 1	Neighborhood or city	A land use index of 0 denotes low sustainability and 1 highly sustainable.	Song & Knaap (2004); Song & Rodriguez (2005)
	Land use frequency	Frequency	Neighborhood	A high number of complementary land uses per neighborhood is desirable for sustainability, unlike low mixing intensity.	
	Land use change	Percentage	City or town	Land use change impacts all the other indicators. A change from natural ecosystems to urban use is generally unsustainable.	
Urban sprawl	Global Moran I	-1 to 1	Global	A value close to 1 denotes compactness, which is highly sustainable, a value close to 0 indicates random scattering, while -1 denotes a dispersed pattern, which is highly unsustainable.	Anselin (1995, 2003, 2005)
	Local Moran *I*	A positive value denotes spatial clustering and a negative value indicates presence of outliers.	Neighborhood	HH and HL denote hot spots, which are relatively unsustainable, whereas LL and LH denote cold spots that are relatively sustainable.	
	Spatial cluster and outlier identification	High-high (HH), low-low (LL), low-high (LH) and high-low (HL). HH and LL are spatial clusters while LH and HL are outliers.			
Built up-area	Building density	Buildings per hectare	Neighborhood	20 or less building units per hectare (bu/ha) is regarded as low density, between 20 to 50 bu/ha medium density and greater than 50 bu/ha as high density	Angel (2010); Ewing (1997); Urban Land Institute (2010)Jabereen (2006); Jones & MacDonald (2004)
	Building height	Storey's	Neighborhood	2-12 storeys reduce environmental, social and social costs. Above 12 storeys increases cost significantly	Ding (2013); McLennan (2009); Yabuki, Miyashita & Fakuda (2011)
	Impervious services	Impervious surface per hectare	City and neighborhood	A mix of pervious and impervious required for cities to breathe	Nowak & Greenfield (2012); Weng (2012)

Table 1.1: Urban sustainability toolbox

Component	Indicator	Impact on urban sustainability	Urban planning decisions which the indicators can inform	Ideal data sets
Land use change and land use mix	Land use change (LUC)	Environmental	– Promote efficient use of space by managing change from non-urban to urban uses, that is reduce land transformation and growth of the urban footprint. – Facilitate development of spatial development frameworks, zoning and local plans.	– Land use data – Cadastral data
	Global land use mix (GLUM) index Local land use mix (LLUM) index Land use frequency (LUF)	Socio-economic	– Promotion of mixed-use cities – Planning for spatial and social integration as well as urban designs that promote the pavement-cafe idea (social vibrancy). – Planning for safe and healthy communities – Improved access to socio-economic opportunities	
Urban sprawl	Global Moran index (Moran I) Local Moran index (Moran *I*)s	Environmental and socio-economic	– Identification of urban sprawl hot and cold spots – Land parcel intensification, subdivision and consolidation as well as densification strategies – Promotion of social and spatial interaction through planning of different land parcel sizes. – Efficient use of space to facilitate development of compact cities or the alternative making room paradigm. – Planning for public transport – Planning for new developments that amortize infrastructure costs.	– Land cover – Cadastral data
	Urban extent	Environmental	– Demarcation of urban edge and planning for future growth – Rate of land transformation, i.e. non-urban to urban uses	
Built-up area	Building count and density	Environmental and socio-economic	– Densification and intensification strategies – Service provision, i.e. amortization of infrastructure costs – Provision of public transport, circulation, accessibility, and parking – Other urban planning issues such as flood risk management, informal settlement upgrading, population estimates and disaster management – Encouraging social and spatial integration	– Land cover data
	Impervious surface concentration	Environmental	– Minimizing negative land transformation and indiscriminate growth of the urban footprint – Planning for a healthy mix of built-up areas and open spaces to allow cities to breathe (green infrastructure). – Managing the urban microclimate through landscaping techniques which are important tools in mitigating climate change.	– Land cover data
	Building height	Cross-cutting	– Conserving the cultural heritage – Managing the urban microclimate – Promoting efficient utilization of space, intensification and amortization of service costs	– Digital elevation model – Digital terrain model – Digital surface model

Impervious surface concentration is a vital indicator in the preparation of sustainable urban designs and plans, which allow cities to ‘breathe’ while creating urban microclimates which conserve energy and are comfortable for citizens. The urban extent is important for demarcating sustainable urban growth boundaries as well as a guide for future developments within a defined precinct.

