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Modelling urban spatial change:

a review of international and South African modelling initiatives

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NRF: SARChI Chair in Development Planning and Modelling at Wits

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Disclaimer

Executive summary

The purpose of this report is to examine international and South African urban modelling projects that monitor or simulate urban spatial change. Urban land use modelling involves testing spatial location theories and interactions between various land uses, actors, and other related activities in urban settings. As such, urban growth and land use change models have the potential to become important tools for urban spatial planning and management.

The research addressed the following questions:

- What aspects or components of urban spatial change are being modelled internationally and within South Africa?
- What urban models were used since 2000 and by whom?
- What data and software are utilised for the various modelling projects?
- What modelling methodology, software and visualisation tools might be appropriate for monitoring or simulating urban spatial change in the South African context, specifically in the Gauteng City-Region (GCR)?

At the international level, the report documents five main urban modelling categories: land use transportation (LUT), cellular automata, urban system dynamics, agent-based models (ABMs) and spatial economics/econometric models (SE/EMs). These models can be described as follows:

- *LUT models*, developed and improved over the last four decades, view urban structures as reciprocal relationships between land use and transport. These models are based on the premise that transport planning decisions affect land use development and *vice versa*. A variety of LUT models are used to explain and predict land use and transport relationships.
- *Cellular automata models* apply a set of transition rules on a two-dimensional grid of cells where each cell represents a land use and the change in land use is based on the state of the neighbouring cells. Cellular automata models have been widely applied in modelling land use growth, although in some cases is considered too simplistic for modelling complex systems.
- *System dynamics models*, introduced in the 1960s, treat urban systems as complex, dynamic, and self-organising entities. System dynamics models therefore appreciate the complex interactions that exist within urban systems, such as transport networks, housing infrastructure, water and energy supply networks and social networks. A specific strength of system dynamics is its representation of temporal processes.
- *ABMs and microsimulation*, based on individual behaviours of actors in an urban system, emerged in the past two decades and have been used, especially by scientists in urban and geospatial studies, as effective paradigms for framing the underlying problems of complex and dynamic processes. These models are credited for representing individual agents' actions and behaviour and aggregating them in space.
- *SE/EMs* focus on demography and household-driven demand-supply relations in urban regions, such as housing market developments. SE/EMs rarely consider the environment and feedback loops to the original driver.

A full list of the above models that were reviewed are summarised in Annexure A. This report reveals that instances exist where these models are integrated and overlap, for example, UrbanSim modelling software incorporates LUT models and ABMs.

Within South Africa, the report documents urban spatial change and growth modelling initiatives, a number of which do not strictly fall into international categories as noted above. Except for the UrbanSim project, with the Gauteng model still being developed, and limited academic research utilising cellular automata simulation, the bulk of existing modelling initiatives are primarily geographic information systems (GIS)-based and/or linked to spread sheets containing demographic or housing projections. Remote sensing research focusing on historical land cover change was also prevalent.

As such, the South African urban modelling typologies are categorised differently from the international typologies and include a broader range of urban modelling techniques. Typologies used are the following: provincial government modelling initiatives in Gauteng; municipal government modelling initiatives; other government-funded modelling research; and academic modelling research. The various modelling initiatives described and summarised in Chapter 4 and Annexure B are by no means a comprehensive review of all urban spatial change modelling projects in South Africa, but provide a broad indication of the types of urban spatial change modelling underway. Importantly, the models may form the basis for more accurate and sophisticated urban modelling projects in the future.

This report also identifies key urban modelling opportunities and challenges for short- to long-term planning in the GCR and South Africa.

Urban modelling opportunities

Several short-, medium- and long-term planning initiatives currently underway, such as the provincial G2055 project and Joburg Growth and Development Strategy (GDS) 2040, lend themselves to urban modelling in the GCR.

Establishing a growth forecasting and spatial planning unit

The draft Gauteng Growth Management Strategy proposes a comprehensive growth forecasting and spatial modelling exercise for the province as a whole, as well as individual municipalities. The establishment of a growth forecasting and spatial modelling unit presents an excellent opportunity to embed spatial modelling and coordinated planning in government policy and practice.

Extending current urban planning models

There is potential to refine existing models to serve as a starting point for informing long-term planning, rather than duplicating efforts. This should include improving the process of developing, extending, and applying models and supporting their effective use in long-term projects, such as G2055 and the growth development strategies of individual municipalities. In particular, this should entail improving data collection and quality, mutual agreements on the use of a common set of population projections, and entrenching participatory processes in modelling work. Utilising the Council for Scientific and Industrial Research's (CSIR) UrbanSim project as an integrated modelling platform for the GCR will ensure that the significant amount of money, skills and time invested do not go to waste. This is, however, dependent on overcoming the current data issues affecting the Gauteng model.

Improving an understanding of the role models play in testing policy scenarios

It is important to emphasise that while models are intended to inform policy, they are not crystal balls that can magically predict the future. Models should rather be understood as presenting opportunities for testing the different implications of various policy scenarios. This necessitates a careful selection of the scenarios to be tested. The involvement of stakeholders during the entire modelling process is therefore of utmost importance.

The on-going development and availability of cross-sectional, time series and other data

In line with the GCR's modelling priorities (see Annexure D), a number of factors, such as the availability of three sets of Census data (1996, 2001 and 2011) and 'Quality of Life' (QoL) Survey data (2009, 2011, 2013) for the first time, provide an opportunity to revise and recalibrate the models with accurate and up-to-date demographic variables. From such processes, trends analysis and projections are now also possible.

Development of common modelling platforms

The planned operationalisation of the Gauteng-wide GIS platform, or GeoGCR spatial database by the Gauteng Planning Commission (GPC), and establishment of a national observatory, proposed by the National Planning Commission (NPC), represents an opportunity for integrated modelling coordination and sharing of outputs across different spheres – local, regional and national. Careful consideration should be given to the possible overlapping roles and work of the national observatory and stepSA (Spatial Temporal Evidence for Planning South Africa) programme.

Development of modelling skills at tertiary education level

The continued collaboration between tertiary education and research institutions provide fertile ground for the development of modelling skills in the country. For instance, the proposed development of the University of the Witwatersrand Institute for Data Science and Policy Studies may provide the skills and software to assist with the storage and analysis of large datasets feeding into urban models and development of a new data and modelling skills base.

Development of a range of urban models at different scales and levels of complexity

The highly technical, data hungry and complex UrbanSim model represents the top-end of urban simulation. Other urban spatial change modelling approaches identified in Chapter 3, such as cellular automata, may provide a simpler short-term picture of the future urban form and act as a multi-scaled approach to modelling and guide to policy. For example, a broad-scale GCR model can be developed, together with zoomed in development hotspots modelled in more detail. Research projects in this area, in conjunction with local and provincial government planning departments, should be encouraged.

Urban modelling challenges

There are, however, a number of challenges that threaten the successful development of urban models in the GCR.

Streamlining and coordinating the various modelling efforts currently underway in the GCR and South Africa

There is a degree of duplication within Gauteng where a number of departments/institutions are modelling the same output using different base data and population projections. There is, therefore, a need to ensure that any models developed within each of the frameworks work together – where possible and applicable – off a common base. This is crucial in the development of an integrated modelling approach that will benefit the various long-term planning strategies currently under development by the three spheres of government. Similar to the stepSA initiative, the joint provincial and municipal urban growth forum and growth forecasting and spatial modelling unit proposed by the draft Gauteng Growth Management Strategy should work towards achieving coordinated modelling in the GCR.

A centrally accessible geodatabase for the GCR: GeoGCR

Provincial spatial data are not easily accessible publicly (or even between departments) and a fundamental transformation of the way spatial data are collated and shared at local and provincial level within the GCR is required. This can only be achieved through the establishment of a centrally accessible and up-to-date geodatabase that can host all the key data layers required by the various modelling projects. Correctly implemented, the GeoGCR spatial database, proposed by the Gauteng Provincial Government (GPG), will go a long way to ensuring that all departments involved in any kind of modelling are working off a common spatial database. The development of the GeoGCR database needs to be fast-tracked by the institutions mandated to establish it.

Modelling the wider GCR as opposed to modelling the Gauteng Province

The wider GCR extends beyond the Gauteng Province into neighbouring provinces and represents a vast functioning region with dynamic relationships. This needs to be considered in any long-term strategic plan or model claiming to have a city-region focus. Modelling across such a vast extent raises a range of issues, such as data availability and application of an appropriate modelling scale. As highlighted above, a multi-scale approach to modelling is required.

Report structure

After the introduction in Chapter 1, a definition of modelling and urban spatial change is discussed in Chapter 2. Chapter 3 provides a literature review of urban modelling (focusing mainly on international examples), summarised according to five categories of models: LUT, cellular automata, urban system dynamics, ABM and SE/EMs. Chapter 4 discusses South African urban modelling initiatives. The report ends with Chapter 5 that discusses key modelling challenges and possible modelling opportunities that may benefit and inform long-range development planning processes in the GCR.

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List of Acronyms/Abbreviations

ABM	Agent-based model
AHP	Analytic Hierarchy Process
BAS	Building Application System (City of Johannesburg)
BRT	Bus Rapid Transit
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CLUE-S	Conversion of Land Use and its Effects at Small regional extent
CoJ	City of Johannesburg
CORMAS	COmmon-pool Resources and Multi-Agent Simulations
CRUISE	Centre for Regional and Urban Innovations and Statistical Exploration
CSIR	Council for Scientific and Industrial Research
CSM	Cost Surface Model (eThekwini)
DPSIR	Driving Forces, Pressure, State, Impact and Response
DRT	Department of Roads and Transport (Gauteng)
DST	Department of Science and Technology
DYNAMO	DYNAmic MOdels
EMME	Travel demand modelling software
ETM+	Enhanced Thematic Mapper Plus
G2055	Gauteng 2055 long-term regional plan
GCR	Gauteng City-Region
GCRO	Gauteng City-Region Observatory
GDP	Gross domestic product
GDS	Growth and Development Strategy
GIRIP	Gauteng Infrastructure Renewal and Investment Plan
GIS	Geographic information systems
GITMC	Gauteng Integrated Transport Modelling Centre
GMS	Growth Management Strategy (City of Johannesburg)
GPC	Gauteng Planning Commission
GPG	Gauteng Provincial Government
GSDF	Gauteng Spatial Development Framework
GSRNR	Gauteng Strategic Road Network Review
GTI	GeoTerraImage
GTS 2000	Gauteng Transportation Study
GVA	Gross value added
HDA	Housing Development Agency
HSRC	Human Sciences Research Council
IDP	Integrated Development Plan
IDPM	Integrated Development Planning and Modelling Project
IGU	International Geography Union
ILUMASS	Integrated Land-Use Modelling and Transport System Simulation
ILUTE	Integrated Land Use Transportation Environment
IRPUD	Institute of Spatial Planning of the University of Dortmund
ITLUP	Integrated Transportation and Land Package
ITMP25	25 Year Integrated Transport Master Plan for Gauteng
LILT	Leeds Integrated Land Use model

LUT	Land use transportation models
MARS	Metropolitan Activity Relocation Simulator
MATSim	Multi-Agent Transport Simulation
MCA	Multiple-criteria approach
MEC	Member of the Executive Council
MSFM	Municipal Services Finance Model
MSS	Multispectral Scanner System
MSTM	Maryland Statewide Transport Model
MUSSA	Modelo de Uso de Suelo de Santiago
NGO	Non-governmental organisation
NYMTC-LUM	New York Metropolitan Transportation Council-Land Use Model
OECD	Organisation for Economic Co-operation and Development
PWV	Pretoria Witwatersrand Vereeniging
QoL	GCRO's Quality of Life survey
RDP	Reconstruction and Development Plan
SDP	Spatial Development Plan
SDF	Spatial Development Framework
SE/EMs	Spatial economics/econometric models
SIC	Standard Industrial Classification code
SHSUP	Sustainable Human Settlement Urbanisation Plan (City of Johannesburg)
SLEUTH	Slope, Land cover, Exclusion, Urbanisation, Transportation and Hillshade
StatsSA	Statistics South Africa
stepSA	Spatial Temporal Evidence for Planning South Africa
TAS	Township Application System (City of Johannesburg)
TELUM	Transportation Economic and Land Use Model
TM	Thematic Mapper
TLUMIP	Transportation and Land Use Integration Project
UCT	University of Cape Town
UDL	Urban Dynamics Laboratory (CSIR)
UES	Urban Expansion Scenario
UGM	Urban Growth Model (City of Cape Town)
UGMS	Urban Growth Monitoring System (City of Cape Town)
UJ	University of Johannesburg
UK	United Kingdom
UKZN	University of KwaZulu-Natal
UNCHS	United Nations Centre for Human Settlements
UP	University of Pretoria
USA	United States of America
Wits	University of the Witwatersrand, Johannesburg

1. Introduction

The United Nations Centre for Human Settlements' (UNCHS) *State of the World Cities Report* (2012/2013) predicts that the world is moving into the urban age, where urban areas worldwide are not only becoming the dominant form of habitat for humankind, but also the engine-rooms of human development as a whole (UNCHS, 2012). Rapid urbanisation raises various challenges, including the expansion of slum settlements, a growing backlog in infrastructure investments, and pressure on available resources such as water, energy and food. Planners and policy makers need to drive urban development that is socially, economically and ecologically sustainable in an ever more complex and unpredictable context. It is, therefore, important to develop tools that urban professionals will use to formulate timely and effective policies to monitor and guide urban development.

Urban land use modelling involves testing theories regarding spatial location and interactions between various land uses, actors, and other related activities in urban settings. Due to advances in computer hardware and software, including geographic information systems (GIS), increased digital data availability, and human understanding of natural and social system functions, urban modelling has evolved from simple calculations of the linear relationships between one or two spatial elements to much more sophisticated simulations of entire urban systems. The more advanced models seek to account for the dynamic relationships between multiple elements in various sub-systems – spatial, economic, institutional, ecological, social, and so on. Urban growth and land use change models have the potential to become important tools for urban spatial planning and management (Herold et al., 2005). The application and performance of the models is dependent both on the quality and scope of data available and an understanding of the processes represented in the model (Batty and Howes, 2001).

Across the world, urban observatories have been established as part of the United Nations Global Network of Urban Observatories to gather accurate urban-level data and monitor trends within a specific geographical region (Palmer Development Group, 2007). In South Africa, the Gauteng Provincial Government (GPG) established the Gauteng City-Region Observatory (GCRO) in 2008, as an institutional partnership between the University of Johannesburg (UJ), University of the Witwatersrand, Johannesburg (Wits), and the GPG, with local government also represented on the GCRO Board. One of GCRO's key tasks is to map and analyse urban spatial change in order to determine possible future trends relating to the urban form. The GCRO focuses on the Gauteng City-Region (GCR), an integrated cluster of cities, towns and urban nodes that together form the economic heartland of South Africa (Figure 1). The core of the GCR is the Gauteng Province, anchored by the three large metropolitan municipalities of Johannesburg, Tshwane and Ekurhuleni. Gauteng, according to the latest Census[1], is the smallest province in South Africa (18,179 km^2), but contains 24% of South Africa's population with the highest population density of 675 people per km^2. Gauteng's 2011 population of 12.3 million, which represents a 31% population increase over the past decade, is expected to double by 2055. The GCR's economic footprint extends beyond the borders of Gauteng into the neighbouring provinces of Free State, Mpumalanga and North West, constituting the wider GCR.

[1] See page 2 of the link: http://www.statssa.gov.za/Census2011/Products/Provinces%20at%20a%20glance%2016%20Nov%20 2012%20corrected.pdf

The region is the largest urban economy in South Africa and Africa as a whole – the Gauteng Province alone contributes 34% of national gross value added (GVA), while the wider GCR accounts for 42% (GCRO, 2011). The region is also home to O.R. Tambo International Airport, the largest international airport in Africa and air transport hub of Southern Africa, serving more than 17 million passengers each year (Airports Company South Africa, 2013). Gauteng has experienced dramatic growth over the past two decades with the percentage of urban land cover in the province increasing from 12.6% in 1991 to 18.35% in 2009 (Mubiwa and Annegarn, 2013). It is recognised that expanding urban areas tend to appropriate a disproportionate share of resource inputs and waste sinks, even though urban areas only account for a small percentage of land surface (Schneider, 2006). This is a potential challenge that the GCR is faced with as economic growth and urbanisation can lead to adverse environmental impacts in peri-urban areas due to the rapid increase in urban land use. It therefore becomes crucial to understand the changing patterns and driving forces of urban development, given the rapid growth in urbanisation.

Figure 1: The GCR

Source: GCRO

Within the GCR, the Gauteng Planning Commission (GPC) is tasked with long-term integrated city-region planning and the monitoring and evaluation of the provincial government's performance. The GPC's flagship project is the Gauteng 2055 (or G2055) project – a long-term plan that sets out to "maximise the city-region's potential and its value as a key economic driver for the country, through careful long-term planning aligned with the national vision and other strategic perspectives" (GPC, 2012:2). The G2055 plan is currently being drafted and is underpinned by four strategic pillars: equitable growth, social inclusivity and cohesion, good governance, and sustainable growth and infrastructure. Such long-range development planning processes call for the need to understand more accurately the long-term prospects for urban change and the likely impact of different planning and infrastructure choices and investments on the future urban form.

GCRO is assisting with components of research for G2055 and has a number of projects investigating spatial change in the GCR. From its inception in 2008, GCRO has invested a significant amount of time and resources into collating a diverse spatial database which could constitute an input into a modelling exercise, but has yet to undertake any form of urban simulation. Before embarking on any modelling, GCRO felt it was important to take note of, and critically assess lessons to be learnt from international experience and scholarship on spatial modelling, as well as a number of South African experiments that model future urban development. In 2012, GCRO initiated preliminary research into current international and South African modelling trends through a desktop study and telephone, email and personal interviews.

This report sets out to investigate the following question: What urban spatial change modelling research is currently being undertaken internationally and within South Africa? To answer this, the research explored:

- What aspects or components of urban spatial change are being modelled?
- What urban models were used?
- What data and software are utilised for the various modelling projects?
- What modelling methodology, software and visualisation tools might be appropriate for a GCRO urban change modelling project?
- What modelling would benefit and inform long-term planning in the GCR?

A mixed approach was utilised to gather information. This included: a literature review of urban spatial change modelling and simulation from an international perspective; interviews with experts in specific South African institutions who are busy with projects relating to urban spatial change modelling; and a workshop held in partnership with the GPC.

The report is structured as follows: firstly a definition of modelling and urban spatial change is discussed in Chapter 2. Chapter 3 provides a literature review of urban modelling (focusing mainly on international examples), summarised according to five categories of models: land use transportation (LUT), cellular automata, system dynamics, agent-based models (ABMs) and micro-simulation modelling, and spatial economics/econometric models (SE/EMs). Chapter 4 discusses South African urban modelling initiatives. The report ends with Chapter 5 that discusses key modelling challenges and possible modelling opportunities that may benefit and inform long-range development planning processes in the GCR.

2. Understanding urban modelling

"Urban models: Representations of functions and processes which generate urban spatial structure in terms of land use, population, employment, and transportation, usually embodied in computer programs that enable location theories to be tested against data and predictions of future locational patterns to be generated." Batty (2009:51)

2.1 Urban modelling concepts

Before discussing urban modelling in greater detail it is important to understand a few basic concepts such as 'urban', 'model', 'tool' and 'modelling'.

There is no generally accepted or standard definition for the term urban. The available definitions often vary according to the standards of a country's national statistical agency (Grekousis et al., 2013). In South Africa, for example, Statistics South Africa (StatsSA) categorises Enumerator Areas for the Census into one of four types: urban formal, urban informal, rural formal and tribal areas (StatsSA, 2001).

The existing literature indicates that various features have been utilised to characterise urban areas, such as: (i) population size; (ii) space (land area); (iii) the ratio of population to space (density); and (iv) economic and social organisation (Weeks, 2010). Without going into detail on the debates around the definition of 'urban', this study adopts Weeks' definition of an urban area as "a place-based characteristic that incorporates elements of population, density, social and economic organisation, and the transformation of the natural environment into a built environment" (Weeks, 2010:34).

A model is generally considered to be a simple representation of reality (Giere, 2004) and theoretical abstraction that represent systems in such a way that essential features crucial to the theory and its application are identified and highlighted (Batty, 2009). Models can take on different forms, such as maps or mental models. Various 'tools' in the form of computer programmes or software are utilised to produce models. Useful computer programmes or software include Excel spread sheets, GIS and simulation software. The process of using tools, given an appropriate theoretical foundation, to simulate urban spatial change or growth is referred to as urban modelling.

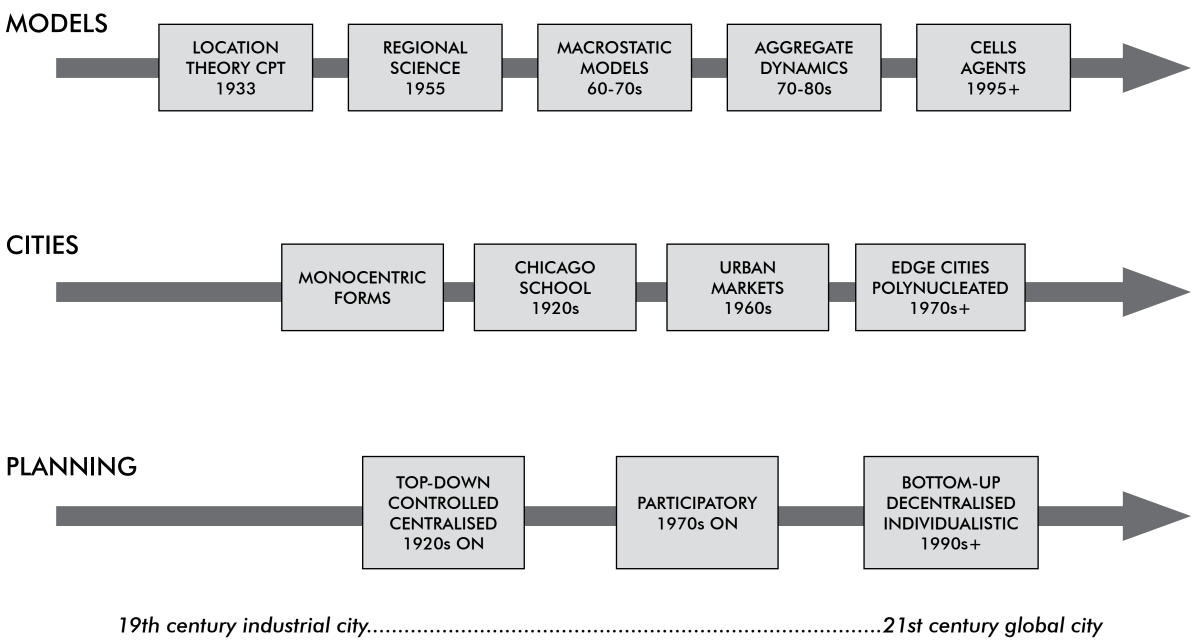
2.2 Evolution of urban modelling

According to Batty (2008), there are three essential issues that have guided the development of urban models: the need for better policy and planning in cities; the availability of data resulting in compromises being made between different model structures; and *ad hoc* theoretical development resulting in a diverse field dominated by differing approaches, paradigms and perspectives on what should be modelled.

The way in which urban models and modelling has evolved with respect to the growth and changes in cities, as well as the need for planning, is illustrated in Figure 2. This section, drawing largely from Batty (2008), underscores that our knowledge of cities has mainly been from the perspective of 19^{th} century industrial city growth where cities were seen as stable structures with dominant functions occurring in the central business district. According to Batty (2008), the growth and development of cities, supported by the development of transportation technologies, occurred around the periphery and a monocentric pattern observed in ancient and medieval cities was reinforced. As can be observed in Figure 2, some cities over time fused together, forming polycentric clusters, conurbations or 'megalopolis'. Batty (2008) adds that urban planning was institutionalised in the 19th century in order to deal with urban problems arising from industrial and population growth. Location control zoning, a top-down planning approach, was used as one of the main instruments to deal with these emerging problems. Later in the 1960s, much of the planning became explicitly transport focussed. However, the ideas behind city planning took a radical shift towards the end of 20th century when the interventions used to deal with the problems were not yielding results. Planning for the city was then seen as requiring a participatory approach, since cities were now regarded as volatile and less stable. The theories and models that were used to inform future planning of the cities were initially closely tied to the top-down and equilibrium dominated approaches. These included models based on economic-locational theory, social physics[2] and spatial/geographical morphology. Over the years, these *ad hoc* and static approaches for sketching future cities took a radical shift to decentralised bottom-up thinking. This radical shift was due to new perspectives on cities, new planning approaches and the advancement in computational capability that accounted for the complexity of cities (Batty, 2008).

