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Abstract

South Africa's largest cities are subjected to high rates of urbanization with a projected 8 million people migrating to these urban spaces by 2030 [1]. Managing and guiding this growth is made more difficult due to the countries 'apartheid city' past - a segregated city form inherited from the pre-democratic order in 1994 where towns and cities were spatially engineered along racial divides. With the advent of a democratic order in South Africa in 1994 a number of policy frameworks have seen the light all of which have indicated the need to spatially transform cities and settlements – to break from the pre-1994 apartheid city. Measuring the progress made in spatial and socio-economic transformation has proven difficult as some information have only been provided at city or Local Municipal scale. To measure spatial outcomes, city performance, quality of life etc. a series of local and international city scale indicators has been developed. These however are only useful when comparing cities; it does not convey sub-city scale change or transformation. This paper profiles an approach that uses a single-sized uniform tessellation to create demographic and economic indicators for nine cities and explores the utilisation of this tessellated framework to analyse and depict demographic and economic change over time.

Keywords (separated by '-')	Spatial framework - Tessellation - Transformation of cities - City indicators - South-Africa

Developing Spatial Indicators Using a Uniform Tessellation to Measure Urban Transformation

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Abstract. South Africa's largest cities are subjected to high rates of urbanization with a projected 8 million people migrating to these urban spaces by 2030 [1]. Managing and guiding this growth is made more difficult due to the countries 'apartheid city' past - a segregated city form inherited from the pre-democratic order in 1994 where towns and cities were spatially engineered along racial divides. With the advent of a democratic order in South Africa in 1994 a number of policy frameworks have seen the light all of which have indicated the need to spatially transform cities and settlements – to break from the pre-1994 apartheid city. Measuring the progress made in spatial and socio-economic transformation has proven difficult as some information have only been provided at city or Local Municipal scale. To measure spatial outcomes, city performance, quality of life etc. a series of local and international city scale indicators has been developed. These however are only useful when comparing cities; it does not convey sub-city scale change or transformation. This paper profiles an approach that uses a single-sized uniform tessellation to create demographic and economic indicators for nine cities and explores the utilisation of this tessellated framework to analyse and depict demographic and economic change over time.

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1 Introduction

Presently, South Africa like many other African countries is experiencing high levels of urbanization with The Presidency [1] projecting that nearly 8 Million people will migrate to these urban spaces by 2030. The United Nations [2] estimates that in 2030, 71% of South Africa's population will be living in urban areas, reaching nearly 80% by 2050. Cities have to track this growth and change in order to adequately respond to and guide (infrastructure) investment decisions. In the past, cities would develop this data for their own use; however, this makes comparison between cities difficult, if not impossible. Developing consistent comparable data allows cities to learn from the experience of other cities and efficiently use their resources to build sustainable cities. An additional and uniquely South African challenge relates to South Africa's Apartheid past which resulted in segregated cities. Apartheid city design, especially the fact that many township areas were placed on the periphery of cities, left a legacy of sprawled, low density,

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two-tier cities that resulted in inefficiencies and unequal access to economic and service opportunities affecting the livelihoods of many South African citizens([3–5]). Since the change to a democratic government in 1994, the need to address the resulting socio-economic inequalities, racially divided cities and to spatially transform cities to provide equal opportunities and sustainable means of living for all citizens has been placed high on the political and planning agenda (See [6–11]).

The term 'spatial transformation' is often used more broadly to refer to far-reaching urban change or urban restructuring. It is also a descriptive term to encapsulate the idea that cities have changed greatly over time due to urbanization (See [12, 13]). However within the South African context, Oranje [14] indicates that spatial transformation relates mostly to those efforts aimed at ***addressing the physical manifestations of Apartheid planning***. Exploring and tracking place-specific progress and spatial transformation is, however, a major challenge, not only in South Africa but in many other fast growing cities in the world and especially in the Global South [15]. Challenges to adequately measure (detect) changes and explore implications thereof include not only identifying and developing relevant spatial-specific indicators or measures, but also issues related to data availability, exploration, temporal and place-based comparisons, resources and the capacity to track change [16]. Spatially-specific indicators are critical, not only in: (1) investigating how the landscape has changed and how much progress has been made with spatial transformation in South African cities during the last 20 years, but also to; (2) contribute towards driving and monitoring just and sustainable spatial outcomes in cities moving forward.