The global Moran and local Moran indexes, building density and count as well as building height constituents of the toolbox are cross-cutting (socio-economic and environmental) indicators of urban sustainability. Building density, count and height as well as the Moran indexes are convenient for formulating densification and intensification strategies, promoting efficient use of space, and the amortization of infrastructure and service costs.

The Moran indexes, building densities and building count are useful for determining the feasibility and capacity of public transport systems and parking facilities and for conducting accessibility studies in urban areas. These indicators also facilitate decision making about practical approaches to urban sustainability that is, selecting between compact-city development or the making room paradigm, depending on the circumstance. Building height is also essential in the conservation of the cultural heritage.

The toolbox can also guide the approval of new urban developments. For example, Stellenbosch is experiencing growth in the number of gated communities marketed as being ‘green’ or ‘sustainable’ (Musakwa & Van Niekerk 2013). The toolbox can test whether these proposed developments are sustainable by applying various indicators to their proposed layouts and the results used for approval of plans or for making suggestions on how property developers can improve their designs and layouts. For instance, the layout of the proposed De Zalze 2 security state (Stellenbosch Municipality 2011) can be analyzed by using the built-up area indicators to test whether the design envisages medium-to-high densities which will enable sustainable urban development targets to be met. Moran analyses can be done on the De Zalze 2 proposal to test if it encourages efficient use. LUC will determine whether the new development will cause indiscriminate transformation of land to urban uses while the LLUM index can be used as a measure of social and spatial integration. Such analyses will help local authorities to approve new developments that are more sustainable.

The urban sustainability toolbox provides the means to monitor sustainable urban land use planning. The toolbox can be applied annually to produce objective sustainability reports and to answer the why, when and what if questions integral to land use decision making. Such reports provide an overview of sustainability status and enables decision makers to identify specific problem areas. In Stellenbosch, Musakwa (2013) revealed that Welgevonden has medium-to-high densities, an average building height of two storeys, a low-low cluster outlier type, and a high (0.8) LLUM index. Such developments should be encouraged at the urban edge because they significantly reduce the environmental, social and economic costs of urban development.

An important feature of the toolbox is that it uses EO data and GIS analysis which enable the visual, graphical and spatial representation of urban sustainability making the information produced more comprehensible and usable for decision making. Unlike tables, which show rate of change, maps show where the change is occurring and this assists decision makers to prepare strategic actions and to target specific areas. The interoperability of EO data with a variety of GIS systems (ArcGIS and GeoDa) is also demonstrated by the toolbox. The indicators in the toolbox can also be incorporated into a SDSS for scenario building.

2.1 Data requirements

The urban sustainability toolbox requires certain data sets. For land use change and the land use mix analyses, land use and cadastral data is needed. Google Earths' Street View, available for major cities and towns in Africa and other developing countries, can help in the classification of vertical and horizontal land use mix. Three-dimensional city models and digital surface models, where available, are also invaluable for identifying mixed land uses and other land use classes such as commercial and industrial.

The calculation of Moran indexes requires cadastral data which is available for most developing countries. Scanned layout plans or designs projected for use in GIS software such as ArcGIS can be used for calculating the Moran indexes because they contain land parcel data. The global Moran I requires urban extent data, which can be derived from land cover maps.

The analysis of building density and count also requires land cover data. Three-dimensional building models derived from light detection and ranging (LIDAR) data can be used to demarcate settlement structure as well as building density and count. Land cover data is also necessary for calculating impervious surface concentration. Improved land cover classification of urban surface material calls for hyperspectral satellite imagery because it can better distinguish urban surface materials (Nichol et al. 2007; Weng 2012). Building height calculations require a digital terrain model (DTM) and a digital surface model (DSM) derived from VHR stereo-pair imagery or LIDAR. DSMs are also useful in land use classification and for demarcating the urban extent.

