THE DYNAMIC INTERACTION OF LAND USE AND TRANSPORT IN A HIGHLY FRAGMENTED CITY: THE CASE OF CAPE TOWN, SOUTH AFRICA

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"Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist". (Boulding, 1966)

"I will be glad and rejoice in you, I will sing the praises of your name O Most High". (Psalms 9:2)

Declaration

I, Hazvinei Tsitsi Tamuka Moyo, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university except as stated below:

Some of the work mainly Chapter 2 is based on the paper published by me and my supervisor in the Journal of Tansport and Land Use Volume 11, Issue 1 entitled Analysing the temporal location of employment centres relative to residential areas in Cape Town: A spatial metrics approach (Tamuka Moyo & Zuidgeest, 2018). I empower the university to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

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Date: 27 June 2019

Dedication

This thesis is dedicated to the memory of my late father, Farai Moyo (Gono), “Benzi bvunza rakanaka”!!! you taught me the value of education and endeavoured to make sure I got one.

To my mother Bessie Moyo you continue to inspire me each day, you have shown me that hard work is surely rewarded.

To my brothers and sister Nelson, Hamadziripiri, Itai and Kudzai you each contributed to this thesis in your own way. Nelson, thank you for being the brother that always remembered to pray for me. To Hamadziripi, I do not think words will ever be enough, thank you for forgoing some of your dreams so that mine could come true. To my sister Itai thank you for always knowing when I needed a chat, you are the best sister anyone could ever have. Kudzai where do I start, you are a best friend and the very definition of a perfect brother. Thank you for those late-night calls that encouraged me to continue pushing when things were tough.

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Keywords

Land use and transport

Transport modelling

Informal settlements

Cellular Automata

Rapid urbanisation

Cape Town, South Africa

Abstract

The need for more inclusive and integrated cities has resulted in a paradigm shift in the South African transport and land use policy environment where transport and land use planning are viewed as a continuum as opposed to isolated planning aspects. Issues such as residential segregation, social exclusion, spatial inefficiencies, inequality, residential informality, marginalisation of the low-income cohort continue to form part of the current planning discourse. While policy acknowledges the need to redress these issues, the urban spatial patterns in South African cities continue to trace the historical planning trajectory. Recently, congestion has become an issue in some of South Africa's cities with Johannesburg and Cape Town appearing in the list of the top hundred most congested cities in the world. It is thus essential to understand how South African cities can address urban accessibility and mobility issues along with redressing apartheid spatial planning to attain sustainable cities that allow for inclusivity of all population groups.

Like most South African cities, Cape Town is a relic of apartheid planning where the urban spatial patterns reinforce social exclusion among other issues. Urban and transport planning in Cape Town focuses on addressing issues of spatial inefficiencies, social exclusion, congestion due to rapid motorisation and the proliferation of informal settlements. It is against this backdrop that the central concern of this research is to understand urban dynamics linked to the spatiotemporal interaction of transport and land use in Cape Town to aid in the formulation of proactive urban policies. There is compelling evidence in the literature that dynamic integrated land use transport models provide an avenue through which the urban change process can be understood to aid in the development of adaptive land use and transport strategies. METRONAMICA, a dynamic land use transport model, is applied in this research to simulate and understand land use and transport change in Cape Town.

A sequential stage-wise procedure was implemented to calibrate the model for the period 1995-2005 and an independent validation was carried out from 2005 to 2010 to evaluate the model. Kappa statistic and its associated variants were applied to assess the ability of the land use model block to reproduce land use patterns while the EMME model and previous transport studies for Cape Town were used to evaluate the transport model. The results from the calibration and validation exercise show that the model can reproduce historical land use and transport patterns. The integration of the transport and land use model through accessibility improved the Kappa Simulation and Fuzzy Kappa Simulation. This showed that the model explained urban change better when land use and transport interacted compared to an independent land use model. This shows that accessibility can be employed in the Cape Town context to enhance the understanding of the urban change process. In addition to the Kappa statistics, the fractal dimension which measures the landscape complexity was used to assess the predictive accuracy of the model. The model performance revealed that the landscape patterns simulated by the model resemble observed land use patterns signifying a good calibration of the model.

The calibrated land use transport model for the Cape Town Metropolitan region (CTMR-LUT) was applied for policy scenarios. Three scenarios were simulated, specifically the business as usual (BAU), redressing social exclusion and the potential for in situ upgrading of informal settlements. The study found that intensive land use development along the Metro South East Integration Zone (MSEIZ) was linked to a reduction in commuting distances to economic activities which is in contrast to the BAU scenario. While these scenarios looked at the urban spatial patterns, the effect of land use patterns on congestion was also explored. The findings from the scenario simulations suggest that despite the reduction in distance to economic centres, the congestion condition in Cape Town will continue to deteriorate. Further, the findings indicate that interventions that only target land use developments are not sufficient to address congestion issues in Cape Town. Instead, to address the congestion problem in Cape Town, mixed land use and compact growth strategies need to be complemented with travel demand management strategies that target private car usage and intensive investment in transport infrastructure, especially rail, to facilitate the use of alternative modes.

With regards to informal settlements, the study found that in situ upgrading could be a viable option to tackle some informal settlements. However, for proper inclusionary informal settlement policy, an approach that resonates with contextual realities would be more suitable to assess the viability of in situ upgrading based on the location of informal settlements relative to centres of economic activities. Additionally, the study revealed that instead of informal settlements locating as stand-alone settlements, some of them located adjacent to low-income housing which might be indicative of a growth in backyard shacks which is an existing housing trend in some low-income suburbs in Cape Town.

While this research has shown that integrating land use and transport in policy is potentially useful in solving urban issues, it has also revealed the value of urban modelling as a platform on which to assess the potential impacts of policies before their implementation. This is a strong case for the utilisation of decision support tools in land use and transport planning in contemporary South African cities.

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Acronyms and abbreviations

BEPP	Built Environment Performance Plan
CA	Cellular Automata
CITP	Comprehensive Integrated Transport Plan
CoTO	Committee of Transport Authorities
CTMR_LUT	Cape Town Metropolitan Region Land Use Transport
CTMSDF	Cape Town Metropolitan Spatial Development Framework
DFA	Development and Facilitation Act
DoH	Department of Housing
DoT	Department of Transport
DS	Densification Strategy
EEA	European Environment Agency
FFC	Financial and Fiscal Commission
IDP	Integrated Development Plan
IUDF	Integrated Urban Development Framework
LUT	Land Use Transport
LUTI	Land Use Transport Interaction
MCK	Map Comparison Kit
NHTS	National Household Travel Survey
NLTA	National Land Transport Act
NLTSF	National Land Transport Strategic Framework
NLTTA	National Land Transport Transition Act
RCM	Random Constraint Match
RIKS	Research Institute of Knowledge Systems
SDG	Sustainable Development Goals
STATSSA	Statistics South Africa
TCT	Transport for Cape Town
TDA	Transport and Urban Development Authority
TOD	Transit-Oriented Development

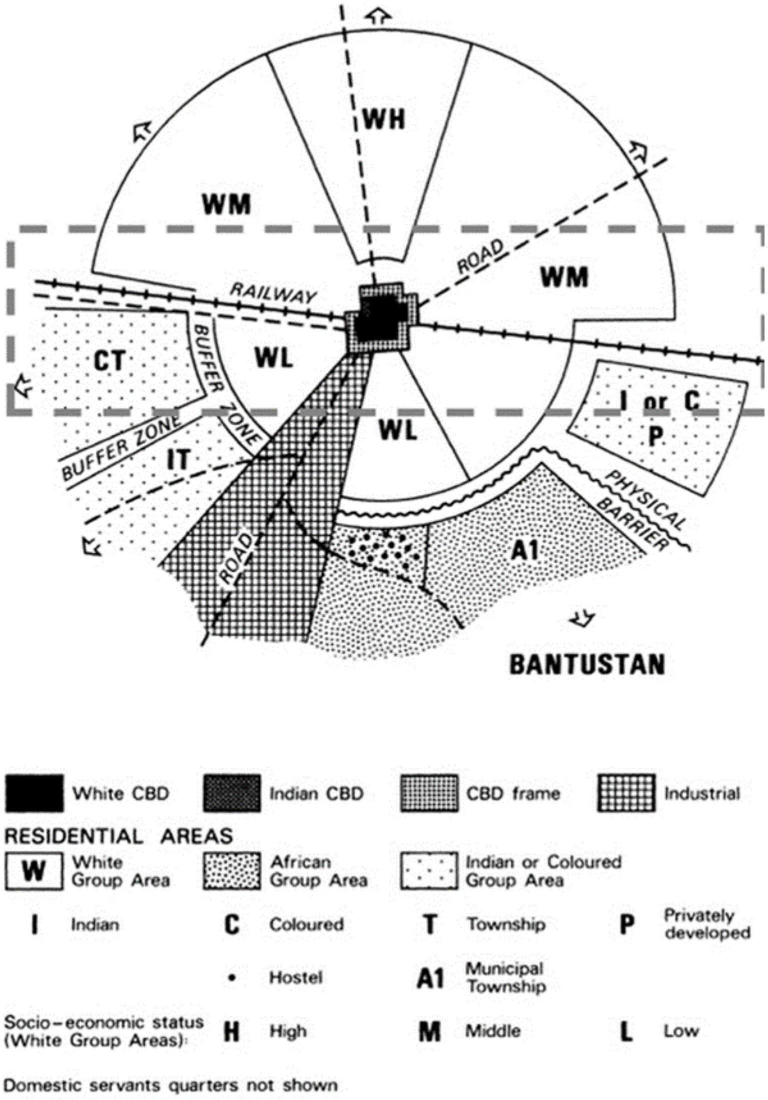
TRAMP	Traffic Assignment Model for Multi-Class Transportation Networks
UDF	Urban Development Framework
UN	United Nations

Chapter 1

Introduction to research

1.1 Background

An outcome of the Group Areas Act of 1950 was a configuration in South Africa's cities in which residential areas were deeply characterised by racial segregation. This spatial structure resulted in the white minority residing in locations closest to economic opportunities while blacks and coloureds were socially and economically excluded (Department of Provincial and Local Government, 2000; Turok, 2001; Massey, 2015). A consequence of this is that South Africa's post-apartheid cities inherited spatial patterns with disparate access to social and economic opportunities, the exurban location of low-income housing, together with segregated and disproportionate access to transport and its infrastructure (Turok, 2001; du Plessis & Landman, 2002; du Toit, 2004; Mchunu, 2006; Goebel, 2007; Dimitrov, 2010). Arguments have been advanced to the effect that land use densities in the country's cities inhibit the viable provision of public transport services and exerts pressure on the fiscus. This makes it challenging to maintain and upgrade transport infrastructure (Palmer, Brown-Luthango, & Berrisford, 2011; Mtantato, 2012). Figure 1-1 represents a typical apartheid city structure.



Source: Simons (1989)

Figure 1-1: Apartheid South Africa's city spatial structure

On the other hand, rapid urbanisation has increased the non-rural population with urbanisation levels of around 56% in 2001 (Van Huyssteen, Mans, & Ngidi, 2013) with predictions that by 2030, 70% of the population will dwell in urban areas and by 2050 this will increase to 80% (UN Habitat, 2016a) . While inadequate finances have limited the government's ability to provide housing to align with urbanisation, poor policy implementation and unemployment also promote the proliferation of informal settlements in the peripheries of South African cities (DoH, 2004; Turok & Borel-saladin, 2014). Consequently, informal settlement dwellers have limited access to employment opportunities and reliable public transport (UN, 2017). Two diametrically opposed arguments exist with regards to these informal settlements. Proponents of one side aver that informal settlements are a thoroughfare to urban poverty alleviation as they provide access to affordable housing and social networks. An opposing argument is that informal settlements entrench low-income earners in poverty (Turok, 2015; Turok & Borel-Saladin, 2016). While these are opposing views, surely those with interest in equitable cities would agree that there is an urgent need to integrate informal settlements into the economy. Indeed, to do this requires an understanding of their morphology and persistence so that the government can intervene to manage and monitor their growth.

Various policies such as the White Paper on National Transport Policy (DoT, 1996, 2017a), Moving South Africa Action Agenda (DoT, 1999) and Breaking New Ground (DoH, 2004) have been crafted by South Africa's government to restructure the country's urban areas through housing and transport interventions. Arguably, this restructuring strategy should instead involve housing market interventions that either shield low-income people from gentrification or unlock low-income housing in areas which allow access to economic opportunities, transport and its attendant infrastructure. Several authors have indicated that despite a panoply of policy initiatives, the economic and social issues in the country's cities are yet to be addressed (Turok, 2001; Watson & Turok, 2001; du Plessis & Landman, 2002; Pieterse, 2006; du Plessis, 2014).

Almost two decades ago, affordable and adequate access to public transport were cited as a problem in South African cities with 13% of the urban population reported living in transport poverty and 19% being captive to public transport which is the most affordable mode but regarded as unsafe and unreliable (DoT, 1999). From a transport provision perspective, suggestions are that to provide public transport efficiently, South African cities need to implement planning strategies that focus on land use densification amongst others (Turok, 2011a; Grey & Behrens, 2013). This has been acknowledged in post-apartheid land use and transport policy (DoT, 1999; Republic of South Africa, 2000, 2009). Yet, over two decades into democracy, cities like Cape Town still experience transport affordability issues with the low-income cohort estimated to spend 43% of their income on transport (TDA, 2012). This is much higher than the transport expenditure national benchmark of 10% set in various policy documents (DoT, 1996; Republic of South Africa, 2000). Additionally, disproportionate access to transport, and its infrastructure, and an unreliable public transport system have triggered rapid motorisation which compounds urban challenges.

The fact that Cape Town and Johannesburg regularly appear in the lists of the top 100 most congested cities in the world (TomTom, 2016) is a cause of concern for all stakeholders.

Indeed, access to public transport, transport affordability, congestion and urban residential informality, call for urgent action to ameliorate some of their impacts on the urban environment. There is unanimity that transport and land use planning policies in South Africa need to be restructured to address urban problems in cities, specifically, redressing the issues of social exclusion, spatial inefficiencies, housing, affordable transport as cited by (Boraine, Crankshaw, Engelbrecht, et al., 2006; Maylam, 2009; Palmer, Brown-Luthango, & Berrisford, 2011; Brown-Luthango, Makanga, & Smit, 2012). Though the policy and legislative framework relating to land use and transport planning have gone through changes, the policies that have been crafted (DoH, 1996; DoT, 1999; DoH, 2004, 2007; DoT, 2017a) are trailing behind in redressing historical apartheid spatial planning and transport challenges.

While these policies are yet to deliver on some of the objectives, a common thread that continues to emerge is that integrating land use and transport could be useful in ameliorating South Africa's urban problems. Emphasis on the integration of land use and transport has led to a series of policies and strategies such as the National Land Transport Transition Act of 2000 (NLTTA) (Republic of South Africa, 2000), the National Land Transport Act (NLTA) (DoT, 2009), the Integrated Urban Development Framework (IUDF) (Republic of South Africa, 2016), the Integrated Transport Plan National Land and the Transport Strategic Framework (Republic of South Africa, 2017) among others. Collectively, these policies acknowledge and discuss land use and transport restructuring as an avenue to ensure efficiency, equity and transport affordability within the country's urban areas. In summary, these policies and frameworks acknowledge the urban problems that exist in cities and propose land use and transport interventions to address them. Integrated land use and transport is a well-established concept and has become standard practice internationally and is increasingly being adopted and considered in South Africa's local urban and transport planning strategies. However, there is potential to improve its implementation mostly through a better understanding and interpretation of the land use and transport relationship and how it affects urban change.

1.2 The Cape Town case

Like most cities in South Africa, Cape Town inherited the consequences of its historical spatial planning. The spatial patterns that exist in the city today reflect a tainted history in land use and transport planning whose outcome is a disassociation between centres of economic opportunities and residential areas that are mainly populated by the low-income cohort (Watson & Turok, 2001; Turok, 2011b; Brown-Luthango, Makanga, & Smit, 2012). Cape Town's population has increased from 529,000 in 1940 to 2.6 million in 1996 (Wilkinson, 2000), to around 3.7 million in 2011 (Western Cape Provincial Treasury, 2012) and over 4 million in 2016 (Western Cape Government, 2017). This could potentially be an underestimation given the magnitude of residential informality that exists in the city. This increase is not only attributed to population growth but is also propelled by urban migration and emigration from other countries, especially African countries. On the other hand, rapid urbanisation has resulted in residential informality which has widened inequality and the urban divide as poor people continue to dwell in the outskirts with limited access to transport and opportunities. Even more concerning is the relegation of the low-income cohort to the peripheries due to inward investment in Cape Town, which has gentrified historically working-class neighbourhoods. An outcome of this is that the low-income band have poor access to the city's transport and infrastructure (Turok & Borel-saladin, 2014).

A result of unemployment and exclusionary urban land markets is the proliferation of informal settlements. For instance, the number of informal housing in the city increased from 50 in 1993, to 230 in 2010, and then to 379 settlements in 2014 (DoH, 2015). This equates to around 20.5% of the city's population in 2013 (CoCT, 2013). As mentioned earlier, informal settlements illustrate the inability of planning for housing and lack of formal affordable housing among others. Therefore, their existence begs the question of how urban land should be utilised to provide housing (Brown-Luthango, Makanga, & Smit, 2012). Given the spatial composition and growth trajectory of informal settlements, they need to be considered in the urban planning discourse as they introduce another dimension of challenges in the city.

While issues of urban spatial planning are important in Cape Town, the increase in car ownership (ITPN, 2013) linked to rapid motorisation (City of Cape Town, 2012) is also a vital concern to discuss. Several studies, (Hansen, 1959; Newman & Kenworthy, 1991, 1996; Bertolini & le Clercq, 2003; Reilly, Mara & Seto, 2009) have shown that transport infrastructure and associated technologies have influenced the urban form by facilitating mobility and accessibility. The need to amplify our understanding of land use and transport interaction has become even more urgent, especially in the context of Cape Town, where policy has begun to look at the inclusion of all socio-economic groups through providing access to employment and transport infrastructure. In that regard, the long-term planning required in the city dictates that there be a more nuanced understanding of urban change and the influence of various policies and infrastructure on future urban form.

The current spatial patterns, which are mainly characterised by low densities, especially along transport corridors, make it expensive to support and provide a viable public transport system due to low seat turnover rates along the routes (CoCT, 2012a). More recently, Cape Town has identified restructuring and integration zones (TDA, 2016) that have the potential to address issues such as social exclusion, access to transport and transport affordability among others. Relatedly, the recent dialogue on equity and social exclusion calls for urban change models that can capture or simulate urban growth to aid in addressing urban challenges. Cape Town is especially unique in the variation of economic classes and the visible polarisation of economic centres in affluent suburbs. Certainly, this calls for research that ignites debate on how to address these disparities

Thus far, it is clear that there is no dichotomy in the solutions that address both the land use or the transport problems in South African cities. Instead, the solutions to these two problems are linked. Therefore, this research hopes to provide a proactive approach to transport and urban planning strategies by acknowledging that changes in the urban form are a response to temporal dynamics and continuously changing interactions that exist between transport and land use. Modelling land use and transport interaction provides an avenue to understanding the urban environment and the different variables that influence its construct. Additionally, understanding these temporal dynamics may be useful in shaping and directing policy formulation.

1.3 The research need

Social exclusion, exurban location of low-income housing, housing informality, congestion and transport affordability are some of the urban issues that South Africa’s cities have to contend with (Boraine, Crankshaw, Engelbrecht, et al., 2006; Donaldson, 2006; Maylam, 2009; Palmer, Brown-Luthango, & Berrisford, 2011; Brown-Luthango, Makanga, & Smit, 2012). While integrating land use and transport is viewed as a viable strategy to address urban problems (DoT, 1996, 1999, 2009, 2017a,b), the country’s cities remain a relic of post-apartheid spatial planning (Turok, 2001; Watson & Turok, 2001; Sinclair-Smith & Turok, 2012; du Plessis, 2015). This is despite the national efforts and municipal interventions.

While policy acknowledges that housing informality is an issue and should be addressed, there is still inconsistent housing policy interventions and poor implementation which has propelled informal settlement growth (Misselhorn, 2008; Tissington, 2011). This entrenches social exclusion, transport poverty and other challenges among informal settlement dwellers (UN, 2017).

Policies like the Urban Development Zone tax incentive have been crafted to incentivise private property developers to revive the inner city and also to unlock low-income housing in areas with access to economic opportunities and transport infrastructure (SARS, 2014). However, there has been limited appetite in investing in low-income housing developments due to low rates of returns on these residential units.

Despite the acknowledgement of the usefulness of integrated land use and transport as a policy tool in South Africa, integrated land use transport remains under-researched. While informal settlements are an important aspect in the country, there is limited research that delves into understanding the influence of residential informality on urban dynamics and the urban change process. Indeed, it is crucial that research not only considers the link between land use and transport but also examines how they interact in the urban environment. Given the spatial composition and growth trajectory of informal settlements, they need to be considered in the urban planning discourse as they introduce another dimension of urban problems in the city and hence are pertinent in the current planning context.

For better urban planning in South Africa, it is pertinent to understand the relationship between transport and land use. The use of frameworks that represent the interaction between land use and transport is increasingly popular as this is a potential way to marry urban planning and transportation planning. Urban models such as METRONAMICA-Xplorah implemented in Puerto Rico to evaluate land use and transport policies and Vision Illawarra for regional planning implemented in Australia (Perez, Wickramasuriya, Forehead, et al., 2017), PECAS implemented in Montgomery (Hunt & Abraham, 2009; Clay, 2010) among others have been utilised to provide evidence-based approaches to land use and transport planning. As such, land use and transport policy that emerges from modelling tools can be useful in directing land use and transport planning.

1.4 Research aim, objectives and questions

The previous sections set the stage for understanding and identifying the various issues that exist within South Africa and the focus of the study, Cape Town. From the above discussion, it is starkly clear that Cape Town continues to encounter and grapple with several issues that slow down the process of attaining urban forms that are equitable and inclusive. Themes that have emerged from the previous discussion include inefficiency due to the spatial relationship of residential land uses and economic activities; residential informality due to lack of formal housing; inequality due to disproportionate and expensive access to transport and its infrastructure; a congested transport network and rapid urbanisation. Anchored in these issues is land use and transport planning and how they influence each other. It is evident that the integration of these two components can be a viable approach to addressing urban challenges. While the integration of land use and transport is currently practised, a paradigm shift is essential where translating and adapting the land use and transport relationship in policy is as important as the interventions. This stems from understanding the symbiotic relationship between land use and transport and its influence on urban change. This is important in a context where transport infrastructure and associated technologies have been observed to influence the urban form by facilitating mobility and accessibility (Hansen, 1959; Newman & Kenworthy, 1991; Bertolini, le Clercq, & Kapoen, 2005; Reilly, Mara, & Seto, 2009) Indeed, understanding land use and transport is potentially useful in comprehending urban change as these two aspects are interrelated. Therefore, the research presented in this thesis analyses the spatial and temporal patterns of land use as well as the land use and transport relationship in Cape Town to facilitate alternative and more strategic policies for urban and transport planning.

The overarching aim of this research *is to understand the urban dynamics associated with the spatiotemporal interaction of land use and transport in Cape Town to help with formulating proactive approaches to integrated land use and transport planning in the city. This is done by implementing a dynamic land use and transport model.*

The following key objectives *direct* this research:

Objective 1: To understand the growth trajectory of residential, commercial and manufacturing land uses in Cape Town between 1995 and 2013.

Objective 2: To calibrate and validate a land use transport model that can be utilised to understand urban change in the city.

Objective 3: To formulate a set of policy strategies that may provide insight into the impacts of policy interventions on urban change in Cape Town.

The research objectives divide the research into three parts. The first part, which provides a quantitative background to the study, uses spatial metrics to analyse the growth trajectory of residential, commercial and manufacturing land uses in Cape Town from 1995 to 2013. The second component considers land use and transport interaction modelling by calibrating and validating a land use transport model for Cape Town. The penultimate section applies the model for exploratory policy scenarios.

To address the research objectives, the following research questions were formulated:
Research question 1: What is the spatial relationship between residential land use and centres of economic activities in post-apartheid Cape Town?
Research question 2: How can the relationship between land use and transport in Cape Town be conceptualised to understand its influence on urban change?
Research question 3: How can a dynamic land use transport modelling tool be used to provide proactive approaches to transport and land use planning?

It is anticipated that addressing the above questions and objectives will ignite a dialogue on the utility that integrated land use transport modelling tools have in forming proactive approaches to land use and transport planning in the city. There is a great need for urban change models that are fully dynamic, both spatially and temporally, and consider the role of transport in shaping land use and vice versa. Therefore, this research is relevant in a city like Cape Town as it expands its understanding of land-use and transport dynamics and how this may facilitate future growth and urban change, while also advancing alternative and more strategic policies for urban and regional transport planning. Furthermore, this research is valuable in that it provides the potential outcomes of different policy strategies that focus on addressing some of Cape Town's problems in the current conjuncture.

Notwithstanding the research that has been carried out in Cape Town, this research provides an opportunity to trigger a discussion on how to ensure that the growth of Cape Town, and possibly similar cities, can potentially be structured to enable affordable access and mobility, among other things, for all societal groups. The following aspects were identified which support using Cape Town as a case city:

- There is a bias in the spatial location of activities towards the affluent suburbs. Thus, restructuring urban change to locate the urban poor much closer to opportunities is a crucial issue in contemporary South Africa. Therefore, based on an understanding of dynamics within the Cape Town urban environment mostly land use and transport, this research tests the prospects and potential benefits that can accrue from interventions aimed at restructuring the urban environment. This is executed through developing a set of exploratory scenarios that test different interventions which may aid in attaining spatial efficiency in Cape Town.

- Densification of transport corridors is regarded as an essential aspect of ensuring affordable transport provision. By introducing density articulation on transport corridors as an urban planning strategy, this will provide an opportunity to understand and quantify the possible impacts on the urban change process.

1.5 Scope of the research

Though the study is motivated by the myriad of problems that exist in South Africa, as a consequence of its historical planning and current land use and transport policies, the scope of the research is limited to the Cape Town metropolitan region. While in this research the modelling tool is only calibrated and validated for Cape Town, given the stark similarities between South African cities, it is possible that the methods developed in this research are transferable to some of the country's other cities.

Cape Town has several mechanised modes of transport; however, this study only considers two public transport modes (minibus taxi and the bus) and car to simulate traffic onto the road network thus excluding the Metrorail train services and MyCiti Bus Rapid Transit.

1.6 Contribution to knowledge

The contribution to knowledge of this research is two-pronged, that is theoretical and practical.

Practical contribution: South Africa has moved from apartheid to democracy and this represents a form of "shock" to the system, i.e. a shift from strong (political) to "weak" (policy) zoning. Despite the change in the planning ideology from a politically driven to an economic driven approach, the growth trajectory of the city continues to trace apartheid strategies. Therefore, from a practical viewpoint, this research provides a picture of land use and transport change in Cape Town and evaluates whether the shift in the planning ideology is visible in the spatial location of land uses.

Secondly, though there are studies in South Africa that analyse the mutual interaction of transport and land use, no studies have been identified that utilise a cellular automata (CA) based land use transport model to understand urban change in South Africa. Further, this research adds to the utilisation of the METRONAMICA land use transport model (M-LUT) to analyse land use and transport interaction (LUTI). Currently, the M-LUT application is limited to (Shahumyan, Convery, & Casey, 2010; Aljoufie, Zuidgeest, Brussel, et al., 2013; Perez, Wickramasuriya, Forehead, et al., 2017). By calibrating and validating the LUT model for Cape Town, this will be an opportunity to contribute to the land use transport modelling literature in an African context while implementing a slightly different methodological approach compared to earlier studies.

The delineation of residential areas by income allows the Cape Town model to incorporate socio-economic variables in the calibration of land use transport models. Additionally, the issue of formalising informal settlements and providing appropriate infrastructure and services confronts both Cape Town and Jeddah, Saudi Arabia. However, in Aljoufie, Zuidgeest, Brussel et al. (2013), informal settlements are treated as a feature land use which makes it difficult to assess the dynamics associated with their morphology and how they influence the urban environment. For land use and transport policy to address urban issues relating to informal settlements, it is essential to understand the dynamics that lead to their morphology in specific locations. The Cape Town application adds to the Jeddah application as it considers informal settlements as a dynamic land use that influences the behaviour of land uses within their neighbourhood. This approach allows for the assessment of the growth of informal settlements and manage their growth from a policy perspective.

Theoretical Contribution: Cape Town is highly fragmented along income lines which affects mode choice decisions (Hitge & Vanderschuren, 2015). Recently, the urban policy environment has begun to aspire for inclusion and transformation. There is a growing interest in evaluating the progress the city has made in dismantling apartheid planning spatial patterns. Attempts have been made to understand how the post-apartheid spatial structure of Cape Town has changed (Sinclair-Smith & Turok, 2012) these discussions implement a theoretical approach to assess the progress the city has made. The theoretical contribution of this research is two-pronged. The first theoretical contribution is that this study uses statistical approaches, specifically spatial metrics, to trace the growth trajectory of residential land uses and economic centres in Cape Town from 1995-2013.

Second, this research contributes to literature by testing the ability of METRONAMICA to model urban dynamics where there is fragmentation along income with regards to residential locations. Furthermore, given the differences in socio-economic circumstances of different income groups, a characteristic used to distinguish different residential areas in this study; this provides more information with regards to calibrating neighbourhood rules where socio-economic aspects play a vital role in location choices. With that in mind, this thesis provides an approach that incorporates social aspects in the calibration of CA-based models. An additional contribution to literature is examining the usefulness of land use and transport modelling tools for exploratory policies with the view of providing proactive approaches to transport and land use planning in South Africa.

1.7 Thesis outline

This thesis is comprised of ten chapters which can be grouped into five research blocks as shown in Figure 1.2.

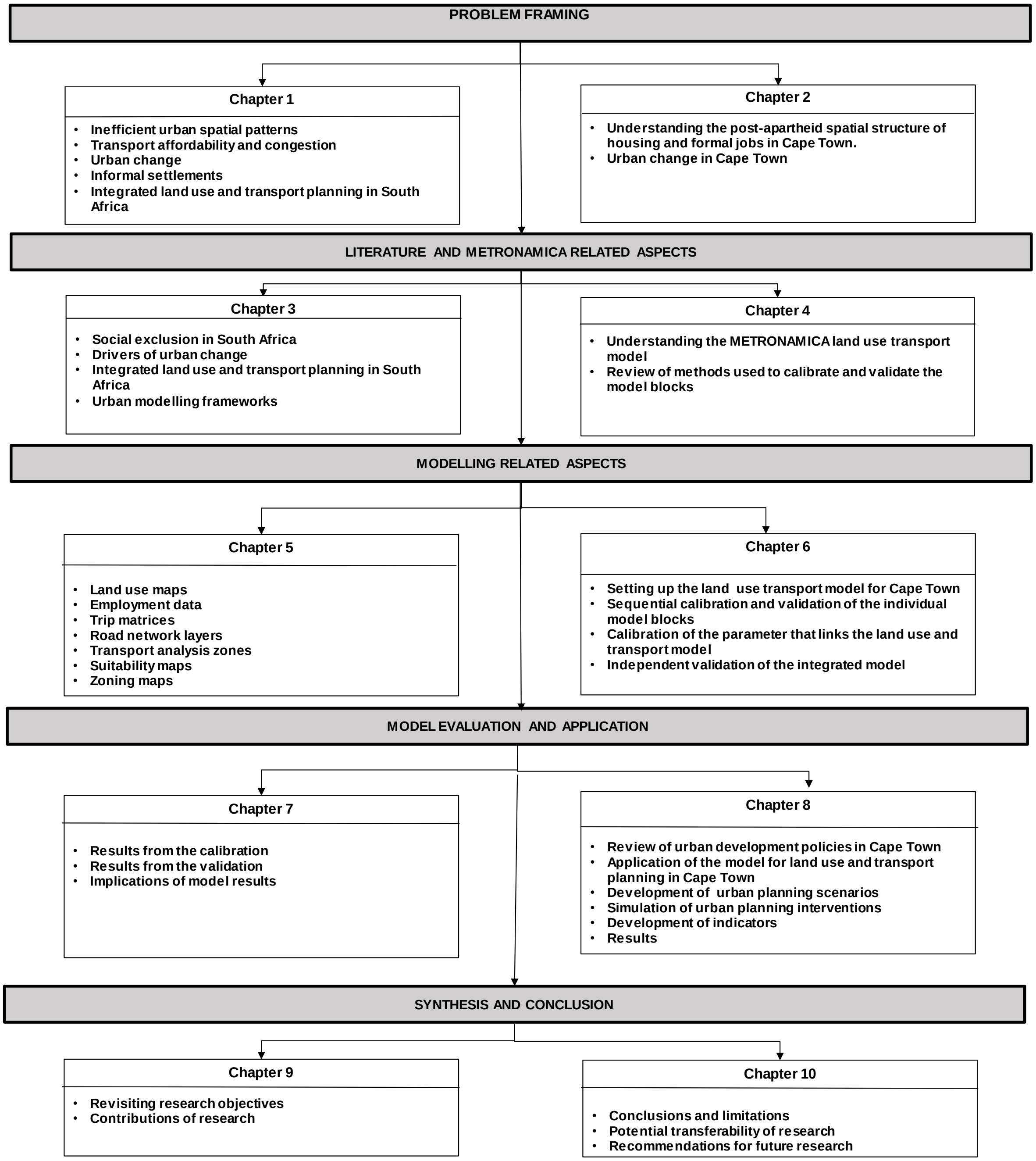


Figure 1-2: Research development chart

The preceding sections provided a brief overview of urban problems such as social exclusion, transport inequity, inefficient urban densities and the impacts on transport among other issues in the South African context. These sections introduced the research by providing a background hence motivating this research. The problem statement, research aims, objectives and questions were also introduced.

Chapter 2 uses spatial metrics to chart the spatial location of residential land uses relative to centres of economic activities. This sets the stage for understanding the relevance of this study and the discussions around integrated urban planning approaches in South Africa – using Cape Town as a case study.