This article showcases the results and methodologies used in developing particular explorative, standardised and replicable sub-city level spatial indicators which were developed to track spatial change and progress with spatial transformation at sub-city scale over the last 20 years in South African cities. It reflects work undertaken to support the 2016 State of Cities Report[1], published by the South African Cities Network.

2 Developing Indicators to Track Spatial Change in South Africa

In 2014, a 'Spatial Transformation of Cities' Conference was held in Johannesburg and the event reaffirmed that in order to gauge if actions to transform cities are manifesting in actual change, evidence needs to be tracked. There is thus a need to identify and develop a suite of suitable indicators to measures and track transformation. Kusek and Rist [17, p. 65] define indicators as "the quantitative or qualitative variables that provide a simple and reliable means to measure achievement, to reflect the changes connected to an intervention, or to help assess the performance of an organization against the stated outcome". Before creating any indicator it is important to know what objective needs to be achieved. Indicators are only appropriate "when they are measured against an objective" [17, p. 57].

The starting point in the development was to consider the existing data sources, from which spatial specific indicators can be developed, to determine their use and viability.

[1] http://www.socr.co.za/.

Currently most locally relevant spatial data sources for metropolitan cities are presented using the local municipal demarcation. Some items do goto a finer grain using statistical spatial units such as Wards, Sub-places or even Small Area Units (units used in South Africa by the local census bureau, Statistics South Africa). These items allow for not only city-to-city comparison, but also intra-city comparisons. However, these demarcations vary from one census to the next which does not allow comparability over time.

3 Objectives

One of the key objectives of the research project was to develop indicators to explore spatial change, levels of growth and spatial transformation on an intra-city level over time. In other words, particular indicators relating to bridging the data gap and **exploring sub-city level changes were the focus**. The intention was to identify spatial patterns and concentrations of people and activities, growth areas and linked changes in urban structure, resource allocation and effectiveness of public services provision (e.g. public transport). It should be acknowledged that spatial change can be depicted innumerous ways and that no single indicator can provide a clear indication of spatial transformation as it relates to the subjective experiences of people within cities. It can however be utilised to provide an objective overview of major socio-economic shifts. Spatial indicators can, however, add value in providing some indication of embedded spatial patterns and the areas undergoing the biggest changes within cities (in terms of population density, concentration of economic activity), and also in addressing questions related to the spatial relationships between such changes. The intent was to spatio-temporally track aligned data to identify:

- spatial specific patterns of population concentration and growth;
- spatially embedded formal economic concentration, agglomeration and growth patterns; and
- enable comparative analyses of fine-grained spatial patterns and changes in spatial patterns within cities – comparing place specific spatial change, as well as comparing spatial change and growth patterns between cities.

4 Developing Spatial Specific Indicators – Challenges and Principles

4.1 Challenges When Developing Spatial Indicators

There are a number of challenges associated with the development of spatial indicators. Some of the most noticeable challenges include the unavailability or incompleteness of data, difficulties collecting source data, methodological changes in the capturing of source data, incomplete time series data and inconsistent statistical methods used in the indicator-development phase. The spatial unit used when capturing data poses additional constraints, such as, (1) size variation, creating a statistical bias also known as the modifiable areal unit problem (MAUP) and (2) significant boundary changes between data collection periods (e.g. census years).

The scalability of data (e.g. South African voting districts which do not align to units such as sub-place or main place or even small area layers) also adds additional constraints in indicator development. It is also the objective to have indicators that are more spatially-specific or of a sufficiently fine resolution to allow the observation of localised changes in the data. This overcomes some of the generalisation that occurs when using larger administrative units such as local municipal boundaries.