For this research, the focus was limited to reviewing models that relate to urban spatial and land use growth and change.

Figure 2: Intersecting time line of urban model development with the growth of cities and evolving planning approaches



Source: Batty (2008:6)

[2] According to Batty (2009:51) this is the "application of ideas from classical 'Newtonian' physics to social systems usually in the form of analogies with Newton's laws of motion as reflected in the concepts of potential energy and gravitational force."

2.3 Types of urban models

Urban models are mainly computer-based simulations that are utilised to test theories regarding spatial location and interaction between land uses and other related activities (Batty, 2009). It is acknowledged that the model types listed here are not all encompassing, since new models are developed regularly. Therefore, the list only offers the broad category of urban models that are currently used.

2.3.1 Land Use Transportation (LUT) models

These entail aggregate static models of economic and spatial interactions where the urban system is considered as "a static entity whose land uses and activities were to be simulated at a cross section in time and whose dynamics were largely regarded as self-equilibrating" (Batty, 2009:53). Their theoretical foundations are mainly in regional economics, location theory and new urban economics. LUT models currently incorporate transportation modelling processes of trip generation, distribution, modal split and assignment explicitly and are consistent with discrete choice methods[3] based on utility maximising, specifically in their simulation of trip-making (Akiva and Lerman, 1985). More recently, a new generation of micro-simulation models that attempt to account for the behaviour and interactions of individual agents in space and time have been developed (Iacono et al., 2008). A few examples of newer LUT models include: UrbanSim (Waddell, 2002), Integrated Land Use Transportation Environment (ILUTE) (Salvani and Miller, 2005) and Integrated Land-Use Modelling and Transport System Simulation (ILUMASS) (Moeckel et al., 2003; Strauch et al., 2003).

2.3.2 System dynamics models

These are dynamic, temporal urban models that have been empirically applied (Batty, 2009). Early attempts at this modelling were observed in Forrester (1969), whose focus was on the development of non-linear growth and change theory that results in discontinuities coupled with non-linearities, threshold effects or random perturbations (Batty, 2009). System dynamics models treat urban systems as complex, dynamic, and self-organising entities. System dynamics therefore models the complex interactions that exist within urban systems, such as transport networks, housing infrastructure, water and energy supply networks and social networks. The main strength of system dynamics models is the representation of temporal processes.

2.3.3 Cellular automata models

Cellular automata models are based on a two-dimensional grid of cells derived from remote sensing images. Each cell represents a land use and a set of transition rules determine its future state based on the values of the neighbouring cells. The utilisation of cellular automata in urban modelling has become a preferred technique since the pioneering work of Tobler (1970), followed by Couclelis (1985), who identified the potential of cellular automata in modelling urban dynamics. Many efforts have been made in cellular automata to study land use changes (Li and Yeh, 2002; Almeida et al., 2008), future scenarios of urban landscape (Barredo et al., 2003; Han et al., 2009), urban growth and sprawl (Batty, 1997; Batty et al., 1999; Al-kheder et al., 2008) and urban ecological security (Gong et al., 2009).

[3] "A development of computable microeconomic theory in which individuals maximize a utility, subject to constraints on their choices which can be tailored to reflect how decisions are made in complicated situations." (Batty, 2009:51)

2.3.4 Agent-based models (ABMs) and microsimulation

ABMs is an emerging modelling approach that has in the past two decades been increasingly adapted by social scientists, especially scientists in urban and geospatial studies, as an effective paradigm for framing the underlying problems of complex and dynamic processes (Chen, 2012). The greatest attention this modelling approach has attracted is the ability to represent the actions and behaviour of individual agents located in space (Batty, 2009). Several examples of ABMs include UrbanSim and TRANSIMS. A parallel, but significant approach to individualistic modelling is based on microsimulation which essentially samples individual behaviour from more aggregate distributions and constructs synthetic ABMs linked to spatial location (Clarke, 1996).

2.3.5 Spatial economics/econometric models (SE/EMs)

SE/EMs are set up as formalised relationships between the population, and related housing market and residential land use (Haase and Schwarz, 2009). These models can be dynamic (when model parameters are treated endogenously) or quasi-dynamic (if model parameters are fixed or exogenous during the modelling exercise). Drivers of change emanate as demand(s) from the population. SE/EMs rarely incorporate feedback loops back to the original driver.

A more detailed description and examples of these models will be reviewed in the next chapter.

3. Literature review of urban spatial change models

A systematic literature search of peer-reviewed journals and research reports was conducted to provide a broad description of urban spatial change modelling projects and identify the latest international trends.

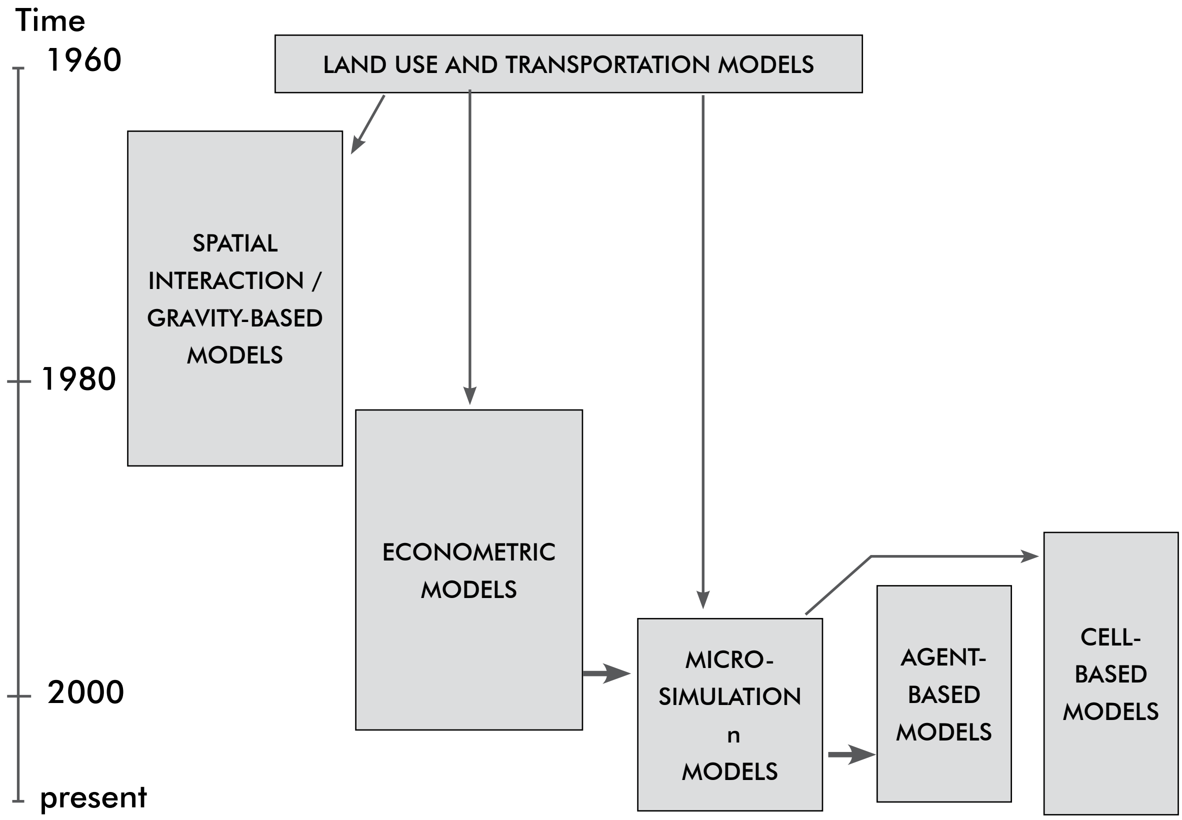
The literature search revealed five main urban modelling categories: LUT, cellular automata, system dynamics, ABMs and SE/EMs. A few of the studies integrated different types of models and there may be some overlaps – for example, LUT and ABMs (such as UrbanSim). Each of the five categories of urban models will now be discussed in brief, with relevant studies summarised in Annexure A.

3.1 LUT models

LUT models have been developed on the premise that urban structures can be understood on the basis of a reciprocal relationship between land use and transport (Chang, 2006; Iacono et al., 2008). That is, transport planning decisions affect land use development and land use conditions affect transport activity (Litman, 2012). For example, a new transport network link may result in an increased investment in land and subsequent land use changes; or if a land use is rezoned this in turn may influence demand for travel. Urban researchers have for the past four decades attempted to formalise models that help to explain and predict these land use and transport relationships (Iacono et al., 2008).

A variety of large-scale LUT models have been developed to assess the possible impacts of urban development and land use change on transportation patterns. Figure 3 reflects on the development of LUT models over the past four decades. The majority of LUT models are based on spatial interaction and econometric models (Iacono et al., 2008; Batty, 2009). The Model of Metropolis was widely considered to be the first operational spatial interaction simulation model of land use, developed by Lowry in 1964 (Borning et al., 2008; Iacono et al., 2008). The model was based on the Lowry gravity model, "which adapted the law of gravity from physics and applied it to predict the flow of travel between locations as a function of the sizes of origin and destination and the ease of travel between them" (Borning et al., 2008:8). Other examples include: ITLUP (Integrated Transportation and Land Package) (Putman, 1976), LILT (Leeds Integrated Land Use model) (Mackett, 1983) and the Institute of Spatial Planning of the University of Dortmund (IRPUD) model (Wegener, 2011).

Figure 3: Chronological development of land use and transportation models



Source: Iacono et al. (2008:325)

Lee's critique of the first generation of large scale urban models concluded that they were too expensive, complicated and technical, exceedingly aggregated and required huge amounts of data (Lee, 1973). Aggregate spatial interaction models were also criticised for the use of inappropriate theory to describe the behaviour captured in the model. As a result a new generation of models based on the study of disaggregate behaviour using random utility theory to describe choices among discrete alternatives (such as travel mode) were developed (Iacono et al., 2008). These models apply an econometric or spatial input-output modelling approach derived from the United States of America (USA) economy monetary flow models from the 1970s (Borning et al., 2008) and consist of two types. First are regional economic models, such as MEPLAN and TRANUS. Hunt et al. (2005:332), describes MEPLAN, developed in the United Kingdom (UK) by a private consulting firm called Marcial Echenique and Partners Ltd, as "an aggregate model: space is divided into zones, quantities of households and economic activities (called 'factors' or 'sectors') are allocated to these zones, and flows of interactions among these factors in different zones give rise to flows of transport demand". TRANUS also employs a spatial input-output model but is differentiated from MEPLAN through the application of a more restricted set of functional forms and modelling options within its framework (Hunt et al., 2005).

The second type of econometric models are land market models. These models have developed an improved land market representation within the econometric approaches to land use transportation models, with residential and commercial real estate markets now at the core of the analysis (Iacono et al., 2008). Examples include: MUSSA (Modelo de Uso de Suelo de Santiago), a model of urban land

and floor space markets developed in Chile that provides equilibrated forecasts of land use and travel demand used to study various transportation and/or land use policies; and NYMTC-LUM (New York Metropolitan Transportation Council-Land Use Model), developed for the New York Transit Commission which models the interactions between residential housing, commercial floor space, labour and non-work travel markets (Hunt et al., 2005). A recent application of econometric modelling is the Maryland Statewide Transport model (MSTM) applied in Washington DC (Mishra et al., 2011) to analyse traffic congestion levels and shifts in travel patterns as a result of land use changes.

According to Iacono et al. (2008), the majority of spatial interaction and econometric models employ a top-down approach with a set of aggregate relationships between land use and transport based on the behaviour of a representative individual (usually from a mean calculated from a representative sample), whereas micro-simulation models disaggregate population and simulate changes from the bottom-up using small units of analysis such as grid cells or parcels. Table 1 summarises the new generation of micro-simulation models such as ILUTE, ILUMASS, RAMBLAS (Regional plAnning Model Based on the microsimuLation of daily Activity patternS) and UrbanSim that attempt to account for the behaviour and interactions of individual agents in space and time. The UrbanSim model developed by Waddell (Waddell, 2002) is regarded as the most highly developed of the LUT models (Batty, 2009). Recent surveys have indicated that UrbanSim is the most widely used land use modelling system in the USA (Waddell, 2011a) and will form the main focus of the remainder of this section.

Table 1: Summary of micro-simulation LUT models

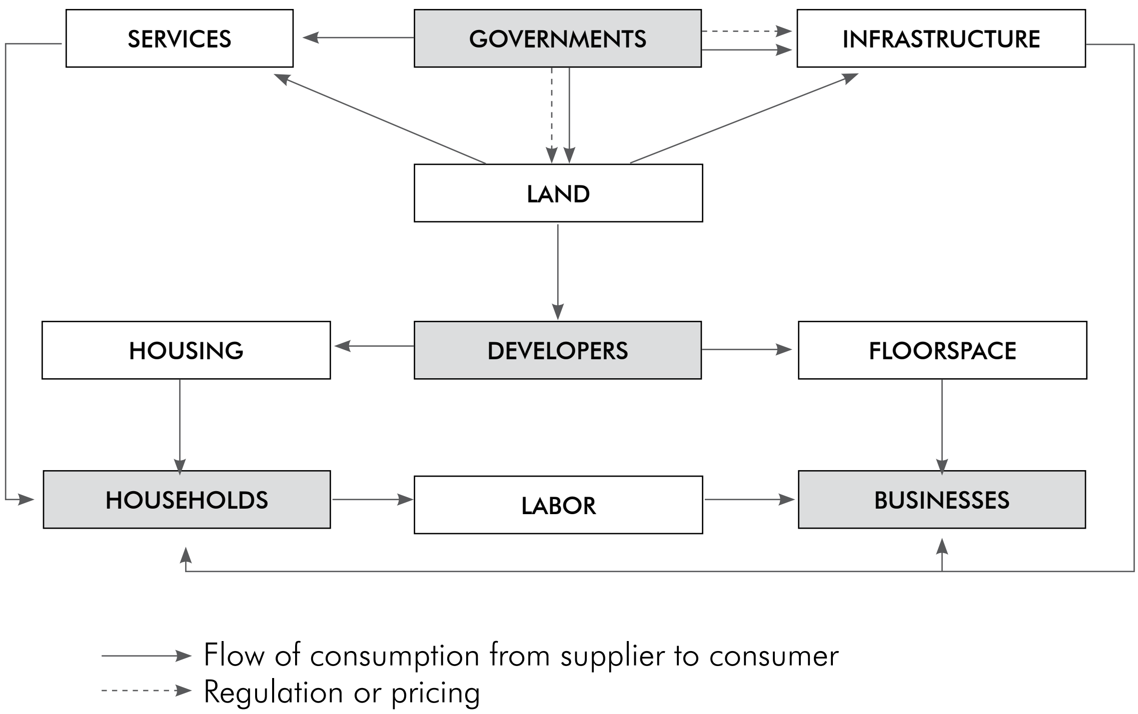
Model	Description	Reference
ILUTE	Comprehensive urban system micro-simulation model; structured to accurately capture temporal elements in urban change; activity-travel model include household member interactions; disequilibrium modelling framework.	Salvani and Miller (2005)
ILUMASS	Descendent of IRPUD model; incorporates microscopic dynamic simulation model of traffic flows and goods movement model; designed with environmental sub-model.	Moeckel et al. (2003); Strauch et al. (2003)
RAMBLAS	Entirely rule-based model framework; designed to simulate very large populations.	Veldhuisen et al. (2000)
UrbanSim	Land use model incorporating microsimulations of demographic processes; land use development; parcel-level land use representation; high level of household type disaggregation; open-source software developed for general use	Waddell et al. (2003)

Source: Iacono et al. (2008:333)

In the 1980s, Paul Waddell recognised the ineffectiveness of metropolitan planning models due to a lack of behavioural realism, insufficient theoretical underpinnings, insensitivity to important public policies, and a lack of credibility with both technical planners and policy makers (Borning et al., 2008). UrbanSim was therefore developed in the late 1990s as a response to (i) the shortcomings of existing metropolitan planning models; and (ii) new federal legislation and state growth management programmes that required improved and better integrated models to link land use, transportation and environmental planning (Waddell, 2002). UrbanSim simulates the key decisions and choices impacting urban development such as mobility and location choices of households and businesses, and development choices of developers (Center for Urban Simulation and Policy Analysis, 2008). A micro-simulation strategy is adopted whereby agents and the choices they make are directly represented in a behaviourally natural and intuitive manner and can be readily understood, at a basic level, by non-technical stakeholders, such as the general public (Waddell, 2011b).

UrbanSim has an emphasis on behavioural theory and transparency which leads to a more explicit treatment of individual agents such as households, jobs, and locations, and to a microsimulation of the choices that these agents make over time (Borning et al., 2008). Figure 4 illustrates the interaction of these agents in the urban property market; with the choices and model components of households, businesses, developers (including government) and the real estate market reflected in Table 2. Developers utilise land to provide housing for households and floor space for businesses, with households in turn providing labour for the businesses. Governments provide infrastructure, land and services, and in some cases regulate or alter the pricing of land and infrastructure provision. Governments, therefore, need to plan for an increase in households or change in households and set policies or make investment and development decisions. UrbanSim attempts to draw relationships between these dynamic process by developing a range of models that show how demographic transitions interact with household location choices, which in turn impact on real estate prices and business location choices.

Figure 4: UrbanSim model agents interacting in urban markets



Source: Waddell (2011a:10)

UrbanSim can be considered as a family of models which applies a series of approaches and techniques such as aggregate non-spatial modelling for the economic and demographic transition models and agent-based discrete choice simulations for the household location choice component (Waddell, 2002). A number of exogenous variables, such as travel times, are also required. These enter the model exogenously via external travel/accessibility models, for example, travel demand modelling software (EMME2) or Multi-Agent Transport Simulation (MATSim).

Table 2: Agents, choices and models in UrbanSim

Agent	Choice	Model
Household	In- and out-migration	Demographic transition model
Household	Residential moves	Household relocation model
Household	Residential location	Household location choice model
Person	Work at home	Work at home model
Person	Job choice	Workplace choice model
Business	Birth and death	Economic transition model
Business	Business relocation	Business relocation model
Business	Business location	Business location choice model
Developer	Parcel development	Real estate development model
Market	Real estate prices	Real estate price model

Source: Waddell (2011b:218)

UrbanSim software was developed as an open source project to allow free access to the source code, encourage collaboration, improve the openness and transparency of the model system, and increase the robustness of the software and models (Waddell et al., 2003). Originally released to run at a grid-cell level, UrbanSim now offers parcel or zone-based geometry versions[4].

The application of UrbanSim to provide policy analysis of metropolitan growth scenarios was first applied in the State of Oregon's Transportation and Land Use Integration Project (TLUMIP) in the USA, as "an ambitious effort to develop new integrated models to evaluate the interactions between transportation and land use" (Waddell, 2002). The simulation was tested from 1980 to 1994, with the model validated against observed 1994 data. Although the results correlated well to the observed data over the period of 15 years, the model did not predict isolated events (such as the opening of a new shopping mall), but nor was it designed to – an important reminder of the limits of modelling (Waddell, 2002).

UrbanSim has been applied to a number of cities across the USA, including Detroit, Honolulu, Houston, Phoenix, Salt Lake City, San Francisco, and Seattle. Outside the USA, UrbanSim has been utilised in Accra, Amsterdam, Beijing, Brussels, Paris, Rome, Seoul, Taipei, Tel Aviv, Turin and Zurich (Waddell, 2011a). The application of UrbanSim within South African cities by the Council for Scientific and Industrial Research (CSIR) will be discussed in detail in Chapter 4.

3.2 Cellular automata

The cellular automata modelling approach was invented in the late 1940s by two mathematicians, John von Neumann and Stanislaw Ulam, who were working at the Los Alamos National Laboratory in the USA (Barboux and Collet, 2012). Although the term cellular automata has had many interpretations by various authors, most describe it as a simulation represented by a grid of cells (similar to a remote sensing data format), based on a set of transition rules that determine the attribute of each cell in its locality (Almeida et al., 2008). Cellular automata therefore consists of a lattice of discrete cells whose values change on

[4] The current release of the software, version 4.4, is available for download from the UrbanSim website, www.urbansim.org.

discrete time steps according to rules that also consider neighbouring effects. For example, the ability of cellular automata to simulate urban growth is based on the theory that past urban development affects the future urban form through local interactions between land uses (Sante et al., 2010). According to Esbah et al. (2011), one of the more commonly used stochastic models is the cellular automata Markov chain[5], which due to its flexible and practical characteristics, has been applied to numerous urban areas to forecast future urban development, such as Atlanta (Yang and Lo, 2003), Lisbon and Porto (Silva and Clarke, 2002), Desokata (Sui and Zeng, 2001) and Dongguan in China (Li and Yeh, 2000). Table 3 describes the main cellular automata elements.

Table 3: Cellular automata structure and rules

Cell space	A cell, which can be any geometric shape.
Cell state	Represents any spatial variable. For greater flexibility, two groups of cell states are integrated: fixed and functional.
Time steps	The cellular automata model evolves at a sequence of discrete time steps.
Transition rules	A transition rule specifies the state of a cell before and after updating based on its neighbours' conditions. In the classic cellular automata, transition rules are deterministic and unchanged during transition. More recently, the rules are modified into stochastic expressions and fuzzy logic controlled methods.
Spatial neighbourhood	A neighbourhood, or area surrounding the cell, defined as either a limited neighbourhood (Von Neumann) including four adjacent cells or an extended neighbourhood 14 (Moore) including the eight adjacent cells.

Source: Adapted from Barboux and Collet (2012:12)

The advantages of cellular automata are numerous, namely: flexibility in formulating and generating complex behaviours from simple rules (Lathi, 2008) and an ability to show spatio-temporal dynamics (Sietchiping, 2004). Nonetheless, cellular automata's simplicity relative to other models (such as ABM) is at the same time a desirable attribute and a significant limitation; and in most cases is inappropriate for modelling complex systems (Iacono et al., 2008). Sietchiping (2004) adds that cellular automata is restricted to general rules and cannot create its own dynamics. Therefore, according to Sietchiping (2004), cellular automata is considered a bottom-up approach that cannot handle human or socio-economic factors. However, the combination of cellular automata models with the visualisation capabilities of GIS and remote sensing data makes cellular automata particularly suitable for land use modelling (Torrens and O'Sullivan, 2001).

An illustration of cellular automata applications include modelling land use policy in Wuhan China up to the year 2020 (Shi et al., 2012), modelling urban growth at township level in the USA (Al-kheder et al., 2006), modelling the spread of informal settlements in Cameroon (Sietchiping, 2004), simulating compact development in China (Li et al., 2008), and simulating urban growth in California (Teitz et al., 2005), Australia (Liu and Phinn, 2003), Turkey (Demriel and Cetin, 2010), Dublin (Barredo et al., 2003), Gorgan City, Iran (Mahiny and Gholamalifard, 2007) and Brazil (Almeida, et al., 2008). In South Africa, Le Roux (2012) has applied the Dyna-Clue cellular automata model to perform urban simulation in Johannesburg to the year 2030.

[5] According to Norris (1998), a Markov chain is a mathematical process that undergoes transitions from one state to another assuming only a finite set or countable set of states, retaining no memory of its past. This means that only the current state can influence its transition and the lack of memory property permits the prediction of how a Markov chain may behave.

3.3 System dynamics models

The origin of system dynamics is traced from the work of Forrester (1961), who developed an approach to understand problems in complex dynamic systems. System dynamics is grounded in theory of non-linear dynamics and control theory (Coyle, 1996; Sterman, 2000). It is considered a top-down approach suited to the investigation of socio-economic driving forces and simulation of complex systems.

Early modelling approaches were mainly static or comparative equilibrium models that were based on theories that assumed that systems converge towards stable equilibrium (Berling-Wolff and Wu, 2004). Static models mainly deal with data for one point in time and the model is consequently built as though the system operates in a state of equilibrium.

However, urban systems are undoubtedly complex, dynamic, self-organising entities and rarely, if ever, in equilibrium (White and Engelen, 1993). According to Ahmad and Simonovic (2004:331), dynamic systems differ from static systems due to their three main characteristics, namely: "spatial structure and relationships among system elements, interactions among the spatial elements, and changes or alterations in the structure and function over time". Any effort to understand and describe a dynamic system requires the ability to deal with these interrelated aspects. Understanding urban systems and guiding transitions to a more sustainable future requires appreciation of the complex interactions that exists within the urban systems, such as transport networks, housing infrastructure, water and energy supply networks and social networks (Cosnet Wiki, 2011).