Chapter 3 discusses the relevant literature that locates the research into an already existing body of work. It begins by discussing rapid urbanisation as an urban concept and its influence on the urban form. Informal settlements as a phenomenon in developing cities are discussed by focusing on their effect on service delivery especially transport. The literature on urban modelling is discussed focusing on urban growth and land use change models. Drivers of urban change are discussed in which the land use and transport link is unveiled. This sparks a discussion on the land use and transport link and its significance in land use and transport planning – thus providing the methodological and theoretical significance of this study. In this chapter the notion of urban areas as complex systems is discussed and how this has influenced integrated land use and transport modelling initiatives. The chapter also contextualises the research by discussing issues of equity, social exclusion and informal settlements in the context of South Africa. A discussion on the evolution of land use and transport planning policies in South Africa is also carried out. The chapter concludes by providing a brief discussion of the modelling tool considerations for this research and the need for this research in South Africa.

This leads to Chapter 4 which discusses the theoretical underpinnings of the METRONAMICA Land use Transport (M-LUT) modelling framework which is implemented in this study. An in-depth discussion of the constrained cellular automata land use transport modelling framework ensues by mainly focusing on the modelling blocks that will be operationalised in this study. This introduces the dynamic cellular automata land use model operationalised and discusses the dynamic components of the transport model that are incorporated in the research.

Chapter 5 describes the data that is utilised in the research and the processes involved in the data processing.

Chapter 6 which is the methodology chapter, introduces the METRONAMICA land use transport model for the Cape Town Metropolitan Region (CTMR_LUT). This chapter also discusses the calibration and validation procedures implemented in the model.

Chapter 7 presents the results from the calibration and validation of the model. These results are then discussed in the context of the performance of the model and how this impacts the usability and applicability of the model to simulate policy scenarios in the Cape Town context.

Chapter 8 discusses the application of the CTMR_LUT model for exploratory scenarios in Cape Town. Three policy scenarios are simulated. The chapter concludes by discussing lessons that emanate from utilising the model in land use, transport and general urban planning and policy implementations.

Chapter 9 ties the thesis together by discussing and articulating the extent to which the thesis has addressed the research objectives. This chapter also marries the key elements and research findings. Also, the main contributions to knowledge of the research and the implications of the research on transport and land use reform in Cape Town are noted in the chapter.

Chapter 10 concludes the study by highlighting the main conclusions flowing from the research and the limitations of the study are also pointed out. The chapter also discusses the potential of transferring the research methods implemented in the research to other cities similar to Cape Town. The chapter concludes by providing possible future research trajectory, specifically for the Cape Town context. Some general recommendations are also made in this concluding chapter.

Chapter 2

The post-apartheid city: the growth trajectory of residential land uses relative to economic activities in Cape Town from 1995 -2013

2.1 Introduction

Chapter 1 introduced the typical urban issues South African cities are faced with. One theme that came out strongly was the issue of spatial mismatch of low-income residential areas and centres of economic activities, which has subsequently led to a high transport bill for low-income households. This is estimated to be around 43% of income compared to 10%, which has been set as the benchmark by the government of South Africa (DoT, 1996; TDA, 2017a). Further, new low-income housing was also identified to locate in the peripheries (Watson & Turok, 2001); this has precipitated marginalisation of this cohort of individuals. Additionally, informal settlements which are an integral part of the Cape Town urban fabric continue to grow, which presents a unique land use characteristic and associated challenges to the current transport provision strategy.

The constant citing of urban inefficiencies, especially low urban densities which have affected transport provision (du Plessis & Landman, 2002) calls for restructuring with regards to transport planning and land use policies. Turok (2001) argues that post-apartheid planning ideologies have resulted in the polarisation of economic centres in affluent suburbs with good access to transport leaving the low-income segregated, which is starkly clear in Figure 1-1. The debate surrounding the polarisation of centres of economic activities in the affluent suburbs has led to urban development strategies such as the Cape Town Spatial Development Framework (CTSDF) (Vision 2040), which emphasises on the integration of land use, economic and transport planning. This is envisaged to improve access to economic and social activities while reducing the marginalisation of low-income earners (South African Government, 2012). Despite these documents providing a rubric for desired city structures and “economic articulation”, the current spatial patterns indicate the necessity of increased intervention to solve issues of spatial mismatch with regards to low-income residential areas and centres of economic activities.

Indeed, it is essential to tailor land use planning in Cape Town such that the urban densities and spatial patterns allow for access to economic activities and affordable provision of public transport. However, a clear understanding of the spatial distribution of land uses on the landscape is required. In that regard, this chapter applies a quantitative approach to analyse the growth trajectory of the Cape Town urban environment from 1995 to 2013. The aim is to evaluate the spatial relationship between residential land uses and centres of economic activities in post-apartheid Cape Town. Specifically, the evaluation of the spatial relationship and the growth trajectory of residential, manufacturing and commercial land uses in Cape Town. The findings from this analysis are linked to the various policies that have been implemented in Cape Town to get a more nuanced understanding of whether policy, actual land use planning and observed land use trends are aligned. Further, this provides an avenue to understanding the trajectory of land use change in Cape Town and how this translates to improved access to employment either through the mixing of residential land uses and employment activities. Relatedly, this chapter sets the stage to discuss the importance of urban growth in the context of land use and transport planning in Cape Town given its history and how this can be used to redress inequality.

2.2 Evaluating the evolution of the Cape Town urban landscape: choice of the evaluation approach

Spatial metrics have been applied to understand the ecological processes involved in the interactions between spatial and temporal patterns of a landscape and its related surroundings. Given that similarities exist in the temporal and spatial dimensions within landscape ecology and spatial planning (Antrop, 2001), approaches that are used in understanding ecological processes can be implemented to understand spatial structures in urban processes (Botequilha Leitao & Ahern, 2002; Corry & Nassauer, 2005; Steinitz, Anderson, Arias, et al., 2005; Botequilha Leitão, Miller, Ahern, et al., 2006; Kim & Ellis, 2009). Additionally, spatial metrics techniques have been used to aid in the validation and calibration of urban growth models (Herold, Scepan, & Clarke, 2002; Petrov, Lavalle, & Kasanko, 2009; Aguilera, Valenzuela, & Botequilha-leitão, 2011; Kong, Yin, Nakagoshi, et al., 2012; García, Santé, Boullón, et al., 2013), thus spatial metrics can be implemented to enhance the knowledge on urban landscapes.

This section uses spatial metrics to understand urban growth trends within the City of Cape Town. To facilitate this, landscape properties that can be quantified using a set of ecological properties were first identified. This entailed understanding the degree of aggregation, dispersion and clustering of land uses that serve as trip origins and trip destinations in Cape Town. Based on that, a class level analysis of landscape metrics is performed to evaluate the degree of aggregation, dispersion and clustering of different land uses on the Cape Town landscape.

2.2.1 Data utilised

As mentioned earlier, the analysis seeks to understand land use change between 1995 and 2013. Four land use data sets 1995, 2005, 2010 and 2013 maps are used. Initially, each land use map had eighteen land use types; which was too detailed for the present analysis as some of the land uses are not key trip origins or destinations. Additionally, some of the land uses relate to transport infrastructures such as roads, bridges, power stations and others. The land use categories were reclassified and condensed into nine land uses: low, middle and high-income residential, informal settlements, commercial and manufacturing services, other urban land uses, non-urban land use and the airport. These land use categories were considered as adequate in characterising the Cape Town urban landscape while showing key trip generating land uses. Residential areas were delineated by income using the Census data for 1996[1] and 2011, and the Community Survey of 2001 (STATSSA, 2014).

The 1996 census data was used as a reference point to verify the location of residential areas, whereas the 2011 census data was used as a consistency check of the locations of residential areas. Given that residential areas tend to persist in their locations; the consistency check emphasised on the evaluation of shifts in the location of well-established formal residential areas. Where persistence was not observed, this acted as a red flag on the integrity of the data set. Further, in Cape Town, some suburbs are historically known as low-income, middle or high-income residential areas, this historical knowledge is utilised as a second check for the consistency of the data especially the 2005 data set. The low-income band consisted of people earning below ZAR 2000 per month while ZAR 2001 to ZAR 4000 was categorised as middle-income. The high- income band comprised of people earning about ZAR 4000 and this is based on 1996 prices.

The 1996 income levels were used as a proxy for the 1995 income[2]. As there was only a one-year gap between the two data sets, the assumption was that there would be no significant income changes between the two periods. The same assumption was made in determining 2010 income levels where the 2011 income levels were used as a proxy. The average wage earnings for South Africa were estimated to be 4% higher in 2005 compared to 1995 (Burger & Yu, 2007). This

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[1] ZAR to USD in January 1996 averaged 0.27448 available at https://www.poundsterlinglive.com/bank-of-england-spot/historical-spot-exchange-rates/usd/USD-to-ZAR-1996

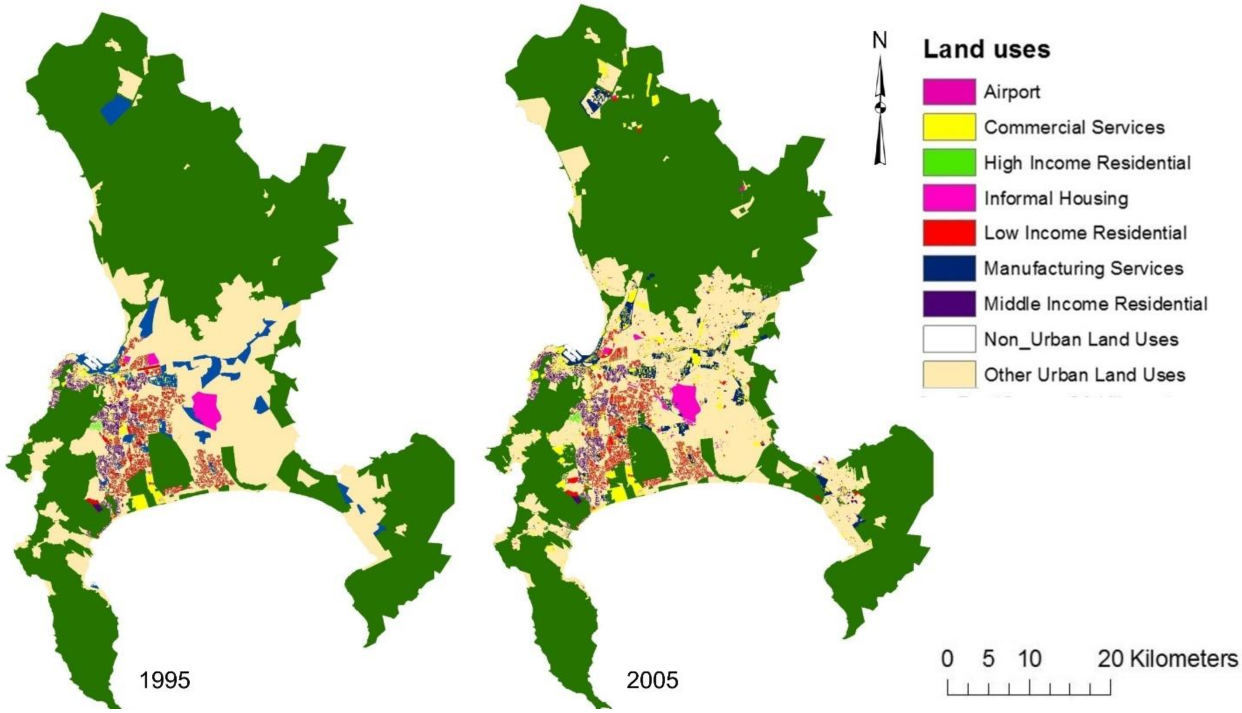
[2] Based on the derivation of incomes in (Yu, 2009) “The comparability of census 1996, census 2001 and community survey 2007)

percentage was used to calculate the 2005 income levels. Table 2-1 shows the land use categories used in the analysis.

Table 2-1: Land use/Land cover types

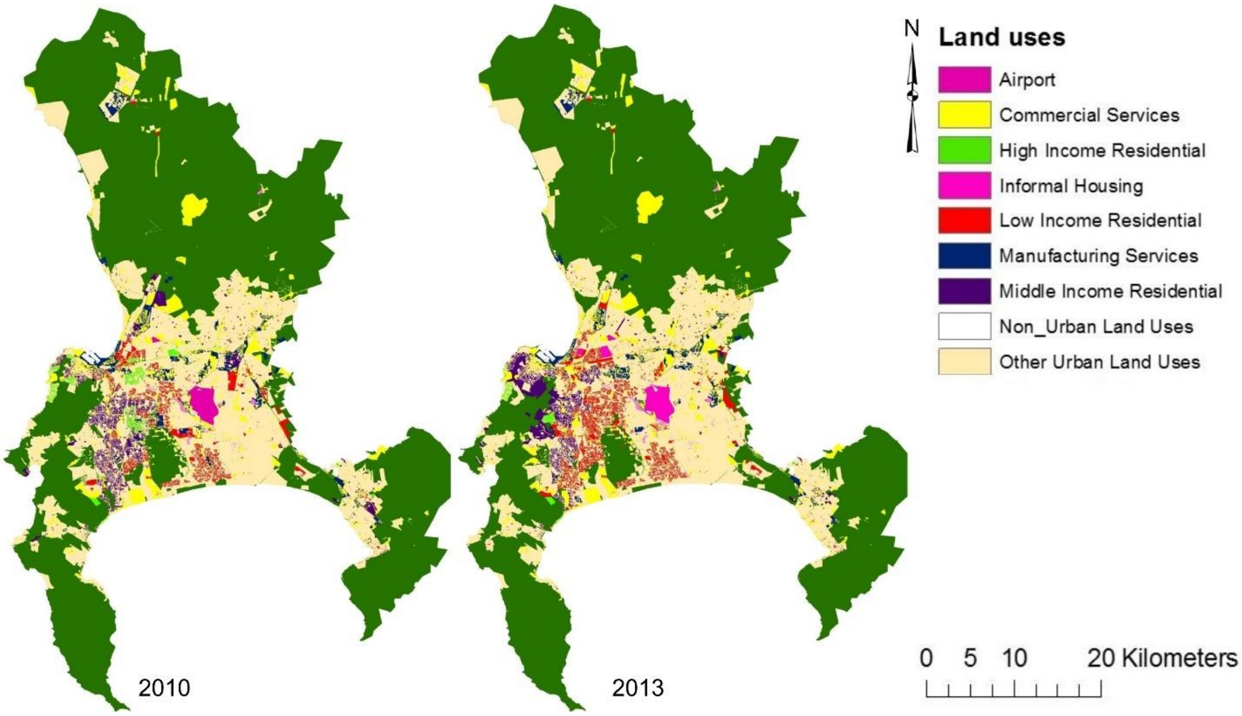
Land use type	Description
Informal settlements	Housing that is on land where people have no legal claim.
Low-income residential	Residential areas for people per capita monthly income of ZAR00 - ZAR 2000 in 1996 prices.
Middle-income residential	Residential areas for people per capita monthly income of ZAR 2001-ZAR 4000 in 1996 prices.
High-income residential	Residential areas for people with per capita monthly income greater than ZAR 4001 in 1996 prices.
Trade and services	This includes business services, insurance, banks, retail, restaurants etc.
Manufacturing services	This includes industrial areas and other manufacturing.
Other urban land Uses	This includes vacant open areas designated for urban land uses, schools, clinics and other urban uses.
Non-urban land Uses	These include nature reserves, forests natural waters, mining and quarry areas.
Airport	This includes the Cape Town International Airport and the Military base.

The 1995, 2005, 2010 and 2013 land use maps were converted into raster format of 50m by 50m cell resolution for analysis in FRAGSTAT which is a spatial pattern analysis tool (McGarigal, Cushman, Neel, et al., 2002). This cell resolution was coarse enough to exclude roads as a stand-alone land use while allowing the analysis to focus on the main land uses. Figures 2-1 and 2-2 show the land use maps with the nine land use types that are utilised.



Source: Prepared by the author from City of Cape Town data

Figure 2-1: Land use maps for 1995 and 2005



Source: Prepared by the author from City of Cape Town data

Figure 2-2: Land use maps 2010 and 2013

2.3 Operationalising landscape metrics

2.3.1 Understanding urban growth

Issues of urban expansion, urban pattern change, and conversion of land uses, urban population growth, social development and economic development play a significant role in the transformation of the urban form. Landscape metrics have been applied in transport to understand rural planning (Wu, Kuo, & Zhang, 2015), urban planning and development (Botequilha Leitao & Ahern, 2002), urban sprawl, land use transition and analysis of urban growth (Botequilha Leitao & Ahern, 2002; Herold, Scepan, & Clarke, 2002; Herold, Goldstein, & Clarke, 2003; Weng, 2007; Xu, Liu, Zhang, et al., 2007; Ji, 2008; Shrestha, York, Boone, et al., 2012; Aguilera-Benavente, Botequilha-Leitão, & Díaz-Varela, 2014; Nkeki, 2016) and transportation planning (Ree, Jaeger, Grift, et al., 2011) among others.

2.3.2 Choice of landscape metrics

The landscape characteristics under evaluation informed the choice of metrics implemented; this approach is also applied in other studies (Haines-young & Chopping, 1996; Uuemaa, Antrop, & Marja, 2009). For the Cape Town landscape, aspects such as the degree of aggregation, dispersion and clustering are evaluated. Therefore, topological aspects, such as spatial association, isolation, and dispersion, can be used to understand the landscape. Given that, the percentage of land (PLAND), number of patches (NP), Euclidean nearest neighbour-area weighted mean (ENN-AM), proximity index (PI), clumpiness index (CLUMPY), percentage of like adjacencies (PLADJ), interspersion and juxtaposition index (IJI) and aggregation index (AI) are implemented.

Structural aspects such as isolation or compaction can be quantified using ENN, PI, CLUMPY, AI, IJI and AI (McGarigal, Cushman, Neel, et al., 2002). ENN-AM measures the distance between patches, which fall into the same land cover type. The area weighted mean assesses the relative importance of each patch in relation to the patch size. Therefore, in this analysis, the area-weighted mean is selected to understand the spatial distribution of patches of the same land use class in a landscape. High ENN_AM values indicate that patches are far from each other, while low ENN_AM values show that patches are close together (Botequilha Leitão, Miller, Ahern, et al., 2006). On the other hand, the proximity index measures the degree of spatial isolation of patches of the same land use class. Given the close relationship between these two indices, ENN and PI are used in conjunction to understand the degree of isolation of different patches (Botequilha Leitão, Miller, Ahern, et al., 2006). Table 2-2 lists the indices and the aspect of the landscape they explain.

Table 2-2: Applied landscape metrics

Landscape Aspect being measured	Index	Range or Unit
Size	Percentage of Land (PLAND)	%
Fragmentation	Number of Patches (NP)	Count
Isolation	Nearest Neighbour Distance (ENN)	Metres
Isolation	Proximity Index (PI)	Metres
Compactness or Dispersion	Clumpiness Index (CLUMPY)	-1≤CLUMPY≤1
Dispersion	Percentage of Like Adjacencies (PLADJ)	0≤PLADJ≤100
Dispersion	Interspersion and Juxtaposition Index (IJI)	0≤IJI≤100
Compactness or Dispersion	Aggregation Index (AI)	0≤AI≤100

2.3.3 Land use analysis

As mentioned earlier, this chapter seeks to analyse the spatial relationship between residential land uses and centres of economic activities in post-apartheid Cape Town. The rationale is to evaluate whether the location and growth of employment centres relative to residential areas follow a pattern that is attentive to solving issues of social exclusion and transport affordability which are vital in addressing the spatial mismatch in the city. The analysis is carried out using the FRAGSTAT software (McGarigal, Cushman, Neel, et al., 2002). The metrics were calculated using an eight-cell neighbourhood radius and a 2,000m search radius. This chapter argues that centres of economic activities are biased towards the affluent suburbs and that it is essential to restructure land use development such that the low-income cohort has access to economic opportunities. The main mode of travel for this cohort is walking, by implementing a 2km search radius an evaluation of access to employment through walking can be carried out.

The analysis considers commercial and manufacturing areas as the main trip destinations while residential areas including informal settlement are the main trip origins. In the case of informal settlements, there is a potential discrepancy in the reporting of their number and location in the data reports by the City of Cape Town. Efforts were made to fill the data gaps by using interactive maps. However, given the extent of informality, there is still a possibility that there is still some missing data. This potentially has an impact on the various metrics calculated for informal settlements. Informal settlements are an integral part in the Cape Town urban fabric and the current discourse of social and economic exclusion, hence it was essential to report on the findings to provide some insights into their growth[3]. The results will only consider the available data set keeping in mind that there may be an over or under-estimation of some of the metrics.

Pairwise comparison is also used to compare residential land use patterns relative to commercial and manufacturing land uses. For each of the pairwise comparisons, the residential land use classes were classified into the same land use category with either commercial or manufacturing while keeping the rest of the land uses constant. For example, to make a comparison between low-income residential and commercial, the two land use classes were combined into one land

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[3] Although the discussion does include informal settlements, where possible the spatial metrics calculated for informal settlements are presented to alert the reader on the presence and share of informal settlements on the Cape Town landscape.

use class: mixed low-income and commercial services while high and middle-income residential, and manufacturing services were kept as individual land use classes. The pairwise comparison only uses the proximity index, Euclidean nearest neighbour, percentage of like adjacencies, aggregation index and the interspersion and juxtaposition metrics. The percentage of land and number of patches are only used to quantify the landscape composition for individual land uses.

2.4 Characterising and evaluating the landscape characteristics

2.4.1 Land use composition

An analysis of the land cover in Cape Town using the percentage of land (PLAND) showed that the amount of land space occupied by the commercial sector increased from 0.29% in 1995 to around 2% in 2013. The manufacturing sector occupied a significant part of the landscape, which was around 1.2% in 1995 and reduced to around 0.6% in 2013 due to a decline in productivity in the sector (Quantec, 2016). The decline in productivity resulted in the closing down of some manufacturing companies. These locations in some cases became brownfields or were converted to other land uses. Commercial areas have the highest count of land use patches (3,196) in 2013 followed by low-income residential areas (1,081). The results show that the share of informal settlements has increased over the period 1995-2013. Figure 2-3 presents the number of patches and the total space in percentages that each land use occupies.

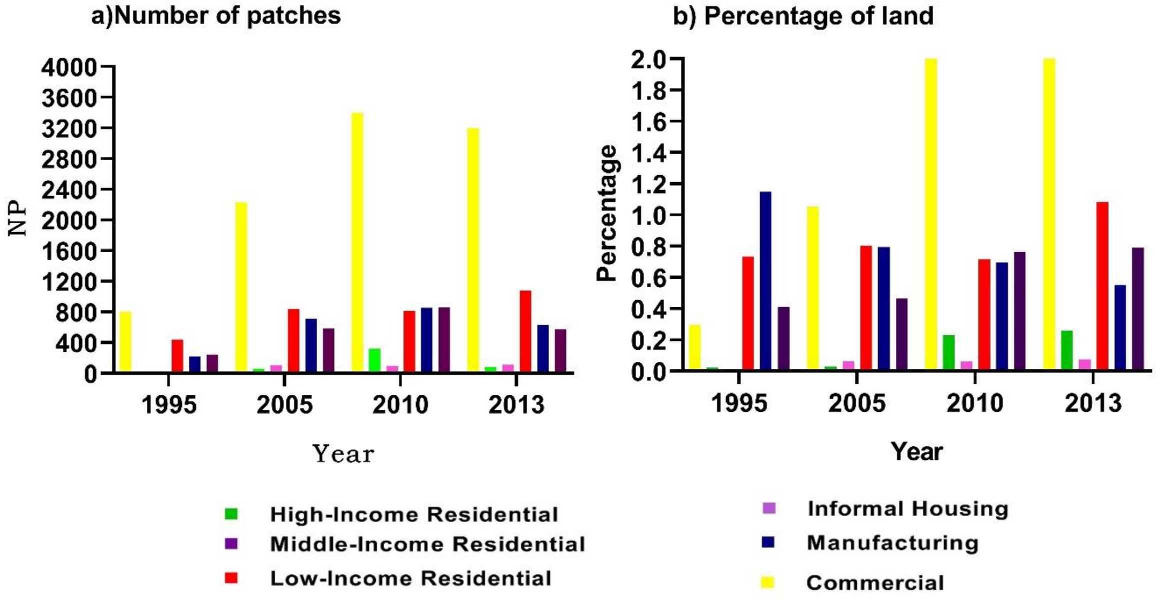


Figure 2-3: Land use composition

2.4.2 Evaluating the degree of isolation between land use patches

The distance between patches of the same land use class explains the degree of compactness of the landscape. The ENN, PI, CLUMPY, IJI, PLAND indices are reported for the individual land uses and for the pairwise analysis to evaluate the level of compactness of the Cape Town landscape. The Euclidean distance and proximity index are used to complement each other as they help in better explaining the degree of isolation of land uses (Botequilha Leitão, Miller, Ahern, et al., 2006) especially those falling within the same land use class.

For individual land uses; the area-weighted mean ENN (fig 2-4a) shows that manufacturing services have the most distance between patches in 1995 and the number significantly drops for the rest of the study period. The decrease in the distance between patches could be linked to the closure of some companies in the textile manufacturing sector due to competition with cheap imports. The proximity index (fig 2-4b) supports this finding as seen by the low values in the index for manufacturing patches. This suggests that the remaining land use patches are within the same manufacturing sector hence most likely located close together. Further, the results show that between 1995 and 2013, low-income residential areas consistently have short distances between patches indicating that this land use is growing in large patches. Relatedly, as the low-income residential patches increased, they also tend to cluster together thus resulting in large compact low-income patches. The spatial pattern of low-income residential land use shows that new low-income residential areas tend to locate near already existing low-income residential areas. However, an interesting trend is also observed between 2005 and 2010 where the proximity index declines. This further supports the notion that low-income residential areas grow in clusters. However, between 2010 and 2013, there is an increase in the proximity index indicating that there is a development of low-income residential areas in new locations. Overall the growth of low-income residential shown in Figure 2-4 is consistent with the genesis of the low-income residential neighbourhoods and the subsequent exurban location of new low-income housing found in Cape Town.

Additionally, Figure 2-4b shows that between 2005 and 2013, the distance between informal settlements has marginally increased indicating the development of informal settlements in new locations which are closer to already existing settlements. However, the overall spatial structure shows that the existing informal settlements have grown to form large continuous patches.

Middle-income residential areas have consistently shown low average distances (low ENN -AM values) between patches over the study period. This suggests that new middle-income patches have generally located close to already existing middle-income areas. However, a slight increase in the distance between patches is observed (fig 2-4a) between 2005 and 2010. What this result suggests is that new middle-income residential areas maybe be located a little further from other middle-income residential areas. There is also a potential that there are mixed land uses in the suburbs with middle-income residential areas which might explain the spatial patterns of this land use. This is especially true given that policies such as the Integrated Development Plan advocated for mixed land use developments. The mixing of land uses is further explored using pairwise comparisons of middle income residential and commercial land uses in section 2.4.5.

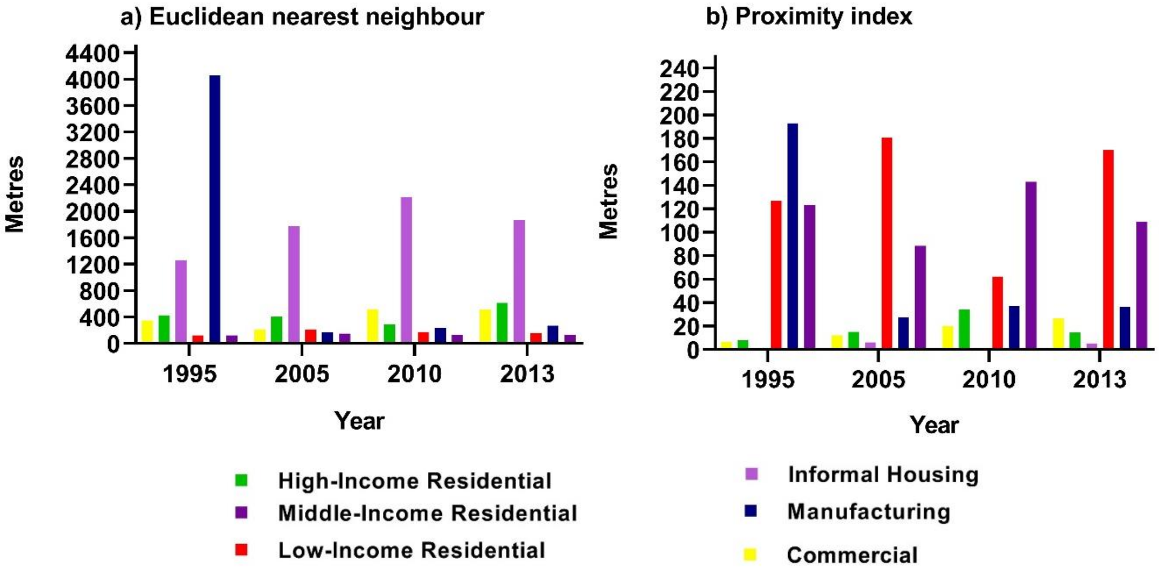


Figure 2-4: Distance between patches

High-income residential areas were also observed to locate close to other high-income residential areas (fig 2-4b). This development pattern suggests that high-income homeowners prefer to locate close to other high-income residential areas.

2.4.3 Urban sprawl in Cape Town

Urban sprawl leads to urban spatial patterns that are fragmented (Poelmans & Rompaey, 2009). The costs and impacts associated with dispersed urban development have been cited with particular concern on their inefficient nature and the impact on productivity (Fallah, Partridge, & Olfert, 2011), mobility and accessibility to critical activities such as jobs, schools, hospitals and others (Ewing, Schroeer, & Greene, 2004; Ewing, Hamidi, Grace, et al., 2016). In Cape Town, the lack of a viable and efficient public transport can be linked to peripheral low-income housing development and low urban densities which makes it difficult to provide affordable public transport

(Watson & Turok, 2001; Palmer, Brown-Luthango, & Berrisford, 2011). The clumpiness index is implemented to evaluate the degree of compactness of urban land uses which indicates the degree of sprawl. The index ranges from -1 to 1 where one indicates aggregation and -1 shows disaggregation of land uses (Kew & Lee, 2013). If the difference in the clumpiness value between different years is positive, this may be indicative of land uses becoming more compact (RIKS, 2008).

The results from analysing the clumpiness of land uses (fig 2-5) indicate that all land uses have relatively high clumpiness values showing that land uses within the same land use class are found near each other. Further, this suggests that most land use classes are in continuous patches making it difficult for other land uses to appear close to them. Such land use structures encourage outward growth of urban areas thus presenting a limited opportunity for infilling and mixing of land uses. On the other hand, middle-income patches have become relatively more compact compared to any other land use. This is shown by the increase in the clumpiness value from 0.59 to 0.73 in the period 1995 to 2013. However, a comparison between 1995 and 2005 shows a 3.81% decrease in the clumpiness index. Though the value is relatively small, this outcome suggests that there may be other land use classes that emerged. Another possible explanation is that the middle-income residential areas were converted into new land uses. However, given that residential land uses tend to persist in their original locations and have a high degree of persistence, the emergence of new land uses close to middle-income areas is a more plausible explanation for a change in the index.

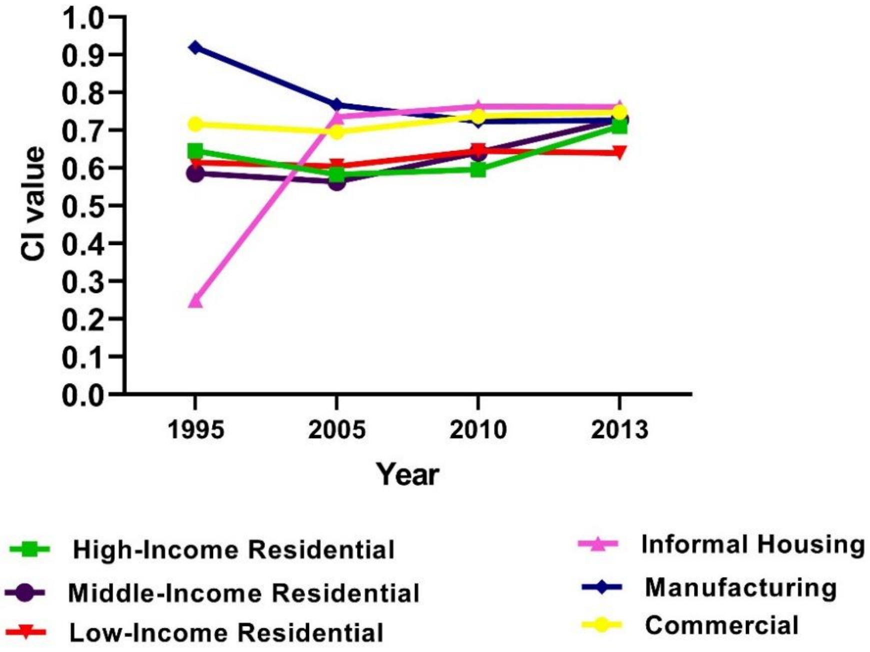


Figure 2-5: Sprawl measure (CI)

Relative to other land uses, the clumpiness index for 1995 for informal settlements is low. However, growth in the index is observed from 1995 to 2005 for informal settlements which can be explained by an increase in rural to urban migration without a reciprocal increase in the supply of formal housing. This period coincides with the end of apartheid and a potential rural to urban areas in search of economic opportunities. The index stabilised between the period 2005 and 2013.

Regarding low-income residential areas, the clumpiness has significantly increased between 1995 and 2005 and from thereon are constant. The increase in the clumpiness values shows that low-income land uses are becoming more compact, which implies that there is a development of new low-income housing patches close to already existing low-income patches. Given the historical location of low-income residential areas, the growth in these patches is most likely to happen towards the urban fringe hence perpetuating previous low-income spatial patterns. This growth trajectory perpetuates mono-use land uses and the eventual sprawling of low-income residential areas away from centres of economic activities which is a characteristic of the Cape Town urban landscape.

2.4.4 Compactness and the potential of mixed land uses

Evaluating the degree of compactness and the potential for mixed land uses is an essential exercise in this discussion as it provides insights into the spatial relationships between land uses. This can potentially explain some of the trip characteristics that are observed in Cape Town. To evaluate the occurrence of similar land uses, degree of compactness, distribution of land uses and the mixing of land uses on the landscape, the Percentage of Like Adjacencies (PLADJ) and the interspersion and juxtaposition index are used. These indices are presented in Figure 2-6.