Urban planning has traditionally used VHR 0.5 m aerial photographs for mundane tasks such as property identification. The availability of VHR 0.5 m spatial resolution satellite imagery holds great potential for assisting urban planning because it has the required finer spatial resolution to discriminate urban features and a high temporal resolution to detect changes at high frequency. Consequently, it is possible to produce up-to-date data sets of land use and land cover, which is crucial for understanding human-nature interactions.

The urban sustainability toolbox is flexible and can be modified by adding indicators or by choosing specific indicators depending on the issue in question. For transport issues, for instance, the requisite travel-related data can be added. The toolbox is also not confined to urban sustainability studies as it can be applied for population estimates, disaster management and telecommunications planning. This flexibility and applicability ensures cost-effectiveness and data sharing, which can lead to better urban planning decisions.

The urban sustainability indicators used in the toolbox are normalized and presented in standard format. This implies that they are universally applicable and can be used for rapid comparative studies of urban centers and development of place-independent models. Furthermore it facilitates rapid comparative studies of urban centers, learning from best practices, knowledge sharing (particularly in developing countries), identification of problem areas, modeling of future scenarios, and the effecting of policy changes

2.2 Limitations

Paradoxically a weakness of the toolbox is the reliance on remotely sensed data (satellite imagery and aerial photographs). The presence of errors in EO-derived data sets (e.g. land use, land cover, building height) is acknowledged and should always be taken into consideration when the indexes are used in decision making. Fortunately, the relatively high accuracies of (>75%) attest that EO is a reliable source of spatial data (Musakwa & Van Niekerk 2013). A further limitation of the toolbox and EO in general is the difficulty of determining mixed land use using remotely sensed imagery. This is a major constraint for automating land use mapping using remotely sensed imagery, as field surveys are in most cases necessary for producing accurate land use maps of urban centers. New sources of data, such as Google Earth's Street View product, holds much potential for reducing expensive and time-consuming field surveys for determining vertical and horizontal mixed land use. This data is, however, not yet available for all urban areas.

The use of cadastral data in calculating the various indices by the toolbox can also be regarded as a potential limitation of the toolbox because it may not be available in all urban centers. This type of information is difficult to extract from remotely sensed data, particularly in urban areas. Air pollution data is important in monitoring urban sustainability (NASA 2009; Nichol et al. 2007), but it not available at a suitable resolution. Hopefully new initiatives such as the scheduled launch of a space borne sensor for monitoring air pollution in 2017 (Geoinformatics International 2012) will address the lack of such data. Travel-related data is also critical for urban land use planning but is normally not available at an intra-urban scale in developing countries. The lack of travel-related data is a general problem in developing countries (Hicken 2009). Cellphones equipped with global navigation satellite systems (GNSS) and volunteered geographical information (VGI) may provide a solution to monitoring movement of people in urban centers, but this kind of data was not explored in this research.

Census data, another important data source for urban planning, is not used in the toolbox It has, however, been shown that EO can be employed to monitor population dynamics (Almedia et al. 2011; Ural, Hussain & Shan 2011).

3 Conclusion

Local authorities often rely on various formats of data, some of which are inadequate, unreliable and outdated. This inevitably makes the monitoring of sustainable land use planning and urban growth unworkable, hindering local authorities capacity to leverage resources towards sustainable development. The use of EO data and GIS analysis is a resolution to the issues of unavailability, out-datedness and unreliable forms of data experienced in most developing countries undergoing rapid urbanization which makes it difficult to monitor and plan for sustainable urban development. Consequently the toolbox enables local authorities to carry out a holistic, systematic and objective view of the trajectory of sustainable urban land use development. The developed toolbox empowers role-players to make evidence-based decisions as opposed to incremental planning, subjective decisions and advocacy planning or merely accepting compact development as the only sustainable urban development paradigm.

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