4.2 Challenges of Scale

It is important to note that although some of the information collected by various metros, departments and institutions might be collected at local sub-city level, the information presented in the various indicators are regularly aggregated and aimed at a broader scale and intended for a comparison of cities. The reporting units being used for city-level indicators are administrative units (mostly local municipal unit) which do not reflect the true spatial grain of features such as population distribution, land-use patterns, etc. [18]. Metropolitan areas, such as Gauteng, stretch across local municipal boundaries, yet are mostly reported within a particular local municipality (the seat of Metropolitan area). The measurement of items is influenced by the scale that is used, when aggregating information, a measure of generalization occurs [18]. This is particularly relevant when considering an item that is scale-dependant where the geographic extent is sensitive to the spatial arrangement [20, p. 200]. This begs the question – what is its usefulness in measuring spatial transformation? To enable sufficient pattern detection of spatial features it is necessary that the scale be sufficiently fine (for purposes of detecting spatial transformation for example). When the size of measurement unit decreases the spatial variance or heterogeneity also decreases [21]. Appropriate finer-grained information is more useful to grasp the spatially explicit realities which in turn can contribute more to policy–relevant information. A constraint can, however, be in the computational complexity required if a completely new or unaligned fine spatial unit is used.

4.3 Grain of the Tessellation

The resolution of the spatial unit used to present the information can impact on what is portrayed. Using different units to group information can create different statistical and visual results. This is the result of group aggregation and inferencing underlying (continuous) data into different sized zones and is more problematic when larger zones are used [22]. MAUP (a term coined by Openshaw and Taylor in the late 70's) is a well know spatial statistical bias problem when analysing and representing spatial data with varying spatial scale and resolution. This is a particular and noticeable problem when representing quantity mapping (e.g. population densities) [23].

This problem is clearly observed in Fig. 1 showing population changes from 1996 to 2011 using two zone types: map a reflects sub-place units where as map b reflects information using a fine grained uniform hexagon tessellation. The result of what is reflected in terms of growth and decline appears substantially different – aggregation

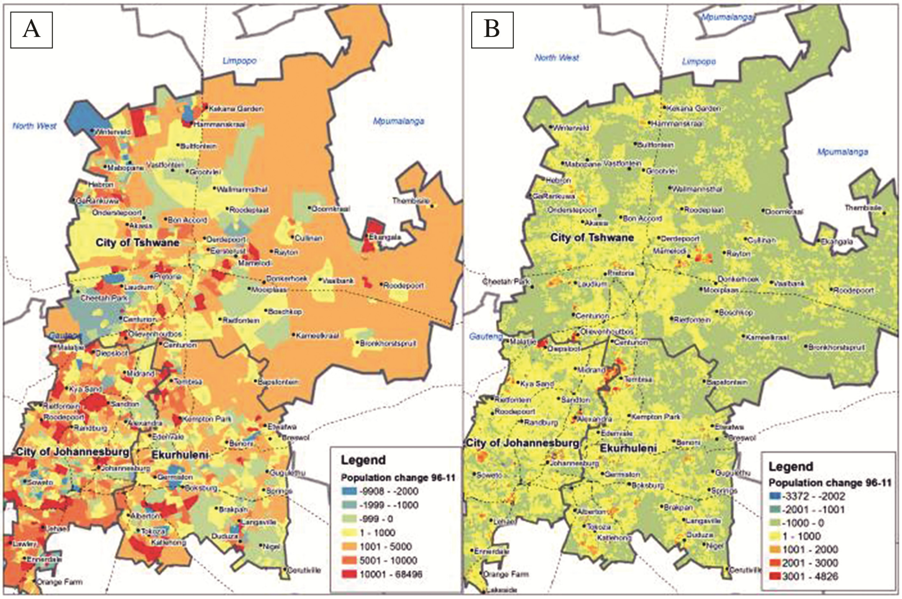

Fig. 1. Change in total population per sub-place 1996–2011 compared to hexagon tessellation for the Tshwane, Johannesburg and Ekurhuleni metros [24].

using the coarser sub-places unit reflects what appears to be substantial increases in quite large areas (and the opposite in cases of decline) whereas, when looking at the same change in a finer grained map (using the same density increments for the thematic map categories), the changes are much more isolated or focused making the areas of change appear less dramatic. This does however allow much more focused analysis of the causes with a high probability that the casual deductions will be more accurate due to less generalisation in the area of influence being considered or then help with a more focused intervention.