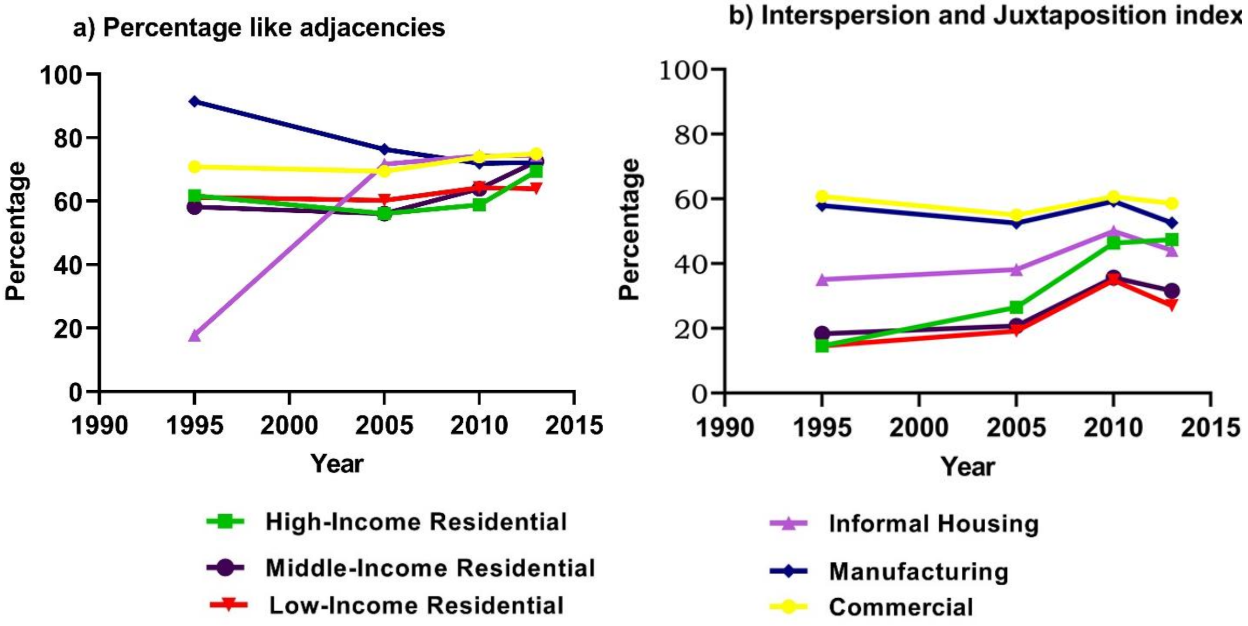


Figure 2-6: Potential for mixed land uses

The PLADJ as an assessment measure allows to evaluate the potential dispersion or mixing of land use classes, the results are summarised in Figure 2-6a. Commercial and manufacturing services had the highest PLADJ values in 1995 with a noticeable decline in the index for manufacturing services between 1995 and 2013. As mentioned earlier, the manufacturing sector experienced a decline in productivity which led to the subsequent closure of some companies; this may account for the change in the index. For middle and high-income residential areas, the percentage like adjacency values decrease between 1995 and 2005 and then increase till 2013. There is an estimated 3% increase in PLADJ for low-income residential areas between 1995 and 2013. This finding is consistent with the results from the clumpiness index, which showed that the growth trajectory of low-income residential shows a coalescing of low-income residential areas thus resulting in large continuous patches.

The use of the interspersion and juxtaposition index (IJI) in this study also brought a new dimension which aided in better understanding the distribution of land uses across the landscape (Botequilha Leitão, Miller, Ahern, et al., 2006). High interspersion values indicate an even distribution of land use patches across the landscape. Figure 2-6b presents the interspersion results, the results show that the interspersion values for all land uses are relatively low with commercial services reporting the highest value in 1995 while the low-income residential has the lowest values. Manufacturing and commercial services values fluctuate over the period. The high-income residential category shows an increase in the interspersion percentage from around 15% in 1995 to 47% in 2013. This represents the highest change across all land use classes. Given that the interspersion values for most land uses are below 50% between 1995 and 2013, this indicates an uneven distribution of land uses across the landscape.

Relatedly, the low interspersion for middle and high-income suggests that these land uses are to some extent disaggregated. This spatial pattern encourages the development of new land uses in areas close to high and middle-income residential areas. This is especially possible in the case of middle income given a decrease in the clumpiness index (fig 2-5) between 1995 and 2005. The potential mixing of land uses in areas with high and middle-income residential areas supports the notion of suburbanisation of employment to the high and middle-income residential areas which has been observed by other studies (Naude, 2008; Turok, 2011b). Further, the growth of middle-income estates with mixed land uses in Cape Town could be a plausible explanation for the results.

The extent of aggregation of similar land use patches was evaluated using the aggregation index. AI approaches 100 when patches are aggregated such that they become a single compact patch (Botequilha Leitão, Miller, Ahern, et al., 2006; Ramachandra, Aithal, & Durgappa, Sanna, 2012; Ramachandra, Aithal, & Sreekantha, 2012). The results for the AI are presented in Figure 2-7 for all land uses. The results show that for all land uses; there are high levels of aggregation with most land uses having substantial compact patches. This finding supports previous findings in section 2.4.2 relating to the clustered growth of land uses within the same land use class.

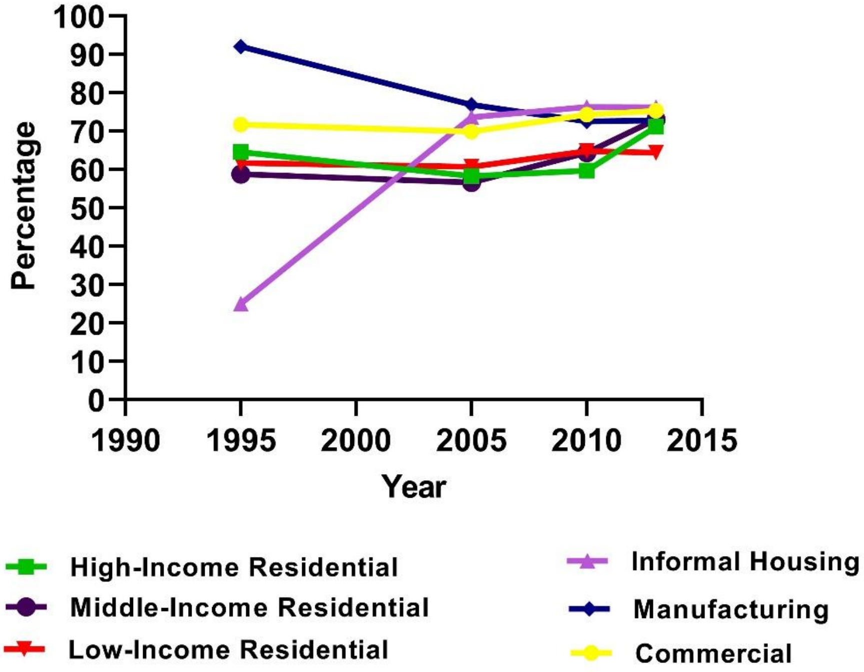


Figure 2-7: Aggregation index for all land uses

2.4.5 Potential for mixed land uses

The discussion on the interspersion index alluded to the possibility of suburbanisation of employment in middle and high-income suburbs in Cape Town. This notion is explored further by carrying out a pairwise comparison of land uses. This analysis ties together the discussion by focusing on the pairwise comparison of residential and commercial or manufacturing land use classes. The same metrics that were utilised to understand individual land use are employed to carry out the pairwise analysis. Figure 2-8 reports on the findings from the pairwise analyses of land uses.

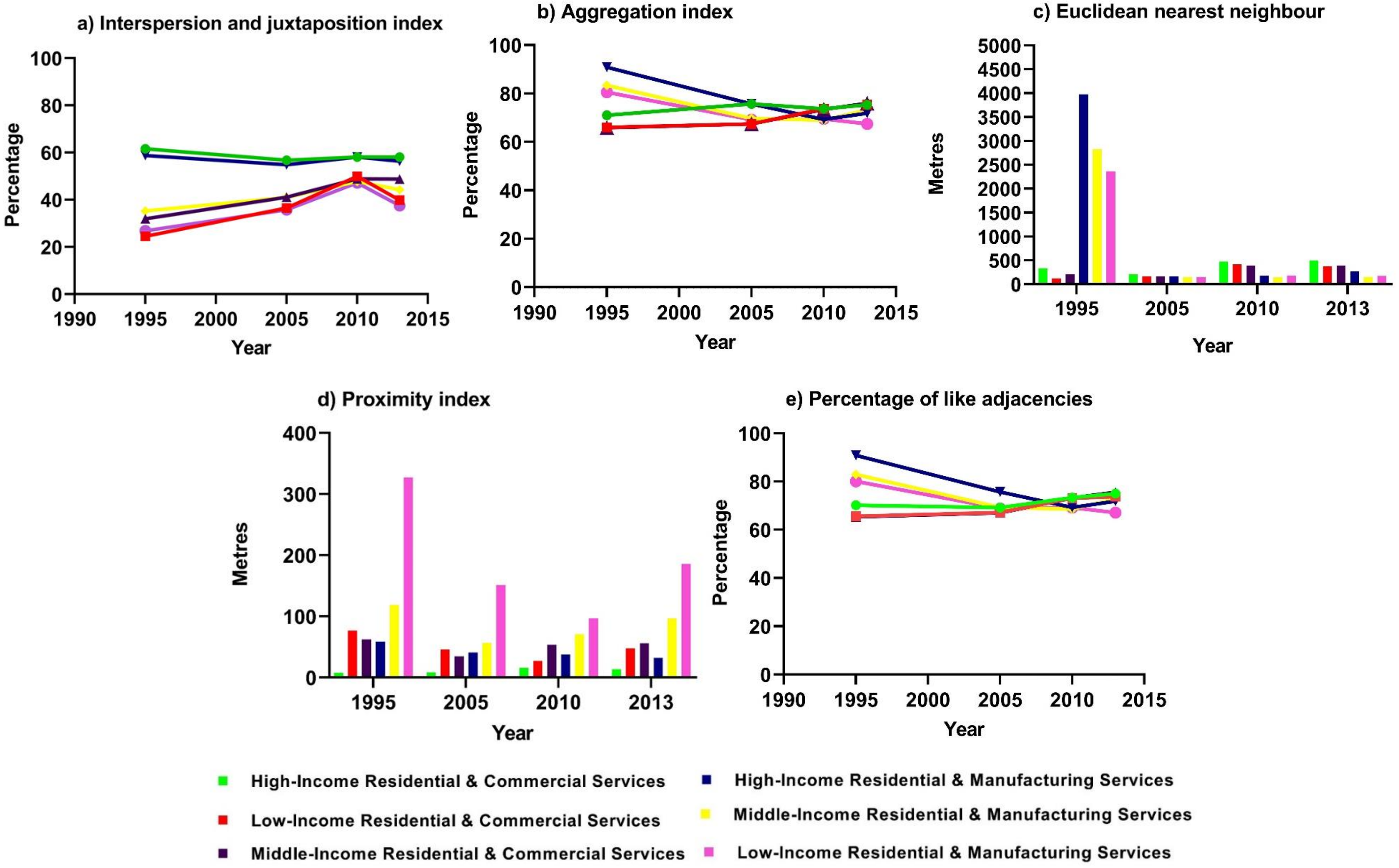


Figure 2-8: Potential for mixed land uses

The results show high interspersion values (fig 2-8a) for high-income residential combined with commercial land uses thus indicating aggregation of these land uses. This can be construed to indicate a spatial mixing of high-income and commercial services in some areas. Low-income combined with commercial services shows low interspersion values revealing that these land uses are not nearby across the metropolitan area. However, these values have increased over the period with a total positive change of around 25% between 1995 and 2005 for low-income residential and commercial and a change of around 11% for low-income residential and manufacturing. These findings suggest that vacant land between low-income residential provide an opportunity for infilling by other land uses. Given the policy initiatives in Cape Town, it is possible that commercial and manufacturing land uses are found in these areas hence possible mixed land uses, this finding is corroborated by other studies (du Plessis, 2015).

The observed results for all pairwise comparisons show that the index for compactness, the aggregation index AI (fig 2-8b), has remained relatively high over the period. The pairing between high and middle-income residential areas combined with manufacturing services showed a decrease in the AI. This is not an unexpected observation given that middle and high-income residential areas tend to locate further from manufacturing services. For high and middle-income land uses combined with commercial land uses, the AI has increased for the same period and this is characteristic of the growth trends of these land uses in Cape Town. The aggregation index for low-income land use combined with commercial land use has also increased; however, compared to other land use pairs; the index remains low between 1995 and 2013. This shows an uneven distribution between low-income residential and commercial land uses hence a separation between these land uses. An explanation that could help in understanding this trend is the need for highly skilled labour for this sector resulting in commercial services locating in areas where there is access to a labour pool (Watson & Turok, 2001). Further, the education trends in low-income neighbourhoods (STATSSA, 2012) resonate with low skills; hence it is plausible for only a few commercial services especially in the financial services to locate close to low-income areas. This has the potential to perpetuate the spatial mismatch between low-income residential and commercial services sector job locations.

The ENN (fig 2-8c) analyses show that for all land uses the nearest neighbourhood distances range between 145-264 metres. The nearest neighbourhood distance for high-income residential areas combined with commercial services has decreased over the years while for low-income residential areas combined with commercial services the nearest neighbourhood distance has increased. For middle-income residential combined with either commercial or manufacturing services the analysis shows that the distance has fluctuated over the time period. This can potentially be linked to the closure of manufacturing services due to a loss in productivity in this sector. On the other hand, the high-income residential areas paired with commercial and manufacturing relationship shows a decrease in the average ENN distances. A plausible explanation is the increase in mixed-use land use developments in the middle-income suburbs

Finally, the proximity index (fig 2-8d) is used to complement the Euclidean distance in understanding the general structure of the landscape. Low-income residential paired with manufacturing has the largest distances; however, this has reduced between 1995 and 2013. The distances for middle-income and high-income residential combined with commercial have remained relatively low over the period. For high-income residential combined with manufacturing the distances have reduced over the period. Overall, these distances have been considerably low from the beginning of the period of assessment which may suggest a possible mixing of these land uses. The percentage like adjacencies (fig 2-8e) shows that the distance between low-income residential and manufacturing has consistently decreased between 1995 and 2010 with a slight increase observed between 2010 and 2013 whilst the distance between low-income residential and commercial has steadily increased between 1995 and 2013 showing a tendency of commercial services to locate away from low-income suburbs. This is consistent with the suburbanisation of employment especially in the commercial services sector in the affluent suburbs.

2.5 Conclusions

This chapter used spatial metrics to understand the spatial structure and spatial location of land uses in the Cape Town metropolitan area. The focus was on residential, commercial and manufacturing land uses which serve as the main work trip origins and destinations. The first main finding shows that between 1995 and 2013, new low-income housing continued to locate in the peripheries thus perpetuating the apartheid spatial structures. This precipitated lack of access to economic activities for the low-income cohort while the affluent had easy access to economic activities. This is in line with other studies (Sinclair-Smith & Turok, 2012) who observed that urban growth in Cape Town was biased towards the affluent suburbs which consequently attracts economic growth in these areas. Further, this finding suggests that the growth trajectory of the city is not that different from apartheid planning strategies, a finding that was observed by earlier studies (Turok, 2001; Turok & Parnell, 2009).

While the historical growth trajectory has been maintained, the results also show a decrease in the average distances between low-income housing and manufacturing services suggesting that the disparity between these two land uses has decreased over the years. This is an encouraging finding as it reveals the positive outcomes emanating from the efforts through policy to increase access to employment for the low-income cohort.

The study appreciates the City's efforts to provide housing for low-income earners; however, a re-evaluation of the spatial planning model for low-income residential areas is needed. The results have revealed that the planning trends are perpetuating apartheid spatial structures, which not only increase the transport subsidy bill but also exacerbates the social and economic gap between income groups. Incentives such as the Urban Development Zone (UDZ) are a step in the right direction; however, there has been limited success in unlocking low-income housing in accessible areas. Hence, the question remains whether there are sufficient incentives to encourage private stakeholders to invest in the construction of low-income housing within the identified UDZ. It is essential to evaluate the missing linkages within the planning context to identify aspects that perpetuate the current spatial trends. Whereas the government is encouraging private property developers to invest in low-income housing close to established infrastructure, ambivalence in the government's housing policy stalls progress. For example, the Reconstruction and Development Programme (RDP) spearheaded by the government has resulted in low-income housing locating in the outskirts. This is a disincentive for private property developers to invest in low-income housing within the UDZs which are relatively more expensive compared to the outskirts. While the redevelopment of brownfields and infilling of open spaces close to economic centres to accommodate low-income housing is a step towards filling the inequality and social exclusion gap; there needs to be cohesion between the municipal housing policy and the proposals it put outs to the private developers.

There is potential to 'unlock' investment from the private sector if there is alignment of government policies and actual investment, for example, construction of low-income housing in the UDZs by government. This can potentially incentivise private sector developers, especially in low skills so that they locate closer to low-income residential areas. For these incentives to propel investments in the low-income suburbs, the city authorities need to show that investing in these areas is as lucrative as investing in the middle and high-income residential areas.

Therefore, the city authorities need to set precedence by taking the risk and potential loss in profit and construct low-income housing in these UDZs if there are indeed "benefits" for the developers. Through this strategy, the city can express commitment to redress and restructure

Cape Town to reduce the disparities due to past planning policies. Market forces which mostly lead to rent-seeking influence the spatial dimension of land use location in Cape Town; this makes it challenging to incorporate the needs of the disadvantaged without jeopardising market performance. However, the government can play a part in incentivising the private sector, especially in low skills so that they locate closer to low-income residential areas. For these incentives to propel investments in the low-income suburbs, the city authorities need to show that investing in these areas is as lucrative as investing in the middle and high-income residential areas.

From a policy perspective, there needs to be more intervention to ensure that in the next 20 years, a similar analysis would reveal a change in the planning ideology visible through the spatial configuration of the urban landscape that shows a more inclusive and integrated urban form. It is, however, important to acknowledge that solutions to Cape Town's urban problems do not lie in tackling land use development only; instead, a combined effort of both land use and transport related interventions is required. Hence, the solutions to address urban problems identified in this chapter potentially lie in looking at land use and transport planning as a continuum as opposed to separate policies. This means understanding land use, transport, the transport infrastructure and their combined influence on urban change. It is against this background that the next chapters of this thesis delve into understanding the land use and transport nexus, land use, transport planning and land use and transport modelling as a policy tool that can be used for policy formulation and assessment.

Chapter 3

Literature review

"The transport system shaped the growth of the city, but on the other hand the previous growth of the city shaped and in particular constrained the transport alternatives that were available. So, the pattern of activities and land uses in the city, and the transport system existed in some kind of symbiotic relationship."

(Peter Hall, 1994)

3.1 Introduction

The previous chapter discussed the growth trajectory of Cape Town's urban landscape between 1995 and 2013. Rapid urbanisation was observed as an urban phenomenon in the city which has precipitated residential informality and exacerbated social exclusion and urban inequalities as low-income housing continued to locate in the peripheries. On the other hand, the middle and high-income residential areas were observed to be well located with easy access to transport infrastructure and economic activities. While the results show efforts to mitigate some of these issues through policy interventions, there is a need for further intervention to ensure that future development of Cape Town allows for integration that facilitates inclusion and equality for its populace. However, to ensure an equitable and socially inclusive city, it is essential to understand the impacts of rapid urbanisation on urban change and approaches that can be taken to predict and plan for these changes. Further, it is essential to understand and identify the drivers of urban change and how they shape the urban environment.

It is against this backdrop that this chapter discusses the challenges of urbanisation and how it influences urban change in the context of developing countries which resonates with the South African case. Social exclusion in a South African context and developing countries is also discussed. This leads to a discussion on urbanisation and its linkage to residential informality and social exclusion. To understand the urban change process, the interlinkage between land use and transport is explored, this leads to a discussion on urban modelling and how it can be employed as a tool to understand urban changes.

3.2 Rapid urbanisation

The United Nations projected that by 2050, 68% of the world population would be living in urban areas with developing countries projected to have the largest share of megacities by 2030. While urbanisation is linked to economic growth they are not always mutually inclusive (Annez & Buckley, 2006; Chen, Zhang, Liu, et al., 2014, Fay & Opal, 2000; Chen, Zhang, Liu, et al., 2014; Jedwab & Vollrath, 2015; Onjala & K'Akumu, 2016). This is especially clear in many developing countries suffering from high levels of poverty and increasing inequality (Glaeser, 2013). In developing countries, urbanisation, especially over a short period has made cities vulnerable to environmental, financial and social problems (Barredo, Demicheli, Lavalle, et al., 2004; Annez & Buckley, 2006; Darkwah & Cobbinah, 2014).

Understanding urbanisation in the context of urban change is essential given the potential implications of urbanisation on the transport system, mobility, energy provision and its influence on urban morphology (Wang, 2014; Kammen & Sunter, 2016; Rode, Floater, Thomopoulos, et al., 2017). Compared to their developed counterparts, transport issues in developing countries due to urbanisation have outpaced transport infrastructural improvements (Henderson, 2002). Issues of inequitably developed infrastructure further threaten sustainable development as concerns about economic and social exclusion arise. Hence, urban issues, especially relating to mobility in the global South are different from those in economically developed countries as these countries are well equipped to absorb urbanisation demands (Cervero, 2013). While popular rhetoric advocates for sustainable urban development, it is pertinent to appreciate that in developing countries the complexity and unpredictability of the urban environment are higher compared to developed countries, which make it challenging to attain sustainable development (Barredo & Demicheli, 2003).

3.2.1 Challenges of urbanisation in developing countries

In 2000, the United Nations projected that by 2020, the population of slum dwellers would be at least 100 million (UN, 2007) while in 2006, 72 per cent of the urban population was estimated to live in slums (Cohen, 2006). Urbanisation in developing countries has resulted in urban residential informality (Cervero, 2013; Cobbinah, Erdiaw-Kwasie, & Amoateng, 2015; Jones, 2017) which has resulted in income disparities, inadequate provision of infrastructure, as well as a spatial mismatch between housing and jobs. A close look at these issues shows that most of these problems can be attributed to the way urban development is occurring (OECD, 2018), especially poor planning for formal housing in response to urbanisation. Barredo et al. (2004) assert that unplanned growth in urban systems can result in adverse environmental, financial and social consequences. Worryingly, developing countries continue to face informal urbanisation which has led to poverty as it is mainly characterised by rural-urban migration where people have poor job prospects (Hofmann *et al.*, 2015), this challenges achieving sustainable development (Cobbinah, Black, & Thwaites, 2013). Despite these warnings, in the absence of complementarity between rapid urbanisation and planning the former will, indeed, continue to challenge the fundamental aspects of land use and landscape patterns (Deng, Wang, Hong, et al., 2009). This has already manifested in many developing countries where there are limited financial resources to provide adequate housing and infrastructure for all urban dwellers.

3.2.2 Influence of urbanisation on sustainable cities

Among other definitions, sustainable development is concerned with forms of growth which relate to the improvement or maintenance of environmental quality for present and future use while conscious to concerns around social inequalities (Haughton & Hunter, 2004). Rapid urbanisation has been characterised as an impediment to sustainable cities (Zhao, 2010; De Vos and Witlox, 2013; Boyle and Michell, 2018). This is related to the complexity inherent in urbanisation, especially the proliferation of informal settlements that is linked to this phenomenon (Jones, 2017). In developing countries, the concept of sustainability is more complex; as poverty alleviation is more pressing compared to environmentalism (Punekar, 2006). As such, it is argued that urban sustainability in developing countries should be achieved by addressing issues relating to urban poverty (Boyle & Michell, 2018).

From a planning perspective, rapid urbanisation has led to urban sprawl and the expansion of slums (UN-Habitat, 2008; Cobbinah, Erdiaw-Kwasie, & Amoateng, 2015), which has an impact on the sustainability of cities. Barredo and Demicheli (2003) argue that the progression of urban sprawl signals a shortcoming in the current planning tools and policies in explaining the urban growth process. Hence, the overall sustainability of urban areas relies on the interpretation of urban problems and the ability to respond and forecast potential urban change (UNCHS, 1997). Additionally, the ability to respond or react to these changes hinges on the understanding of the various components of the urban ecosystems that contribute to influencing the urban system (Yigitcanlar, Fabian, & Coiacetto, 2008).

In developing countries, urbanisation accompanied by poor governance, lack of planning and failure to provide affordable housing has resulted in urban sprawl. This has created fragmented and unplanned growth of urban fringes characterised by low densities. In most cases, these areas are not sufficiently serviced with municipal infrastructure (Cobbinah & Amoako, 2012) which separates economic centres from residential areas (Cervero, 2000). Interestingly, though urban sprawl between developed and developing countries is a different phenomenon (Adaku, 2014) and occurs for different reasons, in both contexts, it has manifested in the form of long commutes which has challenged the provision of public transport in a cost-effective manner (Carruthers & Ulfarsson, 2003; EEA, 2006; OECD, 2018). However, the impacts of urban sprawl are more distressing in developing countries where there are limited resources to supply public transport to residential areas located in the peripheries (Allen, 2009).

While integrated land use and transport policy is a possible corrective measure to urban sprawl (Cervero, 2001a), in developing countries, its importance is yet to be reiterated (Cervero, 2013). As the urban landscape changes, the interactions associated with these components continuously change in response to dynamic socio-spatial patterns (Pacione, 2005). This makes it even more complex and challenging to plan and manage fast-growing areas (Leao et al. 2004). Therefore, the implications of rapid urbanisation call for a paradigm shift in urban planning, one that does not isolate land use and transport, but rather integrates these two aspects and their influence in shaping the urban environment.

3.2.3 Urbanisation, social exclusion and informal settlements

An estimated 1 billion people live in informal settlements where there is limited access to jobs and infrastructure (UN, 2018). With urbanisation, the growth of informal settlements has intensified (Cobbinah, Erdiaw-Kwasie, & Amoateng, 2015; Hofmann, Taubenbock, & Werthmann, 2015; Inostroza, 2017), which has contributed to environmental degradation (Dubovyk *et al.*, 2011; Jones, 2017). Sustainable Development Goal Target 11 acknowledges that people in informal settlements experience social, spatial and economic exclusion while other segments of the population benefit from urbanisation (Jones, 2017; UN, 2018). Whereas informal settlements are frowned upon, in developing countries they are part of the urban environment, and in the presence of rapid urbanisation with unmatched housing provision, informal housing provides an affordable housing market (Baross, 1990; Dowall, 1991). As a result, informal settlements/housing not only has a value, but they are also a means through which value is exchanged (Ward, 1982). Therefore, urban planning should pay attention to the spatial patterns that are unique to informality and how this impacts urban development (Inostroza, 2017).

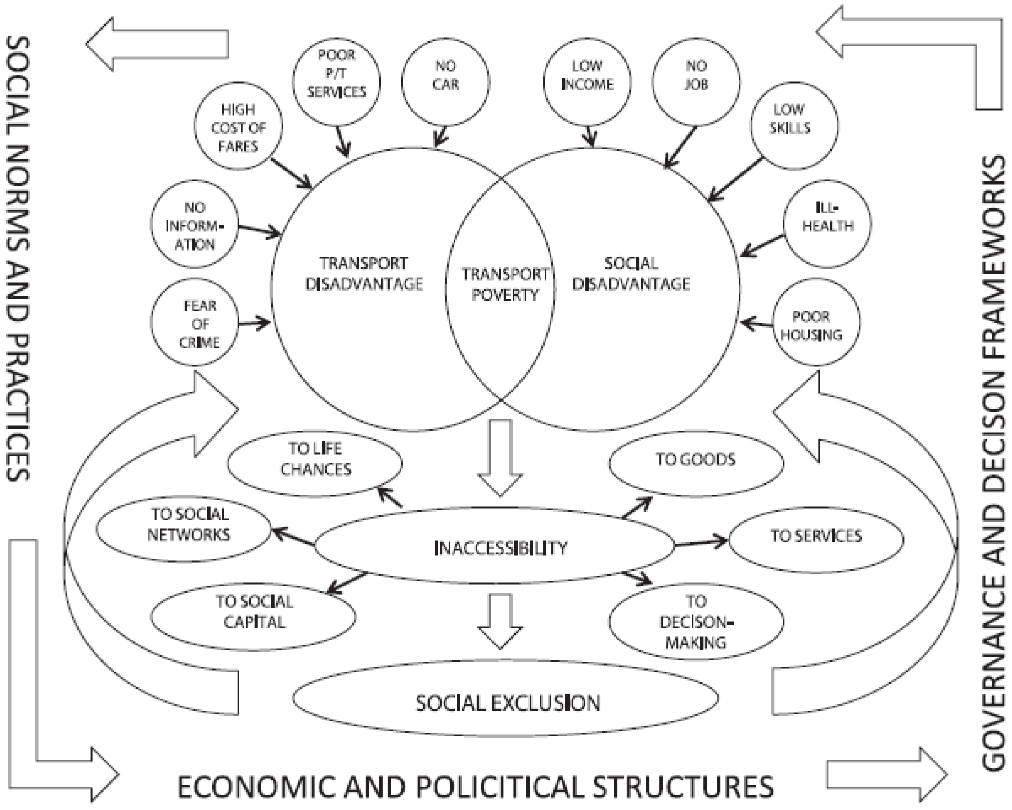
While informal settlements are a response to the lack of planning (Roy, 2005; Hermanson, 2016), they are an organic process and require some form of planning. Polarised opinions with regards to informal settlement exist. One argument suggests that informal settlements are an avenue through which people are uplifted out of poverty as they provide affordable housing while giving its dwellers access to the urban labour market (Misselhorn, 2008; Turok, 2015). On the other end, informal settlements are viewed to perpetuate poverty as they are mostly located in the peripheries where there is limited access to transport and its infrastructure. This makes it difficult for their dwellers to access opportunities (Turok, 2015). Regardless of the side of the aisle one sits in this debate, it is essential to plan for informal settlements, either to limit their growth or to upgrade them such that people who live in these areas have better access to transport and the opportunities it provides. In South Africa, in situ upgrading of informal housing has been proposed as a viable response to informal settlements (Misselhorn, 2008; Del Mistro & Hensher, 2009; HDA, 2015; Brown-Luthango, Reyes & Gubevu, 2017).

3.3 Social exclusion

In Chapter 1, a discussion on urban issues in South African cities was carried out where discussions around housing and service backlogs, inequalities in the allocation of municipal resources, spatial inefficiencies and growth of residential informality emerged. While several policies have been crafted to address urban issues, Chapter 2 revealed that cities like Cape Town still grapple with poor access to economic activities, social exclusion and segregation, especially among the low-income cohort. In a context where there is a growth in informality and urbanisation, it is pertinent to understand the concept of social exclusion as a global concept and in South Africa and how it has manifested.

Social exclusion as a concept relates to the lack of resources and the inability to take part in activities or normal relationships which most people have access to (Adato, Carter, May, et al., 2006; Levitas, Pantazis, Fahmy, et al., 2007; Lucas, 2012). Several studies have expressed the resonance between social exclusion and transport as transport allows people to access opportunities (Mackett, Achuthan, & Titheridge, 2008; Özkazanç, Nihan, & Sönmez, 2017). While social exclusion can take many dimensions and transport plays an integral role, it is essential to discuss the link between social exclusion and transport from the demand and supply side of transport (Church, Frost & Sullivan 2000). Among other aspects, the demand side encompasses access to transport and how it influences travel patterns while the supply side considers the quality of transport and the level of access different people have to the public transport system. Although it is widely accepted that transport can reinforce social exclusion (Currie & Delbosc, 2010; Delbosc & Currie, 2011; Lucas, 2012), transport-related social exclusion and transport disadvantage are not always related (Currie & Delbosc, 2010). Hence there are differences in the way social exclusion manifests in different societies.

Transport and social exclusion have been linked through social, economic and infrastructural aspects (Kenyon, Lyons, & Rafferty, 2002; Lucas, 2012). The literature identifies several dimensions that relate to social exclusion (Kenyon, Lyons, & Rafferty, 2002; Lucas, 2012; Jianhong, Nesbitt, Daley, et al., 2016). However, Lucas (2012) succinctly identifies social exclusion dimensions. Figure 3-1 provides a summary of social exclusion dimensions as defined by Lucas.



Source: Lucas (2012)

Figure 3-1: Linking transport disadvantage, social exclusion and social disadvantage

Themes that are magnified include access and mobility as avenues through which social exclusion can be addressed as they translate to access to opportunities, social network, goods and services. Unfortunately, it is the poor neighbourhoods that are affected by limited mobility as they have low income and are segregated from economic activities (Kenyon, Lyons & Rafferty, 2002; Hernandez, Oviedo & Titheridge, 2016; Özkazanç, Nihan & Sönmez, 2017). While improving accessibility and mobility can help alleviate social exclusion (Preston & Rajé, 2007; Lucas, Wee, & Maat, 2016), Kenyon, Lyons & Rafferty (2002) assert that this might conflict with the government's environmental policy. Perhaps, introducing non-traditional methods of accessibility such as virtual mobility where people can access activities without physically travelling might be a step in the right direction. While the notion of virtual mobility has been explored as a means through which social exclusion can be addressed, there are still obstacles to its usefulness. This is mainly due to the lack of financial means that allow for virtual mobility which challenges its use in facilitating social inclusion for the poor (Kenyon, Lyons, & Rafferty, 2002). While virtual mobility might be a viable option in some countries, unfortunately, in the African context, including South Africa, the socially excluded group is characterised of low-income and can only be employed in the low skills sector. In most of these cases, virtual mobility is not feasible as most of the low skills jobs require physical labour hence a need for physical travelling.

3.3.1 Social exclusion in South Africa

A close look at Figure 3-1 reveals that there are spatial aspects that provide a linkage between social exclusion, land use and transport and how they are organised within the urban environment (Schwanen, Lucas, Akyelken, et al., 2015). The linkages identified by Lucas (2012) resonate with the South African experience as inaccessible jobs and services for low-income individuals, poor housing, expensive and inadequate access to transport are some of the consequences of apartheid spatial planning that the country's cities continue to face (Turok and Watson, 2001; Lucas, 2011). Further, post-apartheid policies have exacerbated these spatial patterns as low-income housing continues to locate in the peripheries (Turok, 2001). Therefore, understanding transport provision and the importance thereof can help in alleviating social exclusion.