Urban systems have been mostly described and modelled by geographers, who classify them by spatial hierarchy. Traditional modelling approaches utilised by geographers focussed on spatial variation and were static in nature. The continued recognition of the complex linkages and interactions within urban systems has resulted in the need to analyse and formalise the dynamic processes by utilising approaches that take into account these features.

It was, however, not until the 1970s that dynamic models began to feature in urban-related studies. System dynamics modelling has been recently utilised for environmental management in river basins (Guo et al., 2001), land use transportation systems (Haghani et al., 2003; Wang et al., 2008; Pfaffenbichler et al., 2008), planning for airport zones (Liu et al., 2012), sustainable land use and urban development (Shen et al., 2009), land use and land cover change (Yu et al., 2011; Rasmussen et al., 2012) and urban development projects (Park et al., 2013).

A particular strength of system dynamics is its ability to represent temporal processes. However, there are important feedbacks between time and space. For instance, system performance in time is affected by the change of conditions in space. In an effort to understand dynamic urban systems and patterns, time and space need to be examined together. Integrating different modelling frameworks enhance the ability to understand complex systems and help to generate adequate information/scenarios useful in examining and recommending policy decisions. As a result, various studies are now integrating system dynamics with more explicit spatial approaches (GIS and cellular automata) in order to improve the representation of both temporal and spatial processes inherent in urban systems.

GIS is widely used to represent, analyse, and display various spatial data, such as topography, soil type, rainfall and vegetation. However, due to the inherently static property, GIS can only measure the temporal change of landscape through collecting and updating periodic data, but fails to capture the dynamic temporal aspects or characteristics. Attempts to integrate system dynamics with GIS or cellular automata and improve its spatial components can be categorised into three approaches (Ahmad and Simonovic, 2004):

i. An implicit approach where spatial dimensions are introduced in the system dynamics model – a good example is AnyLogic Software.
ii. Translating system dynamics model equations to run in GIS; this involves translating the system dynamics equations into a programming language and interfacing with GIS. A drawback in this approach is the loss of interactive power system dynamics since changes cannot be made during simulation.
iii. Spatial system dynamics, which attempts to address the limitations in the two categories, by coupling system dynamics and GIS.

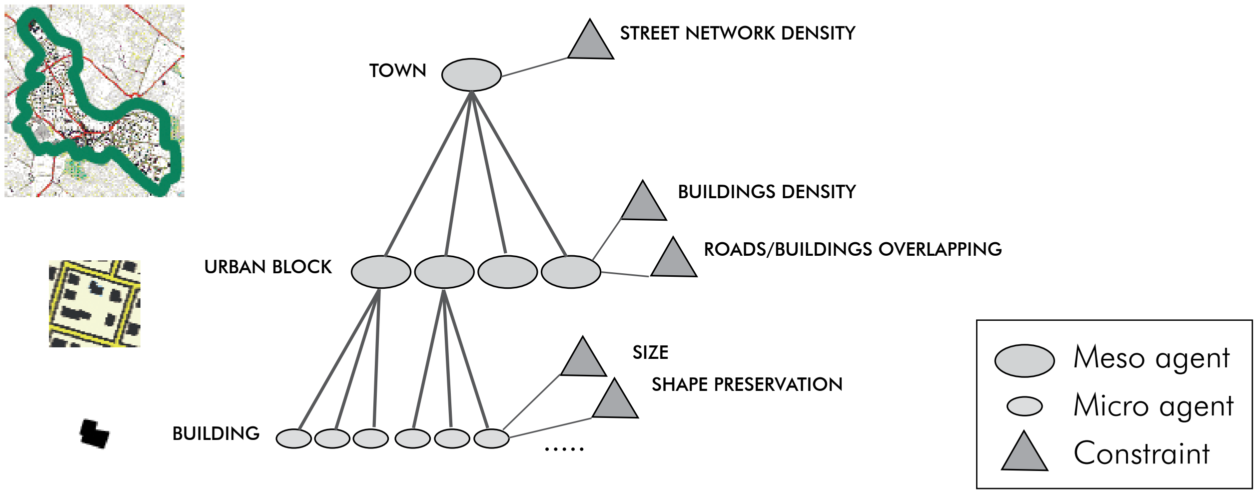
Examples of the integration of system dynamics with GIS or cellular automata include modelling issues relating to urban expansion and growth such as housing decisions and transportation (Han et al., 2009; Lin et al., 2011; Lauf et al., 2012) and understanding the sustainability of urban development and flood management (Ahmad and Simonovic, 2004; Guan et al., 2011; Xu and Coors, 2012).

Unfortunately, we were unable to find information on the use of system dynamics in urban spatial modelling in South Africa. However, it is worth highlighting one of GCRO's strategic projects, 'Metabolic flows and infrastructure transitions in the GCR'. The project falls within the theme of sustainability, and is aimed at understanding resource flows of water, energy, waste, food and other materials and how infrastructure can be transitioned to improve the resource flows. System dynamics is among the approaches that will be utilised in assessing metabolic flows of the GCR. While the project is not aimed at modelling urban spatial change *per se*, there are some outputs from modelling work that are deemed useful for informing urban spatial change modelling – in particular, the drivers of spatial change such as population and gross domestic product (GDP).

3.4 ABMs

There is a large volume of literature reviewing ABMs, for example, Parker et al. (2003); Mathews et al. (2007); and Haase and Schwarz (2009). ABMs, developed since the 1980s, are used to systematically model a collection of agents, who are humans or exhibit human-like behaviour, as autonomous decision-making entities. The modelling procedure operates from the bottom-up, i.e. from the actions of individual actors to an emerging aggregate level or collective behaviour. This is one attribute that makes ABMs superior *vis-à-vis* other models (for a detailed discussion of this see Bonabeau (2002:7280)). Figure 5 shows the relationship between the agents at the micro-level and how their actions aggregate to the macro level in an urban setting. The constraints that agents face as they make their independent decisions are also indicated.

Figure 5: The AGENT: agents and constraints



Source: Duchene and Gaffuri (2008:279)

Agents are *autonomous* and share an environment through agent communication and interaction. The decisions they make tie their behaviours to the environment; for example, in land use conversions based on a set of rules (Sawyer, 2003). ABMs model various actors including households relocating their homes, individuals using transport systems, government, and other institutional bodies (Haase and Schwarz, 2009). ABMs can be used as spatially or non-spatially explicit, with the former explicit on the decision-making processes impacting land use change, while the latter does not. ABMs can also be hypothetical or represent real situations.

Few ABM-related studies that focus on modelling urban land use change or growth are found in Africa and South Africa. Shoko and Smit (2013) employ ABM in Cape Town to develop static, dynamic and interactive behaviour models to simulate future patterns and trends in land occupation change over time in informal settlements. Augustijn-Beckers and Bas Retsios (2011) employed agent-based modelling to develop a vector-based, micro-scale housing model to simulate the growth of informal settlements in Dar es Salaam, Tanzania. Their prototype, a vector-based housing model built on three simple rules of spatial change (infilling, extension and enlargement of existing houses), showed that it is possible to successfully simulate the growth pattern of informal settlements. Young (2010) developed a concept for a spatially-explicit ABM for predicting land use change in Dar es Salaam's informal settlements. The model incorporates several drivers of development, including socio-economic, biophysical, and macro-economic factors. In contrast, more examples, including Bousquet et al. (2001), Roucher et al. (2001), and Lynam (2002) focus on the rural areas.

The significance of ABMs in spatial change is well documented. For example, Mathews et al. (2007) argue that specific advantages of ABMs include their ability to model individual decision making entities and their interactions, to incorporate social processes and non-monetary influences on decision-making, and to dynamically link social and environmental processes. Axtell et al. (2002), writing on the role of ABMs in archaeology, add that ABMs offer intriguing possibilities for overcoming the experimental limitations of archaeology through systematic analyses of alternative histories. The modeller, by changing the agents' attributes, rules and features of the landscape, is able to achieve alternative behavioural responses to initial conditions, social and environmental relationships that would otherwise not be possible. However, ABMs, by relying on the bottom-up modelling approach, are 'data hungry' as they require detailed and fine-grained data.

For agent-based modelling that is devoted to the applied modelling of relationship between societies and their environment, especially the agricultural sector and related integrated natural resources management, refer to the CORMAS (COmmon-pool Resources and Multi-Agent Simulations) website (http://www.cirad.fr/en/home-page). The primary aim of CORMAS, developed by the Green research unit from Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), is to work with developing countries to tackle international agricultural and development issues. For a comprehensive list of references focusing on ABMs, see http://banfentian.blogspot.com/2009/06/list-of-references-on-agent-based-land.html.

3.5 SE/EMs

SE/EMs focus on demography and household-driven demand-supply relations in urban regions, such as housing market developments (Haase and Schwarz, 2009). Earlier examples of SE/EMs include Nijkamp et al.'s (1993) household residential relocation model for Amsterdam, and Mankiw and Weil's (1989) examination of the impact of major demographic changes on the housing market in the USA. In most cases, these models do not consider the environment. Instead they are set up as formalised relationships between the population, housing market and residential land use (Haase and Schwarz, 2009). They can be dynamic (when model parameters are treated endogenously) or quasi-dynamic (if model parameters are fixed or exogenous during the model exercise). Drivers of change emanate as demand(s) from the population. Unlike systems dynamics models, SE/EMs rarely incorporate feedback loops back to the original driver.

As discussed in Chapter 1, the advancement in computer hardware and software has enabled modellers to develop sophisticated modelling techniques from a-spatial mathematical specifications of linear relationships to spatially explicit dynamic simulations that allow feedbacks between model subsystems and account for a divergent set of institutional and ecological factors (Voigt and Troy, 2008). As such, issues of spatial explicitness, level of dynamism and the ability to incorporate complex arrays of model factors have seen the use of SE/EMs competing with other modelling techniques described earlier in this chapter.

Zeng et al. (2008), used autologistic regression to simulate the spatial patterns of different land use types in Yongding County, Hunan Province, China. The model explained the factors that are responsible for land use change. Cheng and Masser (2003) present a spatial data analysis method to seek and model major determinants of urban growth in the period 1993-2000 by a case study of Wuhan City in the People's Republic of China. The model used logistic regression.

Abebe (2011) used logistic regression modelling to examine driving forces that explain informal settlement expansion and densification between 1982 to 2002 and 1992 to 1998, respectively, in Dar es Salaam, Tanzania. Abebe established that distances to minor roads, existing informal settlements, other urban land use and population density, proportion of informal settlements and undeveloped land in the surrounding area, to be predictors of informal settlement expansion. Similarly, Abebe established that population density and distances to minor rivers, other urban land use, central business district, major rivers and major roads as predictors of informal settlement densification. No examples of SE/EM modelling were found in South Africa.

3.6 Summary

The literature review of the five categories of models described in this chapter, and summarised in Annexure A, provides a broad overview of international urban modelling initiatives. A wide range of urban spatial change models are available and have been successfully applied in a number of countries such as the USA to assist with long-term planning. Urban modelling is a dynamic field with new urban spatial change modelling techniques constantly being developed; such as the use of neural networks, fuzzy logic and GIS to model the urban evolution in Athens, Greece (Grekousis et al., 2013) and the use of multi-criteria evaluation techniques for future scenario simulation in Madrid, Spain (Plata-Rocha et al., 2011). In addition, Arsanjani et al. (2013) have recently developed a morphological approach for predicting urban expansion based on spatiotemporal dynamics of urban margins in the city of Tehran, Iran, for the years 1976 to 2012.

However, Wegener (2012) recently made the point that not all of the new large modelling projects have been successful, with many projects lost in data collection and calibration or trapped in the academic environment without reaching a state of policy analysis. The problems of current large scale urban models, and the fundamental changes required to address these problems, are summarised in Table 4 below.

Table 4: The "seven sins of large-scale models" and the fundamental changes required to address these shortcomings

Seven sins	Fundamental changes required
Too much extrapolation of past trends	Less extrapolation, more fundamental change
Too much belief in stable equilibrium	Less equilibrium, more dynamics
Too much reliance on observed behaviour	Less observed behaviour, more theory
Too much attention to preferences	Less preferences, more constraints
Too much effort on calibration	Less calibration, more plausibility analysis
Too much effort spent on detail	Less detail, more basic essentials
Too much focus on incremental solutions	Less forecasting, more back casting

Source: Adapted from Wegener (2012:7-8)

Wegener (2012) calls for a paradigm shift in the philosophy and methods of urban modelling to address the future problems of energy scarcity and climate change protection, which are largely ignored in current urban transport and land use models. Models will need to consider the effect of increasing transport costs (due to energy scarcity and increasing energy prices) relative to stable household incomes, by becoming less dependent on observed behaviour for calibration. Instead, urban models need to become more dynamic, incorporating more fundamental change and theory.

4. South African urban growth modelling initiatives

The literature review revealed only a few studies describing urban spatial change models applied within South Africa. A questionnaire (Annexure D) was therefore developed and circulated to gather information on South African modelling initiatives currently underway in various government and academic departments and institutions. In some cases, follow up interviews were also held with the relevant personnel involved in the modelling projects.

The questionnaire was designed to establish the following:

- What urban models are/were used?
- What aspects or components of urban spatial change are/were being modelled?
- What data and software are/were utilised for the various modelling projects?

Questionnaires were sent to the institutions listed below and names in bold indicate institutions where questionnaires or interviews were completed:

- Metropolitan Municipalities of Ekurhuleni, **Johannesburg** and Tshwane
- **eThekwini and Cape Town Metropolitan Municipalities**
- **GPC**
- **Gauteng Department of Economic Development: Development Planning (now incorporated into the GPC)**
- **CSIR**
- **UJ (Department of Geography, Environmental Management and Energy studies)**
- **University of Pretoria (UP) (Centre for GeoInformation Science , Department of Industrial & Systems Engineering** and Department of Town & Regional Planning)
- **South African Research Chair in Development Planning and Modelling**
- **University of KwaZulu-Natal (UKZN) (School of Geography & Environmental Sciences)**
- **University of Cape Town (UCT) (School of Architecture, Planning and Geomatics**)
- **University of Stellenbosch (Centre for Regional and Urban Innovation and Statistical Exploration (CRUISE))**
- African Centre for Cities
- ESKOM
- Housing Development Agency (HDA).

The majority of the models described in the completed questionnaires could not be categorised in terms of the five key urban modelling typologies used in the previous chapter. The bulk of the models were GIS-based and/or linked to spread sheets that contained demographic or housing projections. Remote sensing studies focusing on historical urban land cover change were also more prevalent than cellular automata simulation. Apart from the UrbanSim project and limited academic urban simulation research, it can be argued that advanced modelling of urban spatial change within South Africa at an institutional level has not reached a high level of sophistication. However, Batty (2009) notes a broadening of model styles, types and computer methods on the edge of the urban modelling domain, for example GIS, that in some circumstances may be considered as models when compared to the key urban model types reviewed in the previous chapter. For this reason, the South African urban modelling typologies were broadened to include GIS and remote sensing land cover change models and categorised differently from the international review, as follows: provincial government modelling initiatives in Gauteng, municipal government modelling initiatives, other government funded modelling research, and academic modelling research. The various modelling projects described in this section (summarised in Annexure B) are by no means a comprehensive review of all urban spatial change modelling projects in South Africa, but provide an indication of the types of initiatives underway which may also form the basis for more accurate and sophisticated future urban modelling projects.

4.1 Provincial government modelling initiatives in Gauteng

4.1.1 Gauteng Integrated Transport Modelling Centre (GITMC)

Traditionally, the Gauteng Department of Roads and Transport (DRT) has commissioned provincial transport modelling to a consortium of transport consultants. There has also been a varied response to transport modelling at a local metropolitan municipal level with a combination of outsourced and internal modelling and a range of proprietary modelling software. Furthermore, the district councils within Gauteng are severely under-capacitated. The result is a fragmented approach to modelling, limited modelling capacity and skills development within government, and a mismatch of macro and micro-scale modelling. The Gauteng DRT, therefore, identified the need for integrated land use and transportation planning and integrated planning tools to inform robust decision-making. In response, terms of reference were issued by the DRT for the establishment of the GITMC with the view to migrate from the current:

- Macro-level modelling approach, to a modelling approach that can successfully integrate and align macro and micro-level modelling in Gauteng.
- Licensed-based modelling software, to an open source software modelling platform accessible to all role-layers (including local and district municipalities).
- Outsourcing model, to that of a fully capable and functionally integrated modelling centre for Gauteng, co-ordinating the needs and pooling the resources of both the province and municipalities (CSIR, 2012a).

The CSIR, in conjunction with the UP was appointed to set up the GITMC as a multi-year project. The specific objectives of the GITMC are to:

- "Co-ordinate and integrate transport modelling needs for governments within Gauteng by pooling resources and expertise.
- Implement relevant software that would best accommodate the needs of all the end-users.
- Assess:
    - the implications of government strategies, policies and plans for transport;
    - public transport patterns, routes, mode choice and frequency;
    - land use patterns, densities, types, densities on macro and micro-level;
    - traffic patterns inclusive of growth and in response to interventions;
    - travel demand management and the effects of tolling;

- alternative solutions to traffic problems;
- speed limits and traffic signal settings;
- traffic generation and impacts; and
- road classification, road network expansion or reduction." (CSIR, 2012a)

Key provincial and municipal transport planning stakeholders met in November 2011 and March 2012 to agree on an appropriate institutional framework that will provide horizontal integration within provincial departments and vertical integration amongst the different spheres of government. The 'cloud 9' institutional model was adopted as the ultimate vision of the project (CSIR, 2012a). Its aim is to create a fully operational modelling centre; co-owned, co-funded and co-staffed by a range of provincial and municipal departments to provide high-end planning and modelling skills for a variety of macro and micro-modelling support services to role-players across the province.

The work programme is envisaged to take place in a number of phases:

- Planning phase (May 2012): consultation and institutional framework finalised.
- Establishment phase (May 2012-April 2013): core training of provincial and municipal staff, modelling at macro scale and various seminars.
- Consolidation phase (April 2013-April 2014): relocation of GITMC to DRT, capacity building, skills transfer, microsimulation and various seminars.
- Operational phase (April 2014): fully operational GITMC that meets the integrated land use transportation planning needs of province and municipalities.

The GITMC will initially build on the data and modelling generated by the CSIR UrbanSim and MATSim simulation project (refer to section 4.3), to generate urban growth scenarios based on different transport infrastructure initiatives. The project is still in the establishment phase with the training of provincial and municipal staff on the use of UrbanSim and MATSim, but if fully implemented with continued development and innovation of the current UrbanSim data and models, will provide an advanced transport and urban spatial change modelling platform for Gauteng.

4.1.2 Gauteng Integrated Transport Master Plan[6]

It is indicative of the current fragmented approach to modelling transport in Gauteng that a parallel transport modelling project is currently underway for the 25-year Integrated Transport Master Plan for Gauteng (ITMP25). In 2012, the MEC (Member of the Executive Council) for Roads and Transport appointed a consortium to take responsibility for the development of the ITMP25. The master plan's core mandate is to enable the Gauteng DRT, in collaboration with other spheres of government, to regulate, plan and develop an efficient and integrated transport system that serves the public interest by enhancing mobility and delivering safe, secure and environmentally responsible transportation. In October 2012, the first phase of the ITMP25, a five-year short intervention plan designed to serve as a foundation for the ITMP25, alleviate blockages and provide short-term road network and public transport improvements, was submitted to the DRT (Gauteng DRT, 2012).

New transport models for Gauteng are long overdue as the previous Gauteng Transportation Study (GTS 2000) model was developed in 2001, based on the 2001 Census information and household travel surveys conducted in the province. The model was updated in 2005 and 2007 as part of the Review of the Strategic

[6] This section is based on information from the GCRO questionnaire submitted by Kobie Nel from Plan Associates.

Road Network for Gauteng (GSRNR 2010). The GSRNR 2010 transportation model (base year 2007) was updated to 2010 to serve as base year model for the ITMP25 study.

Plan Associates were assigned the task to update the land use for the 2010 base year and design years 2015, 2025 and 2037. Future land use was modelled in spread sheets linked to GIS software based on two data sources:

- Demographic and economic development scenarios: external demographic and macro-economic perspectives were developed to provide a basis for the further development of the ITMP25, supplemented with additional projections and forecasts developed by Global Insight, based on the latest available data and/or official sources.
- Land use data: updated to the base year and forecasted through a combination of Census 2001 data, aerial photography and building counts, and Global Insight demographic and economic models. The variables per traffic zone include:
  - Dwelling units
  - Population
  - Economically active population (formal, informal and unemployed)
  - Retail and office floor area
  - Formal workers by type, for example retail, office, industrial, commercial, local serving, agricultural and mining, construction and transport
  - Informal workers
  - Unemployed people.

A total of 833 traffic zones covering Gauteng and surrounding areas have been modelled over a period of seven months. The ITMP25 is due to be completed by June 2013 (Gauteng DRT, 2012). At the time of writing, there was no planned collaboration between the GITMC and ITMP25 modelling initiatives, highlighting the lack of collaboration and possible duplication of modelling efforts.

4.1.3 Gauteng Infrastructure Planning Tool

The Gauteng Infrastructure Planning Tool was developed to assist with the short- and medium-term integrated planning of education and health facilities within the province. Using the current location of schools (primary and secondary), hospitals and clinics, the future demand and location of new facilities are modelled. This provides planners and decision-makers with a tool to test different development scenarios to determine optimal locations of public social facilities (Engelbrecht, 2012).

The tool utilises GIS-based modelling provided by the spatial analyst and network analyst extensions in the Esri ArcGIS GIS software. Three modelling functions have been developed to determine the candidate locations of the facilities, namely:

- Weighted overlay model: uses a raster-based weighted overlay model to determine possible locations influenced by various layers, such as geotechnical suitability and state-owned land.
- Location allocation analysis: to select facilities from the set of potential locations based on a demand generated by the population in each Enumerator Area.
- Capacity balance (part of the location allocation analysis): to balance the capacities of existing facilities with the population demand points.

The tool utilises the following datasets:

- geotechnical suitability
- environmental sensitivity
- state-owned land
- routable road network
- population change
- locations of existing facilities
- matrix of potential candidate locations.

The tool's development was initially commissioned by the Gauteng Provincial Treasury to assist the Gauteng departments of Education, Health, and Local Government and Housing. The GPC has taken ownership of the tool, but it is yet to be implemented or used.

During the tool's development, the appointed consultants identified a number of concerns with regard to data and modelling within Gauteng (Kleynhans, 2012). Firstly, there is a vast range of population projections used by GPG departments and no agreement within GPG on which population projections should be used for forward planning. As is evident in Table 5, the population projection figures used by different departments drastically diverge, with serious risks for the under or over provision of facilities. The recent Census 2011 population for Gauteng of 12 272 263 exceeds a number of the 2015 projections in the table, highlighting the difficulty of projecting populations in a province of migrants. There is also a lack of population projections at an enumerator area level, with future control totals disaggregated using current population distribution and land use. Secondly, integrated planning through the collaboration of the departments involved and implementation of the tool will fail if the necessary professional staff are not appointed (Kleynhans, 2012).

Table 5: Summary of population growth scenarios used by various GPG departments

	Gauteng Transportation Management Plan 2007	Gauteng Department of Health and Social Development Service Transformation Plan 2010-2020 (Dulisenang Scenario)	Gauteng Infrastructure Renewal and Investment Plan (GIRIP) 2008			Gauteng Spatial Development Framework 2010 (High scenario from Gauteng 2055 Trend Paper by Forced Migration Programme (Wits))	Statistics South Africa 2009	Global Insight 2009	Gauteng Vision 2055 (2009)		
Year	Population										
			Low	Medium	High				Low	Medium	High
2001								8,800,000			
2005								9,000,000			
2006		10,197,665					10,197,665				
2007	10,029,112		10,155,309	10,155,309	10,155,309	10,454,553		10,200,000			
2009							10,451,713	10,800,000	10,700,000	10,800,000	10,900,000
2010	11,120,828	11,201,907	10,808,000	10,926,000	11,125,000	11,551,143	11,191,700	11,014,203	11,000,000	11,100,000	11,200,000
2014											
2015	11,704,775	12,264,594	11,937,000	12,280,000	12,874,000	12,320,100	12,374,955	12,518,182	12,300,000	12,400,000	12,800,000
2020		13,200,000	13,085,000	13,683,000	14,587,000				13,900,000	14,000,000	14,600,000
2025	12,843,005	14,474,383	14,293,000	15,188,000	16,480,000	15,126,908	15,343,507	16,170,283	15,000,000	15,100,000	16,200,000
2055	19,394,277	25,162,681	25,264,293	29,706,147	36,931,531	28,000,000	29,246,080	34,853,522	21,300,000	22,500,000	27,000,000
Annual average change	1.01383	1.01860	1.01917	1.02261	1.02726	1.02074	1.02173	1.02593	1.01508	1.01608	1.01991

Source: Gauteng Department of Finance (2012:10)

Note: Red figures are extrapolated for comparison purposes. Blue figures are extrapolated from the graph in the Gauteng Vision 2055 report.