5 Research Approach and Methodology

The development and exploration of sub-city indicators required several steps which included; basic research into each item, data extraction (or update if already available), preparation, and calculation of the indicator, as well as considering and reflecting on the standards with respect to developing indicators. However, it also required the development of a separate new uniform tessellation to correct for the spatial bias introduced by the sub-place boundaries.

To improve the spatial resolution of information at sub-city level, a single fine grained uniform hexagon tessellation (using 1 sqkm hexagons) was created for each city. Total population and economic information was assigned to this hexagon tessellation using a dasymetric mapping process, which is defined generally as the use of an ancillary data set to disaggregate coarse resolution data to a finer resolution [25]. This was done for both population and total economic production (process explained later in this section).

5.1 Creation of Tessellation

To accommodate for the statistical bias introduced by size and scale variation (discussed in the previous section) we propose that a 1 sqkm hexagon be used as the basic spatial analysis unit. The unit was considered to be of a fine enough resolution maximising spatial granularity while preserving computational processing time. In order to ensure that the indicators were comparable between cities the hexagons had to nest with the main administrative boundaries of the cities. The process followed to derive the 1 sqkm hexagons included; (1) Selecting all administrative boundaries of participating cities and (2) Subdividing the administrative boundaries of the cities into a fine equal-sized resolution. Various iterations were run to ensure that the finest grain resolution were chosen that still allowed for optimal computational processing time when aggregating the disaggregated data layers.

The administrative city areas were systematically divided into 1 sqkm equally sized hexagons using the 'Repeated shapes for ArcGIS' tool developed by Jenness [26]. Each one of the hexagons derived had a unique assigned spatial ID to serve as the primary key. This basic analysis unit (1 sqkm Hexagon) corrects visual distortions and statistical bias and allows a fine enough resolution to make comparisons of quantities (how much is located were) feasible and statistically significant. Such a unit proves particularly useful for spatial analysis and visualisation due to its equal size and fine resolution.

5.2 Dasymetric Assignment

The population data was assigned to the analysis units (hexagon tessellation) based on an algorithm developed by the CSIR and which is based on the principles of dasymetric mapping. A dasymetric map is the result of a procedure applied to a spatial dataset for which the underlying statistical surface is unknown, but for which the aggregate data already exists. The aggregate dataset's demarcation is however not based on variation in the underlying statistical surface but rather the result of convenience of enumeration [25, 27]. The production of a dasymetric map involves transforming data from the arbitrary zones of the aggregate dataset to recover (or try to recover) and depict the underlying statistical surface. This transformation process incorporates the use of an ancillary dataset that is separate from, but related to, the variation in the statistical surface [25]. Dasymetric mapping therefore has a close relationship with areal interpolation – the transformation of data from a set of source zones to a set of target zones with different geometry [26, 29, 30]. Areal interpolation is mostly an aerial weighting procedure and does not take ancillary sources into consideration when the spatial distribution of data is refined. Many areal interpolation methods can be incorporated into dasymetric mapping methods to improve the detail of a choropleth map below the level of the enumeration unit [29, 31]. As can be deduced from the principles of dasymetric mapping as a method of areal interpolation, the accuracy of the depiction of the data is heavily dependent on the quality of the ancillary data used to predict the variation in the spatial distribution of the variable in question. Another consideration is also that the ancillary data used must be updated regularly (at least yearly) to ensure consistency for future updates [32].

The ancillary data set used in this specific instance was a reclassified version of the SPOT Building count [31], of which ESKOM the national electricity provider, is the custodian. This is a spatial dataset consisting of about 14,000,000 points. Each point representing a building structure in the country. CSIR then went through an incremental process of classifying these points according to the underlying land cover. Then, based on the underlying land cover and amount of people according to the census within the area the point is based in, an approximate number of people – potentially residing in this structure – was assigned to the point. The result is that each point has a potential weight (number of persons residing there) relative to all other points in the country. The points therefore represent, or try to represent, the underlying statistical surface of the census data. As a result of assigning these potential population weights per point a flexible data frame was created to allow the transference of any socio-economic census data (household based data) from any of the census demarcations to a demarcation of choice by the user. This allocation and re-allocation procedure is represented by following inputs and processing steps [32]:

Input variables:

1. Population total per origin unit
2. Points that represent houses for the whole country
3. Weight per point representing potential household size

Process Steps:

4. Link points to origin units
5. Sum the weights of the points belonging to each origin unit
6. Per origin unit divide the weight of each point belonging to that origin unit by the sum of the weights as calculated in (5) above (thus proportional contribution of each point per origin unit)
7. Multiply the proportional contribution of each point with the population of the origin unit that point belongs to (thus redistribute the population per origin unit proportionally to the points inside that origin unit based on the relative weight of the point, getting the population per point)
8. Link points to destination unit
9. Sum the population per point (7 above) for the destination unit a group of points belong to.

5.3 Visualization

There has been large uptake of 3D information through applications such as virtual earth, Google Earth and second life and it is proving very useful for urban planning [34]. Through technology advancement, more application of 3D is becoming available to the mainstream public user. The advantage of presenting spatial information in 3D is that complex information can be provided to audiences with little or no cartographical or GIS experience [35]. In this project the spatial information created in 2D was converted to 3D using ArcGIS Pro. A 3D scene was created using both background layers as well as online maps. Values such as population or economic production numbers were used to create the elevation item. The landscape was titled to portray the 3D extruded values of the hexagon values for the relevant cities. The hexagon information was not only used in 3D map form, the data was also further analysed using transects and is arithmic maps.

An added advantage of using a fine grained uniform hexagon tessellation to portray and analyse the data is that it allows for more aesthetic maps without any MAUP effect. The regular sized grid also contributed to easy and accurate communication of the transect data as each value unit is equal in distance when portrayed on a graph which eliminates any distortions and leads to easy interpretation and communication.

6 Application

Using this fine grained uniform hexagon tessellation enables users to see a less distorted picture of the information because the information is sufficiently fine grained. It can also be displayed in different ways, primarily aimed at the identification and comparison of:

- Spatial patterns of concentration and growth of a particular trend i.e. population density within a city, and also across boundaries – highly useful in discussions regarding nodes, corridors, identification of growth areas in and on border areas, etc. (See Figs. 2 and 3);

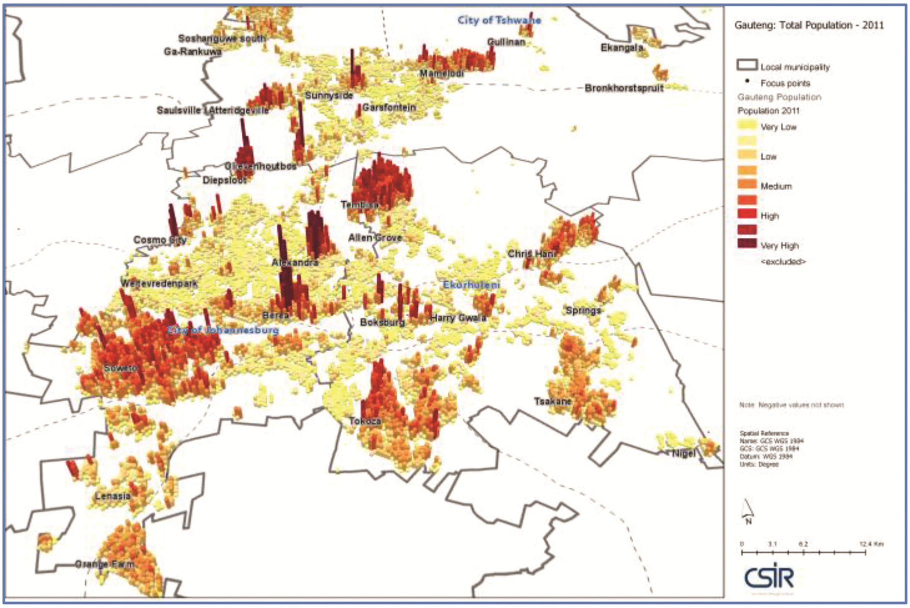

Fig. 2. Spatial patterns of population concentration reflected for the three metropolitan areas in Gauteng for 2011 [24].