Stanley & Vella-brodrick (2009) state that social inclusion can only be achieved by intentionally formulating policies that target the source of the disadvantage. Hence, the discussion on social exclusion and remedying the apartheid spatial patterns in South Africa starts with identifying the aspects within the urban environment that need restructuring. It is only then that areas that need redressing can be identified and aide in navigating the policy environment to address these issues. Understanding transport poverty is essential to the discussion of social exclusion in South Africa. The following aspects are related to transport poverty in the country's urban context:

- Limited access to private transport and public transport services;
- High transport costs,

- Over-reliance on minibus taxis which are not safe;
- The apartheid planning structure and post-1995 housing development patterns;
- A high share of individuals who walk on poor non-motorised infrastructure (Dimitrov, 2010; Lucas, 2011).

While these issues relate to transport poverty, they also resonate with social exclusion and are at the core of land use and transport related urban policies in post-apartheid South Africa (DoT, 1996, 1999, 2009, 2017a). Therefore, understanding the South African policy environment and marrying land use and transport related policy might help in identifying policy gaps and how policy might have played a role in perpetuating urban inefficiencies. Concurrently, this will shed light on the value of integrated urban planning policies and the value of land use and transport modelling in aiding policy.

The current discourse on urban planning in South Africa has begun to understand the interdependence of land use and transport which has resulted in the adoption of integrated land use transport as a policy tool that can lead to the development of efficient urban areas (Mchunu, 2006). However, given that the urban planning concerns within the South African context are multifaceted, approaches to land use and transport planning implementation may be different from those applied elsewhere. The income structure in South Africa calls for land use and transport integration policies that are pro-poor as this cohort of individuals is negatively impacted by urban inefficiencies.

3.4 Review of land use and transport policy in South Africa and Cape Town

This section discusses the land use and transport policies for South Africa and Cape Town that are relevant to this study.

The White Paper on National Transport Policy (1996)

This policy recognised that successful land passenger transport planning is critical in the social and economic development of the country. Flowing from this realisation, the strategic and policy objectives stated in the White Paper, which are relevant to this study are:

- Reducing inequalities with regards to access to opportunities by ensuring that the transport network provides access and mobility for all groups;
- Encourage the provision of viable and affordable public transport services;
- Implementation of infrastructure that allows multimodality in marginalised areas;

- Control of urban sprawl and suburbanisation beyond city limits;
- Put in place strategies that regulate the location of new developments such that there is infilling, densification, mixed land uses and development along transport corridors.

To fully implement the strategies, the White Paper implied an integrated land use and transport planning frameworks (DoT, 1996). In the updated White Paper on Transport from 2017, equitable and reliable access to transport that allows for access to economic and social opportunities remains essential. However, there is recognition that integrated and coordinated planning is a crucial aspect to aid in fulfilling the objectives. Further, given the issue of congestion and social exclusion due to poor access to transport and its infrastructures, improving public transport is considered a vital tool in addressing these issues. Specifically, interventions that favour public transport utilisation over private cars and the provision of affordable and reliable public transport are at the core of the policy. While these interventions have the potential to address the issues in South Africa's urban areas, there needs to be an improvement in public transport to attract private car users (DoT, 2017)

The Development and Facilitation Act (DFA) 67 of 1995

The guiding principles of this act have strong roots in the realisation that the South African urban form established through the previous land use policy frameworks was not sustainable. Given the urgency for interventions and corrective measures, the DFA was established to facilitate the implementation of reconstruction and development programmes with regards to land in order to direct land development in South Africa. The following principles were deemed to be important for the present research as they focussed on redressing inefficiencies due to historical planning:

- Integration of land use types especially residential and employment-related land uses, this is related to mixed land use developments. This would address spatial mismatch hence allowing access to employment even for the disadvantaged;
- Controlling urban sprawl was envisioned as an avenue to provide better public transport as it would reduce the commuting time and monthly public transport cost;
- Compact and sustainable urban form.

The Urban Development Framework (UDF) of 1997

This document focused on the development of urban policies that ensure effective urban reconstruction through directing policy development and strategies of all stakeholders that are involved in the urban development process. Given that, the following aspects were vital in its implementation:

- City integration to redress some of the apartheid spatial inefficiencies,
- Upgrade infrastructure and housing by ensuring the construction of housing and transport infrastructure provision for previously under-serviced areas among other issues,
- To promote economic development to alleviate poverty and generate local economic activities,
- Creating institutions for service delivery which is strongly related to the cooperation of different branches of the economy.

The Moving South Africa Policy Document (1999)

This document revealed the government's awareness that spatial planning was at the core of transport planning. The core issue was the effect of poor spatial planning as a result of both apartheid spatial distortions and current dispersion patterns. These hinder non-motorised and public transport to satisfy the mobility needs of the populace thus resulting in high average commute distances. The policy also points to expensive access to the public transport system, where 13% of urban public transport riders are characterised as living in transport poverty and 19% using public transport which is the most affordable mode. Furthermore, it emphasises on integrated land use transport planning through transport corridor densification, which enhances the ability of the government to subsidise public transport without breaking the fiscal bill (DoT, 1999).

The National Land Transport Transition Act. 2000 (NLTTA)

The NLTTA focuses on restructuring and iterates that the functions of land transportation must be integrated with land use and economic planning by focusing on the development of transport corridors, high land use densities, infilling and proper transport planning. More importantly, NLTTA state that transport planning in South Africa should focus on directing employment; residential and mixed land uses into already established public transport corridors thus discouraging urban sprawl (Republic of South Africa, 2000). Emphasis is made on the development of nodes and corridors in South African cities.

The National Land Transport Act (2009)

The National Land Transport Act of 2009 repealed the NLTA of 2000. The document focused on the integration of land use and transport planning. Regarding land use restructuring, the NLTA states that the integration of land transport with activity locations, economic planning and development through transit-oriented development, densification, infilling and transport planning is essential. Further, it iterates that transport plans must be developed to encourage economic centres to locate in areas that will have a high utilisation of public transport, mixed land use areas while discouraging urban sprawl (DoT, 2009).

The Integrated Urban Development Framework (IUDF) of 2016

The Integrated Urban Development Framework (IUDF) reiterated issues outlined in the UDI of 1997. The overarching aim of the initiative was to direct the development of urban settlements that are inclusive and resilient and responded to the challenges present in the country's cities. This would be achieved through:

- Spatially integrated urban settlements, transport, social and economic areas;
- Ensuring that there was the eradication of social exclusion by facilitating access to social, economic services and opportunities for all people;
- Utilising the dynamic characteristics of the urban environment to ensure sustainable economic growth and development;
- Collaboration between the state and the citizenry to attain spatial and social integration.

The failure of these land use transport policies is attributed to the implementation of policies motivated by pressure to deliver housing to previously disadvantaged groups and also market forces which favour private sector developers (Palmer, Brown-Luthango, & Berrisford, 2011).

National Land and Transport Strategic Framework (NLTSF) (2015)

The National Land and Transport Strategic Framework was established to guide land use and transport planning in South Africa. The core thrust of the strategic framework is to ensure that transport schemes especially those concerning public transport investment are developed with sustainability through integrated and efficient transport systems of which land use contributes immensely. Though the NLTSF is not a policy, the objectives it details are reflected in the Land Transport Framework (LTF) and the Integrated Transport Plans (ITP) (DoT, 2017c). More importantly, the NLTSF acknowledges the importance of integrated land use and transport planning in restructuring and integrating South African cities.

The Cape Town Metropolitan Spatial Development Framework (CTMSDF)

The development of the Cape Town Metropolitan Spatial Development Framework (CTMSDF) begun in the early 1990s followed by a series of reviews. The overarching aim of the MSDF is to guide spatial restructuring and to manage urban growth to ensure that there is a balance between competing land use demands while ensuring that there is a focus on redressing apartheid spatial planning and its legacies (CoT 1996, 2012a, 2017a; Watson, 2012). Issues that are pertinent to this discussion include urbanisation, inefficiencies due to the current spatial planning and the role of integrated urban planning (specifically transport and land use) in addressing Cape Town's urban problem. The municipal vision expressed in the first MSDF focuses on the following aspects:

- Pursuing urban growth and development that focuses on the development of nodes, activity corridors and clearly defining the urban edge;
- Ensuring that there is a compact urban form for long-term sustainability;
- Ensuring that there is access to employment opportunities.

Private property developers own the largest share of housing and commercial developments in Cape Town. Recent updates of the MSDF focus on directing the location of new urban developments to allow for better management of the potential impacts of urban development (CoCT, 2012c). Updates to the MSDF include the following aspects:

- Encouraging commercial property, high-density residential and industries to locate on well-established public transport routes and services;
- Reducing the distance between places of employment and residential areas.

Integrated Development Plan (IDP)

The IDP began in the form of short to long-term plans for the city that would guide urban growth; mainly emphasising on economic, social, environmental, spatial and infrastructural development of the city (CoT, 2004, 2007, 2012b, 2017b). Embedded in the IDP is the acknowledgement that the spatial patterns within Cape Town reinforced poverty and inequality as low-income households have long commutes and spend a significant portion of their income on transport (CoCT, 2004). Strategies such as the Integrated Transport Plan (ITP) were initiated to address some of the issues.

Integrated Transport Plan (ITP)

The ITP charts the short, medium and long-term plan of the city as it relates integrated transport in the city. The objectives within the ITP that are crucial to the discussion in this thesis include:

- Integration between land use and transport that allows for sustainable development in Cape Town;
- A competitive public transport system that benefits the community (TCT, 2015).

The theme that summarises the policies and frameworks discussed above is the importance of land use and transport in addressing urban problems found in South African cities. These documents acknowledge that for South African cities to operate efficiently while social and economically inclusive, they need to be well coordinated. This is attainable through integrated land use and transport policies a theme which comes up in the policy documents.

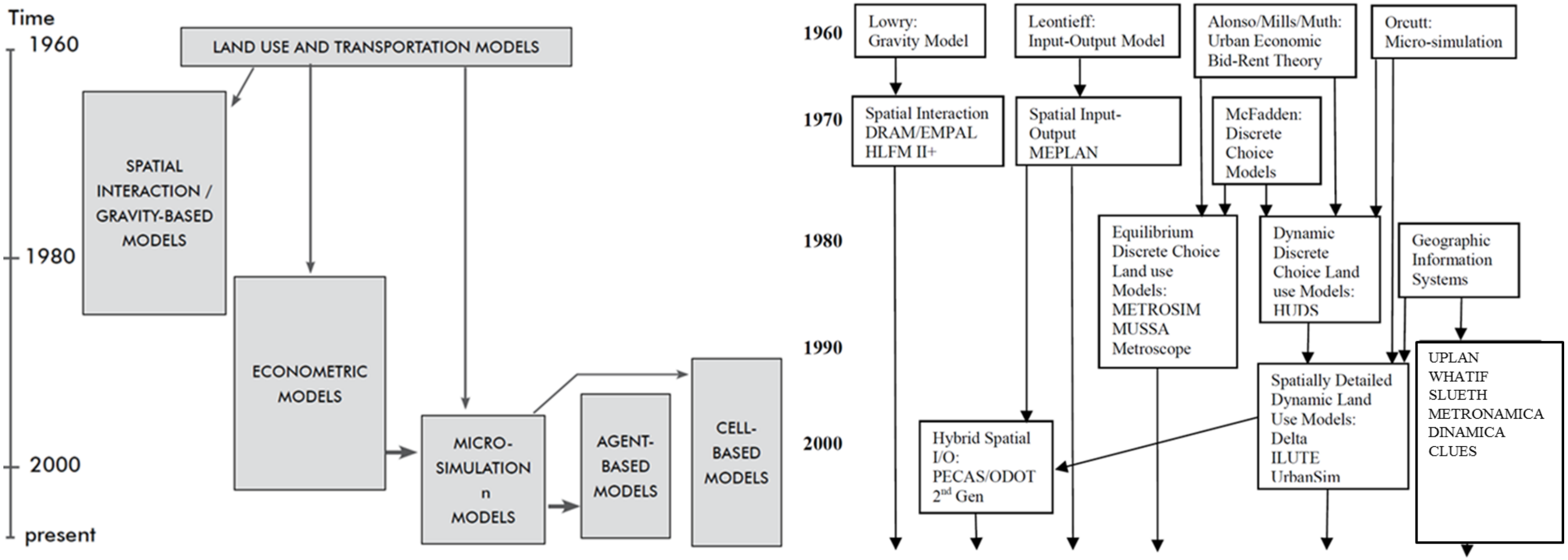
3.5 Urban modelling

Having discussed rapid urbanisation and its influence on the urban environment, the conclusion that flowed from the discussion is that better urban planning approaches are essential to managing urban change and urban growth. While it may be challenging to predict urban change, it is prudent to plan for its potential impacts. Urban modelling provides an avenue through which cities can predict and plan for the consequences of urban change. Batty (2009) defines urban modelling as the process where theories to urban change are explained through formal or mathematical models that can be expressed through computer programmes which can be populated with data, calibrated, validated and verified before they can be used for forecasting. This results in models that are a simplification of reality where the integral aspects of the urban systems are reflected (Batty, 2009). Dynamic urban spatial models are an essential tool aid in the assessment of urban growth and plan for it in a way that is responsive to its consequences. The current trends of rapid urbanisation and urban sprawl, mostly in developing countries call for approaches to urban modelling that are cognisant of the complexity and dynamism that exists in urban areas.

Thus far, the discussion on urban areas has revealed that the processes that lead to urban change and urban growth are complex. Hence, the discourse on urban growth and urban change modelling cannot continue without an understanding of complex systems. Holland (1995) posits that complex systems are adaptive; this enables them to maintain their core structures even when exposed to shocks. On the other hand, Batty (2009) defines complex systems as unpredictable with unanticipated behaviours. Thus, complex systems allow elements within them to evolve on a trajectory that is not predictable thus allowing new behaviours within the system to form (Batty & Torrens, 2001; Colander & Kupers, 2016). These are the characteristics of cities where there is the interaction of people, and social organisations within built environments, while infrastructure plays a crucial in role in servicing and facilitating participation in different activities (Torrens & O'Sullivan, 2001; Bettencourt, 2013; Wilson, 2014). As such, complexity theory has been implemented to enhance the knowledge and understanding of urban dynamics (Batty, 2005; Silva & Clarke, 2005).

3.5.1 Frameworks for modelling land use and transportation

This section begins the discussion on land use and transport models by identifying and discussing the evolution of land use and transport models and the theoretical frameworks used in operational models. The general guiding principles in these models is that there is a reciprocal relationship between land use and transport and this influences the spatial location of land uses in the urban environment (Chang, 2006; Iacono, Levinson, & El-geneidy, 2008). Based on the relationship that exists between land use and transport, several theoretical frameworks have been developed to try and understand the relationship between transport and land (Chang, 2006; Iacono, Levinson, & El-geneidy, 2008). Figure 3-2 summarises the models.



Iacono & El-geneidy (2008) and Waddell 2005 in (Sivakumar, 2007) respectively

Figure 3-2: Evolution of land use transport models

The first land use transport models were aggregate models based on gravity-based or spatial interaction models developed by Lowry in the 1960s. They predict the number of trips between zonal pairs in a city for different activity purposes. The underlying assumption in the models is that the number of trips generated by a zone is determined by the population in a zone while trips between zones are inversely proportional to the distance. This implies that trips that are farther are less attractive compared to trips that are close by as distance is a deterrence to travel (Sivakumar, 2007). Despite advances in urban modelling, several criticisms were levied against urban models. The most prominent critique was the absence of a theoretical framework on which the models were based (Lee, 1973; Waddell, 2018).

In response to some of the criticisms, Wilson (1967) developed entropy theory which established the theoretical underpinnings of the spatial interaction models. The core thrust is that interaction between workers, jobs and housing within the urban environment is influenced by the spatial location of activities and results in the equilibrium of trips or distribution of the population. In spatial interaction or gravity-based models, agents minimise transport costs to activities. Some of the operational land use transport model based on the gravity and spatial interaction theory include MEPLAN (Echenique, Flowerdew, Hunt, et al., 1990) applied in Leeds and Dortmund.

The spatial interaction models in their most basic form utilise the following formulation with regards to the transport model:

$$\mathrm{T_{ij}} = \mathrm{A_i B_j O_i D_j e^{-\beta c_{ij}}} \tag{1}$$

where:

T_{ij} = the number of trips between a pair of zones (zone i and j)

$A_i \ and \ B_j$ = balancing factors

O_i = the number of trip origins in zone **i**

D_j= the number of trip destination in zone *j*,

c_{ij}= measures the impedance or cost of travel between zones *i* and zone *j*

β= the impedance factor that discounts the impedance.

A double constrained formulation is used where the number of trips between origin and destinations is equal and given by:

$$\sum\nolimits_{j} \mathrm{T_{ij}} = \mathrm{O_i} \tag{2}$$

and

$$\sum\nolimits_{i} \mathrm{T_{ij}} = \mathrm{D_j} \tag{3}$$

Therefore, A_i and B_j represent the balancing factors that ensure that equation *2* and *3* hold (Ortuzar & Willumsen, 1994). The linkage between land use and transport, in this case, is through the origins and destinations which are functions of land uses and are linked by the transport system related variables such as travel time. Travel time represents the ability of the transport to provide a service within a given time frame (Wilson, 1998).

Further developments in land use and transport modelling led to the development of models that captured the behavioural aspects and how they influence land use and transport. This led to the development of land use transport models grounded in random utility theory grounded in economic theory after McFadden (1973). The underlying principle in the models is that the choice between alternatives is based on the attributes of the alternatives assuming that the preferences and socio-economic characteristics and differences between agents are taken into consideration. They incorporate decisions at an individual level in trying to understand choice behaviour dynamics and their influence on land use and transport related decisions (Domencich & McFadden, 1975). While gravity-based models focus on location choice and how it is influenced by price, random utility-based models go further and incorporate neighbourhood characteristics and their influence on location choices. A general formulation is provided in equation 4 below.

$$U_{ij} = V_{ij} + \varepsilon_{ij} \tag{4}$$

where:

V_{ij}= a vector of attributes for the agent or household

ε_{ij}= is the random error term

Using the bid-rent theory, Alonso (1964) provided a framework for understanding land use and transport based on urban micro-economic theories. The assumption is that the price of housing changes with distance from the central business district and the price is determined through a bid-auction process where landowners rent or sell the land to the highest bidder. One essential characteristic of the bid-rent model is that relative to the central business district; all locations are assumed to have the same characteristics such as access to transport, employment and goods and services. Based on that, land use patterns and locations within bid-rent models are mutually determined which means households play an essential role in setting land values (Chang, 2006).

Another family of models which incorporate behavioural aspects are agent-based models (ABM) (Sivakumar, 2007). They simulate urban areas at the individual, household, firm level to the entire population (Levinson, & El-geneidy, 2008). The modelling framework starts with individuals and then aggregates to come up with a collective of agent's behaviours, implying it is a bottom-up approach. One of the key aspects in these models is that the travel patterns of an agent are influenced by the spatial and temporal location of activities. In agent-based models, agents are viewed as autonomous decision makers (Sivakumar, 2007; Haase & Schwarz, 2009); therefore, these models are intuitive and represent the land use and transport relationship well (Sivakumar, 2007). Further, agents are assumed to be relational; hence the behaviour of other agents in a household also influences the activities of other household members. Additionally, urban systems are dynamic and comprise of sub-systems that interact and respond at different rates (Jin & White, 2012), thus making the dynamic and in a continuous state of disequilibrium (Batty, 2012). This makes ABM models well positioned to model urban dynamics.

With the rise in the use and understanding of complexity theory, another family of models emerged. Cellular-based models developed on cellular automata (CA) theory utilise complexity theory to understand urban environments. These models consider agents within an urban environment as self-organising and agents are assumed to be relational (Wegener, 2004). CA models simulate urban change on a grid of cells and land allocation is guided by rules that influence the characteristics of each cell (Almeida et al. 2008). They have enabled land use and transport modelling to depart from the traditional and aggregate approach where land uses are represented at the zonal level. Instead, CA models are disaggregate models (Batty, 2009) and present a simpler and more accurate representation of land uses as they represent land uses on a grid of cells which are a much smaller unit compared to the zones (Iacono, Levinson, & El-geneidy, 2008). The simulation of urban change in CA models is based on transition rules where land use changes are likely to occur according to an observed probability. Further, urban change is also influenced by the behaviour of adjacent land uses (Wegener, 2004; Iacono, Levinson, & El-geneidy, 2008), as such, cities grow or change in response to organic processes (Batty, 2012).

An interesting aspect that emerged in this discussion is that some of these models have captured the land use transport interaction, mostly through the accessibility component

(Sivakumar, 2007). Accessibility, as determined by the land use aspects, feed as inputs into the transport model which creates a feedback loop between the two systems (Chang, 2006; Sivakumar, 2007).

3.5.2 Urban areas as complex systems with dynamic interactions

Cities grow as a response to organic processes such as individual decisions on where to locate and decisions made by various decision makers (Torrens & O'Sullivan, 2001; Batty, 2012). In some cases, this leads to unplanned growth; this is especially visible in cities where there is some degree of informality either through informal transport or residential areas. Cheng (2003) iterates that cities can be defined as complex systems due to the self-organising, self-similarity and non-linear behaviour of land use dynamics, a characteristic inherent in the urban area. Issues of urban expansion, urban pattern change, conversion of land uses, urban population growth, social development and economic development also contribute to shaping the urban environment. All these processes operate at different temporal and spatial scales. The interactions and feedbacks between these non-linear relationships compound the instability and unpredictability, especially in large complex systems. What this points to is the notion of disequilibria within the urban system. One of the arguments raised in the literature is that cities are part of the urban system, as such are not isolated from the wider world, this implies that they are in a constant state of disequilibria (Batty, 2012).

The essence of complexity is to underscore that what is observed at the macro level in an urban system is a result of interactions that exist at the micro-level (Allen & Sanglier, 1979; Batty, 2012). More specifically, the traditional view of city planning that isolates spatial planning, housing, transport and energy among others in addressing drivers of urban change is insufficient (Ruth & Coelho, 2007). What this alludes to is that understanding cities stems from understanding the various sub-systems therein and how they interact (Allen & Baldwin, 2008). This means being aware of factors that change the state of each sub-system, i.e. what drives the systems to change. By knowing how these sub-systems work and how they influence change, the urban change process can be understood. Additionally, given the complexity of urban systems, the archaic view that cities develop around the CBD does not apply for 21st-century cities (Batty, 2008). Cities have become dynamic systems which rely on other urban processes and go through different stages of change. To that end, land use models that can represent these dynamics and the changing state are a useful tool in modelling the evolution of the urban environment.

3.6 Modelling the complexity of urban growth and urban change

From the discussion thus far, it is clear that cities are a by-production of the association between human and physical aspects within space and time (Linard, Tatem, & Gilbert, 2013). These interactions determine the pace at which the urban environment changes. While urban modelling provides an opportunity to understand and plan for urban change, to use it properly there needs to be an understanding of how to model the complexity of urban growth. This means understanding the spatiotemporal aspects of urban growth, sources of complexity and the underlying mechanisms (Musa, Hashim, & Reba, 2017). Bretagnolle et al. (2006) posited that urban objects are relational and that there are interactions that exist between and within levels. They further argue that such a setup poses problems in experimenting with urban systems as it is difficult to isolate these interactions from a theoretical and practical perspective. Therefore, properly defining the sources of complexity within the urban area provides a better understanding of how to plan and manage the factors that initiate urban growth and change. Noteworthy is that complexity is a product of non-linear relationships between an amalgamation of components within the urban system, which lead to the development of unexpected dynamics and self-organising tendencies. Hence, the question to be addressed is what models are suitable to model urban growth.

3.6.1 Drivers of land use change and urban growth

The urban environment and its surrounding areas are comprised of different ecosystems which influence the growth trajectory of urban areas. While urban change and urban growth are complex processes, understanding the drivers that influence these processes is essential in formulating appropriate land use development strategies (Sun, Sun, Yang, et al., 2016; Li, Sun, & Fang, 2018). Land use change is not a localised process as there is interconnectedness between the social and ecological process that are geographically separated (Meyfroidt, Lambin, Erb, et al., 2013). Further, non-biophysical aspects such as policy, political and social, contribute in shaping and directing the growth of cities (Verburg, Schot, Dijst, et al., 2004). Hence, drivers of urban change can be divided into proximate and underlying drivers. Proximate drivers relate to the impact of human activities at a localised level on landscape change. Relatedly, underlying drivers consider the social and natural drivers that reinforce the spatial drivers (Plieninger, Draux, Fagerholm, et al., 2016).

Natural drivers relate to soil and topographical characteristics as they dictate the type of land use developments that emerge. This is especially essential in the context of agricultural land, tropical forests, barren lands and wetlands which are sometimes displaced by urban development due to a growth in urban population. Further, the need to protect agricultural land also calls for an understanding of the drivers of agricultural land change (van Vliet, de Groot, Rietveld, et al., 2015; Lasanta, Arnáez, Pascual, et al., 2017). With urbanisation, understanding where growth is most likely to take place is pertinent as urbanisation has been attributed to desertification and loss of agricultural land (Varghese & Singh, 2016; Wang, Cheng, Li, et al., 2017).

At the same time, social and economic aspects such as income, population growth among others also influence urban change. The need to access spatially distributed activities lead to the development of infrastructure that facilitates access. Therefore an improvement in transport infrastructure influences the city structure and economic development. Further, the distribution of population within cities is influenced by transport as it dictates the level of accessibility to opportunities (Baum-snow, 2007). Interestingly, different transport infrastructure types have been linked to influencing urban change as it determines the spatial distribution of land uses (Cervero, 2001b; Fan, Wang, Qiu, et al., 2009; Aljoufie, Zuidgeest, Brussel, et al., 2011; Cervero & Kang, 2011). What this points to is that transport is an important driver of land use change (Braimoh and Onishi, 2007; Aljoufie *et al.*, 2011; Linard *et al.*, 2013; Puertas *et al.*, 2014; Li *et al.*, 2018) as it connects new land use developments and transport infrastructural changes. This is mainly through its influence on accessibility and the attraction of new land use developments to locations which offer good access.

The role of exogenous factors such as policy in regulating or directing urban development also influences the urban form (Yaping & Min, 2009; Sanesi, Colangelo, Lafortezza, et al., 2017). As land use needs evolve, policy can intervene to restrict or stimulate urban growth, for example protection of the urban green space (Bengston, Fletcher, & Nelson, 2004; Koomen, Dekkers, & van Dijk, 2008), protection of conservation areas, restricting residential development on flood-prone areas, stimulate urban development to solve inner-city urban decay inter alia.

From a modelling perspective, the number of drivers incorporated in a model is determined by the extent and type of urban change that is modelled. For example, models that consider variations of land use conversion might incorporate many drivers to ensure that issues of suitability and access are incorporated into the model. While several drivers of urban change exist, it is important to ensure that the drivers that are incorporated in a model can represent the urban system being modelled. Verburg, Schot, Dijst, et al. (2004) state that the selection of drivers depends on the construct, theoretical and behavioural assumptions utilised in modelling the urban system. This is mostly dependent on the modelling approach that is implemented.

Urban growth models utilise simulation techniques to understand theories relating to the spatial and temporal relationships between land uses and activities (Triantakonstantis & Mountrakis, 2012; Wray & Cheruiyot, 2015). In that regard, they can be used as policy support tools to evaluate the drivers and consequences of land use change (Verburg, Schot, Dijst, et al., 2004) However, there are limitations to the extent urban models can predict urban growth as there are temporal and spatial complexities that exist within the urban environment (Cheng, 2003; Munroe, Southworth, & Tucker, 2004). Spatial complexity manifests through the various systems within the urban environment both biophysical and socioeconomic whereas temporal complexity relates to the capability of the models to predict urban growth and urban change over time (Triantakonstantis & Mountrakis, 2012).

Early attempts in urban change and urban growth modelling utilised ground surveys, aerial surveys and remote sensing, with improvements in modelling leading to the integration of geographic information systems (GIS) and remote sensing. This approach is perceived to be more accurate in the assessment of urban growth (Musa, Hashim, & Reba, 2017). The rapid rate of urbanisation and its impact on the physical environment has led to the development of models that focus on understanding urban expansion, land use dynamics and the prediction of urban change and growth (Triantakonstantis & Mountrakis, 2012). While these models seek to understand urban growth and urban change, they are grounded in different theoretical frameworks some of which have been discussed in section 3.6.

A review of urban modelling frameworks revealed that most urban modelling tools originated in developing countries where there is proper regulation with regards to residential land use developments. While rapid urbanisation is a global concept, in the global South it has led to the growth of informal settlements (Hofmann *et al.*, 2015; Inostroza, 2017). This has resulted in informal housing occupying a large portion of urban economies in developing cities (UN-Habitat, 2008). The question that emerges is whether urban models mostly developed to predict urban change in developed cities can capture the behaviour of slums or informal settlements-a concept that is foreign to the context for which the models were developed.

3.6.2 Modelling informal settlements

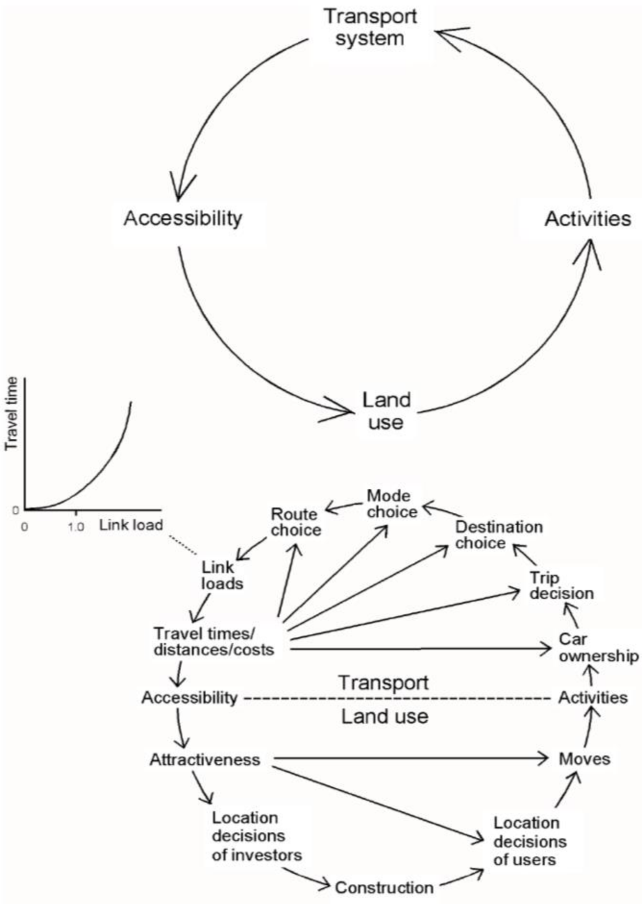
One of the themes under SDG 11 is the need to upgrade informal settlements (UN-Habitat, 2016a). This has resulted in an influx of policies aimed at managing residential informality (Roy, 2005). However, the success of these policies lies in the ability to identify the drivers of informal settlement growth and persistence. Understanding the drivers of informal settlement growth and development is essential to successfully manage their growth (Sietchiping & Yoon, 2010).

Additionally, there is a necessity to apply this knowledge in the development of proactive plans that equip cities to relate to informal settlements (Dubovyk *et al.*, 2011). While urban models can generally simulate land use changes, slums or informal settlements are a new concept for some of these models. With the rampant increase in informal settlements, it is pertinent to develop methods that facilitate the prediction of informal settlement growth. Given that informal settlements are a by-product of urbanisation simulating informal settlements could provide solutions on how to manage the impacts of housing shortages due to urbanisation (Augustijn-Beckers, Flacke, & Retsios, 2011; Roy, Harold, Palavalli, et al., 2014).

While several theories explain the formation and growth of informal settlements (Sietchiping, 2004), models that simulate informal settlement growth are grounded in mathematical formulations which capture the drivers of informal settlement growth (Hofmann, Taubenbock, & Werthmann, 2015). These approaches are useful in predicting and understanding the morphology of informal settlements. Conventional approaches to modelling informal settlements implement agent-based methods (ABM) or cellular automata. The attractiveness of ABM to model informal settlements lies in the ability of these models to depict the behaviour of individual agents as well as the relationship between individual decision makers and their social dimensions and how they interact with their surroundings. This characteristic of ABM models enable them to capture the dynamism inherent in the morphogenesis of informal settlements (Patel, Crooks, & Koizumi, 2012; Hofmann, Taubenbock, & Werthmann, 2015). Unlike ABM, in the initial stage, CA models represent static behaviours and do not capture the behaviour of individual agents and how they relate to the environment. The state of cells in CA models changes during a simulation and this is determined by a set of predefined rules. For example, CA models fail to make linkages between the socio-economic characteristics of an agent and their choice of residential unit (Augustijn-Beckers, Flacke, & Retsios, 2011). Being able to make this connection allows ABM models to capture the synergies between different agents that influence the shape and formation of informal settlements. These differences in characteristics between CA and ABM models have led to the use of hybrid methods which combine both CA and AB models to predict the growth of informal settlements. The most well-discussed models include the Informal Settlement Growth Model (Sietchiping, 2004, 2008), location of low-income housing in the peripheries (Peripherisation model) (Barros, 2012), slumulation that identifies the drivers that reinforce the formation and persistence of slums (Patel, Crooks, & Koizumi, 2012), hybrid methods implemented to model the formation informal settlements around industries in Dhaka, Senegal (Stouffs, Janssen, Roudavski, et al., 2013). These models have managed to represent and predict the behaviours linked to informal settlement growth.