4.1.4 Gauteng Spatial Development Framework (GSDF)[7]

The 2011 Gauteng Spatial Development Framework has been developed to "provide a clear future provincial spatial structure that is robust to accommodate growth and sustainability", with a clear set of spatial objectives for municipalities to pursue (Gauteng Department of Economic Development, 2011:2). Five models were developed to assist in analysing existing urban patterns and dynamics in Gauteng, as well as serving as a basis for future spatial strategies for the province, and supporting policy and planning decisions. The GIS-based models, summarised in Table 6, were developed at a provincial scale over a six-month period during the planning phase of the GSDF.

Table 6: The GIS-based models utilised in the GSDF

Model	Description	Data sources
Urban profile	Sets out to provide users with an in-depth understanding of the urban system in any number of ways. Gauteng is divided into a 10m by 10m grid of cells, providing the option to 'drill-down' into any one or groups of these cells and gain a full appreciation of the associated urban profile and the implications of the GSDF for that particular point.	• Existing land use • Existing zoning • Existing road and rail network • Existing public facilities • Existing municipal Spatial Development Framework (SDF) proposals • Existing natural elements (open spaces, ridges, etc.)
Urban morphology	Focuses on the spatial and structural underpinnings of the GCR as an urban system. Morphologically, urban systems can be described in terms of elements, types or characteristics of urban development (zones of urban consolidation, urban development corridors, etc.). The urban morphological model therefore describes what's there, assessing urban performance and proposing structural adaptations, amendments or fundamental changes required in morphological terms. Morphological types around which urban structure should be re-considered and minimum urban performance criteria that need to be met when developing within these types are established in the model.	• Existing land use • Existing zoning • Existing road and rail network • Existing public facilities • Existing municipal SDF proposals • Existing natural elements (open spaces, ridges, etc.)
Connectivity	Provides a spatial representation of connectivity highlighting areas that are well integrated and more accessible, and areas that are more segregated and less accessible. It is a tool for examining the possible impacts of additional infrastructure aimed at increasing the urban integration of an area. The connectivity model therefore assists in: (a) detecting the lack of connection; and (b) testing what infrastructural improvements would be most effective in improving connectivity.	• Provincial road network • Proposed PWV (Pretoria Witwatersrand Vereeniging) K road network • Provincial rail network • Gautrain rail network

[7] This section is based on information from the GCRO questionnaire submitted by the Gauteng Department of Economic Development: Development Planning (now integrated into the GPC) and the Gauteng Spatial Development Framework document (Gauteng Department of Economic Development, 2011).

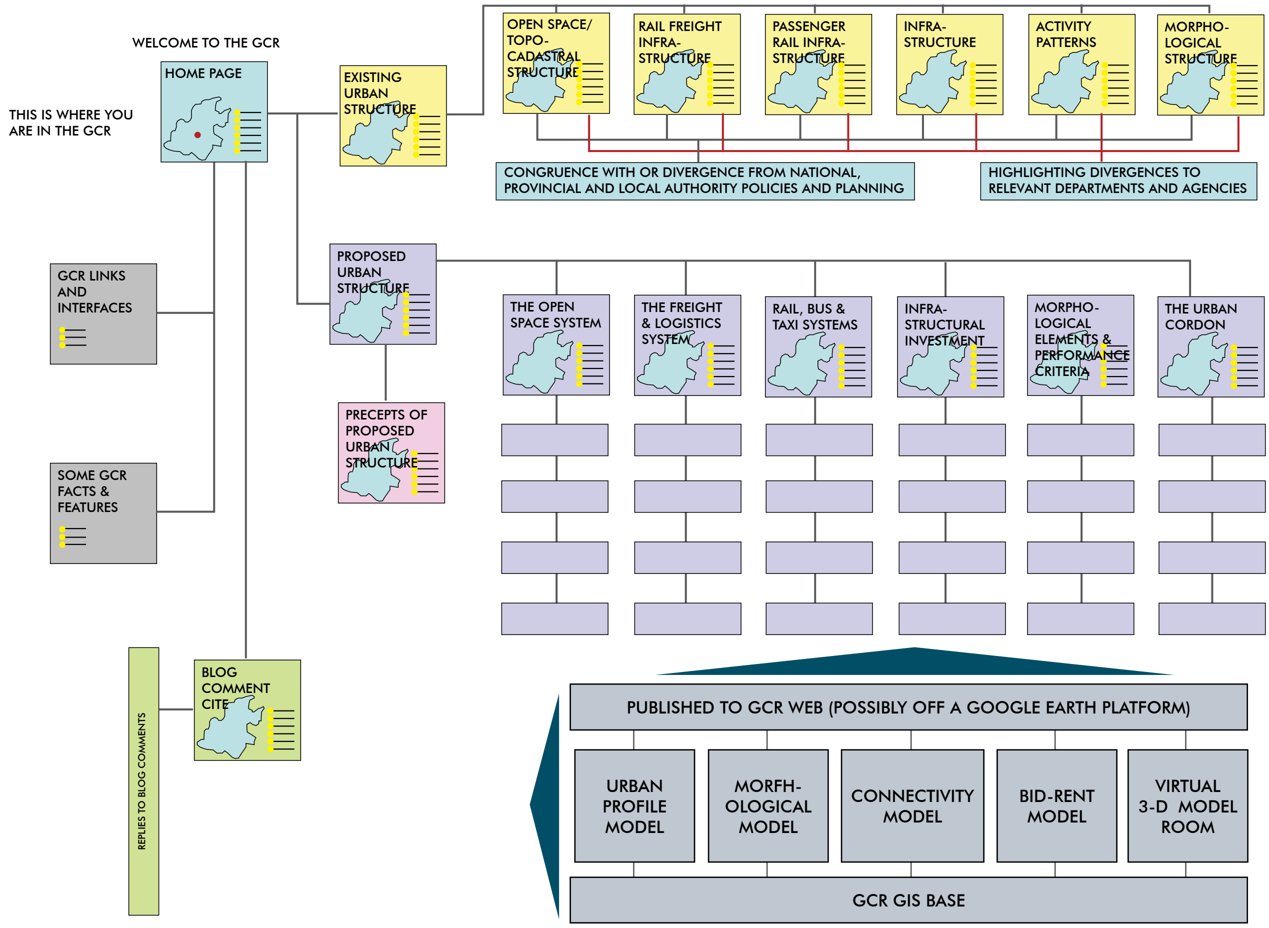
Bid-rent	Developed to describe an indicative urban potential, in 'bid-rent' terms of any given point within Gauteng. The model, therefore, indicates relative urban development value, as opposed to an indicative land value, where the urban potential of any given point in relation to its existing position in the urban structure, urban fundamentals (such as visibility and access) and infrastructure investments in the area, is indicated.	• Existing land use • Existing zoning • Existing road & rail network • Existing public facilities • Existing municipal SDF proposals • Existing natural elements (open spaces, ridges, etc.)
Virtual model room	Established to provide indicative, illustrative, 3D visualisations of the nature of the urban environment planned in different areas, allowing users to envisage possible urban future as a result of the interventions, policy directives, guidance and encouragement inherent in the GSDF.	• Appropriate current project proposals to be modelled

Source: Compiled from Gauteng Department of Economic Development (2011)

The GSDF was envisaged as a GIS-based planning tool to be used by all government departments in the GCR, non-governmental organisations (NGOs) and private stakeholders. It was designed to be made available through a web mapping tool (see Figure 6) but is yet to be publicly accessible. However, the key issue remains: what plans the GPC has to build on the five tools and make them publicly accessible three years after the finalisation of framework?

The official release of the GSDF was slightly delayed due to a Provincial Executive Council decision to rescind the provincial urban edge in favour of the provincial boundary representing the urban edge. This led to a subsequent editing of sections of the GSDF and new planning approaches to be considered by the GPC for controlling urban growth. The Gauteng Growth Management Strategy is one of the approaches currently under consideration and is intended as a mechanism to enable the GSDF by outlining the planning tools required to manage and direct urban growth towards the desired patterns of growth set out in the GSDF (GPC, 2013a). The draft strategy makes specific mention of the need to set up a joint provincial and municipal urban growth forum, to ensure coordination and cooperation between all stakeholders, and the establishment by the GPG of a growth forecasting and spatial modelling unit, sufficiently staffed and funded to provide a specialised modelling service.

Figure 6: The structure of the GSDF according to the proposed web application



Source: Adapted from Gauteng Department of Economic Development (2011:40)

4.1.5 Gauteng Planning House

The GPG has initiated a process to establish a Gauteng Planning House – a state of the art venue to visualise the future development plans of the GPC and G2055 project (GPC, 2013b).The concept is based on similar initiatives in other countries, including the Singapore City Gallery in Singapore and the Chongqing Urban Planning Exhibition Hall and Shanghai Urban Planning Exhibition Hall in China. The future development plans of the GPG will be conveyed to a wide range of stakeholders including citizens, tourists, land developers and public and private investors through the following proposed initiatives:

- A scale architectural model of the GCR demonstrating current, existing and future development aligned to G2055.
- A 270-degree panoramic sights and sounds show.
- Scale models of key developments that have transformed Gauteng, such as Constitutional Hill and future infrastructure including transport routes and systems proposed in the ITMP25.
- A theatre room housing a 360 degree screen with a 3D flythrough of the future GCR, as envisaged by Gauteng Vision 2055 (GPC, 2013b).

Although the Planning House is not a modelling project *per se*, it will rely on the visualisation of various modelling outputs. Most importantly it will “act as a single entry point for data in the GCR with a well-functioning GIS able to respond to the spatial data needs of the Gauteng Provincial Government” (GPC, 2013b:3).

4.2 Municipal government modelling initiatives

The three metropolitan municipalities in Gauteng, i.e. Ekurhuleni, Johannesburg and Tshwane were sent questionnaires, with only the City of Johannesburg responding. Information was also received from the City of Cape Town and eThekwini. UrbanSim modelling of Ekurhuleni, eThekwini and Nelson Mandela Bay are covered in more detail in the CSIR UrbanSim project write up in section 4.3.

4.2.1 City of Cape Town[8]

The city uses a range of methods, tools and data to monitor urban spatial change. According to Petzer from the City of Cape Town's Economic, Environmental and Spatial Planning Directorate, geospatial analysis is used to:

- compile a vacant/undeveloped land database
- monitor urban density
- monitor informal settlements
- assess infrastructure risks
- report on building activity
- study, explain, predict and influence spatial economics.

These analyses cumulatively provide a useful prediction of future urban development and are important inputs into the prediction models. In future, the city is planning to develop a LUT model using EMME3 transport and UrbanSim modelling software. The remainder of this section discusses two key current models or systems used to monitor urban growth and estimate how much land is required for the city's growth.

Urban growth model (UGM)

The GIS-based UGM is used to model urban growth by mapping where the growth is likely to occur and in addition estimates residential dwelling units and future industrial and mixed-use land use. The outputs from the UGM assist in planning for what investment in municipal services is required. This estimation process is a culmination of bottom-up spatial planning and proposals that emanate from the city districts. It considers how vacant land can be used, what percentage of the site can be developed, the residential densities and the likely timeframe for its development.

However, according to the literature provided by the City of Cape Town, the UGM model has a number of weaknesses, namely:

- Only future growth on current vacant land is modelled. A comprehensive model should ideally also include modelling future growth in redevelopments (brownfields development) as well as infill developments, such as backyard shacks.
- The modelling exercise does not incorporate the development of informal settlements.
- The model equally regards all vacant land as developable during the planning period, despite evidence indicating that vacant land in some areas remains vacant for many years.
- Besides incorporating the desires of spatial planners, the UGM does not recognise that ultimately private investment decisions and other practicalities (especially in the development of state housing by public institutions) influence the prevailing urban development.

[8] This section draws from literature supplied by Jaco Petzer, Principal Planner Professional, City of Cape Town.

Urban growth monitoring system (UGMS)

With the help of an external consultant, the city has built a spatially-explicit UGMS used to provide up-to-date urban growth information and monitor urban growth (i.e., rates, patterns, and direction). The UGMS is also used to inform the Integrated Development Plan (IDP), SDF and other city policies.

The UGMS has two distinct information elements.

1. Residential, i.e. estimates of households and population, based on 2007 data projected to December 2011. It provides updates of the total number of units of occupied and formal dwellings. Similarly, using the 2001 Census data, estimates of population totals at Census sub-place, planning district, ward, and sub-council level have been provided. The data output can be queried via Excel and other reporting tools.
2. Economic, i.e. commercial, industrial and businesses, based on 2009 data projected to December 2011. Economic growth is measured as a change in the usage of land, physical development, and the consumption of services. The change in economic activity per parcel of land is provided on a month-to-month basis. Economic activities captured in the model are: property development, subdivisions, changes in land uses, type of new development, value and size of new and additional developments, number of units developed; electricity, water, and sewerage consumptions and connections; and population growth (formal only).

4.2.2 eThekwini municipality[9]

The eThekwini municipality is involved in various modelling projects.[10] Initially relying on outside consultants, these modelling projects assessed the impacts of various projects on the spatial development trajectory of the municipality. These involved small exercises where control for inputs is possible. Past efforts at customising an eThekwini UrbanSim model are still on-going as challenges including UrbanSim's complexity and a lack of expertise and resources in the municipality remain.

Infrastructure investment finance model

As a result of pressure from developers and land owners who complained about the lack of infrastructure in the city-edge areas, in mid-2007 eThekwini embarked on a process to unblock development in these areas. The municipality initiated the modelling of the infrastructural impacts of land uses proposed in the Spatial Development Plans (SDPs). Specifically, the modelling exercise set out to identify critical infrastructure projects based on eThekwini's service delivery charter and determine the extent and cost of the required infrastructure. A further consideration was the impact that these infrastructural investments would have on the municipality's capital expenditure and operating revenue portfolios.

An Excel-based infrastructure model was customised for eThekwini by the Palmer Development Group, South Africa[11]. Three sub-metropolitan regions, i.e. the north, south and west regions, were modelled. Modelling involved comparing the three regions on the basis of the yield of different land uses, the extent of current and likely future private development pressure, public housing yield, the modelled cost of

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9 This section draws from: (a) personal (telephone) communication on November 6, 2012 between Cheruiyot and Ken Breetzke; and (b) Breetzke, K. (2009) From conceptual frameworks to quantitative models: spatial planning in the Durban metropolitan area, South Africa – the link to housing and infrastructure planning. Available from http://www.unhabitat.org/grhs/2009.

10 According to Breetzke, they are not really simulation models. Rather they are 'assessment tools.'

11 According to Kim Walsch of the Palmer Development Group, approximately 40 municipalities have used the Municipal Services Finance Model (MSFM) to track their capital infrastructure investment plans and the implications such investments will have on their budgets.

infrastructure required and the estimated rates of income. The exercise proposed the northern region for infrastructural investments aimed at unblocking development. Within the northern region, further microsimulations, i.e. in the Mdloti, Ohlange, and Tongati catchment areas, were carried out to establish the right package of infrastructural investments that the municipality should prioritise given capital costs and associated premiums.

With results that are spatially explicit (in terms of maps and tables) and easily understood, the unblocking development project has reinforced the urban edge concept and highlighted the financial impact of leap frog or scattered development. In addition, the project has assisted eThekwini's Planning Department to commit to a course of action. The implication of failing to make explicit choices and limiting infrastructure growth will result in holding back municipal growth.

Cost surface model (CSM)

Similar to other metropolitan areas in South Africa, the planning of public housing in eThekwini has led, and infrastructure and spatial planning has followed. The CSM was therefore developed and implemented to calculate the costs of providing bulk infrastructure in various locations with respect to the provision of public housing. The CSM, by showing that it is more expensive to provide services in peripheral locations, supported the argument for better location of public housing. This GIS-based model provides the predicted costs of bulk servicing of housing projects at a glance. This has improved decision-making in eThekwini as early as the planning/feasibility phase since the costs of bulk infrastructure can be calculated. In the past, these costs could only be determined in the project package stage. It has also improved the much needed cross-disciplinary dialogue and integration within the municipality in terms of project planning, budgeting and implementation.

Specifically, the CSM is providing strategic level input to the medium- and long-term budget planning within eThekwini through the calculation of the cumulative cost of infrastructure required to serve the more than 700 proposed projects within the municipal housing plan (Breetzke, 2009).

Accessibility model

eThekwini uses the spatially explicit Accessibility Model to understand the future social services requirements of its housing planning projects. Based on population numbers, incomes, and age profiles, the model simulates the supply of and demand for social facilities across the municipal area. It also takes into account the existing backlog in facilities. The Accessibility Model uses GIS and modelling to generate quantitative information. So far it has reinforced the need to cluster public investment in nodes and along corridors as well as aid decision making in housing planning exercises. Being a micro-model, it has signified a move beyond broad and conceptual spatial planning through the formulation and use of standards. As the model has proved useful in matching the supply of and demand for social facilities, it has helped to avoid unnecessary and wasteful development in this regard.

4.2.3 City of Johannesburg[12]

The City of Johannesburg (CoJ) is involved in a number of modelling projects. The projects are either futuristic or retrospective and apart from the UrbanSim project are meant to track trends rather than simulate scenarios. The projects involve: (a) monitoring development trends for the Growth Management Strategy (GMS); (b) the urbanisation plan; and (c) the CSIR UrbanSim model. The development and implementation of these models enable the city to track the impacts of the various land use developments.

Monitoring development trends

Since 2007, the CoJ has captured town planning and building plan applications within Johannesburg through the Building Application System (BAS) and Township Application System (TAS). These development trend systems assist the city to monitor urban change and development in terms of what land use changes are being considered and the impacts (in terms of square metres, number of units, etc.) the building applications may have. According to Ahmad from the CoJ's Development Planning and Facilitation Directorate within the Department of Development Planning, tracking building applications is more reflective of the actual change taking place, as opposed to the future planned development captured by the town planning applications. The approval of building applications and awarding of building rights shows the intent by developers to build and is therefore useful to the city in terms of estimating the Rand value of the approved development. A better understanding of the property market is also provided as it answers questions around what is being requested, what the market is asking for, what is being approved and where development is happening.

Monitoring the development trends captured by the BAS and TAS systems is key to assessing the outcomes of the GMS, adopted in 2008 to support the existing Spatial Development and Capital Investment Frameworks[13]. The strategy supports the values and principles set out in the city's long-term Growth and Development Strategy (GDS), Joburg 2040, such as "ensuring social inclusivity in market-driven growth areas; aligning development to emerging public transport networks and infrastructure; and stimulating a diversity of development and economic opportunities in marginalised areas, those areas located far from job centres, social services and public transportation links" (CoJ, 2012a:1).

The development trends are used to check if the city's SDF is matching the infrastructure investments that the city is making in terms of the GMS. Conversely, it is also useful in determining if the city is getting value for its infrastructure investments. An analysis of the development trends are published annually as the *Growth Management Strategy: Growth Trends and Development Indicators Report*. Technically, the development trends analysis is implemented in an Excel spread sheet, generated from the city's Land Information System. The spread sheet is joined to GIS map layers to provide maps of urban spatial change (from 2007 to the present) within the city.

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[12] This section draws on: (a) personal communication on October 5, 2012 between Wray, Cheruiyot, and Pete Ahmad; (b) Growth Management Strategy: Growth Trends and Development Indicators. A presentation prepared by CoJ's Directorate of Development Planning and Facilitation for the Fourth Annual Assessment: Adapted Stakeholder Presentation. September 2012; and (c) Sustainable Human Settlements Urbanisation Plan. A presentation prepared and presented to the Human and Social Mayoral Sub-Committee. 3rd August 2012.

[13] "As an integral component of the GMS, five functional Growth Management Areas have been designated which direct the City's priorities in terms of its Capital Budget as well as its evaluation of development applications. These five Growth Management Areas cover the full extent of the City and indicate the priority the City has prescribed in terms of short, medium and longer term public investment per area" (City of Johannesburg, 2011:1)

Urbanisation model

The city has prepared a Sustainable Human Settlement Urbanisation Plan (SHSUP), commonly referred to as the urbanisation plan, to guide the city's spatial development. SHSUP has a specific focus on the housing needs of the growing number of city households. The lower threshold estimation of the number of new households is pegged at 400 000 by 2030, while a higher estimation threshold estimates one million new households needing housing. According to Ahmad, the latest Census data indicate that this is potentially a significant undercount. However, taking the more conservative lower threshold of 400 000 households and the existing backlog of 450 000 informal households that need be to be housed, the city will be required to plan for housing an additional 850 000 households by 2030. The urbanisation plan is intended to consider where to locate these new additional households, the appropriate densities, the impacts on physical and social amenities, and the required planning initiatives and land acquisitions. In short, the existing scenario is not very optimistic and the city has to plan accordingly, balancing addressing formality in the face of burgeoning informality.

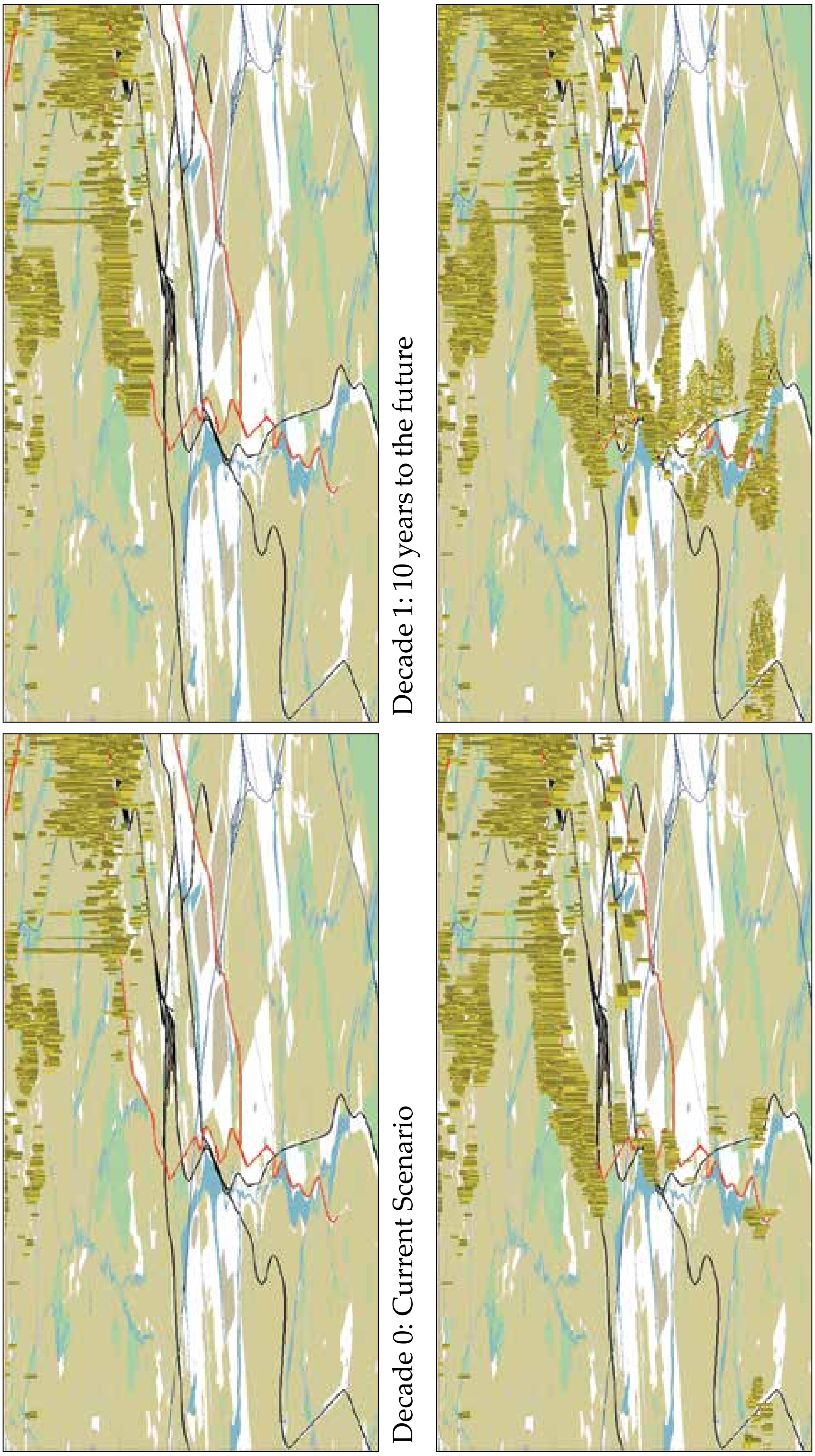
The city has worked with Esri South Africa to model a 3D visualisation of the city in a number of development corridors identified by the city to encourage development densification. The 3D models are based on the SHSUP densification projections in these areas and cover three decades with the extent of development concentration in each decade identified. These corridors include the Soweto Bus Rapid Transit (BRT) and Rail Precinct Development Corridor, Louis Botha BRT corridor, Turfontein Re-development Corridor, Randburg to Alexandria Corridor, and Diepsloot Corridor. As an illustration, Figure 7 shows in 3D how the CoJ envisages the development of the Soweto BRT and Rail Precinct Development Corridor through the various decades to 2040. Esri's 3D modelling software CityEngine[14] was used to generate the city models of the densification projections in these corridors.