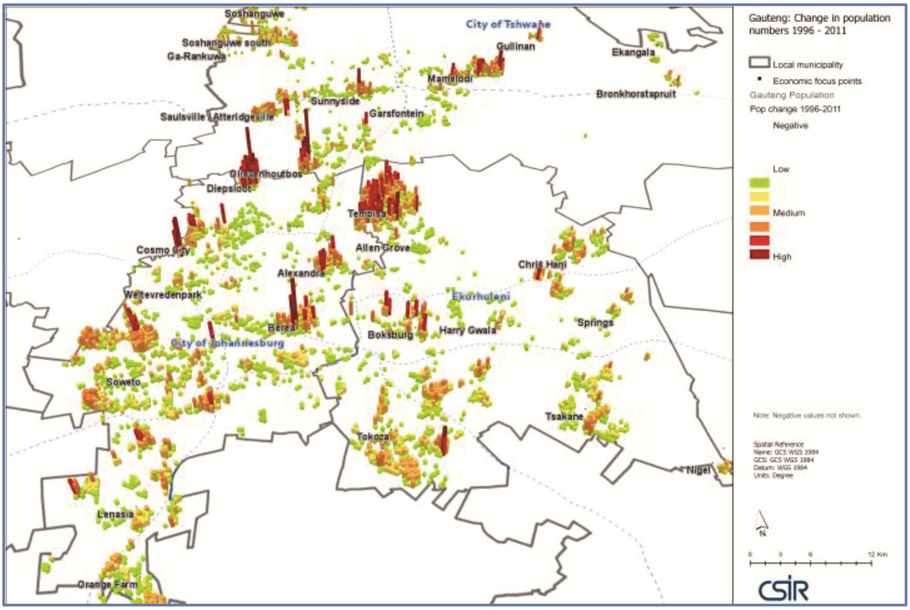

Fig. 3. Spatial patterns of population growth reflected for the three metropolitan areas in Gauteng [24].

- An indicator across time between cities, i.e. increase and change in population density across different cities to explore possible patterns, i.e. increased densities and development on the outskirts of cities;
- Spatial concentrations and changes/embeddedness of patterns of population and economic growth within a city across time (See Fig. 4).

Using a fine grained uniform hexagon tessellation as depicted in Fig. 2 enables a comparable depiction across space. Using GIS software a 3D-bar landscape map is created with the extruded values representing the value of the attribute (population or total economic production). Looking at the 3D tessellation of population further assists in 'reading' the values. The advantage is that the areas of largest growth or highest value can be easily observed more clearly. Dense versus less-densely populated areas are clearly visible. Taking the same spatial surface but comparing only the change in population (Fig. 3) helps to visualize whether the growth that materialised was aligned with development objectives such as 'not developing township type settlements on the periphery of cities', etc.

Using this approach, different items can be depicted for the same area – Fig. 4 depicts the change in population as well as in economic production. Although the actual numbers cannot be compared one-to-one, the change when reflected along a relative scale can be useful when comparing change in population versus economic production.

Considering the locational and strategic planning context it then becomes easier to judge the result of policies such as densification, corridor development or economic development growth points. Comparing planned with actual development can assist in informing planners and city managers whether their efforts in transforming cities, in line