3.7 On the causal link between land use and transport

Section 3.5.1 discussed the evolution of land use and transport models and the potential interdependency between land use and transport. This section discusses the land use and transport nexus by delving into understanding the symbiotic relationship between land use and transport and how it manifests in the urban environment. Since the seminal work of Hansen (1959)on the mutual inclusiveness of trip and location decisions, the potential causality between land use and transport has become a topical issue and essential in land use and transport planning policies. Hansen concluded that areas with good accessibility were more likely to be developed compared to areas with poor road network connectivity. Several propositions (Brotchie, 1984; Wegener & Fürst, 1999) have since aided in explaining the interlinkage between transport and land use. Perhaps the most insightful and most implemented proposition to conceptualising the symbiotic relationship between land use and transport is provided by Wegener & Fürst (1999) popularly known as the land use transport feedback cycle. In this proposition, the underlying concept is that transport facilitates the interaction between spatially distributed land use activities. Essentially, transport accessibility in space and time facilitates how people interact with activities within the urban environment and this can determine the location of activities. This can potentially cause the land use system to change. Figure 3-3 represents the interrelations between land use and transport.



Source: (Wegener & Fürst, 1999)

Figure 3-3: Land Use and Transport feedback cycle

Correctly interpreting the causality between transport and land use stems from acknowledging the different components and processes that facilitate land use or transport changes. This entails understanding the urban structural aspects such as land use diversity, density, neighbourhood design, accessibility, travel cost, time and distance inter alia and how they influence travel behaviour (Wegener & Fürst, 1999). While there is consensus that land use and transport influence each other, there are mixed findings on the mechanisms through which land use and transport interact (Wegener, 1994; Handy, Cao, & Mokhtarian, 2005; Aditjandra, Mulley, & Nelson, 2013; Ahmad & Puppim de Oliveira, 2016; Feng, Dijst, Wissink, et al., 2017; Moeckel, Garcia, Chou, et al., 2018). More importantly, appreciating the role of physical, socio-economic, socio-demographic and policy changes that contribute in influencing the land use transport relationship (Antipova, Wang, & Wilmot, 2011; Ding, Mishra, Lu, et al., 2017). From a transport provision perspective, understanding the relationship between infrastructure and travel demand is vital for the smooth transportation of individuals between spatially distributed activities (Cervero, 2013).

3.7.1 Land use impacts on transport

Within integrated models, the land use component has been used to understand the location of housing or jobs and other activities and how these location decisions influence each other over time. The impacts of land use on transport are discussed in relation to their impact on travel behaviour (Cervero, 1991; Cervero & Kockelman, 1997; van Wee, Holwerda, & van Baren, 2002; Litman & Steele, 2018), influence of land use mix on mode choice (Frank & Pivo, 1994; Cervero, 2002), the impact of land use density on driving (Cervero & Murakami, 2010; Duranton & Turner, 2018), how the built environment influences car ownership (Newman & Kenworthy, 2006; Zegras, 2010) among others. Within the discourse on sustainable developments, understanding the impacts of land use on travel can aid in achieving sustainable urban development where, high density and mixed land uses can improve sustainable travel (Newman & Kenworthy, 2006). A clear theme that emerges is that understanding the influence of land use on transport provides invaluable knowledge relating to residential and employment location dynamics its influence on commuting patterns over time. This provides insights into the formulation of transport policies related to congestion as the spatial location of land uses is an important driver (Guo, Agrawal, & Dill, 2011; De Lara, de Palma, Kilani, et al., 2013).

3.7.2 Transport impacts on land use

Whereas land use influences transport, there are also reciprocal effects on land use due to transport changes. When looking at the land use transport nexus, the transport component looks at travel behaviour to aid in the forecasting and managing of travel demand (Acheampong & Silva, 2015). The focus is on trip origins and destinations, mode choice, trip purpose, inter alia and how they respond to transport changes. The influence of transport on land use has been observed where growth in land use developments can be attributed to transport infrastructure changes (Zondag, de Bok, Geurs, et al., 2015). Further, the urban form/city structures and economic development have also been linked to changes in transport-related aspects (Rietveld, 1994; Banister & Berechman, 2003). Therefore, any transport network changes such as new road infrastructure can potentially influence the location of new land developments (Sun, Sun, Yang, et al., 2016) which has an impact on travel decisions (Kelly, 1994). Additionally, the change in transport infrastructure supply also influences land use changes and property values

(Bartholomew & Ewing, 2011; Cervero & Kang, 2011; Fan, Khattak, & Rodríguez, 2011). Transport planning strategies such as transit-oriented development (TOD) have led to the evolution of urban forms that are compact with mixed land uses (Ratner & Goetz, 2013; Guthrie & Fan, 2016). This attests to the role of transport in influencing land use development. Noteworthy is that these transport aspects are influenced by the spatial composition of the urban form and the social and demographic characteristics of individuals or households. Further, when discussing the environmental impacts of transport themes such as pollution, and landscape degradation come into play (Acheampong and Silva, 2015).

3.7.3 Linking land use and transport through accessibility

The previous section discussed the interlinkage between land use and transport where accessibility was identified to facilitate this interaction. While there is no uniform definition of accessibility, there is a vast body of literature that explores the role of accessibility in linking transport and land use (Banister, 1999; Bertolini, 2005; Duranton & Guerra, 2016; Litman, 2018). Several authors relate accessibility to the effort required to reach different activity locations using different modes of transport (Dalvi & Martin, 1976), the potential for different land use activities to interact (Hansen, 1959), the benefits a transport or land use provides to individuals (Ben-Akiva, 1979) and the time and distance to reach economic and other social activities (Geurs & van Wee, 2004; Braimoh & Onishi, 2007; Deng & Srinivasan, 2016).

Land use and transport policy plans are evaluated through accessibility measures, especially by looking at land use, transport, spatial and individual components of accessibility (Wegener & Fürst, 1999). From the definitions of accessibility introduced earlier, accessibility can be expressed in terms of the transport or land use system. The land use component of accessibility considers the land use system or the activity component which looks at the spatial distribution of opportunities relative to the residential locations of people and the supply and demand for the opportunities (Wegener & Fürst, 1999; Halden, 2002; Bertolini & le Clercq, 2003; Geurs & van Wee, 2004; Bertolini, le Clercq, & Kapoen, 2005). On the other hand, the transport aspect considers the transport network as the means through which individuals reach their destinations using a particular mode of transport and the costs associated with accessing and utilising transport (Halden, 2002; Bertolini & le Clercq, 2003; Geurs & van Wee, 2004; Bok & Kwon, 2016). While there is no single definition of accessibility, there is consensus that accessibility provides a metric that can assist in crafting land use and transport policies that have the potential to address issues of social exclusion, equity, transport affordability (Preston & Rajé, 2007; Lucas, 2011, 2012; Bocarejo & Oviedo, 2012; El-Geneidy, Levinson, Diab, et al., 2016).

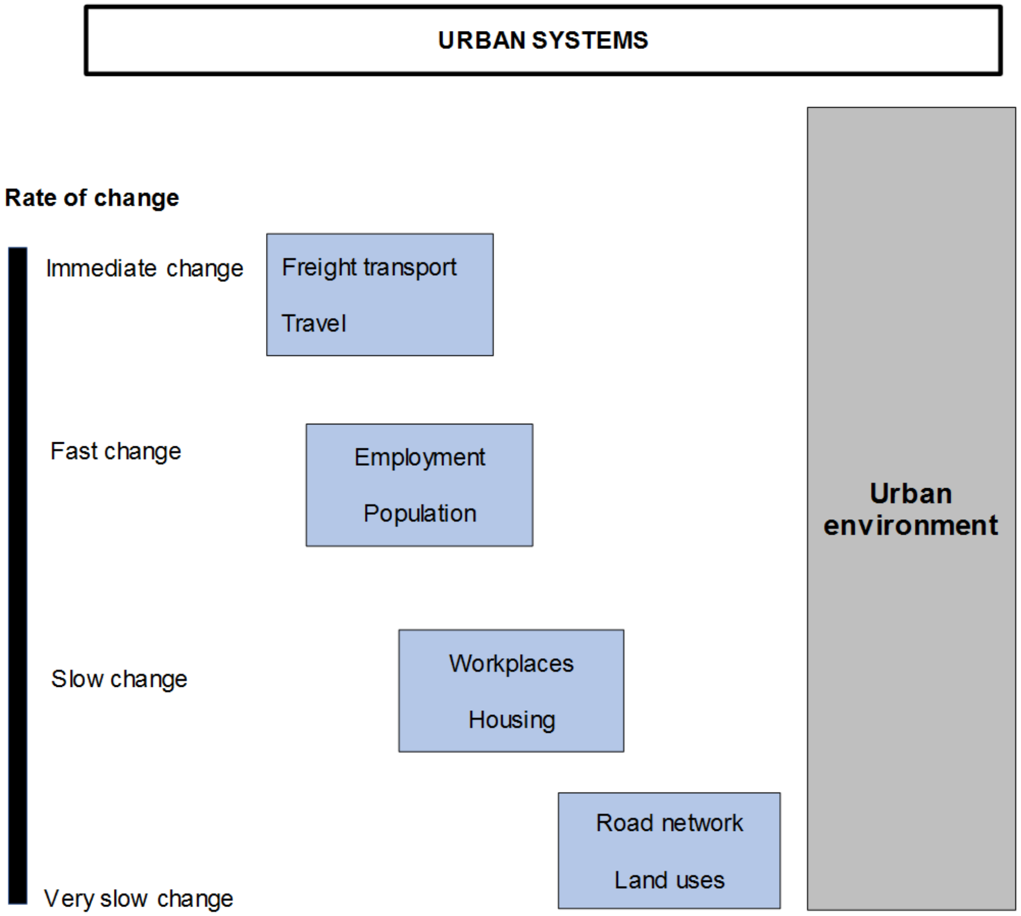
To that end, improved coordination of urban transport and land use can be useful in finding solutions to urban problems (Cervero, 2013). Proper implementation of integrated land use and transport as a planning strategy stems from appreciating that land use and transport are interconnected and that they influence each other (Newman & Kenworthy, 1996; Mazaza, 2002; Rodríguez, Godschalk, Norton, et al., 2004; Wegener, 2004; Litman & Steele, 2018). Accordingly, an understanding of causality between land use and transport and the various impacts can aid in crafting better land use and transport planning policies.

3.8 Integration of land use and transport in policy

As discussed earlier, the causality between land use and transport enables land use policies to be evaluated based on their impact on transport and for transport policies to be analysed from a land use perspective. While previously there have been criticisms on the usefulness of urban models (Lee, 1973; Atkins, 1977), improvements in technology and data acquisition has resulted in an influx of integrated land use and transport models as policy tools to evaluate and predict the impact of land use and transport policies before implementation. This section briefly discusses operational models which have been/are used as planning support systems (PSS) to inform policy. A discussion on the challenges that inhibit the use of these tools in planning is also carried out.

Figure 3-2 provided frameworks and approaches implemented to model land use and transport. While the literature review (Hunt, 1994; Wegener & Fürst, 1999; Timmermans, 2003; Wegener, 2004; Sivakumar, 2007; Iacono, Levinson, & El-geneidy, 2008; Waddell, 2011; Acheampong & Silva, 2015) identified forty-two models based on the theoretical frameworks, twenty-two of these models have been extensively used for policy analysis in an actual urban system at either national, regional or local level (Wegener, 2004). Wegener (2004) indicates that operational models can be classified based on the rate at which the urban change process takes place. The rate of change influences the policy measures that can be implemented within the models as they point out to the responses of elements within the urban system. In that regard, the models can be classified on a spectrum from slow to fast urban change processes.

Slow change pertains to permanent infrastructures such as road networks and land uses which persist in locations once they are constructed. Juxtaposing are fast processes which relate to employment and population aspects which are very responsive depending on their stage in a life cycle. For example, firms expand or shrink due to changes in the economic outlook; this affects employment and work-related travel demand. On the other hand, population represented in the form of households change as households can relocate and change their travel behaviours and travel needs at each stage of their lives (Wegener, 2004). Figure 4-4 represents the rate of change of urban systems represented in operational models.



Adapted from: Wegener (2004)

Figure 3-4: Rate of change of urban systems in operational models

From the diagram, it is clear that the urban environment is complex as it is influenced by human activities; which may lead to immediate effects on the urban environment, for example, air pollution and noise. However, there are also human influences that manifest in the long-term, such as climate change. A key aspect to note is that all urban systems can be influenced by market forces or policy interventions (Wegener, 2004). This tightly knits the land use transport link discussed in section 3.7 into the discussion of the urban change process. In that regard, the urban environment is an essential component as it incorporates all the other systems.

To represent all the urban systems, land use transport models incorporate land use, socio-demographic and transport sub-models which are either integrated consisting of feedback loops or are loosely coupled (Acheampong & Silva, 2015). The land use sub-model focuses on the urban land market and considers space ratios for residential and employment activities, building vacancies, land values and in some cases the redevelopment of brownfields (Acheampong & Silva, 2015). For example, the land use sub-model in UrbanSim applied in Oregon and Paris (Waddell, 2000, 2002), MEPLAN for Dortmund and Leeds (Echenique, Flowerdew, Hunt, et al., 1990), PECAS implemented in Montgomery (Hunt & Abraham, 2009; Clay, 2010) evaluate urban land and housing markets in their land use model. The socio-demographic model considers socio-economic variables that include location choice and travel behaviour of households. In most cases, households are categorised into similar socio-economic groups (Acheampong & Silva, 2015). Relating this to Figure 3-4 indicates that the socio-demographic model captures fast-changing economic aspects. On the other hand, the transport model operationalised in most of these models is a conventional four-step model similar to the one presented by Ortuzar & Willumsen (1994). The transport models typical follow the spatial-interaction or gravity-based approaches. To evaluate the relationship between the spatially distributed activities and how the influence travel time, costs and other related aspects (as discussed in section 3.7), the transport and land use model can be integrated.

While PSS's have been applied for policy evaluation, several scholars (Uran & Janssen, 2003; Couclelis, 2005; Vonk, Geertman, & Schot, 2005; Hull, 2008; Te Brömmelstroet, 2010) argue that there are still barriers that limit their incorporation in daily urban planning. Vonk, Geertman & Schot (2005) aver that factors that hinder the utilisation of PSS can be grouped into human, organisational, institutional and technical. This suggests that the development of a well-established framework that can be used by various institutions is needed for successful land use and transport integration (Curtis & James, 2004; Hrelja, 2015). Closely related, Greiving & Kemper (1999) suggested that for PSS to be utilised in daily planning, there needs to be coordination between sectoral policies at both the vertical and horizontal levels. At the vertical level, this entails coordination between different spheres of government while at the horizontal level, coordination of actual transport and land use policies is required. These approaches can potentially resolve the lack of access and communication between different practitioners (Te Brömmelstroet, 2010) and allow government agencies to pursue similar objectives (Curtis & James, 2004) thus reconciling competing interests.

Despite these barriers, integrated land use and transport (ILUT) is acknowledged as a necessary tool for more sustainable urban forms (Banister, 1999, 2005; Te Brömmelstroet & Bertolini, 2010; Waddell, 2011). This has led to the emergence of applications of integrated land use and transport that look into air quality in urban areas, (Geerlings & Stead, 2003; Steadman, Lautso, Wegener, et al., 2004) and climate change mitigation (Ford, Dawson, Blythe, et al., 2018) which shows the far-reaching benefits associated with this approach. Further, planning strategies such as Transit Oriented Development (TOD) have aided in the alleviation of congestion (Freilich H, 1998; Zhang, 2010) and curbing urban sprawl (Belzer & Autler, 2002; Dieleman & Wegener, 2003; Ratner & Goetz, 2013; Baruah, 2017), this attest to the benefits that can accrue from having ILUT policies. This is especially so as patterns of urban development are highly correlated to growth and progression of urban transport and mobility (Rode *et al.*, 2014). Hence, ILUT has been espoused to achieve more sustainable urban forms (Banister, 1999, 2005; Te Brömmelstroet & Bertolini, 2010; Waddell, 2011).

Interestingly, despite the success and usefulness of urban models in informing policy, a thread that emerged from this review is the scarcity of the use of urban models in the African context. This a worrying finding as African cities continue to grow and are in dire need of urban and transport planning approaches that might help them to cope.

3.9 Urban modelling in South Africa

South Africa like most developing countries faces urban problems such as residential informality, social exclusion, equity, congestion. Urban modelling can provide solutions to these issues as it provides a platform to test policy interventions before they are implemented. Moreover, there is a alleviate poverty and to stimulate economic growth and economic change with transport being at the core (Fedderke, Perkins, & Luiz, 2006; Rust, McCutcheon, & Coetzee, 2008; Hlotywa & Ndaguba, 2017). Relatedly, mobility demand, population growth and urbanisation are some of the issues that transport must also address. However, most of these issues are exogenous to transport itself (Rust, McCutcheon, & Coetzee, 2008). In the South African context, policymakers have begun to craft and implement policies that consider the role of transport in alleviating urban problems. As such, successful intervention, monitoring, managing and planning for urban growth and transformation emanates from understanding the interlinkages between land use and transport.

Section 3.4 identified policy documents in South Africa that recognised the importance of integrating land use and transport in managing urban growth and change. This section builds on that discussion and identifies the empirical modelling initiatives that have been carried out in

South Africa. Developments in the use of urban planning models considered the use of the MINI-TRAMP and DELTRAN models in the country's urban centres in the 1960s (Kane & Behrens, 2002). The focus on urban modelling changed in the 1980s, where research interest shifted to focus on the impacts of apartheid spatial planning on the mobility of the people of colour. While globally, there was an influx and improvements of urban models, in South Africa urban modelling initiatives mostly used the gravity-based EMME model in most of the urban areas.

Attempts to map the evolution of urban modelling initiatives in South Africa (Wray et al., 2013) identify the following modelling initiatives:

- The Gauteng Department of Roads short and medium-term integrated planning for health and education (Gauteng ITMP25) (Engelbrecht, 2012; Kleynhans, 2012);
- Analysing urban patterns and dynamics against the planning policy (Gauteng Department of Economic Development, 2011; Le Roux and Augustijn, 2015);
- Forecasting and simulating urban growth for 30 years (CSIR, 2011; CSIR, 2012);
- Patterns of land occupation change in informal settlements and land use/cover change (Haywood, 2013);
- The City of Cape Town has used the Urban Growth Model (UGM) and the Urban Growth Monitoring System (UGMS) to monitor and identify areas where there is potential for urban growth

Applications that resonate with the present research include:

- Understanding the accessibility and utilisation of primary health care in rural KwaZulu-Natal (Tanser, Gijsbertsen, & Herbst, 2006);
- The use of SLEUTH to simulate future urban expansion and its impact on urbanisation in Cape Town (Watkiss, 2008);
- Modelling informal settlements growth in Cape Town using an agent-based model (Shoko & Smit, 2013);
- The use of Dyna-CLUE to model urban growth while acknowledging backyard shacking and informal settlement growth (Le Roux & Augustijn, 2017);
- The Cape Town EMME transport demand model which simulates traffic for different trip purposes during the morning peak in Cape Town (TDA, 2017a).

While urban modelling has slowly progressed in South Africa, like other modelling initiatives, a theoretical classification using Figure 3-2 shows that these models fall under either gravity-based or spatial interaction, cellular-automata, agent-based approaches. However, what emerges from the review of urban modelling in South Africa is that the application of dynamic models to aid in the development of land use and transport policy is lagging.

An interesting revelation from this review is the scarcity in models that simulate land use and transport and incorporate the growth of informal settlements and the potential for the redevelopment of brownfields, yet this is a critical aspect to understand in the South African context. More so, given the high levels of congestion and the growth in residential informality in the country's cities.

3.10 Modelling tool considerations and specifics for the present study

There is a plethora of models that can be employed to understand LUTI, METRONAMICA developed by the Research Institute of Knowledge Systems (RIKS) is one of these tools. It has been applied to model land use and transport with applications in evaluating future urban development scenarios in Lagos, Nigeria (Barredo & Demicheli, 2003), to monitor urban and regional growth in Dublin (Lavalle, Barredo, McCormick, et al., 2004), strategic integrated spatial planning in Puerto Rico (Van Delden, Van Vliet, Navarro, et al., 2010), to better understand the desertification processes (Kok & van Delden, 2009), understanding urban dynamics in rapidly growing cities such Jeddah (Aljoufie, Zuidgeest, Brussel, et al., 2013), and for integrated regional planning in Australia (Perez, Wickramasuriya, Forehead, et al., 2017) among others. Though this is not an all-inclusive list, it provides a good overview of the application of METRONAMICA as a modelling framework to understand land use and transport dynamics. A brief overview is provided below, which identifies aspects that make METRONAMICA suitable for this research.

- A cellular automata land use model is implemented in METRONAMICA. CA-based models appreciate changes in urban morphology as a dynamic process where there is competition for space between land uses. Further, CA-based models are ruled based; hence, most spatial behaviours can be represented in these models (White & Engelen, 2000).
- One of the urban problems in South African cities is the growth of informal settlements and urbanisation which has put pressure on housing provision. Therefore, understanding the agglomeration of human settlements and the morphogenesis of informal settlements

is essential. CA-based models can mimic these changes in urban environments and have been implemented to simulate the growth of informal settlements (Sietchiping, 2008; Shuvo & Janssen, 2013; Stouffs, Janssen, Roudavski, et al., 2013). Further, CA-based models can model the competition between land uses, and this is an important aspect given that urban land space is a scarce resource.

- This study seeks to understand the land use and transport dynamics in Cape Town. The METRONAMICA modelling framework allows for a transport model to be introduced exogenously which allows for the fulfilment of this research aim.

In addition to the above, data requirements and data availability, financial constraints also dictated the modelling framework implemented in this research. The next chapter discusses the METRONAMICA land use transport modelling framework to understand the different model components and how they are interrelated.

3.11 Summary

This chapter discussed urbanisation and the challenges associated with rapid urbanisation in the context of developing countries. The review revealed that informal settlement growth and urban poverty are intrinsically linked. A discussion on social exclusion was carried out where it emerged that transport can play a crucial role in mitigating some of its effects. The role of informal housing as alternative affordable housing in developing countries was also discussed which brought up the importance of modelling informal settlements to aid predicting and managing their growth. The literature on urban modelling and the frameworks used to model land use and transport was also presented. While some of the models deal with land use or transport separately, they also model land use and transport in an integrated manner. A theme that was prominent in this discussion is the presence of causality between land use and transport and their combined influence on the urban environment. Accessibility was identified as a yardstick to assess the influence of land use and transport changes and has been adopted in urban policy.

The chapter also discussed the land use and transport environment in South Africa and Cape Town which revealed a paradigm shift in the planning context where integrating land use and transport as a policy is appreciated. However, the literature review has shown that while the policy environment has changed, like most developing countries, there is still a low tenor in the use of land use and transport models in South Africa. Yet, urban models can facilitate the development of proactive approaches to transport and land use planning which may aid in addressing some of the problems the country’s cities face. While there maybe be barriers to the use of urban modelling tools in everyday planning, there are potential benefits that can accrue from their use. In the South African context where urban problems continue to divide the country by socio-economic status, there is a great need for urban modelling tools that may help the country’s cities to navigate urban planning to facilitate integration and inclusivity.

Chapter 4

The METRONAMICA modelling suite

4.1 Introduction

Among other things, Chapter 3 revealed that the interaction between land use and transport influences and shapes urban form. This chapter introduces METRONAMICA, a dynamic LUTI model that is utilised in this research. This chapter aims to give a theoretical and mathematical description of the key components of the METRONAMICA land use transport model and the calibration of the key model parameters. Further, the chapter discusses the methods used to assess the quality of the calibration and validation of the individual model blocks. The discussion also focuses on a quantitative description of the main equations in the transport and land use model blocks in METRONAMICA as well as the nomenclature that is used throughout the research in reference to the model parameters. Additionally, a discussion on the linkage between the sub-models is also carried out.

4.2 Concise overview

The METRONAMICA land use transport model (M-LUT) framework comprises of the interaction between the land use activities within the built environment and the transport related aspects. The model assumes that there is an interdependence between the transport and land use activities resulting in feedback loops between transport and land use as discussed in section 3.7. The interaction between these systems in modelled through three model blocks, transport, land use and regional model. The transport model is based on the conventional four-step model with feedback to the land use model (RIKS, 2012). In its aggregated state, the M-LUT is represented in Figure 4-1.

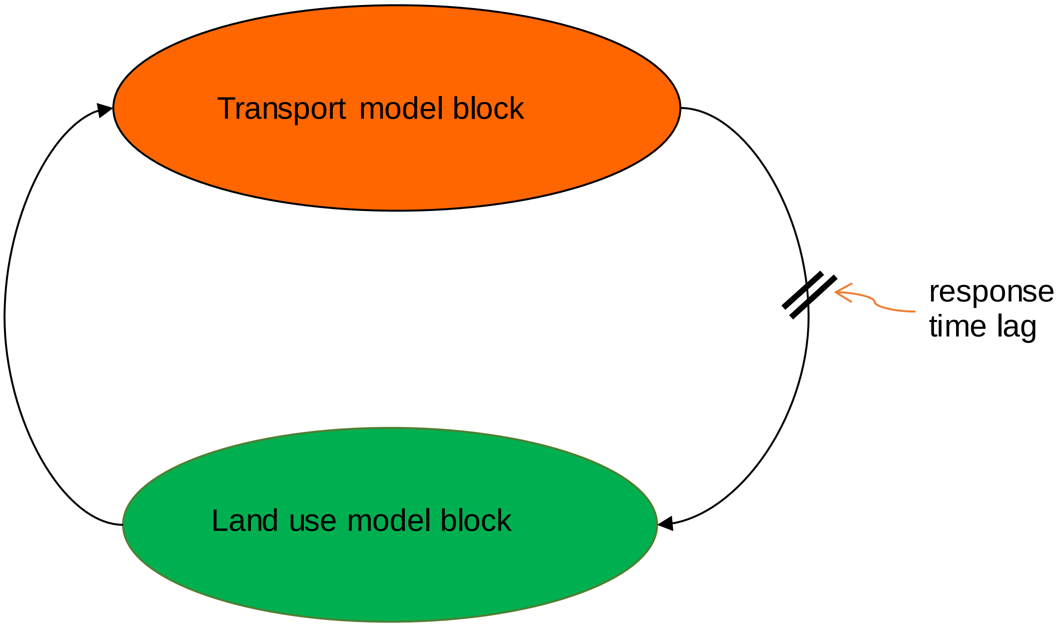


Figure 4-1: Aggregated METRONAMICA land use transport model

In its representation, time lags are shown as changes in the land use component which result in immediate as well as lagged reactions in the transport system especially in the form of change in traffic flow or modal split on the transport network. Changes in the transport system such as the construction of a new road may result in lagged responses in the land use system, for example, there might be an increase in investment on commercial and residential buildings along the road network or close by due to increased accessibility. In METRONAMICA the land use model obtains inputs from a regional model which allocates macro-economic aspects such as population and employment depending on the number of activities in each transport zone. These are translated into land use demands for the different land use activities. Further, land use demands serve as inputs in the transport model block in the form of travel demand predictions (RIKS, 2012).

The transport model in METRONAMICA resembles the conventional four-step transport model while the land use model is CA-based. Based on the travel costs, people choose between different modes of transport either private or public modes of travel. People choose the cheapest route based on the time, distance and pecuniary costs associated with each route (RIKS, 2012). Typically, land use activities in year 1 (Y_t) are used as inputs in the transport model in year 2 (Y_{t+1}) and the input-output relationship continues between the different time steps thus creating a feedback loop. This results in changes which can be immediate or lagged between the land use and transportation systems as shown in Figure 4-1. This makes the M-LUT a dynamic and integrated CA-based land use transport model (RIKS, 2012). Figure 4-2 shows the interdependencies and links between the modules in the METRONAMICA land use transport model.

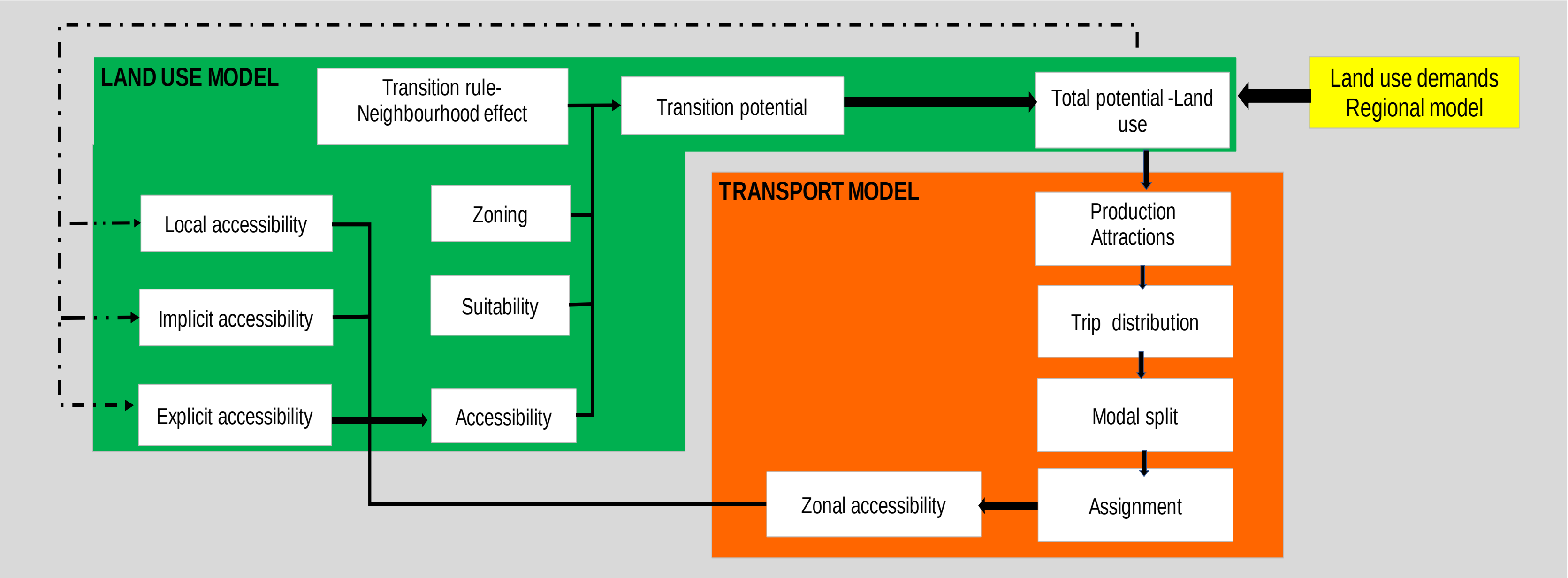
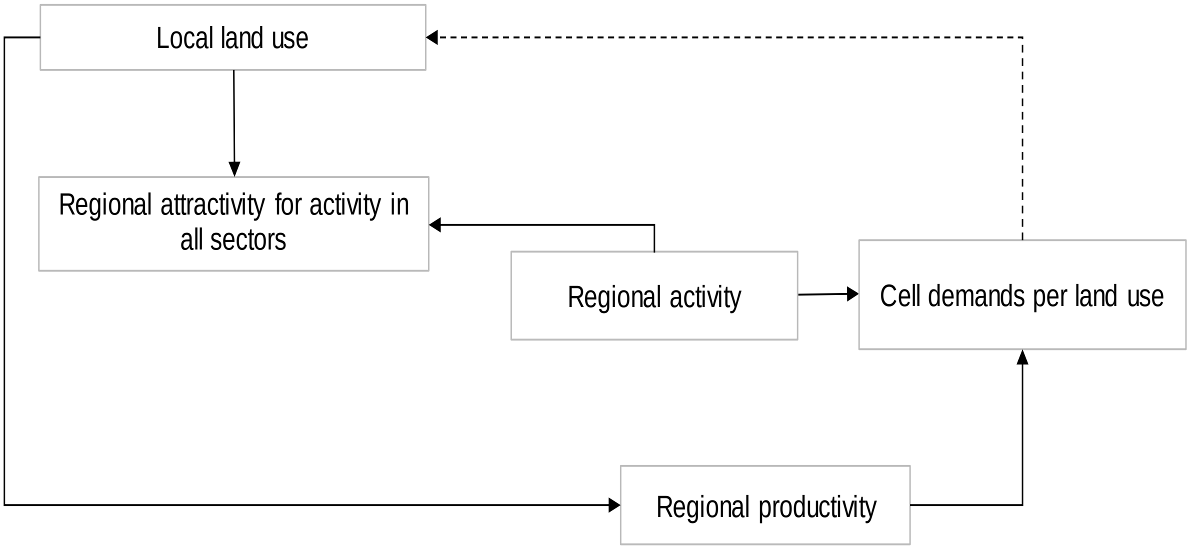


Figure 4-2: Linkage between sub-models in METRONAMICA

4.3 The regional interaction model

The discussion on integrated land use transport models emphasises on the linkage between the transportation and land use component. The M-LUT also links the land use and regional model. The regional model distributes cells to each land use in each economic sector for the whole modelled area based on the attractiveness of each zone. The regional model is a spatial interaction model, which considers activity locations in different sectors. It simulates the growth or decline of the population and economic sectors for a region. The core assumption in the regional model is that different regions compete for economic activities; that is population and jobs. Typically, the regional model subdivides the modelled area (a city or region for instance) into several municipalities, and these municipalities compete for land use activities and population thus migration between municipalities can be modelled within the regional model (RIKS, 2012).

However, the regional model discussed in this section considers a situation where a municipality, such as Cape Town, is subdivided into suburbs which resemble traffic analysis zones (TAZs). Local characteristics relating to the land use aspects influence how attractive a zone is and the amount of activity that is allocated to it. The activities are converted into cells which are then allocated to land uses through the CA land use model. Therefore, the regional model is responsible for modelling the activities in the different socio-economic sector and dictates cell demands within the land use model (RIKS, 2012). A more detailed explanation of the regional model at a national level can be found in (RIKS, 2012). Figure 4-3 provides a representation of the relationship between the regional and land use model.



Source: RIKS (2012)

Figure 4-3: Relationship between the regional and the land use model

4.4 The land use sub-model

As mentioned earlier, the regional model dictates the cell demands in the land use model. Since the land use model implemented is a CA-based model, land uses are depicted on a grid of cells after Couclelis (1985) and White & Engelen (1993, 1997) Typically, the cell resolution ranges between 25m to 1000m depending on the level of analysis of the model. To determine the cell transition and the location of land use activities at every time step, the model uses a distance decay function (Kim & Batty, 2011), which determines the importance of a link type for a land use to fulfil its function. This will be explained further in section 4.4.2.