UrbanSim model

CoJ's Development Planning and Facilitation Directorate has recently collaborated with the CSIR to customise an UrbanSim model using the city's demographic data, economic indicators and development trends. The project captured about five years of data and the model was calibrated to produce baselines with high and low estimation thresholds. The demographic model has been projected to 2030, but is an on-going project between CoJ and the CSIR with the results still to be made publicly available.

[14] http://www.esri.com/software/cityengine

Figure 7: Soweto BRT and Rail Precinct Development Corridor



Source: City of Johannesburg (2012b)

4.3 Other government-funded modelling research: CSIR UrbanSim

According to the Spatial Temporal Evidence for Planning South Africa (stepSA)[15] factsheet, existing land use modelling in South Africa has a number of limitations:

- modelling the extent of urban growth with no indication of where the growth will be located
- modelling only within the administrative municipal boundaries without considering the impact of developments and trends in neighbouring areas
- simulating the outcomes of proposed spatial development plans without considering the market response to these policies or plans (stepSA, 2013b).

The CSIR Built Environment unit therefore established an Urban Dynamics Laboratory (UDL) in 2007 to "bring together a trans-disciplinary team and a package of tools and methodologies in a numerical modelling and simulation capability to study cities and regions as complex, social-ecological systems with emergent behaviour" (Waldeck, 2007:5).

Following a comprehensive literature review of international urban modelling, the CSIR recommended the use of the UrbanSim modelling system (Waldeck, 2007). The first major application of CSIR's urban simulation capability formed part of the Integrated Development Planning and Modelling Project (IDPM), funded by the DST, with the aim of supporting integrated development and planning within South Africa (CSIR, 2011). The simulation project in the cities of eThekwini, Nelson Mandela Bay and Johannesburg, and in Gauteng, is studying the likely patterns of urban growth 30 years into the future based on current spatial policy and investment decisions. A separate modelling initiative, that forms part of the Water Sustainability Flagship Programme of the CSIR, is currently underway in Ekurhuleni. An urban growth simulation is being developed by the CSIR focusing on future demand and consumption patterns for wastewater and sanitation in Ekurhuleni. The modelling is expected to inform infrastructure investment decisions such as outfall sewers and waste water treatment plants (stepSA, 2013b).

The simulation platform chosen by CSIR for these projects is a combination of UrbanSim, for the microsimulation of choices of households and businesses in relation to property and services, developers as suppliers of services and government providing infrastructure and services; and MATSim, an open source agent-based traffic simulation software for simulation of transportation system behaviour from an individual household perspective (CSIR, 2010; CSIR, 2011). The models run independently of each other (with some shared source data), exchanging feedback information after each year of simulation. Flowmap, an open source package that analyses flow or interaction data, is also used for the catchment area analysis, proximity counting and optimisation components of the modelling. CSIR uses the parcel and zone-geography versions of UrbanSim where individual stands are aggregated to street blocks. Figure 5 (in Chapter 3) summarises the UrbanSim agents, with the interactions and the key datasets required to model each of the agents listed in Table 7.

[15] stepSA is a collaborative initiative commissioned by the Department of Science and Technology (DST), in partnership with the CSIR and the Human Sciences Research Council (HSRC), in support of integrated development and spatial planning across different sectors and scales (stepSA, 2013a).

Table 7: UrbanSim data requirements and main data sources

Data	Source
Land/ buildings	Land use (cadastral parcel-based) and residential building count dataset supplied by GeoTerraImage (GTI), derived from aerial/satellite imagery. Property valuations, SDPs and urban development boundaries obtained from each municipality.
Population and employment growth	Census data from StatsSA. Demographic and employment control totals for each year of the simulation run obtained from Global Insight, with demographic control totals broken down by household income, household size, number of workers, number of children, age and race of the head of household; and employment control totals broken down by one-digit Standard Industrial Classification (SIC) code.
Development events	Municipal development proposals and intended infrastructure improvements, such as Reconstruction and Development Plan (RDP) housing schemes.
Development template	A geo-demographic segmentation (Knowledge Factory Cluster+ dataset) of the population at a suburb level which serves as a settlement typology and proxy for deriving missing information.
Transport networks	Municipal EMME2 models imported into MATSim for network and agent plans for private vehicle drivers.

Source: Compiled from CSIR (2012b)

The simulations are run for 30 years from a base year of 2001 (with results for each year), testing policy alternatives such as restricted growth within an urban development boundary or major planned strategic transportation or other infrastructure plans. For example, a fragmented business as usual versus consolidated growth scenario extracted from the GSDF, is planned for the Gauteng modelling. The CSIR has employed a 'living laboratory' approach with direct and indirect stakeholders in each of the cities, where planners, modellers, and decision makers/officials participate at various stages of the project, including the selection of indicators and scenarios to model. The urban growth results are validated against a known dataset, with the release of Census 2011 data providing further opportunities for simulation validation.

Two of the key challenges faced by the CSIR, and ultimately a test of whether urban simulation and the UrbanSim platform can be applied in a developing country context, were: (i) configuring UrbanSim to a South African urban environment, and (ii) obtaining data that can be utilised at an ABM/micro-simulation scale. CSIR has worked closely with the UrbanSim developers to adapt the models to provide for the specific South African context where the government is a major developer and provider of housing. Data issues include a lack of building plans in a digital format and municipal property valuations not distinguishing between land and improvement value. CSIR has overcome these data hurdles through the purchase of new datasets such as the GTI growth indicator, which captures a point per building, and the application of a development template derived from the Knowledge Factory Cluster+ data that serves as a settlement typology made up of 38 clusters, with informal settlements and backyard shacks presenting a uniquely developing country housing typology. However, there have been complications using the GTI data to estimate aggregate densities in given land parcels based on the individual building units. Access to public transport data such as accurate routes and schedules (specifically in Gauteng) is a further data limitation. The data collation and preparation process took approximately 18 months, with an additional year required to produce a model – an indication of the complexity of advanced modelling of an urban system.

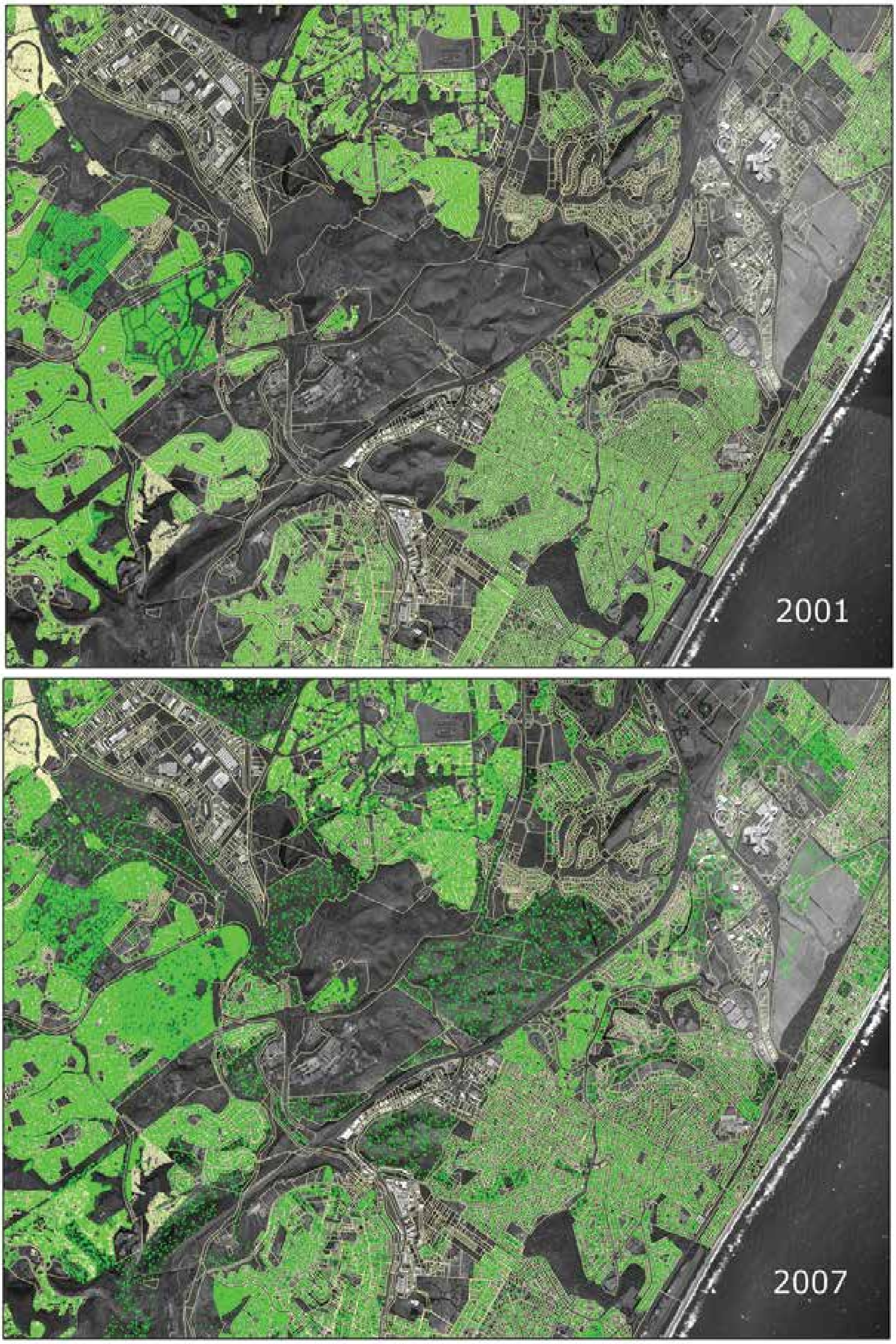
Figure 8 illustrates preliminary results of simulated urban growth in the Umhlanga area of eThekwini from 2001 to 2007. The new housing development modelled by UrbanSim is clearly visible (as dark green dots) on the open land in the centre of the 2007 map. Two future development scenarios were produced:

- A 'trend' scenario with future urban growth based on current development trends with no interventions by public or private developers
- A 'blue skies' scenario that considers municipal densification policies in support of public transport (stepSA, 2013c).

Both scenarios indicated growth along the national N2 and N3 highways but even the blue skies scenario did not indicate that the higher densities set out in the densification policies would be achieved (stepSA, 2013c), prompting a rethink of the municipal SDPs.

A simulated growth model for Gauteng is expected to be completed by mid-2013, but is dependent on resolving the outstanding data issues, such as public transport data. However, the appointment of CSIR to establish a modelling centre for the Gauteng DRT and the possibility of the scaling up of the stepSA project with a new co-funding model shared between a number of government departments (stepSA, 2013a), could serve as the basis for the development of advanced urban simulation models in Gauteng.

Figure 8: Preliminary results of simulated urban growth in eThekwini (Umhlanga region) 2001-2007



Source: CSIR (2012b)

4.4 Academic modelling research

This section will highlight urban change/growth modelling initiatives in a South African academic research context, namely in universities such as, Wits, the University of Stellenbosch, UKZN, UP, UJ and UCT. A few of the studies are still in progress and have yet to be published. Land cover change research commissioned by the GCRO is also described.

4.4.1 South African Research Chair in Development Planning and Modelling

The South African Research Chair in Development Planning and Modelling research programme, funded by the National Research Foundation and based at Wits, was established in 2009. Its broad research area is to describe, analyse, and explain the shifting spatial order of a dynamic GCR, with a focus on the role of development planning and other policies, processes and instruments in shaping spatial outcomes.

The research centre has four strongly related components: the mapping, simulation, and modelling of spatial change; the role of government, and especially of urban planning, in shaping urban space; the spatial outcomes of decision making in the private sector; and culture, community, and spatial transformation. Under the first component – the mapping, simulation, and modelling of spatial change – the research centre aims to not only understand the past and present spatial change but, more importantly, use methods of spatial analysis to predict and simulate future spatial change. This will assist in identifying the suitable development planning frameworks and regulative structures that will lead to desirable spatial and societal outcomes into the future.

To date the research centre has focused on two modelling exercises. First, is a complete and published research report titled *Does density drive development?*, and a second project, titled *Modelling the relationship between the economy and accessibility in South Africa* that has produced a draft report to be finalised in 2013. The first model employed standard regression analysis, while the second model utilised spatial regression analysis. In addition, the centre is in partnership with GCRO in the present project investigating urban spatial change in the GCR.

4.4.2 Centre for Regional and Urban Innovations and Statistical Exploration (CRUISE)[16]

The centre, based at the University of Stellenbosch, relies on systems theory to examine spatial relationships and the various social, economic and ecological sustainability processes that occur in cities. This is intended to bring about a greater understanding of the operation of cities as systems.[17] The centre focuses on cities' urban form, functional linkages and formal and informal linkages.

The urban form research area deals with trends in the urban morphologies of both metropolitan as well as intermediate-sized cities. With lots of data at these levels, various intra-urban level morphology issues are addressed. First is densification – this entails measuring density trends over time. So far, findings from empirical research have shown a different picture from what was envisaged by government policies at various levels, i.e. the national, the provincial, and at the local level. Other morphological issues include the integration of policies and corridor measures.

[16] This section draws on personal communication on November 19, 2012 between Cheruiyot, and the CRUISE Director, Professor Geyer.

[17] See http://www0.sun.ac.za/cruise/

The functional linkages research area focuses on inter-city linkages conceptualised around the differential concept. The differential urbanisation concept, originally formulated by Geyer, argues that a group of urban areas – large, intermediate-sized, and small cities – undergo differentiated urban growth trajectories over time. This differentiated urbanisation (as measured by net migration patterns) is witnessed through six stages of successive periods of fast and slow growth in a continuum of development that spans the evolution of urban systems in developed and less developed countries (Geyer and Kontuly, 1993). So far, empirical results at CRUISE show concentration and deconcentration trends around the country. A joint project between the Organisation for Economic Co-operation and Development (OECD) and CRUISE maps daily and weekly linkages among satellite and inner cities. In addition, empirical results show the resultant urbanisation differs from local government or other government policy intentions.

The formal and informal linkages research agenda has been on-going for the last three years. The research agenda examines the spatial linkages between the formal and the informal business sectors. It uses extensive surveys that have been collected in Cape Town, Ekurhuleni, Tshwane and CoJ. A rich database with a wide array of data, including environmental, logistical, financial, and social data has been built. This has shown structural and spatial linkages in the large and inter-mediate sized cities.

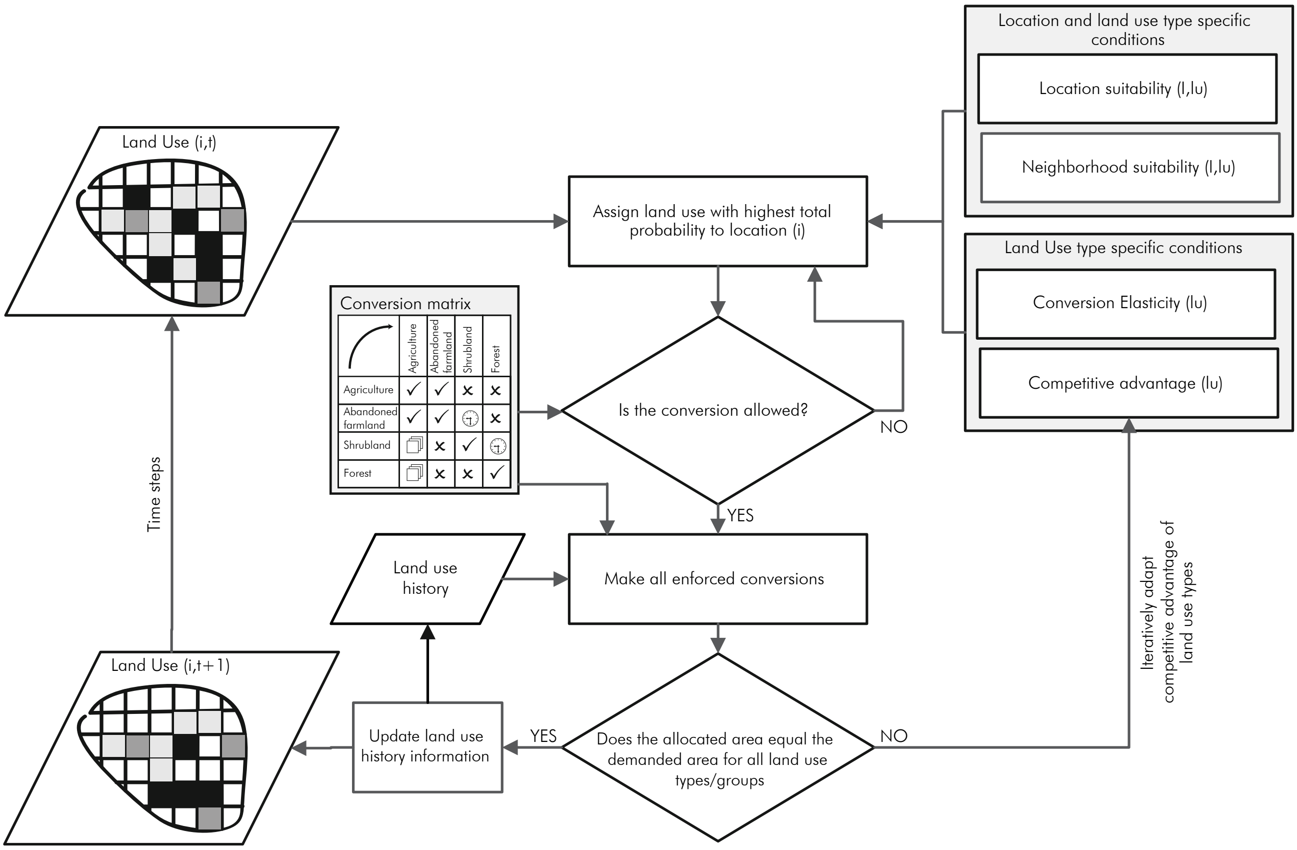
4.4.3 Quantifying the spatial implications of future land use policies in South Africa: reshaping a city through land use modelling

Le Roux's research[18] investigates the consequences of the CoJ's proposed land use policies by comparing the spatial impact of two different simulation scenarios to determine whether spatial equality will be restored to the city by the year 2030 (Le Roux, 2012). The first scenario, referred to as the 'AS-IS' scenario, assumes continued growth from the past decade, whilst the policy-led scenario focuses on the implementation of land use policies and strategies designed to limit growth, densify transport corridors and encourage investment in low cost housing in accessible locations.

The study considered the SLEUTH (Slope, Land cover, Exclusion, Urbanisation, Transportation and Hillshade) and Dyna-Clue cellular automata models, both widely used to model urban growth. According to Le Roux (2012), the Dyna-Clue model (depicted in Figure 9) was found to be more suitable for simulating multiple land use change and understanding the implications of future policies. Unlike the SLEUTH model, human, biophysical and socio-economic factors and policy-led decisions are also considered. The spatial data required for the Dyna-Clue model include: land use maps, locational driving factors and spatial policies and restrictions. The non-spatial data inputs are as follows: policy scenarios, regional driving factors and expert knowledge.

[18] Le Roux is employed at the CSIR in Pretoria. She completed her Master's dissertation at the International Training Centre, University of Twente, Netherlands.

Figure 9: Illustration of the Dyna-Clue model

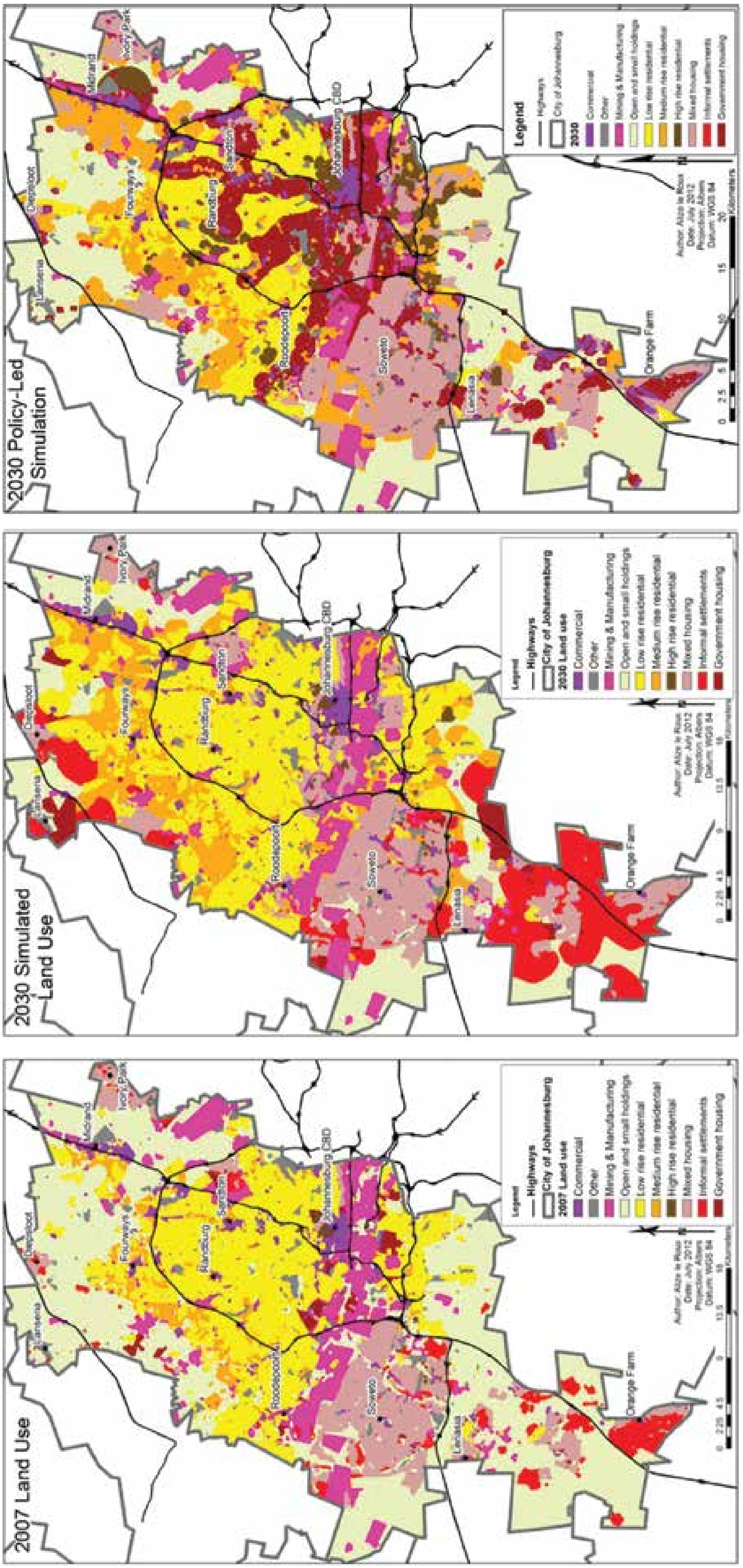


Source: Verburg and Overmars (2009:1170)

The study found that in the AS-IS scenario, if the growth continues on the same path as it has over the past decade, the result will be increased informality, low densities and a large sprawled extent by 2030 (Le Roux, 2012). The AS-IS scenario also provides better economic opportunities to the wealthy northern suburbs of Johannesburg whilst restricting the majority of low-income households to the southern parts of the city.