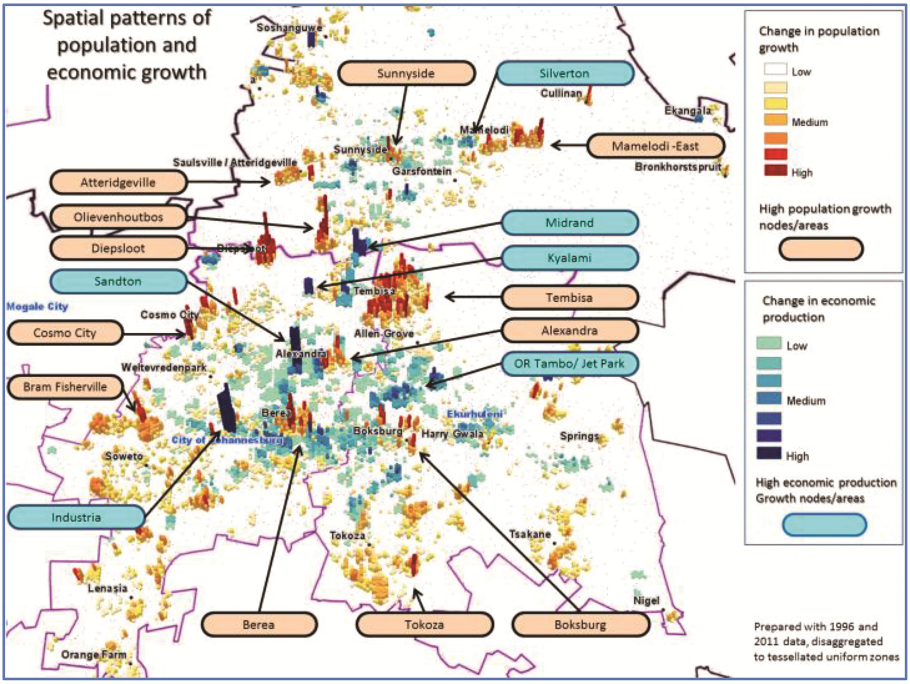

Fig. 4. Comparing spatial patterns of population and economic growth [24].

with their spatial plans, are succeeding or not. The contribution of the spatial concentration and growth indicator is, however, not merely in the identification of patterns as illustrated above, but even more so in enabling advanced spatial analyses related to comparison of patterns across distance bands and over time. An example of comparison of areas across different distance bands is done by developing line transects. Figure 5 uses uniform distance intervals, drawn from this newly developed socio-economic sub-city indicator dataset, where the values are truer when considering distribution and distance than datasets that vary in size. A buffer distance of 5 km is applied along the transect. A more statistically unbiased representation is created because the units along the transect are regular.

In the same vein, comparison of areas across different time scales can be done by developing 'heat contour' maps (see Fig. 6) that also use uniform intervals, where this newly developed socio-economic sub-city indicator dataset enables comparison across time scales whilst data gathering and sub-place area boundaries have shifted.

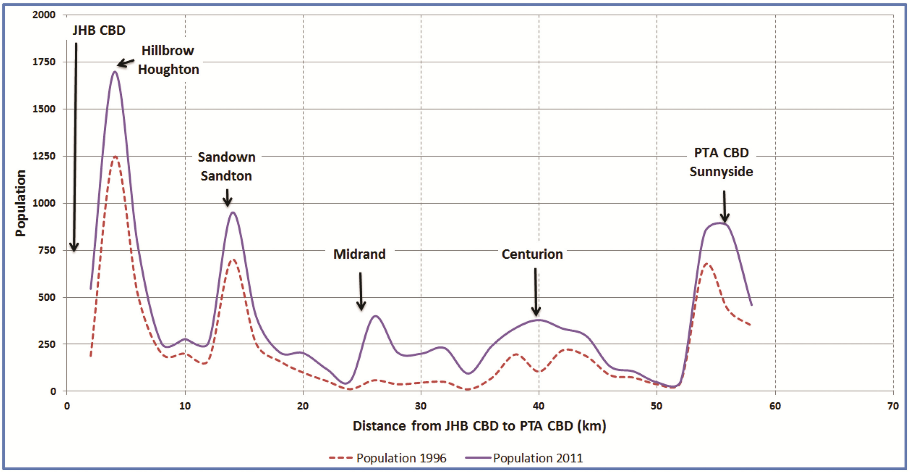

Fig. 5. Linear transect from the JHB CBD to the PTA CBD reflecting the change in population comparing 1996 to 2011 [36].