Three types of land uses are modelled, vacant, function and feature land uses. Vacant land uses are dynamic, and they can change their state between different periods. As a result, these land uses facilitate urban expansion. Like vacant land uses, function land uses are also dynamic, their state can potentially change between time periods and are influenced by their surroundings. On the other hand, feature land uses remain stable and are static hence exogenously modelled. Further, they are not influenced by land uses within their neighbourhood (White & Engelen, 1993, 1997; RIKS, 2012). The key assumption in the model is that the main drivers of land use change are:

- suitability;
- zoning;
- accessibility;
- a set of rules that characterise the relationship between land uses.

Hence during the calibration of the land use model, these are the parameters that need to be determined. The potential of a cell to convert (also referred to as the transition potential) from one state to another land use is determined by the influence of each of the drivers and is given by the following equation:

$$\mathrm{P_{k,i}} = \mathrm{f(r_{k,i}, A_{k.i}, S_{k.i}, Z_{k.i}, N_{k,i})} \qquad (5)$$

where:

$P_{k,i}$= potential for land use class *k* in cell *i*,

$A_{k.i}$= accessibility for land use k in cell *i*,

$S_{k.i}$ = physical suitability for land use class *k* in cell i,

$Z_{k.i}$= zoning status which are laws and regulations pertaining to land use class *k* in cell *i,*

$N_{k,i}$= neighbourhood effect for land use *k* in cell *i* and

$r_{k,i}$ = random perturbation term which controls the scatter and density of land uses on the landscape (White & Engelen, 2003; Wickramasuriya, Bregt, van Delden, et al., 2009; RIKS, 2012; Aljoufie, Zuidgeest, Brussel, et al., 2013).

4.4.1 The neighbourhood effect

As mentioned earlier, the land use model block in M-LUT is a CA -based land use model. The capabilities of CA, to simulate urban growth is based on the notion that past urban development affects the future urban landscape through the interaction that exists between adjacent land uses (Santé, García, Miranda, et al., 2010). Thus, the state of a cell at any point in time is influenced by the cells within its neighbourhood. The neighbourhood effect is determined for each function land use which contributes to the total potential. Therefore, the neighbourhood effect $\mathbf{N_{k,i}}$ is expressed as:

$$\mathrm{N_{k,i}} = \sum_{\mathrm{d,i}} \mathrm{I_{d,i} W_{z,y,d}} \tag{6}$$

where: $= \begin{cases} 1, & \text{if cell } i \text{ in distance zone } d \text{ is in state } y \\ 0, & \text{otherwise} \end{cases}$

and $W_{z,y,d}$ is the weighting parameter applied to cells in state *y* in distance zone *d*;

For vacant land uses, the transition potential is simplified to:

$$\mathrm{P_{k,i}} = \mathrm{f(S_{k,i}, I_{v,i})} \tag{7}$$

where:

$P_{k,i}$= the potential for land use class *k* in cell *I,*

$S_{k.i}$ = physical suitability for land use class *k* in cell *I* and

$I_{V.i}$ = inertia or conversion effect of the vacant land use *v* in cell *i* (RIKS, 2012).

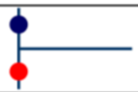
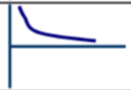
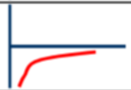
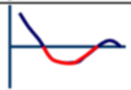
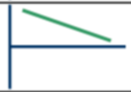
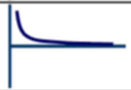
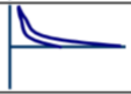
The neighbourhood effect expresses the attraction or repulsion of land uses within a neighbourhood. Table 4-1 represents the main components used in determining the cell state within the CA land use model.

Table 4-1: General components of cellular automata

Cell space	Comprises of cells on a grid, cell sizes generally range from 25m to 1000m.
Cell state	Denotes spatial variables or land uses which can be dynamic (function and vacant land uses) or static (feature land uses).
Time steps	The cellular automata model gradually changes at a sequence of discrete time steps
Transition rules	A transition rule specifies the state of a cell before and after updating based on surrounding cells. 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	The area surrounding the cell, defined based on four adjacent cells (limited neighbourhood or Von Neumann) or eight adjacent cells (extended neighbourhood or Moore).

Source: RIKS2012)

One of the key assumptions in CA is that land uses within the same land use class tend to cluster within the same neighbourhood, and as the distance increases from the neighbourhood of a cell, different land use classes begin to occupy other cells (Verburg, de Nijs, van Eck, et al., 2004). These are the principles that are implemented to determine the land use transitions in the METRONAMICA land use model. The transitions rules regulate the competition between the different land uses and hence are an essential component of the model. The calibration process of the neighbourhood rules is further discussed in section 4.6.2. Figure 4-4 shows the generic distance functions implemented in CA models.

Distance functions	**Meaning of the distance function in socio-economic and geographical terms**
Effect at distance = 0 of the function on itself	
	Inertia: expressing the strength with which the existing land use will stick to its present location.
Effect at distance = 0 of any other function on the function	
	Ease of re-conversion: the ease with which a new land use will take over from the existing land use (in blue: easy re-conversion, such as in-fill and in red: difficult re-conversion for example re-conversion of brownfields)
Effects at distance > 0	
	No interaction
	Attraction: positive agglomeration benefits diminishing with distance.
	Repulsion: negative agglomeration benefits diminishing with distance
	Change in type of interaction: from attraction to repulsion or/ and vice versa.
	Strong interaction with far neighbours, abruptly falling
	Gradual distance decay,
	Strong interaction with immediate neighbours, gradually falling
	Sphere of influence: *short tail*: the interaction is limited to short distances; *long tail*: the interaction effect works over longer distances.

Source: RIKS (2012)

Figure 4-4: Distance rules for CA land use model

4.4.2 Accessibility

Accessibility which determines the influence of the road infrastructure on the location of land uses is a key driver of land use change. It also represents the extent to which activities can be reached and the potential for that land use to perform its function given its location relative to the transport infrastructure (RIKS, 2012). Accessibility is comprised of four components: (1) local, (2) implicit (3) explicit and (4) zonal accessibility. The total accessibility is thus defined by equation 8:

$$\mathrm{A_{f,c}} = \begin{cases} \mathrm{EA_{f,c}} & \text{if } \mathrm{f(c)} \in < \mathrm{LU_I} \\ \mathrm{ZA_{f,z_c}} \times \mathrm{LA_{f,c}} \times \mathrm{IA_{f,c}} & \text{otherwise} \end{cases} \qquad (8)$$

where:

$EA_{f,c}$= explicit accessibility at cell *c* for land use *f* if cell *c* is occupied by an impassable land use,

ZA_{f,z_c}= zonal accessibility of land use *f* in the zone where cell *c* is located,

$LA_{f,c}$ = local accessibility at cell *c* for land use *f,*

f(c) =denotes the land use in cell *c* and

$IA_{f,c}$= implicit accessibility at cell *c* for land use *f.*

While total accessibility is comprised of the four different accessibility types, only the local, implicit and explicit accessibility are discussed here as they are incorporated in the land use model (RIKS, 2012). The zonal accessibility is discussed in section 4.5.4.1 when the link between the land use and transport models is introduced.

Local accessibility

The local accessibility reflects the importance of a road network link for a land use to perform its function. Different land uses are assumed to have different local accessibility needs; and this changes over distance to reflect the importance of a road network link for a land use to perform its function. Positive local accessibility values suggest that a land use needs to be near a road network link type while negative values suggest that a land use does not need a road network link type to perform its function. This is presented through a distance decay function which takes either positive or negative values. Equation 9 represents the mathematical formulation of local accessibility in the land use model:

$$\mathrm{LA}_{s,f,c} = \begin{cases} \dfrac{a_{s,f}}{D_{s,c} + a_{s,f}} & \text{if } a_{s,f} > 0 \\ 0 & \text{if } a_{s,f} = 0 \\ 1 - \dfrac{|a_{s,f}|}{D_{s,c} + |a_{s,f}|} & \text{otherwise} \end{cases} \tag{9}$$

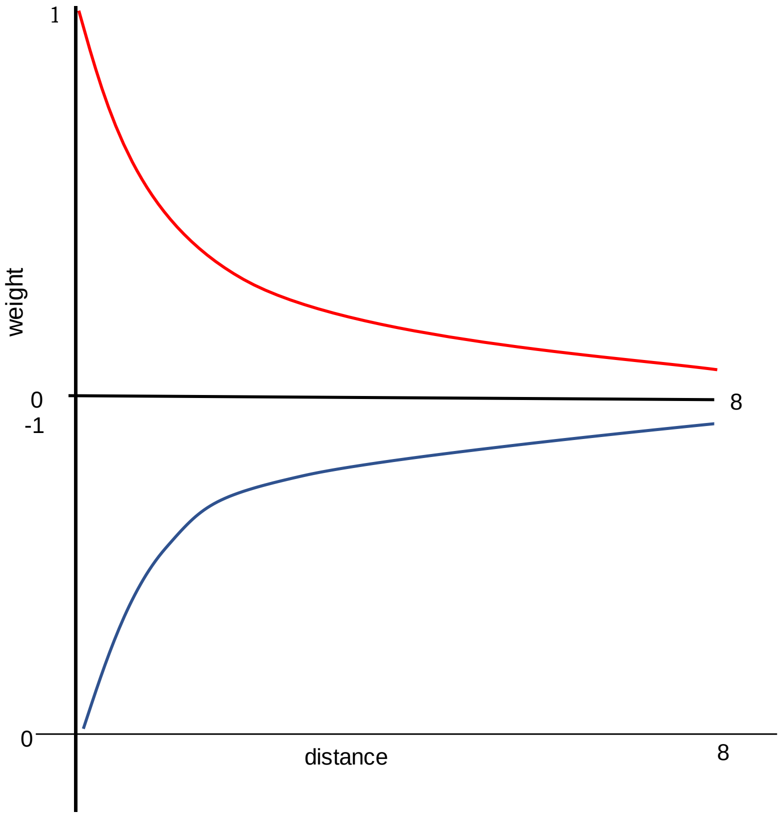
where:

$LA_{s,f,c}$ = local accessibility of cell *c* for land use *f* to link type *s,* in a cell,

$D_{s,c}$ = distance between cell *c* and the nearest link covered by link type *s* and

$a_{s,f}$ = distance decay (calibrated parameter) and represents the change in local accessibility for a link over a distance.

A positive $a_{s,f}$ (distance decay) for a land use type indicates that for a land use to fulfil its functions, it should be located close to a road network link while a negative distance decay shows that a land use is repelled in the locations close to a road network link. Low positive distance decay values indicate that for a land use to fulfil its function, a transport network link is required in the vicinity of that land use (RIKS, 2012). The structure of the distance decay is represented in Figure 4-5.



Source: RIKS (2012)

Figure 4-5: The effect of proximity to the network on distance decay

Implicit accessibility

As mentioned earlier, the road infrastructure influences the attractiveness of a location to be occupied by a land use. Implicit accessibility captures the notion that if an area has an urban land use, infrastructure is put in place to ensure that it is accessible. Hence, implicit accessibility makes a location more attractive in the future as the presence of road infrastructure provides an opportunity for future land use development. Perhaps this represents an instance where transport potentially influences urban development. Implicit accessibility for a land use at a cell is represented by equation 10:

$$IA_{f,c} = \begin{cases} \mathrm{UL}_f, & \text{if } f(\mathrm{c}) \in \mathrm{L}_u \\ \mathrm{NUL}_f & \text{otherwise} \end{cases} \tag{10}$$

where:

$IA_{f,c}$ = implicit accessibility of cell *c* for land use *f*,

$UL_f,$ = implicit accessibility for land use *f* of a cell that has an urban land use,

$NUL,_f$ = implicit accessibility for land use *f* of a cell with a non-urban land use,

f(c) =denotes the land use in cell *c*,

L_u = represent urban land uses

Explicit Accessibility

Within urban areas, there are natural landscapes that are uninterrupted by urbanisation. In some cases, access to land uses close to these natural landscapes is made difficult by the need to circumvent these natural landscapes. This also applies in the case of restricted areas, such as military airbases and airports where road networks do not cut across these land uses, these are examples of impassable land uses. Consequently, road networks around this area are not easily accessible due to the presence of an impassable land use. Noteworthy is that this does not hinder the impassable land use from performing its function or to generate its activities, but the accessibility of the surrounding land uses is affected. Hence, explicit accessibility as a component of total accessibility provides an avenue through which this variation in accessibility can be expressed. It is represented as:

$$EA_{f,c} = \begin{cases} \mathrm{IA}_{f,C}, & \text{if } f(\mathrm{c}) \in f \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

where:

$EA_{f,c}$= explicit accessibility for land use *f* at cell,

f(c) =denotes the land use in cell *c,*

$\mathrm{IA}_{f,c}$ = implicit accessibility of cell c for land use f if it is impassable and

f(c) =denotes the land use in cell c,

Noteworthy is that for impassable land uses, the explicit accessibility is equal to the implicit accessibility. This means for other land uses, the explicit accessibility is equal to zero. This is the case for some feature land uses which generate activities for example nature reserve (RIKS, 2012).

4.4.3 Zoning

Zoning represents the policy measures which drive land use change. It can be explained as the institutional suitability as it interprets the role of policy in influencing the location of land uses over time (RIKS, 2012). Typically, zoning is introduced as a categorical parameter which has four states, actively stimulated, allowed, weakly restricted and strictly restricted. When a zoning status is set at actively stimulated, it means policy is directly influencing land use change. Zoning takes values between 0 and infinity. However, typically the values range between 0 and 1.5 where:

- 0 = strictly restricted, implying that a land use is not allowed to occupy a cell.
- 0.5 = weakly restricted, implying that land use regulations are loosely exercised.
- 1 = allowed
- 1.5 = is actively stimulated, implying that land use actively influences land use development.

For each cell, the zoning status can be determined for different. Period. Assuming that the zoning is determined for three periods, the zoning is determined as follows:

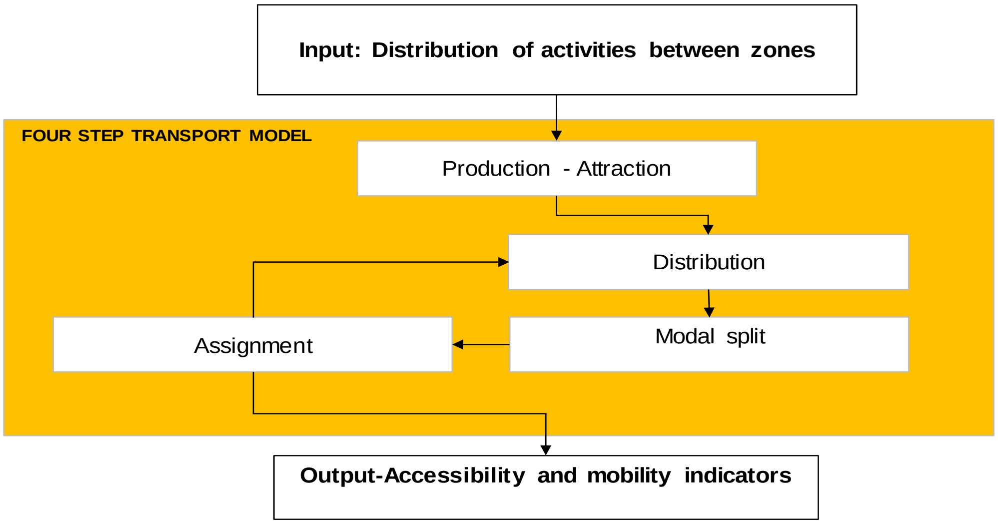
- Zoning period 0 (t_0) =the start of the simulation until a user-defined date (t_1)
- Zoning period 1 (t_1) = the first user-defined date until a second user-defined date (t_2)
- Zoning period 2 (t_2) = the second user-defined date until the end of the simulation.
- Noteworthy is that once a land use occupies a cell, it is allowed for the duration of the simulation (RIKS, 2012).

4.4.4 Suitability

Suitability represents the physical, ecological and environmental aspects that determine whether a location is appropriate for a land use to support a particular land use function (RIKS, 2012). As in the case of zoning, suitability is expressed on a categorical scale. It is introduced and evaluated on a scale of 0 to 1 with 0 representing completely unsuitable and 1 perfectly suitable.

4.5 The transport sub-model

The principles of the conventional four-step transport model after Ortuzar & Willumsen (1994) are adopted in the M-LUT to simulate the flow of transport and its intensity on the transport network. Traffic conditions for a twenty-four-hour period are simulated in the model. The transport model specifies different time periods to reflect the difference in the intensity of transport on the network throughout the day. For example, the model can simulate traffic conditions for a peak hour period and the rest of the day to account for the difference in traffic intensity between these two periods. The regional and land use models are inputs to the transport model by determining the origins and destinations of activities. Figure 4-6 represents the transport model utilised in M-LUT.



Source: RIKS (2012)

Figure 4-6: Conceptual dynamic four step transport model in the METRONAMICA-LUT model[4]

The transport model in METRONAMICA models transport modes either endogenously and exogenously. The endogenous modes, typically the private car, is used to assign trips on the network while different modes of public transport are considered as alternative modes hence are modelled exogenously. The model uses passenger car equivalent to measure traffic conditions on the network. The transport activities are modelled at the transport analysis zones (TAZs). The model accounts for the difference in characteristics and transport activity behaviour between rural and urban areas. Therefore, the urbanisation level which reflects the difference in density of activities such as jobs and population between urban and rural areas is used throughout the model (van Delden & Hurkens, 2011; RIKS, 2012). As in the conventional four-step model, trip productions, trip attractions, trip distribution, modal split and route choice for each of the TAZs are determined which aid in the modelling of congestion and traffic intensity on the transport network

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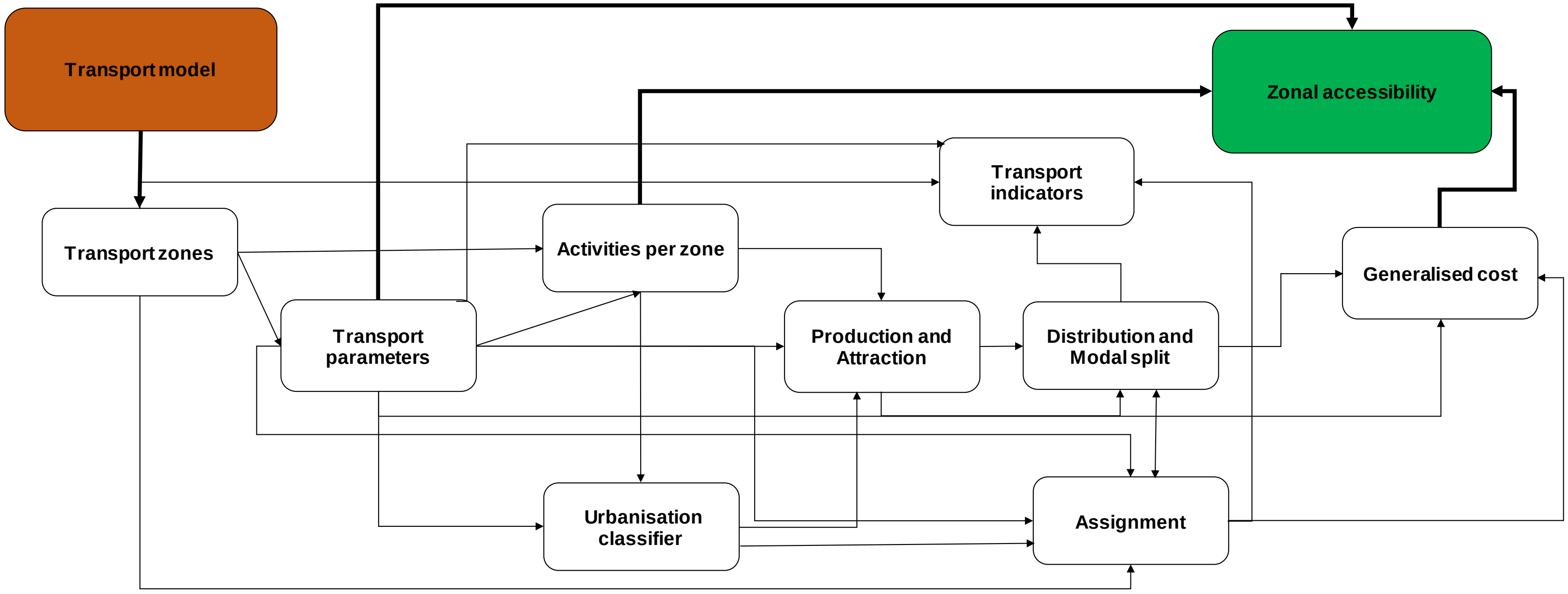
[4] Dotted lines represent steps in the transport model that are simultaneously determined

(RIKS, 2012). These aspects are discussed in detail in section 4.5. Figure 4-7 shows a detailed representation of the components and linkages within the M-LUT transport model block.



Source: RIKS (2012)

Figure 4-7: Detailed representation of the transport model block in METRONAMICA

From Figure 4-7, zonal accessibility is determined for each function land use and is based on the number of activities in the zones which are components of the trip distribution. Transport parameters such as sensitivity to cost which expresses the responsiveness of people to a change in costs associated with a trip purpose also affects the zonal accessibility through the generalised cost. This makes zonal accessibility an important output in the transport model as it is determined by several parameters at different levels within the transport model.

4.5.1 Trip generation sub-model

Activity choices are determined in the trip generation model. The main inputs in this model block are trip generating activities for the different zones for different activity purposes. The trip generation is also dependent on the urbanisation level of a zone as this determines the population and activity densities. Additionally, the trip generation model assumes that mobility behaviour is not constant over time; therefore, a mobility growth factor is introduced in the trip generation sub-model to incorporate the potential increase or decrease of trips in the future. There is a mixture of traffic (trucks, cars, etc.) and people sometimes share a car on a trip, which influences the trip production rates, this needs to be reflected in the model. Hence, the trip generation model introduces multipliers to reflect the influence of trucks and car occupancy on the road network. Therefore, within the trip generation model, the trip origins are determined based on the following equation:

$$O'^{p}_{z,tp} = \sum_{a} (TA_{z,a} * N^{p}_{O,a,uc}) * M^{p}_{tp} \tag{11}$$

While the trip destinations are determined based on the following:

$$D'^{p}_{z,tp} = \sum_{a} (TA_{z,a} * N^{p}_{D,a,uc}) * M^{p}_{tp} \tag{12}$$

As mentioned earlier, trip generation within a zone might change over time and different vehicle types, e.g. trucks and cars influence trip production differently. To reflect this, the following multiplier is introduced to adjust the trip origins and destinations.

$$M^{p}_{tp} = G^{p} * \frac{P^{p}_{tp}}{L_{tp}} * \left(F^{p}_{truck} * E_{truck} + \frac{1 - F^{p}_{truck}}{S^{p}} \right) \tag{13}$$

where:

$TA_{z,a}$ = represents the different activities in a transport zone,
$N^{p}_{O,a,uc}$ = number of trip origins generated by a trip purpose for each urbanisation class,
$N^{p}_{D,a,uc}$= number of trip destinations generated by a trip purpose for each urbanisation class,
$M^{p}_{tp} =$ multiplier that controls for the influence of mobility growth and the influence of car and trucks on the network,
S^{p} = car occupancy, which shows the number of people per vehicle
F^{p}_{truck} = fraction of trucks per trip purpose
$\mathrm{E_{truck}}$ = car equivalent for a truck,
$1 - F^{p}_{truck}$ = is the fraction of cars and,
G^{p} = is the mobility growth factor.

The assumption made in the trip generation model is that the total number of trips originating from a zone is equal to the number of trips generated in a zone. This is calculated based on the following balancing equation:

$$TT^{P}_{tp} = \omega^{p} * \sum_{z} O'^{p}_{z,tp} + (1 - \omega^{p}) * \sum_{z} D'^{p}_{z,tp} \tag{14}$$

where:
$\omega^{p} =$ is the parameter used to balance trip origins and destinations for each trip purpose. The other parameters are as defined earlier.

Because traffic conditions are normally assessed for a peak hour period, it is also essential to determine the actual number of trips originating from a zone ${}^{t}O^{p}_{z,tp}$ and trip destinations ${}^{t}D^{p}_{z,tp}$ per hour. These are determined using the following equation:

$${}^{t}O^{p}_{z,tp} = \begin{cases} \dfrac{{}^{t}O'^{p}_{z,tp}}{\sum_{z} {}^{t}O'^{p}_{z,tp}} .\ TT^{P}_{tp} & \text{if } \displaystyle\sum_{z} {}^{t}O'^{p}_{z,tp} > 0 \\ \dfrac{TT^{P}_{tp}}{nz} & \text{if } \displaystyle\sum_{z} {}^{t}O'^{p}_{z,tp} = 0 \end{cases} \tag{15}$$

$$ {}^{t}D^{p}_{z,tp} = \begin{cases} \dfrac{{}^{t}D'^{p}_{z,tp}}{\sum_{Z} {}^{t}D'^{p}_{z,tp}} .\ TT^{P}_{tp} & \text{if} \displaystyle\sum_{Z} {}^{t}D'^{p}_{z,tp} > 0 \\ \dfrac{TT^{P}_{tp}}{nz} & \text{if} \displaystyle\sum_{Z} {}^{t}D'^{p}_{z,tp} = 0 \end{cases} \tag{16} $$

where:

${}^{t}O^{p}_{z,tp}$= number of trip origins for a zone per trip purpose per hour,

${}^{t}D^{p}_{z,tp}$= number of destinations for a zone per trip purpose per hour,

${}^{t}O'^{p}_{z,tp}$= unbalanced trip origins per hour per trip purpose per zone,

${}^{t}D'^{p}_{z,tp}$= unbalanced trip destinations per hour per trip purpose per zone and

TT^{P}_{tp}= total number of trips per hour per trip purpose

4.5.2 Trip distribution sub-model and mode choice

In this stage, the origin-destination pairs are determined thus linking the production and attractions in the different zones. This is also the stage where the mode choice decisions are determined. Within METRONAMICA, the trip distribution model appreciates that change in behaviour is gradual thus making destinations and transport mode choice dependent on existing and past travel behaviour. Hence, the modal split is determined in the same step as trip distribution and are therefore determined simultaneously. This is where the trip distribution model implemented in METRONAMICA diverges from the classic approach as defined in Ortuzar & Willumsen (1994). The trip productions and attractions are balanced using a doubly-constrained trip distribution procedure, also known as the Furness method, mimicking the gravity model. Equations 12 and 13 (section 4.5.1) are used to balance the trip productions, and attractions and these are similar to equation 2 and 3 introduced in section 3.5. The assumption made in the M-LUT transport model is that travel behaviour remains unchanged in the short-term, this implies there is inertia in responding to new transport conditions. This means that the destinations and mode choice at any point in time are determined by the current as well as the previous transport patterns. Therefore, over time only a fraction of trips in time step are distributed based on the current generalised cost, while the remaining trips are distributed according to behaviour in the previous time step. Hence, the trip distribution model applied in the M-LUT is comprised of two components; responsive and inertia components. The responsive part calculates trip distribution and depends on the generalised cost of travel between zones based on the new travel behaviour while the inertia factor represents the time lag in behaviour change; thus, trip distribution is also calculated based on the previous behaviour.

For example, assuming there are two time periods, *t-1* and *t* and the trip distribution at time t needs to be determined; the transport model assumes that the generalised cost used in calculating the trip distribution is based on travel behaviour at time *t* (responsive part) and *t-1* (inertia part). Therefore, the model first identifies the balancing factors for the responsive and inertia distribution. The balancing factors for the responsive distribution at time *t* is represented by equation 18 which represents the aggregation of the generalised cost across all modes.

$$C^{p,sum\_mod}_{(t)z_{o,}z_d,tp} = \frac{\ln\left(\sum_m e^{-\gamma_p^{\text{purpose}.t-1}} C^m_{z_{o,}z_d,tp}\right)}{-\gamma_p^{\text{purpose}}} \tag{17}$$

Based on the balancing factors, the trip distribution for transport modes at time *t* which is associated with the responsive part is calculated using the equation below.

$$Q^{m,p}_{(t)R,z_{o,}z_d,tp} = \text{Furness}\left(O^p_{(t)z_{o,},tp}, D^p_{(t)z_{d,},tp}, e^{-\gamma_p^{\text{purpose}}} * C^{p,sum\_mod}_{z_{o,}z_d,tp}\right) \tag{18}$$

On the other hand, the trip distribution for transport modes associated with the inertia part is equivalent to the trip distribution in the previous time step *t-1.* As mentioned earlier, the assumption is that change in behaviour takes time. Hence, the model calculates the balancing factors for the inertia distribution for time *t* per trip purpose based on the equation below:

$$OD^{p,sum\_mod}_{(t)z_{o,}z_d,tp} = \sum_m^{t-1} ODP^{m,p}_{z_{o,}z_d,tp} \tag{19}$$

A close look at equation 20 shows the $\sum_m^{t-1} ODP^{m,p}_{z_{o,}z_d,tp}$ is the summation of trip distribution matrix in the previous time period for all transport modes. Based on equation 20, the inertia trip distribution for the individual modes is given by:

$$Q^{m,p}_{(t)\,I,z_{o,}z_d,tp} = furness\left(O^{p}_{(t)z_{o,},tp}, D^{p}_{z_{d,},tp}, e^{-\gamma_p^{purpose*t} C^{p,sum\_mod}_{z_{o},z_d,tp}}\right) \tag{20}$$

The trip distribution is calculated separately for all trip purposes for time ***t*** based on the responsive distribution $Q^{m,p}_{R,z_{o,}z_d,tp}$, the inertia distribution $Q^{m,p}_{I,z_{o,}z_d,tp}$ and the inertia factor ρ^p for the trip distribution. The inertia factor ρ^p determines whether the responsive or the inertia distribution will have more influence in the calculation of trip distribution and lies between 0 and 1. Noteworthy is that ρ^p is a calibrated parameter and determined through trial and error based on known trip taking trends.

The inertia part and responsive part are then aggregated to generate the trip distribution using the equation below:

$$\mathrm{ODP}^{\mathrm{m,p}}_{\mathrm{(t)z_{o,}z_{d,tp}}} = \rho^p * \mathrm{Q}^{\mathrm{m,p}}_{\mathrm{(t)I,z_{o,}z_d,tp}} + (1-\rho^p) * \mathrm{Q}^{\mathrm{m,p}}_{\mathrm{(t)R,z_{o,}z_d,tp}} \tag{21}$$

where:

$\gamma_p^{purpose}$ = sensitivity to cost for trip purpose p,

ρ^p = is the inertia fraction of the trip distribution for a trip purpose,

$1-\rho^p$ = is the responsive fraction of the trip distribution for a trip purpose,

$Q^{m,p}_{(t)I,z_{o,}z_d,tp}$= is the number of trips from zone z_o and zone z_d for mode *m* for trip purpose *p* and time period *tp,* at time *t* assuming that behaviour is inert hence unresponsive to a change in transport conditions and

$Q^{m,p}_{(t)R,z_{o,}z_d,tp}$ = is the number of trips from zone z_o and zone z_d for mode *m* and time *tp* and trip purpose *p* assuming that there is a change in behaviour and hence, the system is fully responsive.

The output from this stage is an origin-destination matrix for different trip purposes for the different modes of transport.

4.5.3 Trip assignment sub-model

This is the final step in the transport model and assigns trips to different routes on the transport network. As mentioned earlier, the endogenous mode is used to explicitly assign transport to the network. For the endogenous mode, traffic is assigned to the road network links considering the influence of existing traffic on the route choices of other vehicles that might enter the network. On the other hand, the exogenous mode assignment only considers time and distance, and these are determined outside the model and normally based on data. In the traffic assignment model, people choose a route with the lowest aggregated cost which is calculated based on distance, travel time and other associated attributes. Hence, the core aspect of the traffic assignment model is to determine the aggregated costs of trip making. The cost per link is used to determine the shortest path, the Dijkstra algorithm after Dijkstra (1959) is implemented. The shortest path is also dependent on the choices of other agents on the network as they influence the intensity of congestion on the road network links.

As people choose a route, this influences the intensity on the road network links which in turn influences the speed and associated travel times. The assignment of traffic to the network is an iterative process (typically 10 iterations), where only a fraction of the trips are assigned to the network at a time, until convergence. What is important to note in the assignment stage is that costs influence the distribution of activities. The output from the assignment stage is two-pronged: an assessment of the transport network such as congestion and the accessibility outputs (zonal accessibility) which acts as inputs in the land uses model. The zonal accessibility provides the linkage between the land use and transport model in the M-LUT.

4.5.3.1 Understanding endogenous mode traffic assignment

As mentioned earlier, only the endogenous mode is used to explicitly assign traffic to the network; therefore, it is important to discuss the components of the endogenous traffic assignment. The way the transport network is operationalised is such that the model finds the shortest path between transport zones based on the central node or special links. The central nodes or special links are pseudo nodes (typically called dummy links) which are used by all traffic to leave or arrive in a transport zone. Though the special nodes play an important role in directing traffic in and out of transport zones, they do not influence the generalised cost of a particular route. Further, the special node is utilised as the initial or final link of the shortest path.

Agents seek to travel between transport zones at the least generalised cost. However, the way traffic is assigned to the network is such that no alternative route results in a lower generalised cost relative to any other route. Given that the assignment of traffic is iterative, the cost per link *l* for an iteration (*it*) for a particular time (*tp*) used to assign cars between zones is determined by the following equation:

$$C_l^{it} = C_x^m . \frac{L_l}{1000} + C_t^m . \frac{L_l}{1000. V_{tp,l}^{-1}} + C_{ext,l} \tag{22}$$

where:

C_x^m = is the cost per km for mode *m* at time *t,*

C_t^m= is the cost per hour for mode *m* at time t and

$C_{ext,l}$ = is the extra cost of link *l* at time *t*

Additionally, the intensity on link *l* for an iteration *(it)* depends on the drainage density which determines the rate at which cars leave a road network. The intensity on the link is given by the following equation:

$$I_l^{it} = I_{tp,l}^{it-1} + F_{it}. \left({}^tOD_{z_o z_d,tp}^m + \frac{ID_{Sl,tp} + ID_{El,tp}}{2} \right) \tag{23}$$

where:

$I_{tp,l}^{it-1}$= is the intensity on the link in the previous iteration,

F_{it} = is the fraction of trips that are assigned in an iteration,

${}^tOD_{z_o z_d,tp}^m$ = is the number of trips between and the origin and the destination for mode *m* and time period *tp* at time *t*

$ID_{Sl,tp}$ = is the drainage intensity at time (*tp*) at the node where link *l* of the road network starts and

$ID_{El,tp}$ = is the drainage intensity at time (*tp*) at the node where link *l* of the road network ends.