In contrast, Le Roux established that by implementing Johannesburg's proposed land use policies in the policy-led scenario, more economic opportunities would be provided to the poorer households in the southern parts of the city: ''Implementing densification corridors and restricting development outside the urban development boundary will see a 14% reduction in urban extent and an increase of 3 dwelling units per hectare compared to the AS-IS scenario'' (Le Roux, 2012:5). However, even with far-reaching policy intervention, segregation within both the northern and southern regions of Johannesburg will remain. Figure 10 illustrates: (a) initial 2007 year land use; (b) the AS-IS Scenario and (c) the policy-led scenario. The sprawled nature of the city is clearly evident in the AS-IS scenario with a large amount of informal settlements in the south and north-east of the city. The policy-led scenario depicts a much more compact city with a concentration of high-rise residences and government housing in the central areas and along transport corridors.

Figure 10: Dyna-Clue modelling in Johannesburg to 2030: (a) initial 2007 land use; (b) the AS-IS scenario; and (c) policy-led simulation



Source: Le Roux (2012:77)

4.4.4 UKZN[19]

Since 2003, a number of Honours and Masters level research projects, supervised by Professor Fethi Ahmed, were completed to assess historical urban land cover change over time using remote sensing and GIS. These include:

1. Yemane, M.M. (2003) An assessment of changes in land use/ cover patterns in the Albert Falls area: a satellite imagery and GIS application.
2. Robson, T. (2007) An assessment of land cover changes using GIS and Remote Sensing: a case study of the uMhlathuze Municipality.
3. Manaka, B. (2007) An assessment of changes in land use/ cover patterns in the Manganeng area. Limpopo Province.
4. Pillay, K. (2010) An investigation into changes in land cover patterns in Mtunzini using satellite imagery.
5. Batho, A. (2011) The use of bird species as indicators of Land cover changes in the Umgeni Estuary.

4.4.5 UP[20]

Dr Joel Botai conducted a study in Pretoria with the main objective to develop a metric to indicate changes in impervious surfaces (pavements, roads, sidewalks) in urban areas within the city. The metric utilises the output of historical land use/land cover data for simulating changes into the future. Satellite imagery, mainly Landsat TM (Thematic Mapper), SPOT 5 2.5m and Aster, was utilised in the study. The software used included ENVI, MATLAB, IDL and R. The outputs from ENVI were imported into the IDL (statistical) software to assist with the projections of changes in land use phenomena into the future.

The university also has a strong transport modelling capacity, within the Optimisation Group and Centre of Transport Development providing expertise for the agent-based transport modelling components of the CSIR UrbanSim and GITMC projects.

4.4.6 UJ[21]

At an Honours-level, a recent study by Haywood (2012) investigated land cover patterns in the Richards Bay area to determine the rate of land cover change. The study utilised Landsat imagery for a 38-year period, namely Landsat 1 MSS (Multispectral Scanner System) for the years 1973 and 1976, Landsat 5 TM for the years 1987 and 1999, and Landsat 7 ETM+ (Enhanced thematic Mapper Plus) for the years 2006 and 2011. The imagery was processed in ENVI, with Microsoft Excel used to perform the land cover change post classification. The study revealed significant urban growth following the development of the harbour in 1976. The percentage of urban residential land cover increased from 6.15% in 1973 to 14.63% in 2011; forestry land cover grew from 9.94% to 17.21%, and grasslands subsequently decreased from 34% to 10.91% (Haywood, 2013).

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[19] This section is based on an interview conducted on the 26th of October 2012 with Professor Fethi Ahmed, originally at the UKZN School of Geography & Environmental Sciences, now based at the UJ Department of Geography, Environmental Management and Energy Studies.

[20] This section is based on an interview conducted on the 12th of November 2012 with Dr Joel Botai from the UP Centre for Geo-information Science, and information provided by Prof Johan W. Joubert from the UP Optimisation Group and Centre of Transport Development, Department of Industrial & Systems Engineering.

[21] This section is based on an interview conducted on the 26th of October 2012 with Professor Fethi Ahmed and the questionnaire completed by Dr Khaled Abu-Bakr Ali Abu-Taleb, a post-doc researcher at the UJ Department of Geography, Environmental Management and Energy Studies.

At the post-doc level, a cellular automata urban change model of Johannesburg was developed by Dr Abu-Taleb. The model monitors urban growth in the CoJ from 1995 to 2010, followed by an urban growth simulation to the year 2030. Satellite imagery from Landsat for the years 1995 and 2010 was used to generate land use/cover, with IDRISI software utilised to combine the land use/cover, road network and slope variables and model the urban growth. The research was presented at the International Geography Union (IGU) urban geography commission conference held in Johannesburg and Stellenbosch in July 2013.

4.4.7 UCT[22]

Various student research projects have been completed on land use and land cover mapping from image classification, with the main objective to develop segmentation and classification rule sets for robust urban land cover/use mapping. The studies focused mainly on historical change (from one to ten years) and not the simulation of future land use change. The software used includes: eCognition, ENVI, ERDAS and ESRI ArcGIS.

A recent study utilising ABM to analyse informal settlements in the City of Cape Town was published by Shoko and Smit (2013). The main objective of the research was to propose a conceptual model for the implementation of an empirically informed agent-based prototype that can simulate future patterns and trends in land occupation change over time. The study incorporates physical, environmental, social and economic factors in structuring behavioural rules for agents in a predictive environment. Social, economic, and physical empirical data were collected for use in the model. The agent-based concept model incorporates a static, dynamic and an interactive behaviour model. Different key actors were identified – settlers, land developers and owners, statutory bodies (e.g. government and councils), and community representation groups – as instrumental in influencing the developmental factors in the city. The conceptual model is expected to aid urban planners and policy makers in better understanding the dynamics and extent of informal settlements, and as such, formulate effective management initiatives (Shoko and Smit, 2013).

4.4.8 North West University

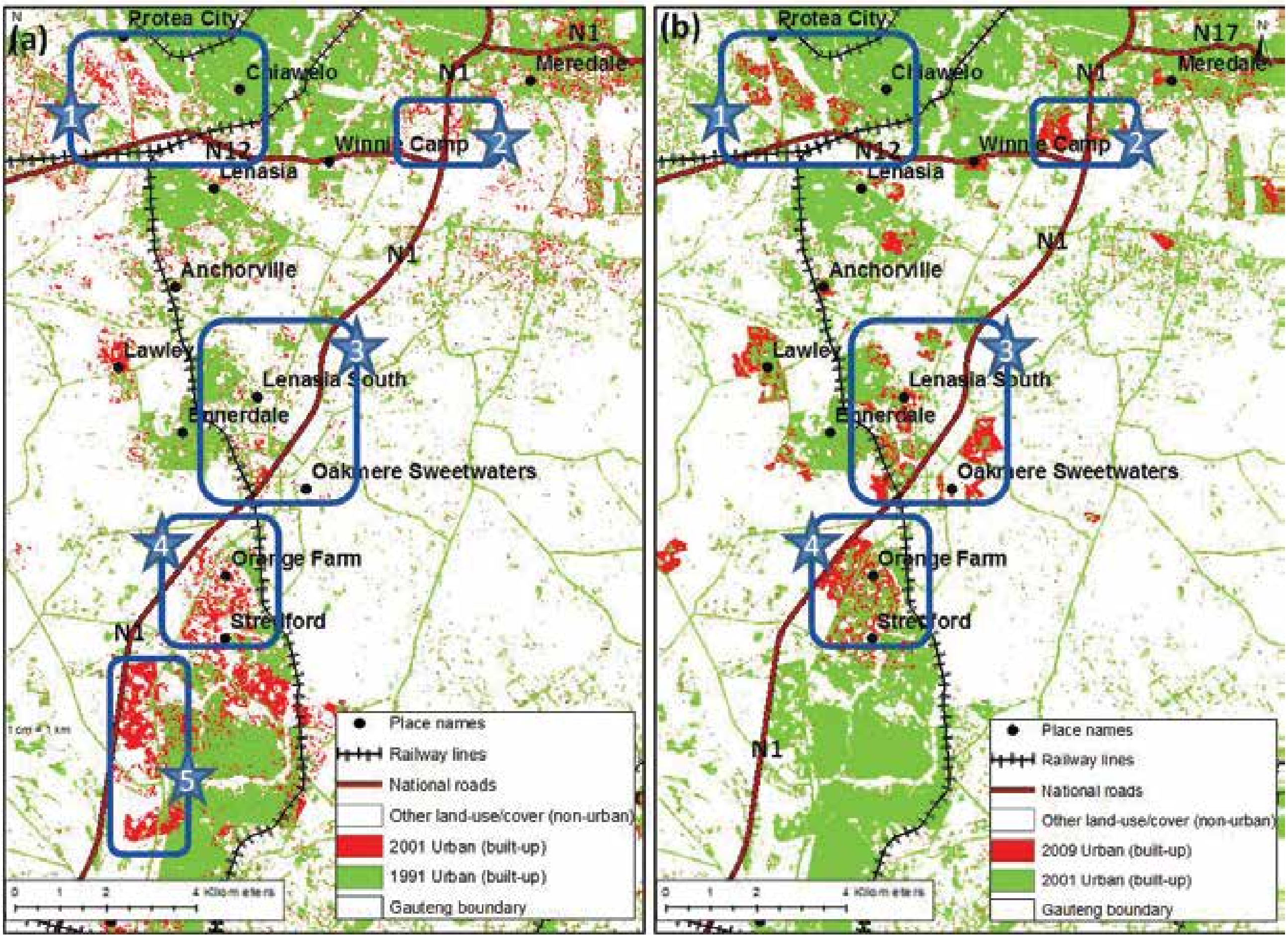
Research on modelling urban spatial change has been carried out at the North West University's School of Geo and Spatial Sciences by Cilliers (2010). Cilliers employed a spatial multiple-criteria approach (MCA) to analyse land use conflicts as well as land use suitability through a GIS-based weighted overlay procedure. According to Cilliers, non-spatial MCA was developed in the 1960s as a tool to assist decision makers in making comparative assessments through the evaluation of different alternatives or scenarios. Spatial MCA has been utilised since the 1980s and is useful to model various aspects, including land use suitability modelling. In his Master's dissertation, Cilliers uses spatial MCA to derive empirical results that are in turn used as inputs for a future urban growth scenario (2030) for the city of Potchefstroom located in Tlokwe local municipality, North West Province. The urban growth scenario from the modelling exercise in most cases reflected the city's future pattern of growth as envisaged in the city's SDF (Cilliers, 2010).

[22] This section is based on a questionnaire completed by Dr Julian Smit from the UCT School of Architecture, Planning and Geomatics and the recently published Shoko and Smit (2013) paper on ABM of informal settlements.

4.4.9 GCRO commissioned research on spatial change within the GCR

In 2010, GCRO commissioned and published an Occasional Paper entitled *Historical Spatial Change in the Gauteng City-Region* (Mubiwa and Annegarn, 2013). The paper draws on Mubiwa's PhD thesis research on generating land cover change from 1991-2009 satellite imagery. The study comprised of two parts: (i) a description of the evolution of urban spatial development between the 1890s and early 1990s; and (ii) a detailed analysis of land use/cover changes and urban development from 1991 to 2009. The land cover change analysis was based on interpretation of Landsat 5 TM (from 1991 and 2009) and Landsat 7 ETM+ (from 2001) satellite images. ILWIS, OpenEV, Multispec and ENVI software was utilised to process the imagery. The growth of the urban landscape from 12.6% of the total land cover in 1991 to 18.35% in 2009, and decline of other land use/land cover classes, is described in detail in the report (Mubiwa and Annegarn, 2013). An example of the drastic urban spatial change in Johannesburg (in terms of massive RDP housing developments and informal settlements from the 1990s) captured by the land use/cover change analysis, is depicted in Figure 11.

Figure 11: Corridor development at the convergence of road and rail in (a) 1991-2001 and (b) 2001-2009



Source: Mubiwa and Annegarn (2013:32)

4.5 Summary of South African modelling initiatives

The projects described in this chapter (and Annexure B) provide an overview of the wide range of urban spatial change modelling initiatives currently underway in South Africa. Most of the academic projects reviewed aren't necessarily simulation models but an analysis of historical land cover change. These could be expanded with the historical change used as the input into urban growth simulation models, for example, projecting forward the urban growth identified in Mubiwa and Annegarn's (2013) land cover change research. However, there are a few examples of cellular automata simulation research focusing on urban growth in Johannesburg. The modelling projects at the South African Research Chair in Development Planning and Modelling and CRUISE provide scope for the on-going development of complex modelling projects and modelling skills at a tertiary level.

Local and provincial modelling projects are mainly GIS-based, tracking trends rather than simulating future scenarios, with future modelling based on population projections. There is a risk, however, that out-dated data, different population projections, duplicated tools and a lack of resources could compromise urban spatial change modelling efforts within government.

Specialised complex urban change models that simulate future urban growth appear only to be currently developed by the CSIR. The CSIR UrbanSim project highlighted the extremely detailed data requirements and highly skilled labour intensive nature of urban growth simulation modelling projects. Although the UrbanSim project has been funded by a national department, it has now been expanded to the Gauteng DRT as part of the GTIMC and there is an opportunity to utilise the UrbanSim project to benefit long-term planning, such as the G2055 project or as part of a growth forecasting and spatial modelling unit proposed by the draft Gauteng Growth Management Strategy.

5. Conclusion: key challenges and potential modelling opportunities

"…. the second generation of modelling and simulation systems have with few exceptions, after more than 25 years of research, not really progressed from the laboratory into the mainstream of policy support. While this is indicative of how difficult it is to model complex systems, progress is being made with understanding how urban systems function as complex, adaptive and self-organising systems." (Waldeck, 2007:28)

The main objective of this report is to obtain a broad overview of international and local modelling projects monitoring or simulating urban spatial change. The research seeks answers to the following specific questions: What aspects or components of urban spatial change are being modelled? What urban models were used? What data and software are utilised for the various modelling projects? What modelling methodology, software and visualisation tools might be appropriate for monitoring or simulating urban spatial change in the South African context, specifically in the GCR?

The review employs a typology that is broadly used in the literature to describe land use modelling techniques available to planners and other policy makers. These are: LUT models, cellular automata, system dynamics modelling, ABMs, microsimulation and SE/EMs. The first part of the review focuses on international literature and discusses in detail the application of these land use modelling techniques. Besides these key modelling techniques, the literature also contains other techniques that do not fit, in the strict sense, in the above categories. This confirms the continuous need for improving the existing models as well as the development of new models to provide improved understanding of complex urban systems. For instance, Wegener (2012) calls for a paradigm shift in urban modelling to take into consideration future energy shortages and climate change that we will face in the near future.

In the South African context, a variety of urban modelling initiatives or tools exist. These range from Excel spread sheet population projections, GIS-based spatial models, land cover change analysis and complex urban growth simulation models using the UrbanSim platform. The projects stem from the ever-growing interest amongst academics and all spheres of government to develop tools that will be useful in monitoring and guiding urban spatial change in the South African context. These efforts include the establishment of a transport modelling centre (GITMC) and the CSIR's UrbanSim project currently simulating growth in a number of cities and the Gauteng Province. Ultimately, the modelling initiatives should be utilised for testing different policy options and to provide guidance for long-term planning and policy, such as assessing the proposed G2055 interventions.

The following sections will highlight key challenges and propose short- and medium-term priorities and opportunities for modelling urban spatial change in the GCR.

5.1 Key urban modelling challenges facing the GCR

There is an urgent need to streamline and coordinate the various modelling efforts currently underway in the GCR and South Africa. Within Gauteng, each of the metropolitan municipalities – CoJ with the Joburg GDS 2040[23], Ekurhuleni with Ekurhuleni GDS 2055[24] and Tshwane with Tshwane 2055[25] – are working on long-term planning or growth development/management strategies. At the provincial level, the G2055 process is nearing a final draft. At the national level, the National Development Plan 2030[26] has been adopted by the government. As these long-term strategies grapple, *inter alia*, with understanding future urban change, a coordinated effort is required to ensure any models developed within each of the frameworks work together – where possible and applicable – off a common dataset. For example, in the Gauteng context, a number of tools and models within GPG departments are using different base data or population projections (as discussed in Table 6). There is a strong possibility of the different models producing vastly different results. Further research is required to establish a commonly accepted set of future population figures that can be used as a population control total for the various models and tools in the GCR and the country at large.

Furthermore, there is a degree of duplication with a number of departments/institutions modelling the same output. For example, the Gauteng Planning Infrastructure tool and the HDA National Human Settlements Land Index[27], both identify land suitable for the development of public infrastructure, such as housing, schools and hospitals. The land suitability models have been built using different methodologies and there should be discussion and agreement regarding the methodologies, or at the very least a comparison and sharing of the results. To fully realise the vision of various long-term strategies, an integrated modelling approach is required. Simply put, collaborative models + open data + integrated systems = smarter cities/regions.

A central, freely accessible geodatabase with all the key data layers is crucial to ensure the same up-to-date base datasets are available for every Gauteng modelling project, with all departments working off a common spatial database. This is a critical requirement, as within Gauteng, provincial spatial data is not easily accessible publicly and is often only available to other provincial and local departments through personal relationships (Wray and van Olst, 2012). In 2008 the GPG proposed a GIS for the GCR, referred to as GeoGCR, to fundamentally transform provincial information service delivery (Gauteng Department of Economic Development, 2008; Kekana, 2010). Figure 12 sets out how this will be achieved through the provision of:

- Access – through the establishment of a single gateway to provincial geographic information
- Enablement – by spatially enabling the public sector.
- Optimisation – by defining the legal, hardware and software requirements to make use of the latest new mapping technologies.
- Leadership – by leading the way in public sector data and infrastructure and meeting the business needs of each stakeholder (Kekana, 2010).

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[23] http://www.joburg.org.za/index.php?option=com_content&id=7343&Itemid=114&limitstart=1

[24] http://www.ekurhuleni.gov.za/gds2055

[25] http://www.tshwane2055.gov.za/

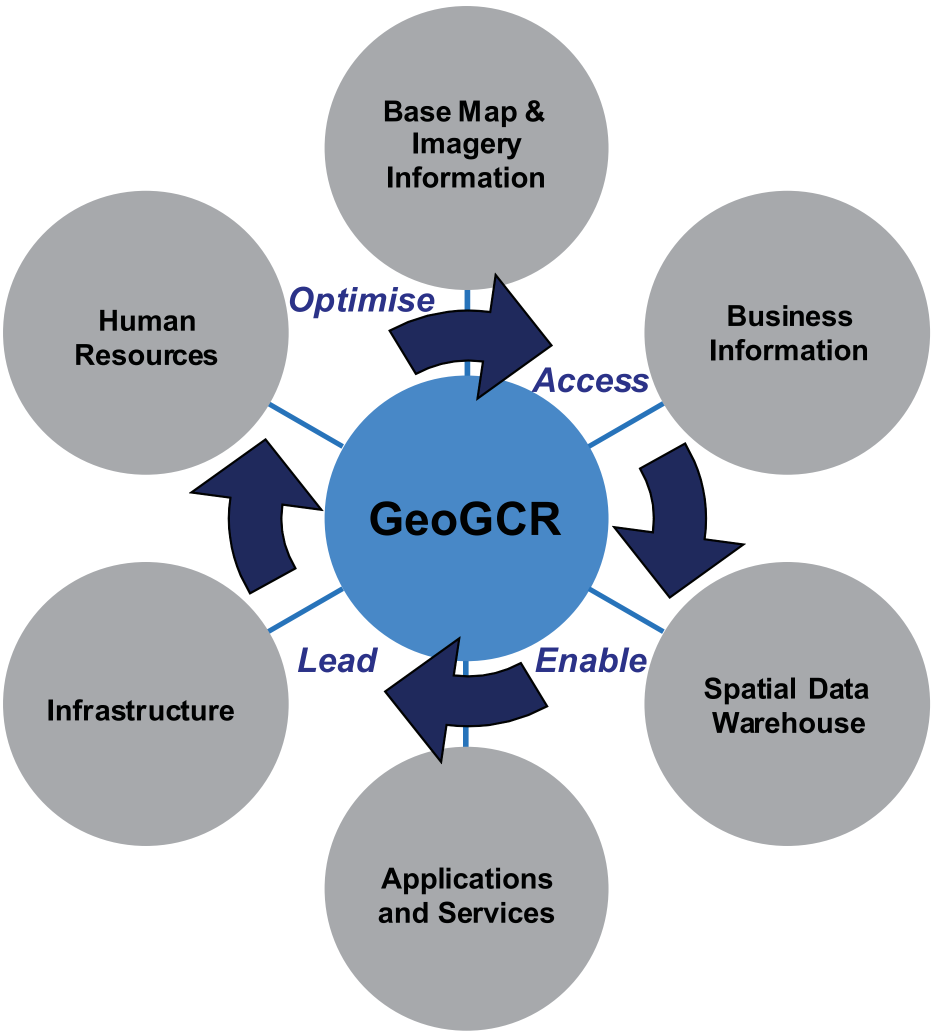
[26] http://www.npconline.co.za/

[27] The National Human Settlements Land Index is "an executive analytical tool to facilitate and guide the formulation of planning alternatives that optimise utilisation of scarce resources and reduce the negative impact of land and property development on the environment" (Busgeeth, 2012:5). It was not reviewed in Chapter 4 as it does not model spatial change but uses a weighted overlay to identify suitable land.

However, after five years and despite various plans, the project has yet to be implemented. We suggest that the relevant institutions mandated to bring the GeoGCR into reality work harder towards achieving this crucial objective that can form the basis of all modelling work in the GCR.

An additional challenge is how to model the GCR as opposed to Gauteng only. As described in the introductory chapter, the wider GCR overlaps into neighbouring provinces. The dynamic relationships external to Gauteng need to be considered in any long-term strategic plan or model claiming to have a city-regional focus. None more so than the transport modelling which should be considering both internal and external traffic flows within and into the province. For example, the swathe of semi-urban settlements situated in the Thembisile and JR Moroka local municipalities in Mpumalanga on the north-eastern border of Gauteng is functionally connected to the Gauteng economy by subsidised bus transport routes, which have historically ferried thousands of workers into central Pretoria on a long-distance daily commute. Modelling across such a vast extent, however, raises a range issues that need to be considered such as data availability and applying an appropriate modelling scale.