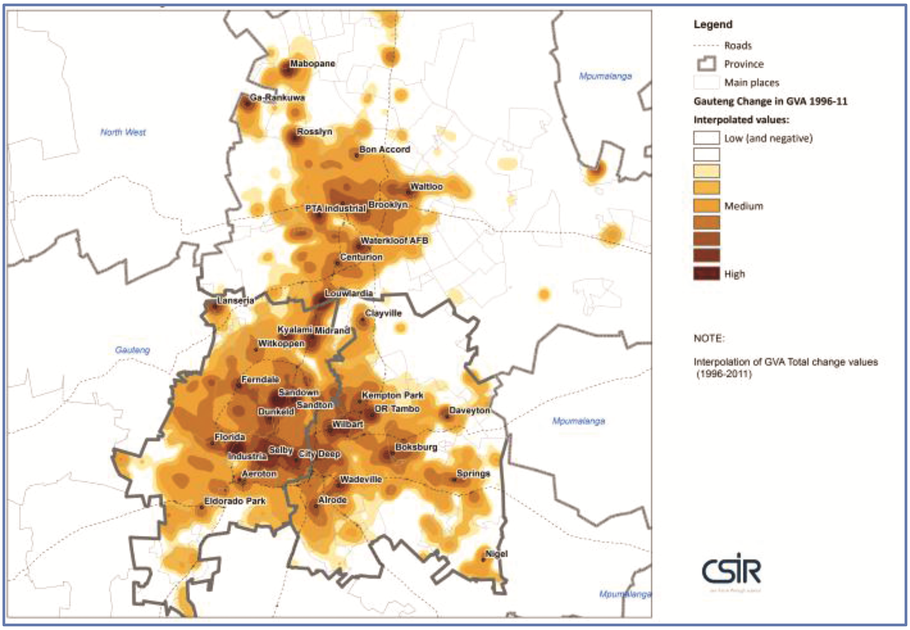

Fig. 6. Highest values reflecting economic nodes in the Gauteng city region, reflecting embedded patterns of economic concentration between the time periods 1996 to 2011 [24].

This paper presented an approach which uses a fine-grained uniform spatial unit to present change and trend data. Given the importance of measuring change and reporting on spatial planning outcomes, the value of finer-grained information becomes obvious.

Considering the examples used it is clear that this is useful in judging the extent of spatial transformation in our cities. Much work still needs to be done to test its application with city authorities and to expand information variables.

7 Reflections and Conclusion

To contribute towards achieving spatial transformation objectives, and tracking progress in this regard, the need for the development, extension and use of spatially and temporally aligned sub-city level indicators is evident. Although there are currently numerous indicators aimed at measuring city performance in South Africa, most utilise only city-level information. This does not reflect the spatial realities underlying change, development or even decay. Such information allows planners and researchers to investigate whether their policies/strategies are having the intended effect. Also critical is that when change is reflected, this also requires that spatial units remain constant (or alternatively it would require an adjustment process where spatial extent has changed). As indicated it is unlikely that a single indicator can measure spatial transformation.

It is crucial to support the wide range of ongoing indicator initiatives in South Africa and internationally, and to strive for the use of trustworthy official data. However, there is also a need to explore the benefits and improvement of spatially refined and aligned sub-city indicators that can provide spatially-specific views on place-specific progress and challenges in the endeavour towards spatial transformation. The innovative approach and findings of the endeavour to develop spatio-temporally aligned sub-city level indicators does not only provide a solid baseline to track change in cities in South Africa, but also provides a basis to explore and improve the development and value of such spatial-specific indicators within the context of developing countries and fast growing cities. In reflecting on the research and development process, a number of key considerations regarding the development, value and use of such indicators can be summarised:

- The value of place-specific views on population increase and decline in specific parts of cities, and especially in city regions (moving beyond the metropolitan/city borders). An indicator built on a finer spatial granularity is more useful to grasp the spatial realities. It can provide a view of population change in the broader area, and not as an aggregate value.
- In order to create fine-grained socio-economic data it is critical to maintain proxy data sets that are used to assign values to such fine-grained spatial units with confidence, in order to create a representative picture.
- It enables spatial analyses and presentation of change in different ways to make comparative analyses possible. It allows for additional analysis - such as creating transects across city space. Keeping the unit type a constant size also makes for better comparison between cities. Should such tessellations be extended beyond the city boundary it will also indicate cross-border change.
- Indicators are often the result of contained data combination or processing, as such it does not represent all realities. For example, depicting economic activity does not include the informal economy.

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