Based on the intensity, the congestion ${}^tCG_{tp,l}^{it}$ on a road network *l* at an iteration at a time period *tp* is given by:

$${}^tCG_{tp,l}^{it} = \frac{\frac{I_{tp,l}^{it} - IP_l}{\sum_{it'=1}^{it} F_{it'}} + IP_l}{CP_1} \tag{24}$$

where:

IP_l= is the existing intensity on link *l,*

CP_l= is the capacity of link *l* and

$F_{it'}$= fraction of trips assigned to the link during iteration *it.*

From the equation, the congestion on a link is computed by determining the intensity to capacity ratio on the link assuming that all traffic is assigned on that link. The iterative allocation of traffic on the links leads to a Nash equilibrium where the costs of all the links are equal. These costs determine the generalised cost which is the sum of all the different costs associated with the trip. For a more detailed explanation on the calculation of the generalised cost see (RIKS, 2012).

4.5.4 The linkage between the Land Use and Transport model

The key theoretical underpinning for this research is that land use and transport are linked, and the interaction of these sub-systems results in dynamics that lead to changes in the urban environment. Given that, it is important to identify how land use and transport are linked and how this impacts their interaction. Land use appears in the transport model in the attraction and the production phase thus making it a key input in the transport model. Transport provides accessibility which allows people to participate in spatially distributed land uses activities. Transport model outputs enter as inputs in the land use model thus resulting in a dynamic model (RIKS, 2012; Aljoufie, Zuidgeest, Brussel, et al., 2013; Perez, Wickramasuriya, Forehead, et al., 2017). Given that, there is interdependence between inputs of the transport model and the land use model, a feedback relationship exists between the land use and transport and is expressed through the zonal accessibility which is one of the outputs of the transport model. As mentioned in section 4.4.2, only the zonal accessibility is incorporated in the transport model as it provides the link between land use and transport models. The intricacies of zonal accessibility are discussed in the next section.

4.5.4.1 Zonal accessibility

The zonal accessibility measures the ease of access to opportunities from a zone and how well the transport system facilitates this access. It is calculated based on the generalised cost incurred to travel between activity zones. It is the only component within the model that is calculated at the zonal level rather than the cell level. Figure 4-8 shows how land use and transport are linked through zonal accessibility.

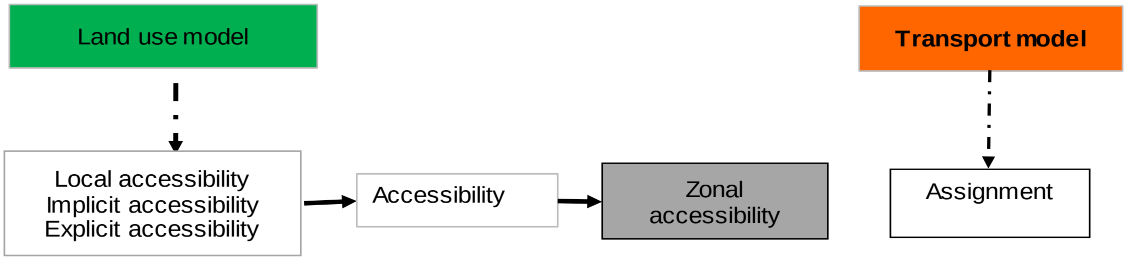


Figure 4-8: Link between land use and transport model

Transport costs and the distribution of activities are the key factors that influence zonal accessibility. These two components make up the generalised cost for travelling between and within zones to access opportunities. Total accessibility has been defined in equation 8, the zonal accessibility which is calculated across different trip destinations is discussed here and is defined in equation 26.

$$\mathrm{ZA}^{\mathrm{activity}}_{\mathrm{z,a}} = \sum_{\mathrm{z}'} \mathrm{TA}_{\mathrm{z'a}} \mathrm{e}^{-\mathrm{C}^{\mathrm{zone}}_{\mathrm{avg,z'z}} \cdot \gamma^{\mathrm{activity}}_{\mathrm{a}}} \tag{25}$$

where:

$\gamma_a^{activity}$ = sensitivity to cost for activity *a*,

$C^{zone}_{avg,z'z}$ = is the average transport costs between zone z' and *z* and

$TA_{z'a}$ = is the share of activity *a* in zone z'.

Given that zonal accessibility is a component of total accessibility, there is a need to determine the maximum zonal accessibility for an activity. Therefore, the maximum zonal accessibility for an activity is defined by:

$$\mathrm{ZA}^{\mathrm{activity}}_{\mathrm{z,a}} = \max\left(1, \max_{\mathrm{z}}(\mathrm{ZA}^{\mathrm{activity}}_{\mathrm{z,a}})\right) \tag{26}$$

Like the accessibility in the land use model, the zonal accessibility ranges from 0 to 1, and the most accessible zone has a value of 1. Noteworthy is that some transport zones have several land use activities; for those transport zones, the zonal accessibility is calculated based on more than one activity. As such, a weighted mean across all activity types is used to calculate the zonal accessibility for a function land use ***f:***

$$\mathrm{ZA}_{\mathrm{f,z}}^{\mathrm{function}} = \mathrm{ZA}_{\mathrm{min}} + (1 - \mathrm{ZA}_{\mathrm{min}}). \sum_{\mathrm{a}} \frac{\mathrm{FA}_{\mathrm{f,a}}. \mathrm{ZA}_{\mathrm{z,a}}^{\mathrm{activity}}}{\mathrm{ZA}_{\mathrm{z,a}}^{\mathrm{activity}}} \tag{27}$$

where:

$FA_{f,a}$ = is the function land use *f* for transport activity *a* and ZA_{min} represents the minimum zonal accessibility.

In the transport model, ZA_{min} is a calibrated parameter. The calibration of this parameter is discussed in section 4.6.4.

4.6 Calibration and validation of the METRONAMICA land use transport model

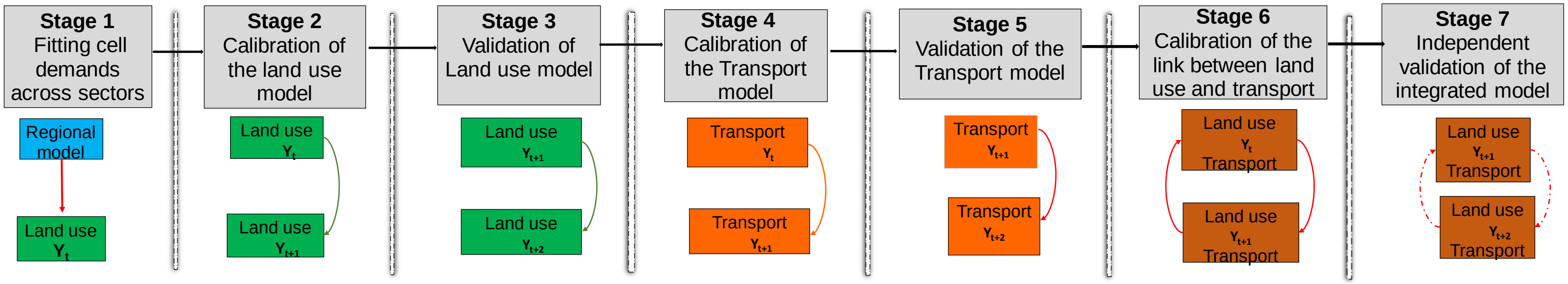
In his seminal paper, Lee (1973), detailed the weaknesses of urban models, while advances in technology and data availability have managed to address some of the issues he raised, calibration and validation of the models is still an issue(Wegener, 1994; Wenban-Smith, van Vuren, & Macdonald, 2009). This section discusses the calibration and validation of the METRONAMICA land use transport model. Ideally, an independent calibration and validation procedure is implemented where different data sets are used to calibrate and validate the model. This implies that the model is calibrated from Y_t to Y_{t+1} and validated for Y_{t+1} to $\mathrm{Y}_{\mathrm{t+2}}$.using a dataset that was not used in the calibration. As discussed earlier, the METRONAMICA land use transport model comprises of three model blocks each with several parameters that are calibrated. Among other issues, the complexity due to interactions of several elements within urban ecosystems and human behaviour are some of the factors that influence the calibration of models. All these factors increase calibration complexity as accurately identifying drivers of urban change becomes more complex (van Vliet, Naus, van Lammeren, et al., 2013). Hence, the calibration approaches implemented need to be cognisant of this complexity and find ways of overcoming some of these issues. As shown in Figure 4-2, the METRONAMICA land use transport model is a modular system comprising of interconnected sub-models. Between the sub-models, several model parameters need to be calibrated. To make the calibration manageable, a sequential calibration and validation approach is implemented where:

- A piecewise strategy is implemented by calibrating the individual models as independent model blocks.
- After that, the calibration focuses on the parameters that link the various model blocks.

The model blocks are calibrated in the following order:

1. The regional model
2. The land use model
3. The transport model.

As the model blocks are interdependent, this approach allows the calibration problem to be divided into smaller pieces which are less overwhelming. The stage-wise calibration procedure is presented in Figure 4-9.



solid arrows represent the dynamics actively modelled at each stage
doted arrows represent feedback loops between land use and transport

Figure 4-9: Conceptual calibration procedure

4.6.1 Calibration of the regional model

As mentioned earlier (section 4.3), the regional model dictates the land use demands which are passed on to the land use model. The regional model is first calibrated to allocate land use demands to each of the function land uses based on the number of activities per sector. The calibration entails identifying parameters for growth in productivity and the decrease in activity potential in each sector with distance from the zone.

4.6.2 Calibration and validation of the land use model

As discussed in section 4.4, the land use potential (equation 4) is influenced by several drivers. The parameters for each of these drivers need to be calibrated or determined. Therefore, the calibration procedure (depicted in fig 4-10) is done to determine and define the following:

- Firstly, the hierarchy of land uses is defined to determine whether land uses are easily converted to new land uses or are inert. Once this is determined, neighbourhood rules $(N_{k,i})$ are set for selected land use pair to represent the relationships and interactions,
- The accessibility $(A_{k.i})$ requirements for each land function is defined,
- The suitability $(S_{k.i})$ which plays a role in the potential of a land use to occupy a cell is determined,
- The zoning $(Z_{k.i})$which considers policy-related drivers which may influence the land use locations is set and
- Finally, the random perturbation $(r_{k,i})$ term which controls the degree of scattering of land uses and the formation of new clusters is determined (White & Engelen, 2003).

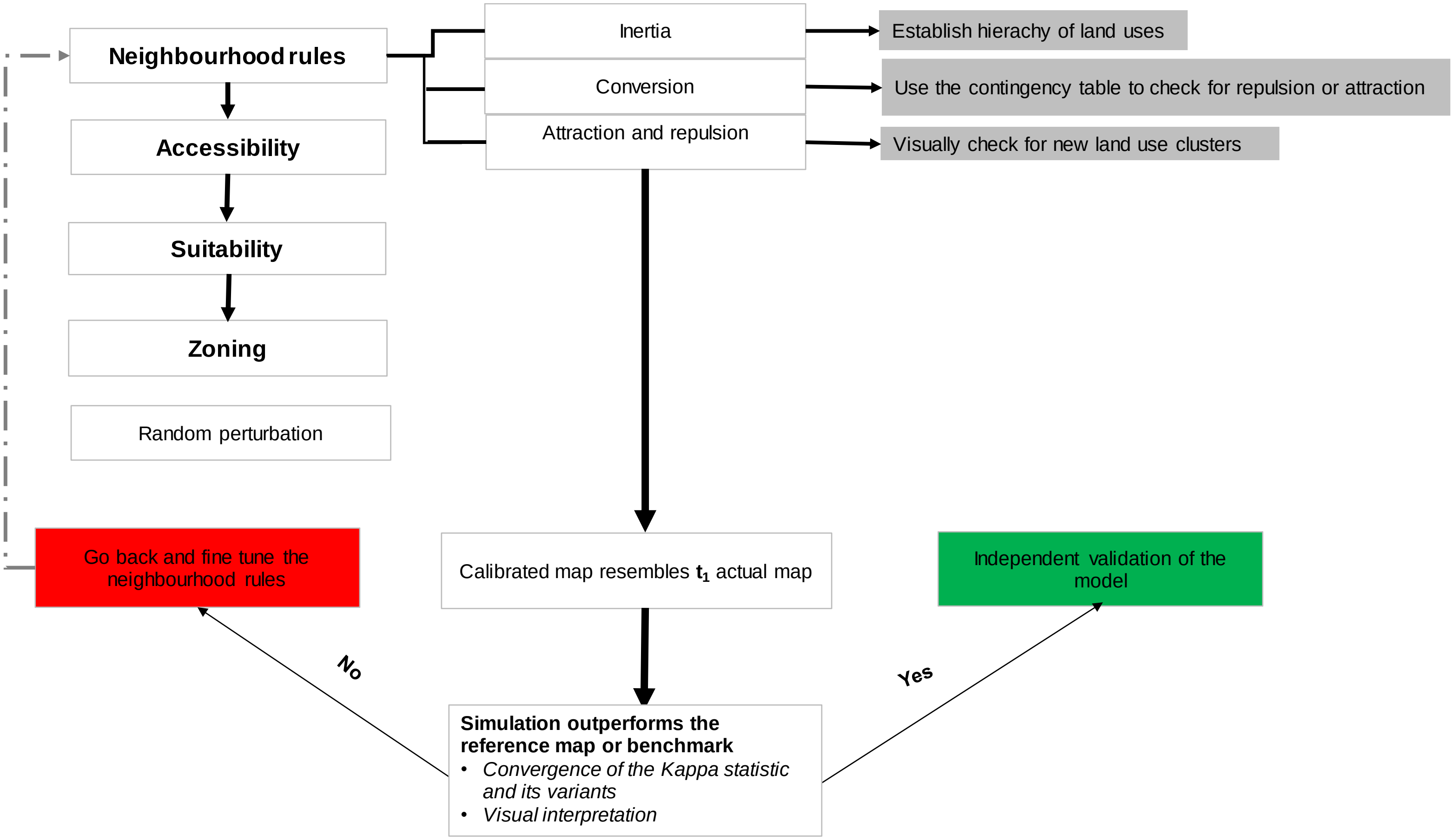


Figure 4-10: Steps in the calibration and validation of the land use model

4.6.3 Calibration and validation of the transport model

As discussed earlier, the transport model operationalised in METRONAMICA is a dynamic four-step model as presented in Figure 4-6. To simplify the calibration process, a stage-wise sequential calibration is implemented to calibrate the different parameters (discussed in section 4.5) in the different sub-models. Among some of the parameters that need to be calibrated, C_x^m, C_t^m and $C_{ext,l}$ can be derived from previous studies as they relate to costs associated with the mode used for each trip. This approach has been implemented in other studies Wenban-Smith, van Vuren, & Macdonald (2009), Shahumyan, Convery, & Casey (2010a) and Aljoufie, Zuidgeest, Brussel, et al. (2013). Further, the mobility growth parameter M_{tp}^p can be determined based on the forecasts on the change in mobility using different modes of travel; this can be from policy documents or previous studies as well. On the other hand, parameters such as trip generation rates can be determined based on the type of land use activity within a zone which can be based on traffic impacts assessment on trip generation rates. While historical data and previous studies provide a starting point in the calibration of some parameters, sometimes the calibration of parameters is based on trial and error methods; this is the case for parameters such as the distribution inertia, activity weight and zonal accessibility.

As the calibration is stage-wise, the land use dynamics are only incorporated when the link between the land use and transport model is introduced. However, as the land use provides activity locations and the productions and attractions, therefore, the land use map at Y_t acts as an input to the transport model. The model simulations are assessed at time Y_{t+1} to compare the model outputs to observed data. Once the model outputs are comparable to reality, the model is validated at time Y_{t+2}.. Section 6.4.4 provides details of the calibration and validation approach for the transport model applied in this research.

4.6.4 Calibration of zonal accessibility.

In the METRONAMICA land use transport model, the relational feedback is captured by the zonal accessibility (ZA_{min}) as discussed in section 4.5.4. This parameter is calibrated by determining the minimum zonal accessibility. The calibration of this parameter is based on trial and error and is evaluated based on the land use patterns simulated by the model. In calibrating the zonal accessibility, the sensitivity to cost ($\gamma_a^{activity}$) is also calibrated as it contributes to the allocation of activities to the different transport zone as shown in equation 23. Hence, in the calibration of the zonal accessibility, every new parameter introduced requires that the sensitivity to cost is revisited and adjusted.

4.7 Methods of assessment of the model blocks

Having discussed the calibration and validation of the M-LUT model, it is essential to discuss methods that are implemented to assess the calibration of the model. The METRONAMICA model has been implemented to explore future land use changes and transport for policy impact assessment (Barredo & Demicheli, 2003; Lavalle, Barredo, McCormick, et al., 2004; Shahumyan, White, Twumasi, et al., 2009; Wickramasuriya, Bregt, van Delden, et al., 2009; Shahumyan, Convery, & Casey, 2010; van Vliet, Hurkens, White, et al., 2012; Aljoufie, Zuidgeest, Brussel, et al., 2013). In each of these applications, the model has been calibrated to replicate either historical urban patterns and/or transport conditions. In some cases, the model has been validated thus providing an extra layer of information regarding the quality of the calibration and the behaviour of the model. However, the pertinent issue is, how to assess the results from the calibration and validation exercises especially when the model is potentially used for policy forecasting. Therefore, it is essential to establish a barometer on which to evaluate the quality of the model. In most cases, the development of a benchmark on which to compare the model is a sufficient assessment of the quality hence the validity of a model (Hagen-Zanker & Lajoie, 2008; Luo, Randerson, Abramowitz, et al., 2012). The assessment of the METRONAMICA is based on looking at individual model blocks as well as the integrated model.

4.7.1 Methods of assessment of the land use model

The procedures used to assess other urban change models are implemented to assess the METRONAMICA land use model block. Normally, this entails assessing the model simulations in year Y_{t+1} to the observed land use patterns. A Random Constraint Match (RCM) model can also be applied as a benchmark on which to assess the model performance (Hagen-Zanker, 2008; Wickramasuriya et al., 2009). For calibration or validation of the model to be acceptable, at the minimum, the model simulation results should outperform the benchmark. Various statistics found in the Map Comparison Kit (MCK) are utilised to assess the results from the calibration and validation of the land use model (Visser & De Nijs, 2006). Not only do these statistics facilitate the understanding of spatial changes in land uses but they also provide an avenue to understanding land use models. Using the MCK, the following aspects of the land use model are considered when assessing the performance of the model:

- Predictive accuracy
- Process accuracy

4.7.1.1 Predictive accuracy of the land use model

Predictive accuracy seeks to assess the extent to which the model can produce land use patterns that are similar to the region or environments under consideration (Brown, Page, Riolo, et al., 2005; van Vliet, Bregt, & Hagen-Zanker, 2011). Therefore, the assessment of the predictive accuracy looks at whether the land use changes predicted by the model are allocated in the right locations. The Kappa statistics and its variations are commonly implemented to measure the predictive accuracy of land use models (Barredo & Demicheli, 2003; Visser & De Nijs, 2006; Shahumyan, White, Twumasi, et al., 2009; van Vliet, Naus, van Lammeren, et al., 2013). Kappa measures the degree of similarity between a simulated map and an observed map and appreciates that similarity could be purely based on chance. This is usually the case for land use classes that are closely related. Another important aspect is to analyse whether the location of land uses changes over time especially for land uses that are known to persist in their location over time (Pontius, Shusas, & McEachern, 2004) for example residential land uses. In that regard, it is essential to be aware of high Kappa statistics as Kappa does not consider the persistence of land uses (Pontius & Millones, 2011)

For a closer look at the behaviour of the model, the Kappa statistic can be decomposed into Kappa location and Kappa histogram to verify the extent to which the model can predict near hits in land use simulation (Pontius, 2000; Hagen, 2002). Kappa location evaluates the similarity of the spatial allocation of land uses while Kappa histogram evaluates the quantitative similarity of land uses (Hagen, 2002).

The Fuzzy Kappa statistics is an alternative to the Kappa statistic as it identifies the global similarities between simulated and actual land use map. It applies fuzzy theory to address similarities in maps by identifying sections of the map where there are strong and small disagreements in the locations of land use classes (Hagen-Zanker & Lajoie, 2008). The ability of Fuzzy Kappa (FK) to account for locational differences makes it more suitable for the evaluation of land use models.

It is also important to differentiate between land use persistence and land use change in a model, Kappa Simulation (KS) and Fuzzy Kappa Simulation (FKS) can be used. Kappa simulation expresses land use transitions and whether the transitions are in the right location (van Vliet, Naus, van Lammeren, et al., 2013). Disaggregating the KS into Kappa transition ($K_{transition}$) and Kappa transition location ($K_{transloc}$) provides information regarding the accuracy of the model to locate land uses correctly ($K_{transloc}$) and whether the model can simulate land use changes

($K_{transition}$). This makes KS appealing in evaluating the predictive accuracy of urban change models (van Vliet, Bregt & Hagen-Zanker, 2011).

4.7.1.2 Process accuracy of the land use model

Process accuracy relates to the ability of a model to replicate processes that lead to land use changes similar to observed dynamics (Brown, Page, Riolo, et al., 2005; van Vliet, Naus, van Lammeren, et al., 2013). As urban systems are complex and unpredictable in their growth trajectories (White & Engelen, 2000; Yen & Li, 2001), methods used to assess land use simulations should consider the goodness of fit as well as the plausibility and feasibility of the model results. Moreso as feedback loops between urban processes result in land use patterns that are path dependent (Brown, Page, Riolo, et al., 2005; Manson, 2007). Path dependency is a measurable characteristic (van Vliet, Bregt & Hagen-Zanker, 2011) and process accuracy can be used to evaluate patterns of urban land use change in models. Specifically, the fractal dimension has been used to assess the process accuracy of land use change models (Clarke, Couclelis, & Clarke, 2005; Varghese & Singh, 2016; Hewitt & Díaz-Pacheco, 2017). The fractal analysis reveals the complexity of land use patches especially urban land (Clarke, Couclelis, & Clarke, 2005). In the assessment of calibration and validation, the fractal dimension for the simulated landscape is compared to the fractal dimension of the actual study area to compare how close the statistics are. The fractal dimension of a simulated map from a well-performing model should be close to the fractal dimension derived from the observed map.

4.7.2 Assessing the transport model block

Validating models is an integral part in assessing the performance of model (Wegener, 2004), yet the lack of historical data on which to validate models continues to be a problem. In the case of transport models, several approaches have been implemented to assess the performance of transport models. These methods are transferable in order to appraise the METRONAMICA transport model block. One of the approaches that has been implemented is the comparison of simulated transport indicators such as commuting distances to observed data. This has been implemented by Pfaffenbichler, Emberger & Shepherd (2008) to assess the calibration of the Metropolitan Activity Relocation Simulator (MARS) for Vienna. Simulated trip distances were compared to observed data based on the Vienna household survey. Another method is to compare simulated results to reference transport studies as applied in Aljoufie, Zuidgeest, Brussel, et al. (2013).

Benchmarking is also another approach where indicators based on model simulations are compared to other models. For instance, traffic flow simulated by METRONAMICA can be compared to the traffic flow simulated by other models. This approach has been implemented by other scholars Pfaffenbichler, Emberger & Shepherd (2008) to evaluate the performance of MARS land use transport model against UrbanSim (Waddell, 2002) and MEPLAN (Hunt, 1994).

4.7 Summary

This chapter introduced the METRONAMICA land use transport modelling framework. The chapter provided the theoretical underpinnings of the different model blocks and discussed the linkages between these models. More importantly, the chapter introduces the zonal accessibility which provides the linkage between the land use and transport model. The concept of the dynamic transport model is introduced by discussing the deviation of the METRONAMICA trip distribution model from the one implemented in the conventional four-step model.

Another important aspect that emerges in this chapter is that transport modes are divided into exogenous (public transport) and endogenous (private cars) where the endogenous mode is used to explicitly assign traffic onto the network. This means that the private car is the only mode that contributes to congestion. This is one area of the model where the transport model implemented in the present study deviates from the generic applications such as Aljoufie, Zuidgeest, Brussel, et al. (2013) and Perez, Wickramasuriya, Forehead, et al. (2017). This is discussed in detail in Chapters 5 and 6.

The chapter also discussed the calibration and validation of the model which led to the discussion on the methods used to appraise the model. Regarding the land use model, the discussion on the assessment focused on the predictive and process accuracy using the Kappa statistics and associated variants. The shortcomings inherent in using the Kappa statistic as a method of assessment are discussed, and the Kappa Simulation and Fuzzy Kappa Simulation are introduced as alternative methods. The fractal dimension is also discussed as a method of assessing the process accuracy of the model. Furthermore, the chapter introduced the Random Constraint Match (RCM) as a tool that can be used as a benchmark on which to assess the performance of the land use model block.

The chapter concludes by discussing the methods that can be implemented for appraisal of the transport model block. Benchmarking was identified as an approach that can be used to assess the transport model. An important aspect identified in this chapter is that there are no specific methods that are utilised to assess the METRONAMICA land use transport model;

instead, assessment methods from other land use transport models can be implemented to evaluate the performance of the METRONAMICA model.

Chapter 5

Data preparation and processing

5.1 Introduction

The previous chapter introduced the METRONAMICA land use and transport model which is implemented in this research. Further, the different model blocks were discussed which introduced the datasets that are inputted into the model. This chapter discusses the datasets utilised to set up, calibrate and validate the model. It also discusses the decisions that were made in preparing the data, challenges encountered, and decisions take to circumvent these challenges. Among other things, Chapter 1 discussed the temporal extent of the land use and transport model utilised in this research. Based on that, the Cape Town model was set up to simulate land use and transport changes between 1995 and 2005 and validated for the period 2005 to 2013.

The model developed in this research is also used for exploratory policy scenarios. Hence, scenario settings and specifications had to be included in the design and development of the model. The policy scenarios evaluated in the model among other things reflects on some of the land use plans discussed in the City of Cape Town's Built Environment Performance Plan. The scenarios relate to redressing social exclusion by locating low-income housing in areas with well-developed infrastructure and exploring the growth of informal settlements. For the model to simulate these scenarios, residential areas are delineated by income with informal settlements having a separate category. The details and rationale for each of the scenarios are discussed in Chapter 7. The datasets required for the model are presented in Table 5-1.

Table 5-1: List of data required for the model

Land use model	Transport model	Regional model
Land use map	Transport zones	Census data
Road network shape files	Number of trip origins	Employment data
Regions maps	Number of trip destinations	Population data
Residential Income classifications	Trip purposes	Economic sectors
	Transport network	
Suitability map	Speed limit	
Slope map	Capacity	
Floodplain layers	Travel-related costs	
Biodiversity network	Transport network	
Zoning maps	Traffic flows	
Heritage and biodiversity map	Travel distances	
Urban development zones	Travel times	
Road networks	Time periods	
	Transport modes	

5.2 Land use model data

This section discusses the data that is utilised by the land use model block. Further, the data that is used in the calibration and validation is also discussed.

a) Land use maps

The unprocessed land use data for the study was in the form of polygons. Land use maps for the Cape Town metropolitan area for the years 1995, 2005, 2010 were collated from several sources. The original land use map files had land uses within the maps categorised into eighteen land use types. Like in section 2.3.1 the land use categories were reclassed into nine land use categories with residential areas delineated by income using the income groups within the Census, 1996, 2001 and 2011 (STATSSA, 2014). The methods implemented to delineate income were already discussed in section 2.2.

As discussed in Chapter 4, METRONAMICA classifies land uses as either function, vacant or features land use classes. The classification of land uses into either vacant, feature and function land uses was influenced by the role of policy in the location of land uses and also by the potential relationships that exist between the different land uses. This was an important aspect to consider as policy influences the change in the urban landscape. The classifications for each land use for the Cape Town application are presented in Table 5-2.

Table 5-2: Land use classification

Vacant	Functions	Feature
Agricultural and animal husbandry services	High-income residential	Education and Campuses
Potential commercial zone	Middle-income residential	Health services
Potential resident zone	Low-income residential	Recreational services
Vacant undeveloped land	Informal housing	Religious, cultural activities
	Manufacturing services	Government/Military facilities
	Trade and services	Utilities and infrastructure
		Nature reserve
		Airport

Land use maps in raster format were prepared in ArcGIS. One of the observations made in the preparation of the data was that there was an inconsistent classification of religious or cultural activities and recreational areas between in the 1995 and 2005 land use maps files that were collated. Further, there were also some land use patches which were vacant or built-ups per field observations, but on the maps, they were classified as either built or vacant. The land use patches were reclassified into their correct category. It was also observed that most of the misclassified land uses were feature class. While these land uses are not dynamically modelled, the proximity of some of these land uses to function land uses is potentially important during the calibration and validation of the model. In cases where the proximity of a land use to a feature land was deemed important, an interaction rule for the feature class and the function land use was introduced.

This is especially important as map comparison techniques are implemented to assess the differences between simulated maps and real land use maps in land use models (Visser & De Nijs, 2006; Hagen-Zanker & Lajoie, 2008). Hence, these discrepancies in data classification might be reflected in the results as a shortcoming in the ability of the model in simulating certain land use categories. Figure 5-1 shows the processes involved in the data preparation, while Figure 5-2 show the final land use maps produced.

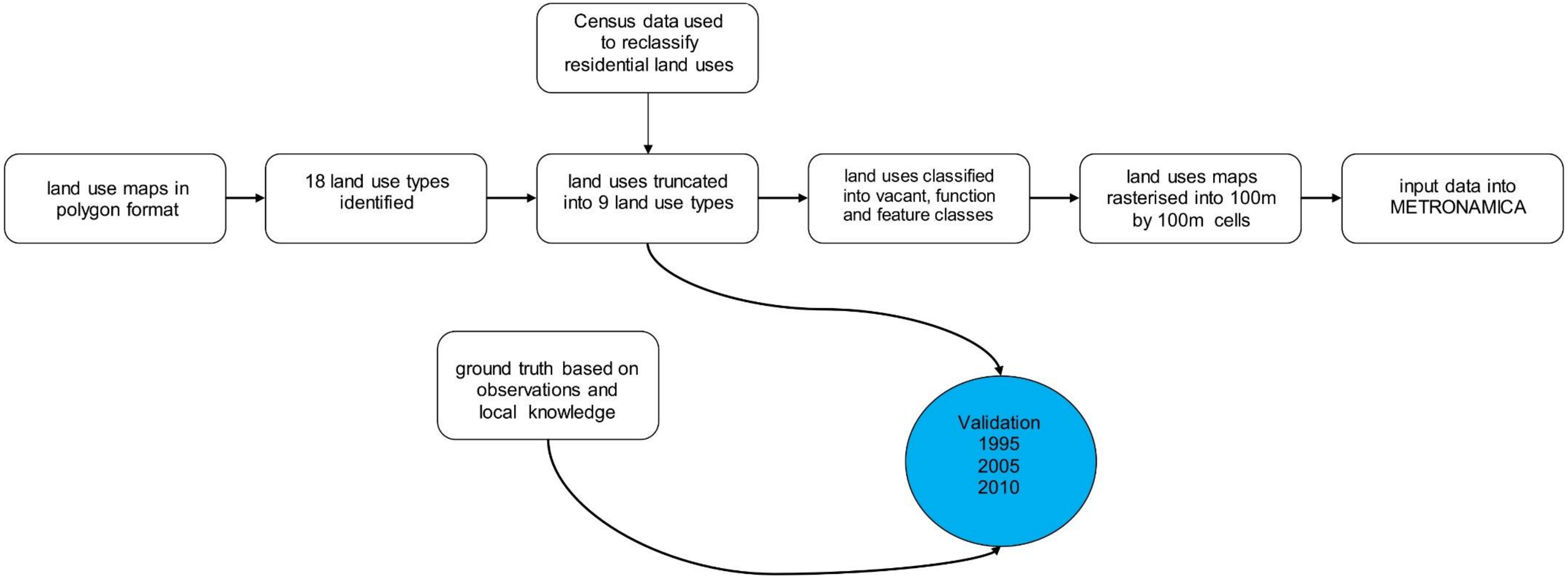


Figure 5-1: Land use map processing

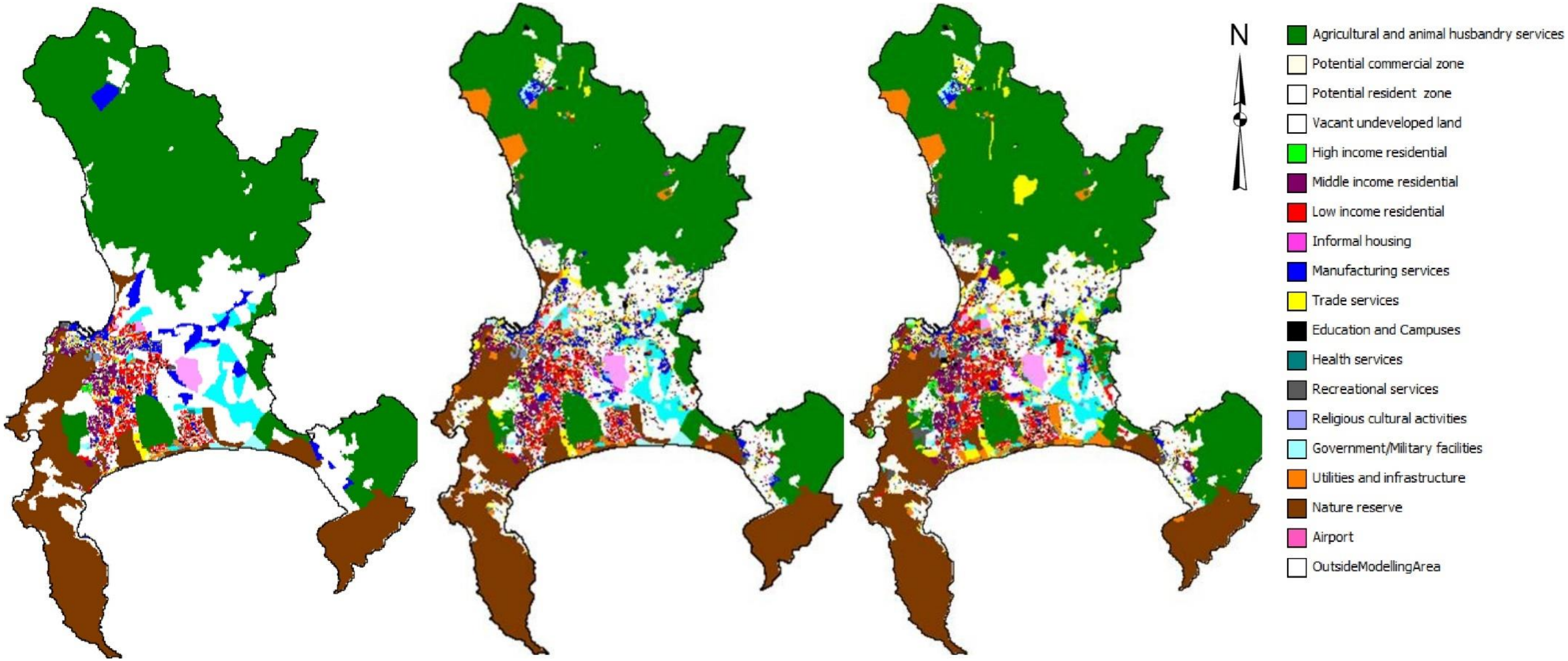


Figure 5-2: Land use map 1995, 2005 and 2010 respectively

b) *Spatial extent*

The scale used in models affects the relationship and interactions that exist between different land uses (Costanza, 1989; Kok, Farrow, Veldkamp, et al., 2001). Additionally, land use models rely on generalisations of reality and in cases where the spatial extent used is coarse there is a tendency of these models to simulate land use maps that have high spatial similarities with actual land uses (Costanza, 1989; Pontius, Huffaker & Denman, 2004). Consequently, this implies that the choice of spatial extent is a critical decision when setting up land use models.