Figure 12: The building blocks of the GeoGCR



Source: Kekana (2010:7)

5.2 Urban modelling opportunities in the GCR

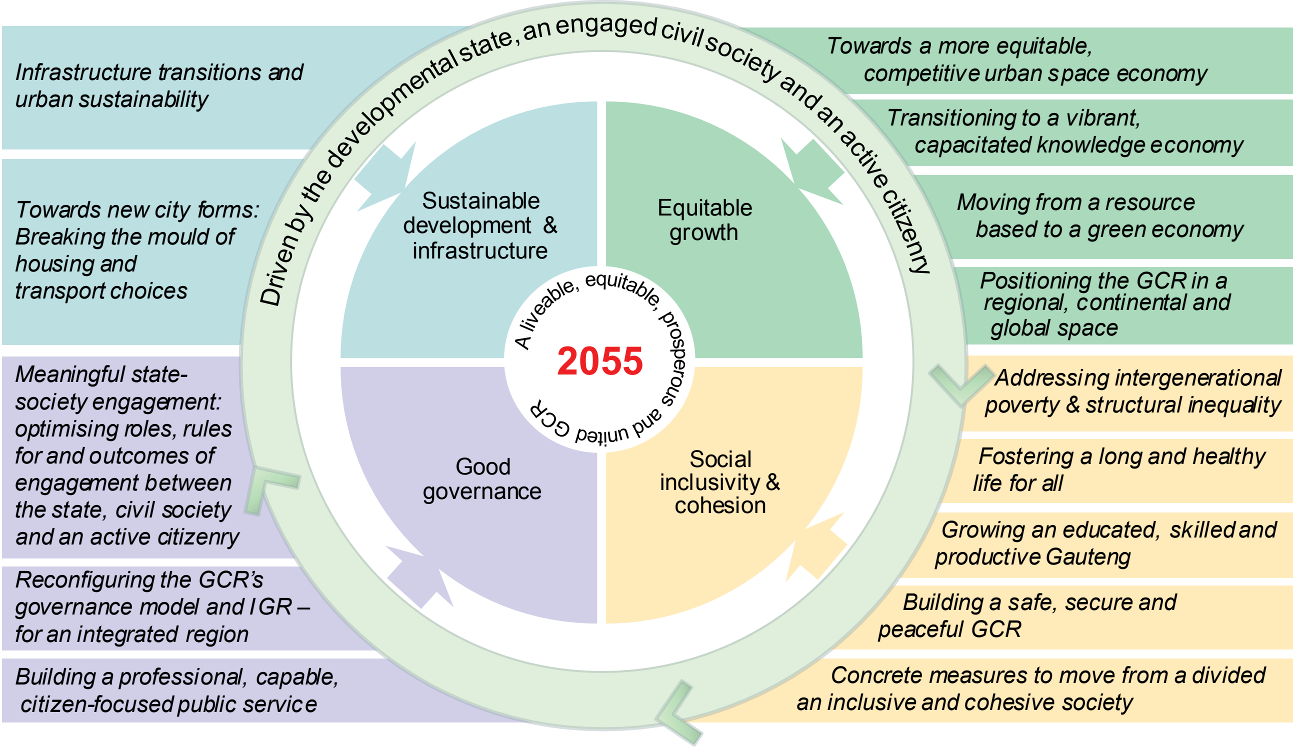
> *"One of the next deliverables that the Provincial Government should focus on is a comprehensive growth forecasting and spatial modelling exercise for the province as a whole but also indicating results for individual municipalities. Based on this information, municipalities can proceed with municipal growth management strategies that work from a single platform." (GPC, 2013a:98)*

How can the range of long-term planning initiatives benefit from urban modelling projects and what are the short- and medium-term priorities for integrated modelling in the GCR? Refining the models that already exist for South Africa and the GCR can serve as a starting point for informing long-term planning, rather than duplicating efforts. The model refinement process should include improving the process of developing, validating, extending, and applying models; and supporting their effective use in long-term projects such as G2055, the Gauteng Growth Management Strategy and municipal GDSs. This should include: improving data collection so that the quality of data available is enhanced; agreement and use of a common set of population projections; and ensuring a participatory process for the modelling work. The joint provincial and municipal urban growth forum and growth forecasting and spatial modelling unit proposed by the draft Gauteng Growth Management Strategy should address the majority of these issues. Furthermore, significant money, skills and time have been invested in the CSIR UrbanSim project. Further discussion on a possible UrbanSim project for the G2055 project and wider GCR is recommended, taking into consideration the outstanding UrbanSim data issues.

An example of possible modelling projects for the GCR is drawn from the G2055 planning process. In response to the strategic pathways defined in the G2055 planning process (described in Figure 13), a range of demographic and spatial modelling priorities were identified by GCR stakeholders, with a snapshot provided in Annexure C. Stakeholders included the GCRO, GPC, CSIR, HDA and representatives from the municipalities within Gauteng. The need to explore the new Census data in more detail and update the models to use the Census 2011 data were identified as short-term priorities for demographic modelling. Longer-term priorities included the need for more research and modelling to understand household densities and the number of schools and clinics required to meet future population growth. In terms of spatial modelling priorities identified by the stakeholders, a short-term simulation project was proposed to evaluate whether there is enough well-located land to cater for future housing development within Gauteng. The UrbanSim platform was highlighted as a possible modelling platform to test this scenario, with a team from the GPC, HDA and CSIR selected to initiate and work on this project. Medium- to longer-term priorities included: modelling development corridors based on various policy options, a 3D visualisation of GCR's future urban form, modelling cross-municipal infrastructure and transport networks, and understanding what connects Gauteng to the wider GCR.

In line with the GCR's modelling priorities identified above, we therefore suggest a number of factors that must be considered for modelling urban spatial change in the GCR. We suggest the urgent establishment of the GeoGCR GIS database. This is seen as a priority to ensure access to spatial data and use of the same base data by the GCR stakeholders. Another factor is the continuous refinement and use of temporal or up-to-date data. The latest Census 2011 data present a wonderful opportunity to update and recalibrate the models with accurate up-to-date demographic variables. With three sets of Census data now available (1996, 2001 and 2011) detailed trends analysis and projections are now also possible if data can be obtained

Figure 13: G2055 framework and 14 strategic pathways



Source: GPC (2013c:61)

at the detailed small area or sub-place level. The GCRO Quality of Life (QoL) survey[28] data also present trends analysis and modelling opportunities, with the third survey to be completed and available by early 2014.

We further believe that once GeoGCR is operational there are opportunities to utilise the outputs from some of the models for multiple applications at multiple scales. The CSIR UrbanSim project, for example, produces a spatial distribution of population (in the form of the location of new housing) for each year of the simulation run. These results could feed into the Gauteng Planning Infrastructure Tool to improve the accuracy of locating future facilities based on a more accurate location of the future population, as opposed to population control totals spatially assigned to current Enumeration Area boundaries. This requires a high level of coordination and agreement. Similar to the stepSA initiative at national level, it calls for a planning/modelling networking group within the GCR – a role the GeoGCR team, joint growth management forum and/or growth forecasting and spatial modelling unit (as proposed by the draft Gauteng Growth Management Strategy) should fulfil once established.

A national observatory, proposed by the National Planning Commission (NPC) in the 2030 National Development Plan (NPC, 2012), represents an opportunity for national data analysis and modelling coordination, as its mandate is to collect, integrate and manage information from various sector departments and agencies. The successful implementation of a national observatory will be key to strengthening and integrating data analysis and modelling across South Africa, with national models

[28] The bi-annual GCRO QoL survey measures the quality of life, socio-economic circumstances, attitudes to service delivery, psycho-social attitudes, value-base and other characteristics of the GCR. The first survey, a 6600 sample survey, was commissioned in 2009. A second QoL survey was undertaken in 2011, this time with some 17 000 sample points across Gauteng.

feeding into city-regional and city-level modelling work. Careful consideration should be given to the possible overlapping roles and work of the national observatory and the stepSA programme.

There is also scope for the development of modelling skills at a tertiary level and on-going research into the application of urban change and simulation models in a developing country context. The highly technical, data hungry and complex UrbanSim model represents the top-end of urban simulation. A few of the urban spatial change modelling projects identified in Chapter 3, such as cellular automata Markov chain simulations or morphological approaches to predicting urban expansion, may provide a simpler short-term picture of the future urban form and provide a multi-scaled approach to modelling and guiding policy. For example, a broad scale GCR model can be developed, together with zoomed in development hotspots modelled in more detail. Research projects in this area, in conjunction with local and provincial government planning departments, should be encouraged. Initiatives such as the Wits Institute for Data Science and Policy Studies currently under consideration as one of the new 21st Century Research Institutes may also provide the skills and software to assist with the storage and analysis of large datasets feeding into urban models.

While predicting the future is fraught with the uncertainty of unknown events, decisions on urban spatial planning have to be made utilising the best available information and modelling processes. At the same time, there is a need for understanding that models inform policy and are not crystal balls that can magically predict the future. Rather, they present an opportunity to test the possible implications of different policy scenarios and interventions. A careful selection of the scenarios to be tested and involvement of stakeholders during the entire modelling process is key to the success of the modelling. Urban spatial modelling should not be seen as modelling solutions, but as a platform that will allow joint learning in understanding the effects of the long-term planning policy scenarios and interventions.

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Annexure A:

Overview of urban spatial change models. This table summarises scholarship on different urban spatial change models and provides a synthesis of international urban modelling from the year 2000.

Model citation	Model type, e.g. ABM	Model description/main purpose	Key model components
LUT models			
Waddell (2002)	Econometric/ microsimulation/ agent-based	The UrbanSim model simulates the key decisions and choices impacting urban development such as mobility and location choices of households and businesses, and development choices of developers. Often used in combination with MATSim which provides traffic simulation.	• Households, (migration and residential moves) • Persons (employment) • Businesses • Property developers (parcel development) • Real estate market (prices)
Miller et al. (2004)	Microsimulation/ agent-based	ILUTE simulates the evolution of an entire urban region over an extended period of time, applied in Toronto Canada.	• Individuals • Households • Businesses
Moeckel et al. (2007)	Microsimulation	ILUMASS is a comprehensive model of land use, transportation and the environment where urban traffic flows are embedded into a model system that incorporates changes of land use and the resulting changes in transport demand and impacts on the environment.	• Land use model includes sub-models of demographic development, residential location, firm life cycles, business relocation and construction of dwellings and non-residential floor space. • Transport model simulates travel and goods movements. • Environment model computes the environmental impacts of simulated transport flows, including greenhouse gas emissions, air pollution and traffic noise.
Veldhuisen et al. (2005)	Agent-based Monte Carlo simulation	The Ramblas model has been applied in Amsterdam to estimates effects of three urban development scenarios in terms of sustainability criteria such as number of kilometres travelled. Uses the entire Dutch population and therefore simulates inter- and cross-regional traffic flows.	• Allocate module: derives the population according to age, gender and marital status. • Planning module: captures planning scenarios based on official planning documents. • Relocate module: models movement of individuals/ households. • Interact module: models activity-travel patterns.

Mishra et al. (2011)	Discrete choice econometric	The Maryland Statewide Transport Model (MSTM) is a four-step travel-demand model with input provided by alternative land use scenarios. Analysis of land use transportation scenarios reveal insights to the region's travel patterns in terms of congestion levels and the shifting travel as per land use changes. Applied in Washington DC.	• Land use scenarios • Regional travel demand model • Regional integrated land use transport interaction model
Zhou et al. (2009)	Gravity based land use model	TELUM (Transportation Economic and Land Use Model) is a GIS embedded version of the ITLUP that produces a 2030 prediction of land use and travel conditions in Texas.	• Disaggregated residential allocation model • Employment allocation model • Land consumption model
Cellular automata models			
Shi et al. (2012)	Cellular automata	Using Metronamica, a proprietary software exploration tool for planners, to simulate and assess the integrated effects of their planning measures on urban and regional development. Seven policy relevant land use change scenarios of Wuhan in China were modelled to 2020.	Neighbourhoods' interaction with regard to land use: • Accessibility (proximity to transport networks). • Physical suitability physical, ecological and environmental appropriateness of cells for development. • Zoning or institutional suitability (zoning status).
Al-kheder et al. (2006)	Cellular automata	This cellular automata model was tested in Indianapolis in the USA, modelling urban growth at a township-level over a period of 30 years. Spatially, the model is calibrated on a township basis to take into account the effect of site specific features, while the temporal calibration is set up to adapt the model to changes in the growth pattern over time.	• Townships
Lathi (2008)	Cellular Automata	The cellular automata model was calibrated with two land use maps and used for predictions from 1956 until 2006. The model was then used to predict urban patterns of the two scenarios of urban growth, planned scenario (compacted growth) and unplanned scenario, indicating sprawl along the transport links, until 2016 in Sydney, Australia.	• Transport network: roads, highways and railways • Slope • Land use (urban) • Housing

Liu and Phinn (2003)	Cellular automata	The study focuses on the development and application of a cellular automata model of urban development using GIS and fuzzy-logic set approaches. Fuzzy- logic was used with cellular automata to simulate urban growth in Sydney, Australia, 1971 to 1996.	Transitional rules applied: • Urban development • Slow development • Very slow development • No development
Sietchiping (2004)	Cellular automata	Cellular automata model with GIS to simulate the spread of informal settlements in Yaounde, Cameroon.	• Informal settlements
Li et al. (2008)	Cellular automata	The study uses cellular automata to provide a new method for retrieving, evaluating, and modifying urban signatures for simulating compact development in the Pearl River Delta, south China.	• Urban and non-urban areas
Demirel and Cetin (2010)	Cellular automata	The main aim of the study was to define a framework and methodology for the urban growth simulation of the Istanbul Metropolitan area by analysing land use trends in past, present and future and assessing urban growth in 2017. The cellular automata Markov model was used to estimate future urban land pattern. It predicted the number of new pixels to be urbanised at a specified time period.	• Land use
Barredo et al. (2003)	Cellular automata	The study focused on the theoretical view why cellular automata should be used for urban scenario generation and also examined complexities of simulated cities. The study also investigates the application of cellular automata, through a simulation of 30 years 1968-1998 in Dublin.	• Land use • Road network
Mahiny and Gholamalifard (2007)	Cellular automata	The SLEUTH cellular automata model was used to simulate and forecast change in urban areas, mainly focusing on spatial pattern of urban growth in Gorgan City, Iran.	• Slope • Land use • Exclusion zone • Transportation network • Hill shade predictor variables
Almeida et al. (2008)	Cellular automata	Cellular automata was used for the urban modelling of a medium-sized town in the Midwest of São Paulo State, Piracicaba, Brazil, between 1985 and 1999. Stochastic cellular automata transition rules were used and neural networks were employed in measuring several biophysical and infrastructure variables considered in the simulation model. Statistical validation was conducted using fuzzy similarity measures.	• Biophysical • Infrastructure

Teitz et al. (2005)	Cellular automata	The SLEUTH cellular automata model was used for modelling the size and pattern urban growth in the San Joaquin Valley in the USA, to 2040.	• Urban development • Farmland conservation • Transportation (railway) • Automobile oriented managed growth
Esbah et al. (2011)	Cellular automata	This study aims to model land use/cover in the western Aydin Province to 2025 by using cellular automata Markov chain and landscape metrics.	• Elevation • Slope • Aspect • Population
System dynamics models			
Guo et al. (2001)	System dynamics	Developed an environmental system dynamics model in support for environmental management for Lake Erhai Basin in China.	The model consists of dynamic simulation models that explicitly considers information feedbacks governing interactions in the system, including: • water resources • population • industry • agriculture tourism • pollution.
Liu et al. (2012)	System dynamics	Applied a system dynamics model to assess the socio-economic and environmental impacts of different planning modes of Zhengzhou Airport Zone in China.	Specifically developed for the Zhengzhou Airport Zone in China.
Shen et al. (2009)	System dynamics	Uses a system dynamics model for the sustainable land use and urban development in Hong Kong. The model is used to test the outcomes of development policy scenarios and make forecasts.	Consists of five sub-systems, including: • population • employment • housing • transport • urban land area
Yu et al. (2011)	System dynamics	Analysed the long-term land use land cover change (from 1977 to 2007) in Daqing City in China, which was derived from Landsat MSS and TM imagery. A system dynamics model was then developed to understand the future land use change with respect to land use driving factors.	The driving factors included: • land use management • population growth • economic policies • social policies.

Haghani et al. (2003)	System dynamics	Uses system dynamics approach with DYNAMO (DYNAmic MOdels) to understand land use/transportation system performance for Montgomery County, Maryland.	The model is designed based on the causality functions and feedback loop structure between a large number of physical, socioeconomic, and policy variables and consists of seven sub-models: • population • migration of population • household • job growth-employment-land availability • housing development • travel demand • traffic congestion.
Wang et al. (2008)	System dynamics	Develops a system dynamics model using Vensim software to understand the urban transportation system for Dalian, China.	The model comprises of seven sub-models: • population • economic development • number of vehicles • environmental influence • travel demand • transport supply • traffic congestion.
Pfaffenbichler et al. (2008)	System dynamics	An Integrated Dynamic Land Use and Transport Model (Metropolitan Activity Relocation Simulator or MARS) applied within Europe and Asia.	• Transport model: simulates the travel behaviour of the population related to their housing and workplace location. • Housing development model. • Household location choice model. • Workplace development model. • Workplace location choice model. • Fuel consumption and emission model.
Park et al. (2013)	System dynamics	Analyses the dynamics of urban development projects in Seoul, South Korea, with a particular focus on the self-sufficient city development policy.	Variables included: • population • housing • business • service facility • education welfare factors.
Rasmussen et al. (2012)	System dynamics	Develops a system dynamics model of the Sahelian agro-pastoral land use systems and demonstrated with a case study in Northern Burkina Faso.	Consists of following sub-models: • land use types (cultivation and pastoral) • agro-pastoral income.

Xu and Coors (2012)	System dynamics and GIS	Utilises an integrated approach for sustainability assessment of an urban residential area in Stuttgart, Germany. A system dynamics model was then developed to quantitatively investigate the developmental tendency of the indicators. The estimated results were displayed in 2D density maps in ArcGIS and 3D visualisation in CityEngine.	Indicators for sustainability modelling were based on merging DPSIR (Driving Forces, Pressure, State, Impact and Response) framework and Analytic Hierarchy Process (AHP).
Guan et al. (2011)	System dynamics and GIS	Combines system dynamics and GIS to evaluate the urban development in Chongqing city, China, which was faced with depletion of resources and degradation of environment.	Different policy options are assessed with respect to their potential effect on the: • economy • resources • environment.
Ahmad and Simonovic (2004)	System dynamics and GIS	Integrated system dynamics and GIS, applied to flood management in Red River basin in Manitoba, Canada.	The model consisted of data on river flow (inflows, outflows, rainfall and evaporation); and the sectoral activities affecting the river, which include: residential, commercial, agricultural, industrial, and infrastructure (roads).
Lauf et al. (2012)	System dynamics integrated into cellular automata	The model focuses on household dynamics according to the concept of the second demographic transition, applying aging and population shrinkage to simulate respective effects on residential choice and the resulting land use change. The model is applied to the Berlin metropolitan region. It displays contrasting growth and shrinkage processes for the period 1990–2008.	Utilised empirical census data, economic data, data on residential satisfaction and numerous types of geo-information representing land use zoning, accessibility and suitability.
Lin et al. (2011)	System dynamics integrated into cellular automata	Their purpose was to understand the urban expansion in Shanghai and assess its environmental impact. Developed two models based on cellular automata and applied to simulate the process of urbanisation in Shanghai from 1988-2004. This was characterised by urban expansion from downtown to the periphery plus expansion along the trunk roads. The model was then used to simulate the impacts of the urban expansion on society, the economy, and especially the ecological environment from 2005 to 2020.	The main factors controlling the urban expansion were the population increase and economic development.

Han et al. (2009)	System dynamics integrated into cellular automata	The model aims at understanding and forecasting the dynamics of urban growth especially against the backdrop of drastic socioeconomic transition. They provide an integrated system dynamics and cellular automata model not only in a socio-economic driving forces analysis but also in urban spatial pattern evaluation. Applied to Shanghai city in China.	• Socio-economic variables: per capita income, GDP, urbanisation level, inter-provincial and intra-provincial migration. • Spatial variables: historical land use patterns, land suitability factors.
He et al. (2006)	System dynamics integrated into cellular automata	Developed an integrated model that simulates Urban Expansion Scenario (UES) and implements it in model in Beijing. The urban evolution from 1991 to 2004 was simulated and the UES from 2004 to 2020.	The models consist of following sub-models: urban land demand which was based on system dynamics; and land use allocation based on cellular automata.
Zheng et al. (2012)	System dynamics integrated into cellular automata	Integrated system dynamics model and cellular automata Conversion of Land Use and its Effects at Small regional extent (CLUE-S) model to address the concerned issues for planning local land use in Changqing, Jinan, China. The coupled model simulates the spatio-temporal dynamics of the future land use in Changqing under different developing scenarios from 2006 to 2020.	CLUE-S model was developed for spatially explicit simulation of land use change based on raster data and was combined with system dynamics to analyse the land use dynamics.
ABMs			
Parker and Meretsky (2004)	ABM +cellular automata model	Hypothetical model; presents an ABM of land use designed to explore the impacts of edge-effect externalities and distance-dependent spatial externalities on land use patterns. Dependent variable: land use composition, land use pattern, and the location of land uses.	• Transportation costs • Market-clearing rent for urban use • Total and proportion of urban parcels • Average urban and agricultural production • Total and proportion of agricultural parcels
Brown et al. (2004)	ABM	Mathematical and ABMs; evaluated the effectiveness of a greenbelt located beside a developed area, for delaying development outside the greenbelt. Dependent variable: resident settlement choices in the presence of a greenbelt. The model was run in Swarm Software.	• Alternative location preferences of the residential population • Information available to residents • Aesthetic quality of the landscape • Locations of services provided to the residential population including jobs, retail, and schools

Loibl and Toetzer (2003)	ABM	Model developed to understand growth and densification processes in polycentric suburban developments in Vienna, Austria. Simulates polycentric development of suburban systems in 2000-2002.	• Migration data • Income • Large and small scale accessibility, i.e. travelling time to the core city and access to motorways • Land prices • Landscape attractiveness • Social and commercial services supply • Traffic exposure obstacles • Land use zoning constraints
Rajan and Shibasaki (2001)	ABM	Study dynamics of urban/rural land use change in the urban fringe in Thailand. Dependent variables: changes in cropping patterns of the agricultural land; expansion of agricultural land; rural-urban migration; spread of urban areas.	• Characteristics of the land: grid-specific economic factor • Demographic data: age and educational distribution • Land use history • Prices
Evans and Kelley (2004)	ABM	Presents a model of land cover change constructed for one township (an area roughly 10 x 10 km^2) in south-central Indiana, USA. Dependent variables: land cover data from aerial photography.	• Land ownership data • Topography data
Otter et al. (2001)	ABM	Hypothetical model. Dependent variable: location decision by households and firms, with respect to two land uses: clusters and sprawl. The model was run in Swarm software.	• Environmental data: land, natural area and sea • Attraction characteristics
Polhill et al. (2001)	ABM	Abstract model. Intended to illuminate aspects of land use change in Scotland (population about 5 million; area about 8 million ha). Agents were land use managers who have to choose a set of land uses using strings of binary digits.	• Biophysical characteristics • Land use types • Climatic conditions • Economic data
Ligtenberg et al. (2001)	ABM + cellular automata	Hypothetical/piloted model applied to a study area near the city of Nijmegen, The Netherlands. Offers a framework for modelling land use processes. The model was run using the Java and Swarm toolkit.	Data on preferences for urbanisation by various actors, i.e. regional authorities, farmers' organisations, and environmentalists.
Deadman et al. (2004)	ABM	Investigated patterns of settlement and land use change in Altamaria, Brazil. Dependent variable: trend and pattern of land use measured as landscape metrics.	• Natural characteristics: soil fertility • Demographic data: household capital resources, household cohort types • Institutional: commodity prices, government credit policies and inflation

Axtell et al. (2002)	ABM	Reproduces the main features of actual history, including population ebb and flow, changing spatial settlement patterns and eventual rapid decline, from 1800 BC - 1300 AD. Dependent variable: agricultural production (kgs of maize per hectare)	• Environmental data • Demographic data: population size, age and fertility • Economic data
Augustijn-Beckers and Bas Retsios (2011)	ABM	Simulated the growth of informal settlement in Dar es Salaam, Tanzania. Spatial change was measured by infilling, extension and enlargement of existing houses.	• Distance to roads, footpaths, flood zones and swamps.
SE/EMs			
Zeng et al. (2008)	Autologistic regression	Simulates spatial patterns of different land use types in Yongding County, Hunan Province, China as a study area. Dependent variables: whether a given land use is arable land, woodland or built-up land.	• Existing land use • Population data • Distances to the nearest town • Distances to the nearest river • Distances to the nearest major road • Geographical data: elevation, slope, aspect and curvature
Cheng and Masser (2003)	Spatial regression model	Presents a spatial data analysis method to seek and model major determinants of urban growth in the period 1993-2000 by a case study of Wuhan City in PR China. Dependent variables: change as a binary variable with a value "1" representing land cover change from 1993 to 2000, value "0" is the unchanged developable land in 2000 (= agricultural + villages + water body - protected - excluded).	• Proximity variables measure the direct access to city centres/sub-centres, industrial centres, major roads, minor roads and railway lines. • A neighbourhood variable quantifies the spatial effect of neighbouring cells. • Population data. • Macro economy variables, e.g. development control. • Land values.
Abebe (2011)	Binary and multinomial logistic regression modelling	Examines driving forces that explain informal settlement expansion and densification in Dar es Salaam, Tanzania. The study used a created settlement consolidation index as the dependent variable.	Model predictor variables included: • distances to minor roads • existing informal settlements • other urban land use • population density • proportion of informal settlements and undeveloped land in the surrounding area.

Annexure B:

Selected South African urban spatial change modelling initiatives

Model	Model Type, e.g., ABM	Main Purpose/description	Key model components
Provincial modelling initiatives in Gauteng			
GITMC (CSIR, 2012b)	Econometric/ microsimulation/ ABM	CSIR, in conjunction with UP, appointed by DRT to establish the GITMC with the aim of coordinating and integrating transport modelling for local and provincial governments in Gauteng. GITMC currently in an establishment phase with the core training of provincial and local government staff.	GITMC will build on the data and modelling created in the CSIR UrbanSim and MATSim simulation project to produce urban growth scenarios based on different infrastructure initiatives.
Gauteng ITMP25 land use modelling	GIS-based with linked spread sheets	The GSRNR 2010 transportation model (base year 2007) for land use updated to the 2010 base year and design years 2015, 2025, and 2037 for the ITMP25.	Modelled variables per traffic zone include: • dwelling units • population • economically active population (formal, informal and unemployed) floor area: retail and office • formal workers by type e.g. retail, office, industrial, commercial, local serving, agricultural and mining, construction and transport • informal workers • unemployed people.
Gauteng Infrastructure Planning Tool (Engelbrecht, 2012; Kleynhans, 2012)	GIS-based models (weighted overlay and location allocation analysis) with linked spread sheets	Developed to assist with the short- and medium-term integrated planning of education and health facilities within the province.	Using the current location of schools (primary and secondary), hospitals and clinics, the future demand and location of new facilities are modelled, providing planners with a tool to test different development scenarios for determining optimal locations of public social facilities.

GSDF (Gauteng Department of Economic Development, 2011)	GIS-based models	Five models were developed to assist in analysing existing urban patterns and dynamics in Gauteng as a whole, as well as serving as a basis for future spatial strategies for the province, and supporting policy and planning decisions.	The models include: an urban profile, urban morphology, connectivity, bid rent and virtual model room.
Municipal government modelling initiatives			
CoJ: Development trends	Spread sheet-based with maps	Monitoring development trends through the capture and analysis of building and township planning applications. The development trends are used to check if the city's spatial development framework is matching the infrastructure investments that Joburg is making in terms of its GMS.	Integrated real-time capture of town planning applications in the TAS and building applications in the BAS. Linked to GIS layers for the analysis and visualisation of development trends and establishment of development trend indicators.
Urbanisation model	Spread sheet-based with 3D visualisations	An urbanisation plan intended to guide the city's spatial development, especially with the housing needs of the ever burgeoning number of city households.	Housing needs of the city residents are examined with a view to clear backlog as well as expand housing for the ever growing demand. CoJ has worked with ESRI to model a 3D visualisation of the city in key development corridors.
eThekwini: Infrastructure Investment Finance Model	Spread sheet-based with maps	Tracks and predicts infrastructural impacts of land uses as per the municipality's spatial development plans. It determines the extent and costs of the required infrastructure and how these costs affect the municipality's capital expenditure and operating revenue portfolios.	Considers yield of different land uses, extent of current and future private developments, public housing yield, modelled cost of required infrastructure, and estimated rates of income.
Cost surface model	GIS-based	Developed to show costs of providing bulk infrastructure in various locations with respect to the provision of public housing in those areas.	Predicts costs of bulk servicing of housing projects.
Accessibility model	GIS-based	A spatially-explicit model used to understand the future social services requirements of the municipality's housing planning projects.	Simulates the supply of and demand for social facilities based on population numbers, incomes, and age profiles.

City of Cape Town: UGM	GIS-based	Models future growth directions by estimating residential, industrial and mixed-use land requirements, spatially and over time. Also estimates the city services' investment needs.	Incorporates how vacant land can be used, what percentage of the site can be developed, the residential densities and the likely development time frames.
UGMS		Used to provide up-to-date urban growth information and monitor urban growth (i.e. rates, patterns, and direction). Also used to inform IDP and spatial development frameworks.	Relies on two distinct information elements: • Residential: households and population estimates. • Economic: commercial, industrial and business estimates.
Other government-funded modelling initiatives			
CSIR UrbanSim (CSIR, 2011; CSIR, 2012a; Waldeck, 2007)	Econometric/ microsimulation/ ABM	Simulates urban growth 30 years into the future in eThekwini, Nelson Mandela Bay, Johannesburg and Gauteng, based on current spatial policy and investment decisions. UrbanSim models are also currently being developed for the GITMC and Ekurhuleni.	• UrbanSim: choices of households and businesses in relation to property and services, developers as suppliers of services, and government provision of infrastructure and services. • MATSim: simulation of transportation system behaviour. • Flowmap: used for catchment area analysis, proximity counting and optimisation components.
Academic modelling initiatives			
UCT (Shoko and Smit, 2013)	ABM	Patterns and trends in land occupation change over time in a Cape Town informal settlement.	A gamut of physical (e.g. proximity to services, closeness to family or peers, nearness to employment opportunities) and socio-economic factors.
CRUISE, University of Stellenbosch		The centre focuses on research that examines the spatial relationships and various social, economic, and ecological sustainability processes that occur in cities.	Examine trends in urban morphologies of both metropolitan as well as intermediate-sized cities. Morphological issues include densification, porosity, and corridor measures.

Le Roux (2012)	Cellular automata (Dyna-Clue)	An investigation into the consequences of the CoJ's current planning policies using the cellular automata Dyna-Clue model. Compares as-is scenario, assuming continued growth, versus implementation of land use policies and strategies to limit growth, promote densification and build low cost housing in accessible locations.	Spatial data required include: • land use maps • locational driving factors • spatial policies and restrictions. Non-spatial data inputs include: • policy scenarios • regional driving factors such as macroeconomic and demographic factors • expert knowledge
UKZN	Remote sensing	Various studies analysing land cover change.	Land cover data derived from remote sensing.
South African Research Chair in Development Planning and Modelling, Wits	Standard and spatial regression	Established in 2009, this research centre based at Wits is currently focusing on describing, analysing, and explaining the shifting spatial order of a dynamic GCR, with an emphasis on the role of development planning and other policies, processes and instruments in shaping spatial outcomes. In addition, the centre is in partnership with GCRO in the present project that investigates urban spatial change in the GCR.	To date the research centre has focused on two modelling exercises. First, is a complete and published research report series titled *Does density drive development?*, which utilised standard regression. A second project, to be finalised in 2013, titled *Modelling the relationship between the economy and accessibility in South Africa* has produced a draft report using spatial regression.
UJ (Haywood 2012, 2013)	Remote sensing	Investigation of land cover patterns to determine rate of land cover change in Richards Bay from 1973 to 2011. The study revealed significant urban growth following the development of the harbour in 1976.	The study utilised Landsat imagery for a 38 year period, namely Landsat 1 MSS for the years 1973 and 1976, Landsat 5 TM for the years 1987 and 1999, and Landsat 7 ETM+ for the years 2006 and 2011. The imagery was processed in ENVI, with Microsoft Excel used to perform the land cover change post classification.
UJ	Cellular automata	Cellular automata model by Dr Abu-Taleb to predict urban growth with the CoJ. The model will monitor the urban growth from 1995 to 2010, followed by an urban growth simulation to the year 2030.	Satellite imagery from Landsat for the years 1995 and 2010 used to generate land use/cover. IDRISI software utilised to combine the land use/cover, road network and slope variables to model the urban growth.

UP	Remote sensing	The development of a metric by Dr Botai to indicate changes in impervious surfaces (pavements, roads, sidewalks) in urban areas. The metric produced will utilise the output historical data of the land use/landcover for simulating changes into the future.	Satellite imagery, mainly Landsat TM, SPOT 5 2.5m and Aster, were used in the study. The software used for these studies were ENVI, MATLAB, IDL and R software. The outputs from ENVI were imported into IDL software, which will assist in the projections of land use phenomena into the future.
North West University (Cilliers, 2010)	GIS-based multi-criteria approach	In his Master's dissertation, Cilliers uses a spatial MCA to derive empirical results used as inputs for a future urban growth scenario (2030) for the city of Potchefstroom located in the Tlokwe local municipality, North West Province. The urban growth scenario in most cases reflected the city's SDF.	A spatial MCA was employed to analyse land use conflicts as well as land use suitability via a GIS-based weighted overlay procedure.
GCRO/ Mubiwa and Annegarn (2013)	Remote sensing land cover change	GCRO commissioned research on urban land cover change in the GCR. The study comprised of two parts: (i) a description the evolution of urban spatial development between the 1890s and 1990; (ii) a detailed analysis of land use/ land cover changes and urban development from 1991 to 2009.	The land cover change analysis is based on interpretation of Landsat 5 TM and Landsat 7 ETM+ satellite images, with land use classes mapped and quantified and the growth of the urban landscape and decline of other land use/ land cover classes described in the report.

Annexure C:

Summary of the GCR's short-, medium- and long-term demographic and spatial modelling priorities identified by GCR stakeholders at a workshop held in November 2012

Steps in the G2055	Demographics	Spatial
G2055 (short-term)	**Discussion** • Participants reviewed the various institutions using different population projections, leading to lack of uniformity in modelling outputs. • For example, GCRO described the systems dynamics model for population projections. In contrast, CSIR uses an exogenous determined population from Global Insight and the South African Environmental Observation Network also computes population projections. • There is a further need to disaggregate population into age cohorts, etc. • There was a call to coordinate such projects in the future and review current urban simulation modelling at all levels **Proposed short-term priorities** • Explore the Census with greater detail to understand nuances therein. • Update GCRO's systems dynamics-based population model with Census 2011 data and link with G2055. • Compare complete/updated results with the CSIR's UrbanSim model.	**Discussion** • Availability of land – there was a concern that perhaps basic GIS analysis may be showing land as available for a certain purpose, whilst it is in fact already being used for other purposes. • It was asked whether there is adequate and appropriately located land for housing in the GCR. • HDA indicated that they have identified vacant areas for development. • Private land should also be considered for government housing projects as private land can be well-located. • A concern was raised when collecting data for spatial modelling, for example, multi-use land parcels need to be taken into account. • When projecting urban growth to 2055, there is a need to have realistic time frames to model, i.e. short-, medium- (2030) and long-term. **Proposed short-term priorities** Facilitate a spatial modelling simulation with the GCRO, GPC, HDA and CSIR using UrbanSim: Is there enough well located land for housing within Gauteng?
Technical output (medium-term and long-term)	**Proposed medium-term priorities** • Housing population: investigating the number of persons per household. Defining various household densities as these are not currently well understood. • Population: identifying the knowledge and skills base and determining how many schools need to be built. • Population and health: how many clinics need to be built?	**Proposed medium-term priorities** • Detailed analysis of development corridors based on various policy options. This is important in identifying appropriate spatial policy assumptions/choices towards realising the G2055 vision. • Undertake modelling appropriate transport and equitable infrastructure investments. For instance, the BRT system across all municipalities in the GCR. • A 3D visualisation of GCR's future urban form based on different policy options. This could take advantage of CSIR's UrbanSim project as well as Esri's CityEngine software. • There is need to consider how local and provincial government look at the GCR as a functional whole. For example, what connects Gauteng with the broader city-region, such as Rustenburg? What are the cross-municipal networks? Which municipal functions work across GCR and which functions don't?

Annexure D:

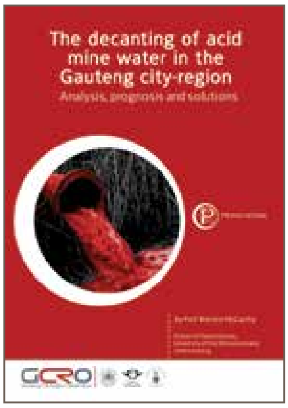
Questionnaire used to understand and document urban change/ growth modelling initiatives in South Africa

1. What urban modelling has been, or is currently being undertaken by your department or organisation to monitor or forecast urban spatial change?
2. What was/is the specific problem or output being investigated?
3. What was/is the purpose of the modelling (e.g. academic, for government or policy) and who is the end user of the modelling outputs?
4. What data (and data sources) were/are being utilised for the modelling project?
5. Were there any problems with the data (e.g. data quality)?
6. What specific variables were/are used in modelling?
7. What software was/is utilised for the various modelling projects? Is the software open source or proprietary?
8. What was/is the spatial unit of analysis used in the modelling (e.g. parcel/enumerator boundaries or a 1 km^2 square grid of cells)?
9. What was/is the extent/scale of the model (e.g. city, province)?
10. What was/is the timeframe for the urban modelling project and each of its phases?
11. Are there any visualisation tools that were/will be developed to make the models accessible on the web (e.g. animations or a 3D fly through)?
12. Are you aware of any other urban change/growth modelling projects in South Africa?

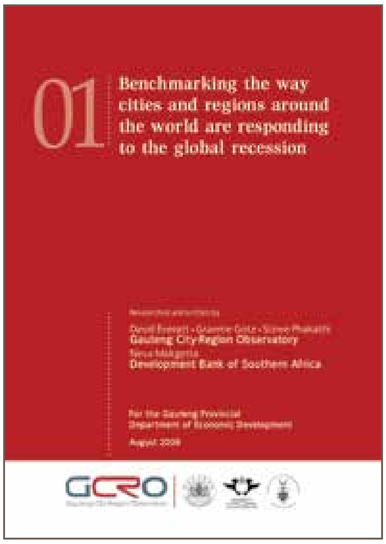
It would be appreciated if any project documentation, reports or website links could be made available to GCRO.

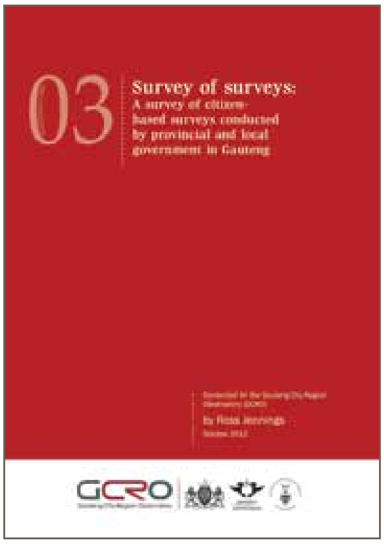
Other Publications

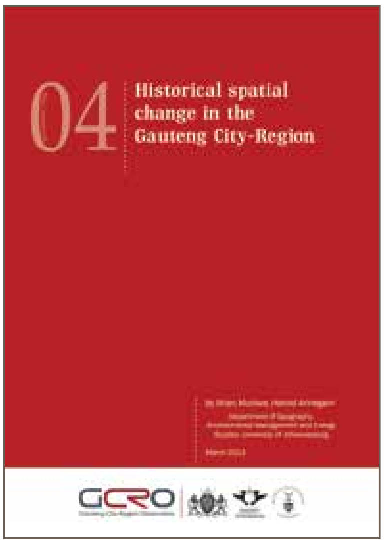
Provocation Series

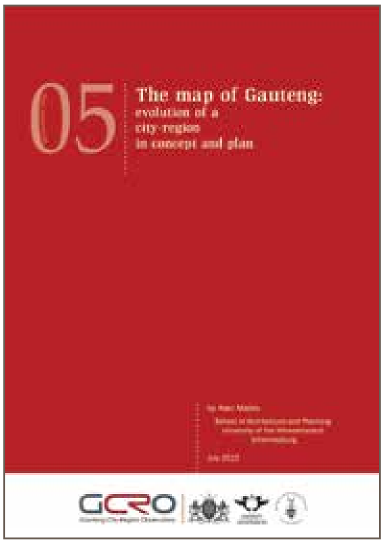


Occasional Paper Series

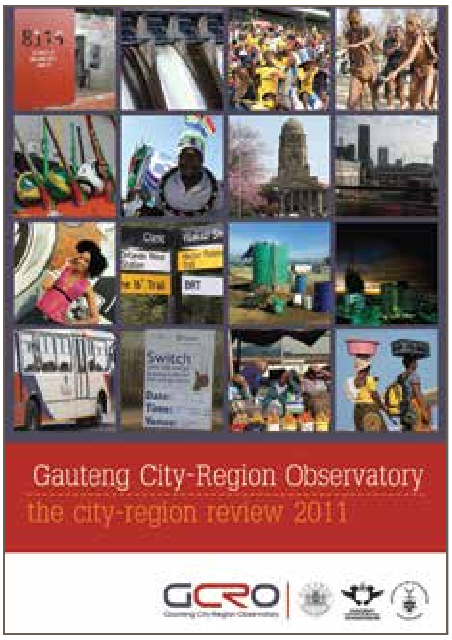


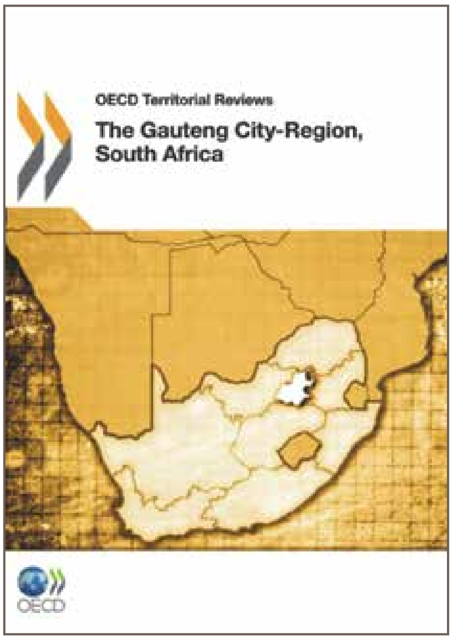




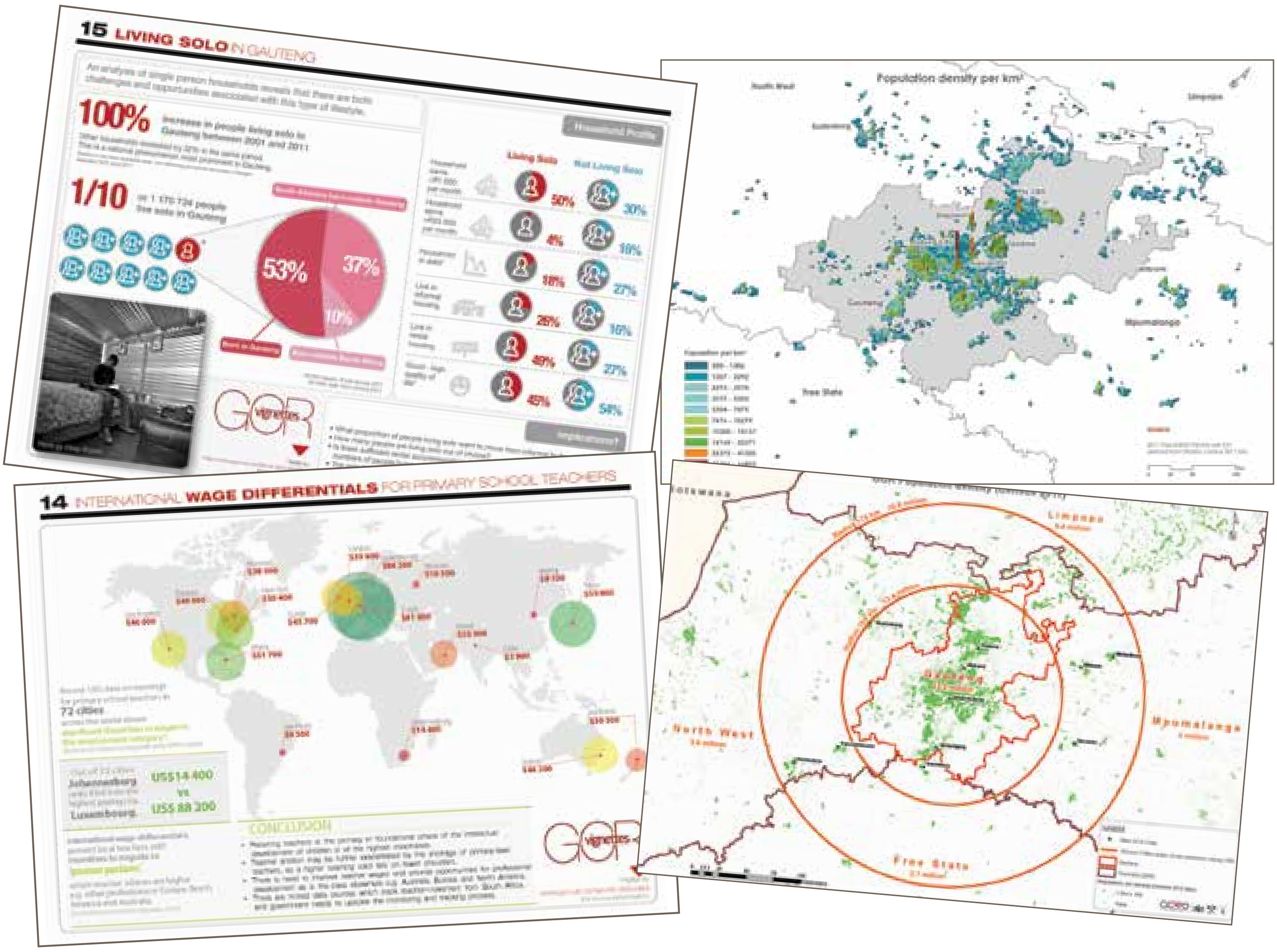


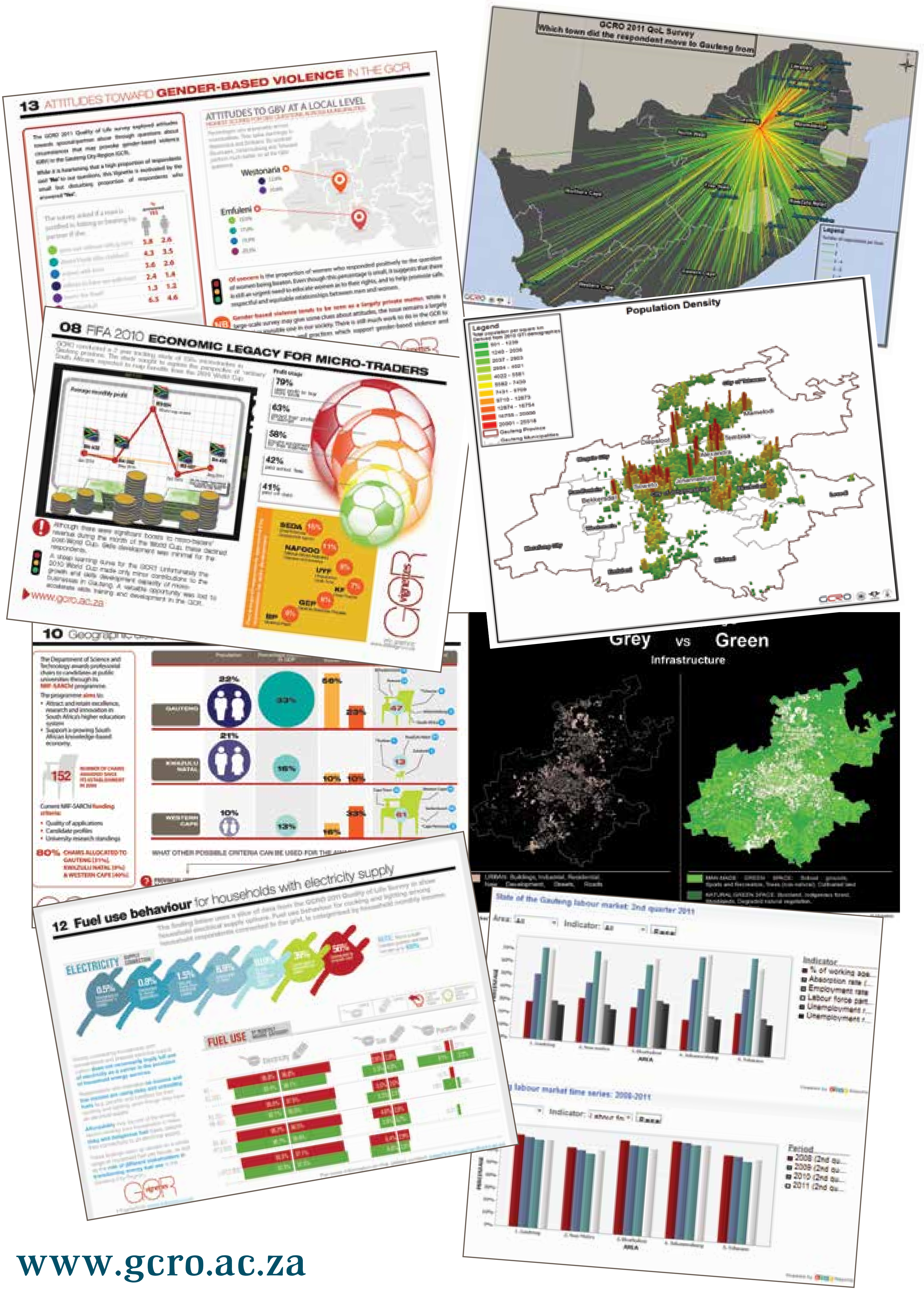
State of the GCR Review 2011 and the OECD Territorial review





Other GCRO outputs





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