As mentioned earlier, the land use model block incorporated in the M-LUT is a cellular automata-based land use model where land uses are represented on a grid of cells. While both coarse and fine cell resolutions can be used, this has an impact on the processing time and the possible conclusions especially those relating to the goodness of fit of the model as discussed in Kok, Farrow, Veldkamp, et al. (2001). Previous applications in the METRONAMICA platform have used cell size that ranges from 25m-1000m (Castilla & Hay, 2006; Shahumyan, White, Twumasi, et al., 2009; Aljoufie, Zuidgeest, Brussel, et al., 2013). For this study, a cell size of 100 m by 100 m with an eight cells radius was used. This translates to a neighbourhood radius of 0.8km which delineates the influence area of urban land use classes. This was concluded as a cell size that was not too coarse leading to an aggregation of land uses which has the potential of confusing high spatial matching to high model performance (Kok, Farrow, Veldkamp, et al., 2001). On the other hand, this spatial resolution allowed for the transport network to be visualised in relation to the land uses.

c) *Temporal extent for calibration*

The research focuses on understanding land use and transport interaction in post-apartheid Cape Town. The land use model was calibrated to simulate land use changes between 1995 and 2005 while the transport model was calibrated to assess transport conditions between the period 1995 to 2003. The validation of the land use model was set from 2005-2010.

The availability of data dictated the approach implemented to validate the transport model. Two validation specifications 2003-2010 and 2003-2013 were used for the transport model. Each of these periods was used to assess different aspects of the transport model. This is discussed in section 6.1.5. The integrated model was validated for the period 2005-2010 to assess the applicability of the model to understand the temporal dynamics of transport and land use in Cape Town.

Accordingly, for policy-related scenarios, the forecasting period was set from 2010 to 2030. The rationale for choosing this forecasting period is that there are land use developments that the City of Cape Town has suggested in the Integrated Transport Plan and the Built Environment Performance Plan. Hence, this exploratory period presents an opportunity to discuss the value that LUTI models like the one implemented in this research can have in providing insights into land use transport policy and their implications. Furthermore, it provides an opportunity to compare the outcomes that the city forecasts from their policy aspirations and those developed in this research.

d) Suitability maps for land uses

Suitability represents the degree to which a cell location is appropriate for occupation by a land use as discussed in section 4.4.4. Physical characteristics determine whether a location is suitable for a land use. Locational suitability is an important driver of land use change and therefore should be incorporated into land use models. Hence, for the CTMR_LUT model, the suitability maps for each of the function land uses were calculated in ArcGIS. The input maps used to calculate suitability include:

- Biodiversity network for Cape Town
- Slope layer
- Floodplain layers
- Land use maps

The biodiversity network demarcated protected areas where land use development is not allowed. The floodplain layers also showed areas that are prone to flooding where there is no land use development from 1995 to 2013. Though some urban land uses are on areas prone to flooding, the 50year and 100year flood layers were used to check for flood-prone areas especially beyond 2013. Further, the land use maps were also useful as they provided more information relating to the neighbouring land uses and the state of a cell at different time steps. This was especially useful in determining the class boundaries for the suitability layers. Based on these layers, one suitability map was generated for all function land uses from 1995 to 2010 and is presented in Figure 5-3.

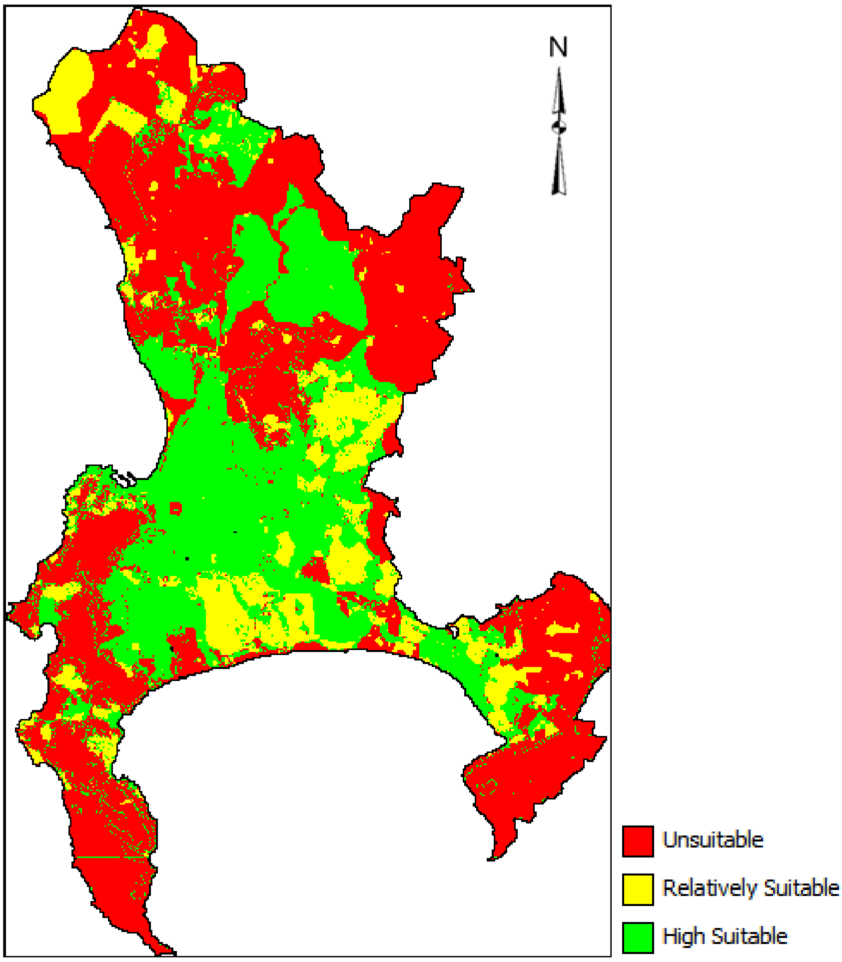
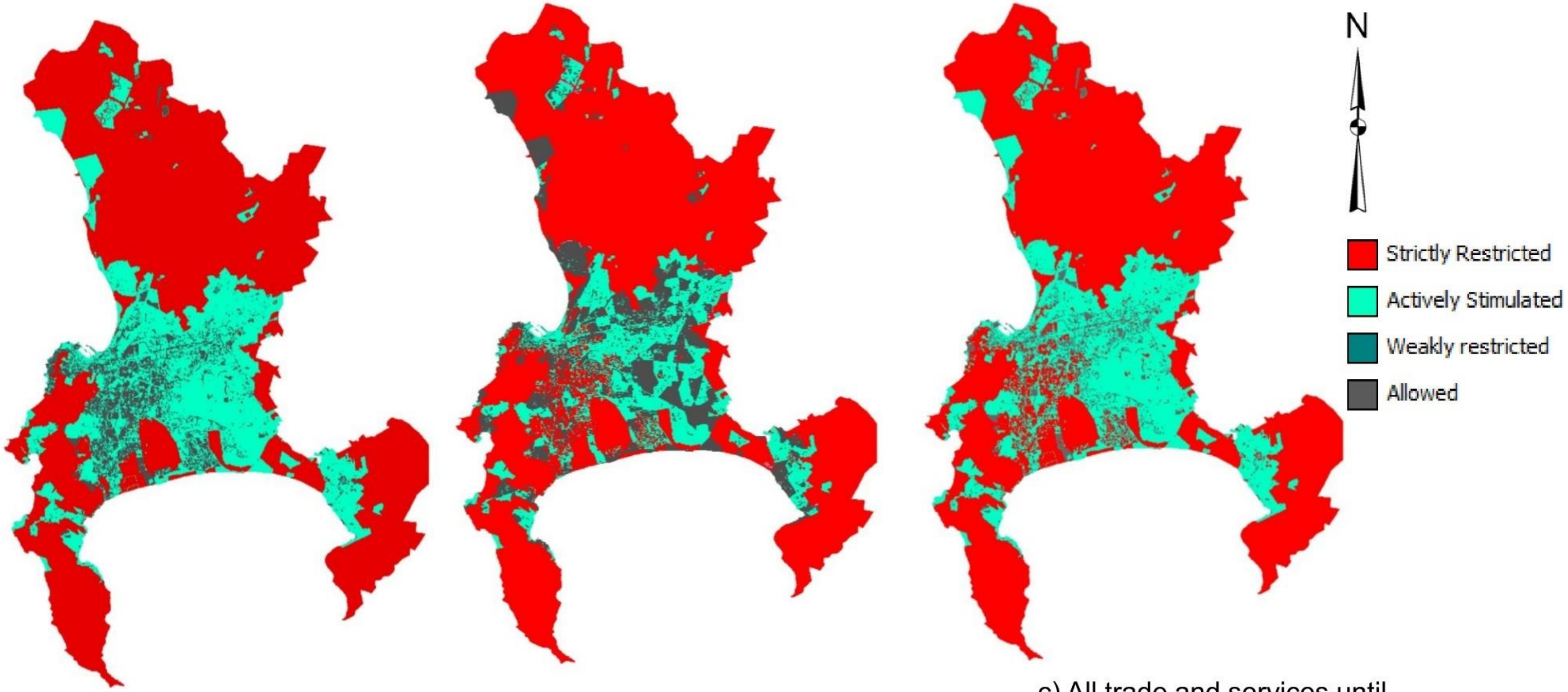


Figure 5-3: Suitability map for all function land uses

e) Zoning map

The Cape Town Development Management Scheme (DMS) which is part of the City of Cape Town Municipal Planning by-Law, 2015, provides the basic guidelines for the land use and development system for the city. An assumption made in the preparation of the zoning maps was that once a land use is permitted to occupy a certain cell, it would be allowed to do so for the duration of the simulation. In Chapter 2, the Urban Development Zone (UDZ) tax incentive was discussed as an initiative to revive the inner city and to also unlock low-income housing in areas with established infrastructure. In addition to the DMS, the Urban Development Zone was introduced as an additional zoning map to direct land use development in the city. The lack of clear and consistent zoning schemes made it difficult to have separate zoning maps for individual land uses. The zoning maps implemented in the calibration and forecasting period are presented in Figure 5-4.



a) All residential areas until 2030

b) All manufacturing services until 2030

c) All trade and services until 2030

Figure 5-4: Zoning maps for function land uses

5.3 Regional model data

Section 4.3 discussed the regional model within the M-LUT model components. As mentioned earlier, the regional model allocates the macroeconomic aspects such as population and employment to the different land use activities. Therefore, the data that is included in this model block population data, number of jobs, income and residential classification and other socio-economic aspects.

a) Socio-economic data

All modelling blocks within the CTMR_LUT model make use of socio-economic data either as an input or for calibration and validation of the model. The following datasets were essential:

- Population data
- Employment data for the different sectors
- Income data
- Residential classification data

b) Population data

Several datasets from Stats SA were used to collate the population data for Cape Town mainly census (1996, 2001 and 2011), the Community Survey (2001, 2011, 2012, 2014). This was also used to determine the population growth trends in Cape Town. The 1996 data was used to interpolate population data for 1995. Population projections for the calibration and validation process were based on the World Population Review (World Population Review, 2017), population projects from the City of Cape Town EMME model briefly discussed in section 3.10 and statistical data for the Western Cape regional profile (Western Cape Provincial Treasury, 2012).

c) Economic sectors -employment data

As in the case for the population data, the Census 1996, 2001 and 2011 data were used to determine the Cape Town labour force. An observation that was made during the processing of the labour force data was the difference in the reporting of employment data between the 1996 and 2011 census data. In the 1996 census, ten employment sectors were reported while for 2011 employment sectors were aggregated into the formal and informal sector. The quarterly labour force data was used to disaggregate employment data in the 2011 census.

Further, ancillary data such as the growth in employment and unemployment rates from the socio-economic profiles of the City of Cape Town were used to supplement the data. However, the study only focused on data relating to formal employment as this is well documented and more accurate at the municipal level. Additionally, looking at the transport infrastructure in the city, it is centred around access to formal job opportunities which makes it difficult to identify the trip ends for the informal sector. Economic sectors were aggregated into three main sectors; manufacturing services, population, trade services.

d) Income groups

Income was used to delineate the different residential areas in Cape Town. Three income groups were used in the model:

- High-income
- Middle-income
- Low-income

Section 2.2.2 discussed the income ranges for each of the income groups. Based on these income categories, three residential land use types were defined:

- High-income residential
- Middle-income residential
- Low-income residential

5.4 Transport model data

This section discusses the data used in the transport model. There was no readily available transport data relating to trip productions and attractions and the subsequent initial trip matrices. Therefore, to derive the productions and attractions for 1995, several sources such as the Census (1996, 2001), October Household Survey (OHS 1995,1997), National Household Travel Survey (NHTS, 2003) and previous transport studies by the City of Cape Town were used to interpolate the data. The transport zones utilised in the model were interpolated from the 2013 City of Cape Town EMME model.

5.4.1 Transport zone refinement

The transport model simulates traffic condition such as congestion on the transport network. Further, the transport network facilitates accessibility and mobility between spatially separated land use activities in different transport zones (RIKS, 2012). Therefore, a transport zone map with clearly demarcated zonal boundaries was required. Over the years, the Transport Analysis Zones (TAZs) for Cape Town have changed. Therefore a starting reference for the transport zones was required. Currently, the City of Cape Town's EMME model has 1,787 zones. For this research, this number of zones was considered too large as it would require a long processing time to simulate the model. Further, acquiring all the data at such a detailed level of analysis was also difficult. The EMME transport zone map was used as the starting point from which to define the transport zones for the Cape Town model. The following criteria in sequential order were used to modify the transport zones:

- Transport zones that were outside the City of Cape Town's municipal boundaries were first deleted;
- After that, the transport zones that were small and had only one land use class were combined with the nearest transport zone. Since an eight-cell radius is implemented in this study, with one land use over a long distance, there are limited land use dynamics that can be represented. The transition potential for a land use in that zone is almost fixed over a long period as there are no interactions within the immediate neighbourhood. However, given that a regional model is incorporated in this research, it is still possible to model aspects such as land use and activity densities that interact over longer distances (White, Uljee, & Engelen, 2012);
- The final step was to ensure that trips relating to the merged transport zones were added to the total number of trips of the new transport zone.

The final transport zone map consisted of 154 TAZ compared to the initial 1787 zones. There are potential implications related to truncating the TAZs as it might result in the under or over-estimation of trips origins and destinations for some transport zones.

Another consideration in the preparation of the transport zone map was that the centroid for each zone needed to be defined. In the M-LUT, it is assumed that all trips originate and terminate at the centroid of each transport zones through the special nodes. Therefore, XY coordinates for each centroid were generated in ArcGIS for each transport zone. Figure 5-5 shows the transport zones in the Cape Town EMME model and those utilised in the CTMR_LUT model. From the figure, it is clear that the transport zones utilised in the EMME model cover a larger spatial extent extending to the Cape Winelands whereas the transport network utilised in this research only consider the Cape Town Metropolitan region.

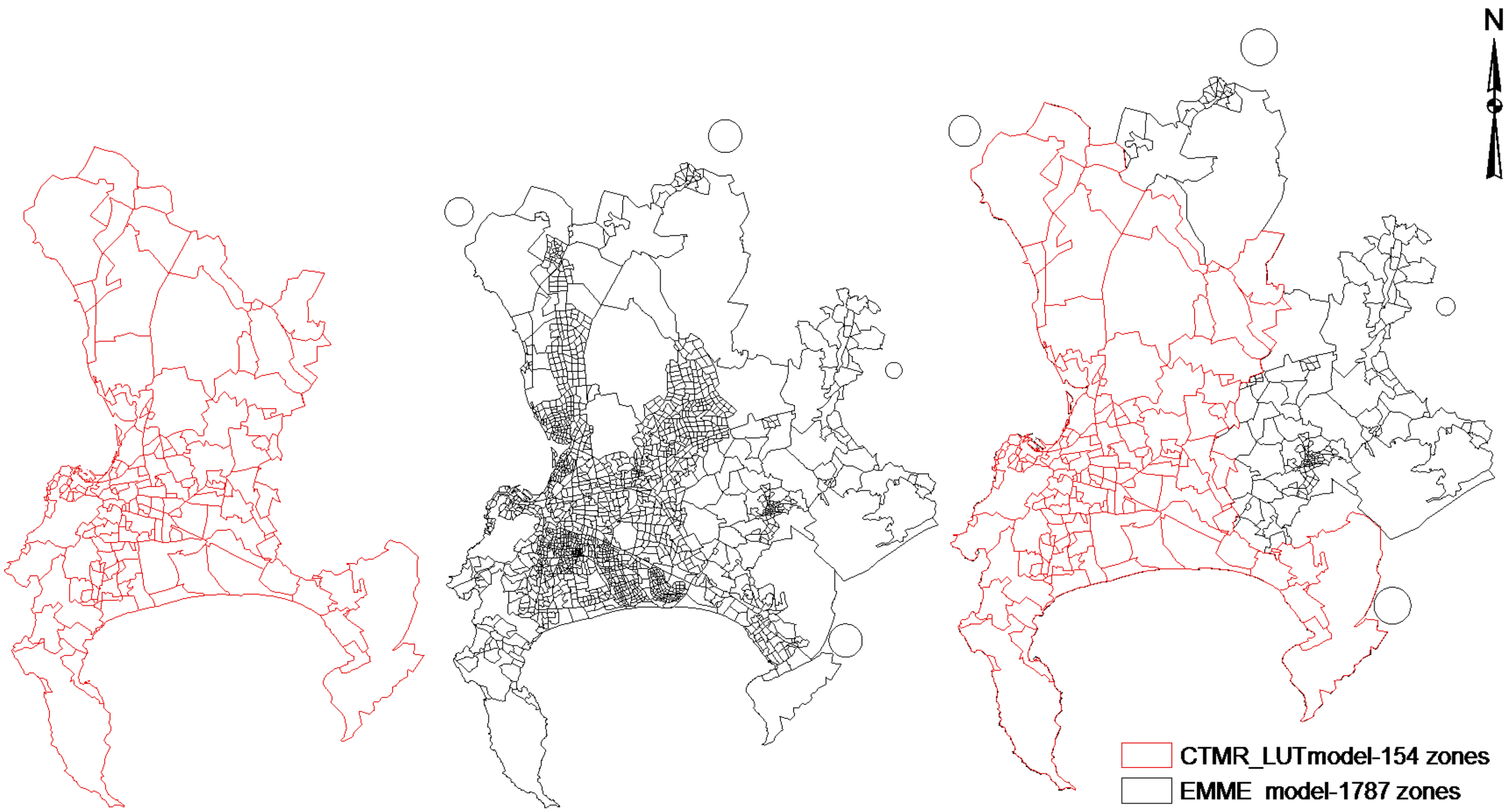


Figure 5-4: Comparison of transport zones

5.4.2 Road network

Accessibility defined as road network connectivity can be used to understand the relationship between different land uses and the importance of a road network in facilitating access to land use activities (Bertolini, le Clercq, & Kapoen, 2005). Hence, in most land use transport models, accessibility is utilised to provide the link between land use and the transport components. The 2000 road network was used as an initial road network layer for the model. The road density in the 2000 layer was very high as it included almost all road network links in Cape Town links in the City including links that only contribute to local accessibility using walking as a main transport mode. The road network was modified such that all links which only provided local accessibility (mostly accessing the neighbourhood) were excluded in the modelling exercise. These links do not contribute to the land use transport dynamics in the model.

Road network changes are included for both 2002 and 2006. An analysis of road network density showed that significant transport infrastructure changes were only related to minor roads; linked to the growth of urban areas. Hence, these changes would only be prominent in the land use model as these roads contribute mostly to local accessibility. The MyCiti network development in 2010 is also another major road network change which was observed. However, this coincides with the end of the validation period. Though the trips by train are not included in the study, the rail infrastructure was incorporated to allow for the impact of the train infrastructure on the land use dynamics. This is especially important in the forecasting period where different land use development scenarios are explored.

Additionally, the METRONAMICA modelling framework assumes that all trips begin and end at the centroid of a transport zone. Therefore, an abstract link (special link or connector) as discussed in section 4.5.3 was added from the centroid of each transport zones to the nearest transport link to facilitate the movement of traffic from the centroid to the road network. The final road network is an undirected network with traffic allowed to pass in both directions on a link.

In the M-LUT, the road network is defined to consist of separate links. For the model to compute traffic flow, the road network links must be connected such that road segments and their associated characteristics such as speed and capacity are clearly defined. Further, in the model, the network structure should ensure that each transport zone node can be reached from every other node with no “breaks” in the road network layer. Network “breaks” result in the model failing to simulate traffic between transport zones. Therefore, the Network Analyst tool in ArcGIS was used to assess the road network characteristics. In instances where “breaks” were identified in the road network, the road network was manually edited to ensure connectivity. The datasets needed to ensure network connectivity include the road network layer, centroids and transport zones a shown in Figure 5-6. In the final road network, all zones were accessible from every other zone.

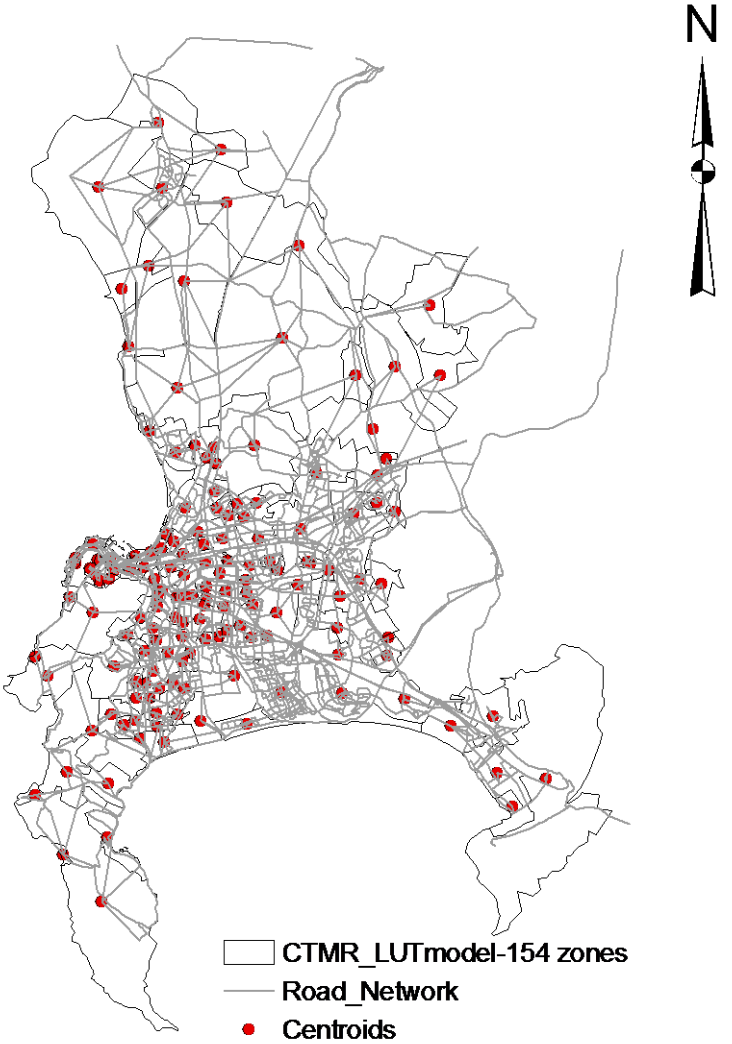


Figure 5-5: Data set to assess the network connectivity

For METRONAMICA to read the road network file, the database linked to the shapefile should have attributes presented in Table 5-3. The attributes, *AccType* and the *RoadType*, are perhaps the most important attributes as they provide information to the model regarding the accessibility each road network link type provides. Hence, there is a need to differentiate between the road network links that facilitate only local accessibility in the land use model and those that contribute to zonal accessibility in the transport model block based on these two attributes. The accessibility type *(AccType)* is used to identify the road network links that are implemented in the land use model in the calculation of the local accessibility. On the other hand, the road type *(RoadType)* is used to determine the link types for the transport model and helps the model to identify links that contribute to local and zonal accessibility. Road tax considers the cost associated with using a road network link. In the Cape Town case, this was set to zero as there are no road tolls between the modelled suburbs. For further explanation of the other variable, see (RIKS, 2012). In the present study, given that the road network density was reduced to remove small links that only contributed to local accessibility, it was assumed that the remaining road network links influenced both the land use and transport model; as some local accessibility links were also used to feed traffic to the freeways.

Table 5-3: Mandatory attributes in the road network

Description	Field name	Unit
Accessibility type	AccType	
Road type	RoadType	
Free flow speed	SpeedLimit	kilometres/hour
Road capacity	Capacity	cars/hour
Road length	Length	metres
Road tax	ExtraCost	€

The capacity of a link determines the maximum number of vehicles (cars) that can pass through a link per hour (RIKS, 2012). Given that the model only considers road-based transport, the capacity was calculated based on private cars (RIKS, 2012) as passenger car equivalent is used in the model to convert traffic on the network. The road network shapefile included road capacity values; however, for links with missing capacity values, this was calculated based on equation 29 (RIKS, 2012):

$$\text{Capacity per link} = \frac{\mathrm{N} \times 3600}{\mathrm{T}_h + \dfrac{3.6 \times L_{\text{avg}}}{\mathrm{U}_{\max}}} \tag{28}$$

where:

N= number of lanes in one direction

$\mathbf{T}_{\boldsymbol{h}}$=time headway between two cars assumed to be 1.5 seconds

$\boldsymbol{L}_{\mathbf{avg}}$= average car length in metres

$\mathbf{U}_{\mathbf{max}}$ = maximum speed limit in kilometres per hour

An average car length of 5 metres was applied to calculate the link after Bester & Silva (2012)

5.4.3 Train network and train stations

Though the trips by train are not included in the transport model, the influence of the train infrastructure on the land use dynamics is still explored. The infrastructure includes the Metrorail and the stations; these are mainly considered as infrastructure that influences local accessibility hence only influencing the local accessibility Figure 5-7 shows the unmodified transport network, road network and Metrorail lines infrastructure that is implemented in the research.

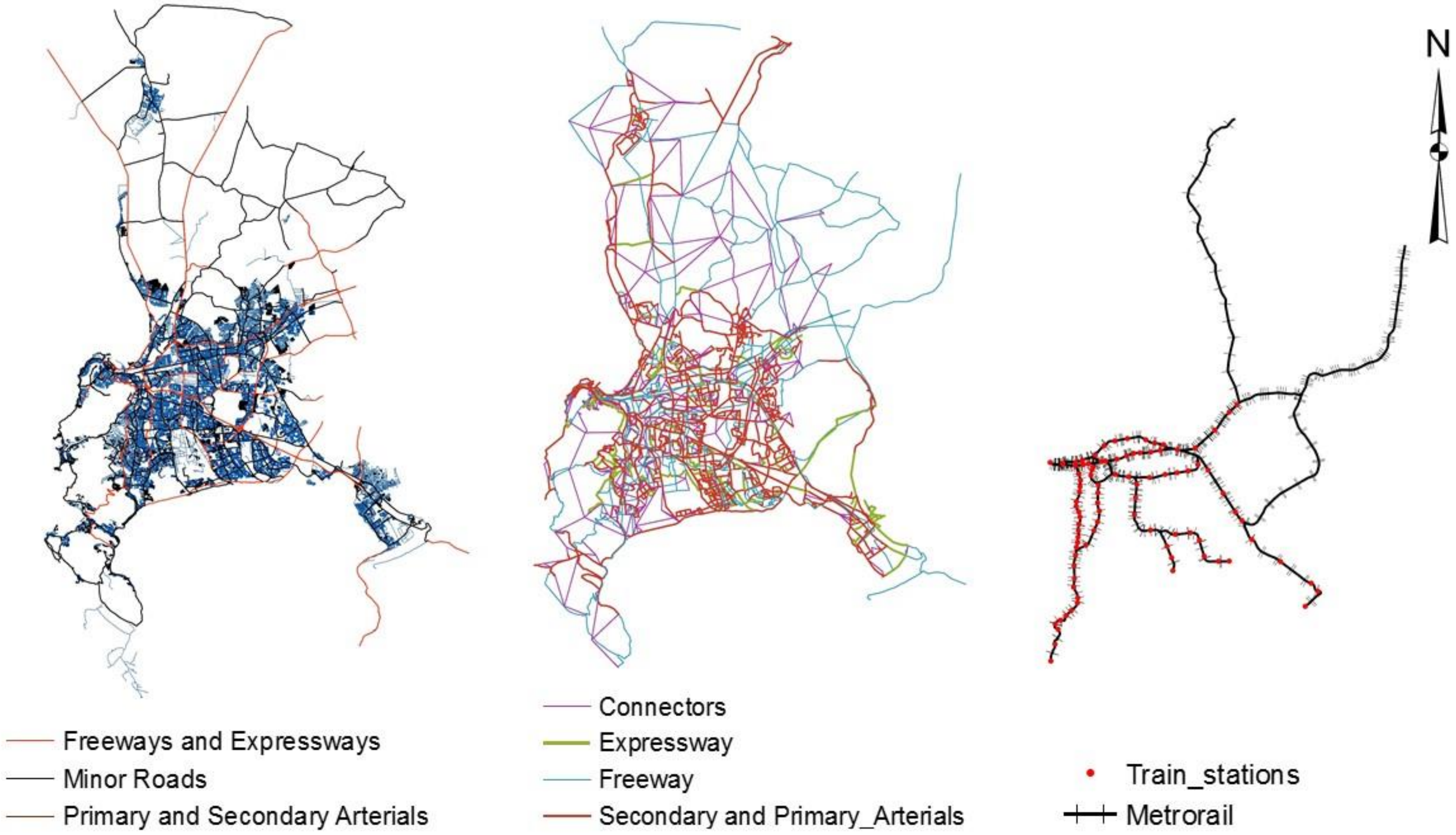


Figure 5-6: Transport infrastructure layers

5.5 Transport model adaptation data Cape Town

As mentioned earlier, the present model diverges from other METRONAMICA applications such as (Aljoufie, Zuidgeest, Brussel, et al., 2013; Perez, Wickramasuriya, Forehead, et al., 2017) by using two endogenous modes: i.e. the private car and the minibus taxi. In previous applications, only private cars are explicitly modelled to assign traffic on the transport with other modes defined as alternative modes hence exogenously modelled as discussed in section 4.5. However, in the Cape Town context, this approach would be inadequate in explaining transport and the related land use dynamics. Therefore, the following aspects were considered important in the formulation of the METRONAMICA application for Cape Town:

- The transport user system in Cape Town constitutes of formal and informal modes of transport;
- The mode choice decision in Cape Town.

The Cape Town road-based transport user system is comprised of both formal and informal modes of transport which utilise the transport network. The general pattern is that high-income individuals use private cars while the low-income utilises minibus taxis and other modes of public transport (Hitge & Vanderschuren, 2015). What this means is that low-income earners have limited options with regards to mode choice and therefore are captive to public transport in this case minibus taxis. This makes the mode choice problem for this cohort of individuals one-dimensional. Hence considering both private cars and minibus taxis as core modes obviates the assumption that private cars are the only mode with high intensity on the road network which has the potential of resulting in wrong assumptions regarding congestion levels. Therefore, incorporating minibus taxis in assigning traffic on the network (endogenously modelled) allows the model to calculate the contribution of minibus taxi to congestion.

5.5.1 Identifying trip productions for the model

Several matrices were used as inputs in the transport model. Since the model was simulated from 1995, the first step was to identify the initial trip productions and attractions for each of the transport zones for the year 1995. Several data sources were used to populate the matrices, mainly, the Census (1996, 2001), October Household Survey (OHS,1995, 1997), National Household Travel Survey (NHTS, 2003) and previous transport studies by the City of Cape Town. The census data was used to determine the population and labour force for suburbs within the different transport zones. Further, the different land use types and building structures in each zone were identified, mostly focusing on commercial and manufacturing services as they are key employment generation activities. The discussion in section 2.2.2

and Table 2-1 provided a detailed description of the delineation of different land uses and the land use category they fall under.

However, additional analysis was required given that the transport model requires more detail on trip generations for different residential areas. Therefore, building structures in the different suburbs were evaluated mainly focusing on whether the buildings were multi-story buildings, schools, commercial areas, mixed land uses and so forth to get a sense of the type of trips that originated and terminated in each zone. This information was then used to determine the trip generation to use as per the South African trip generation rates manual (CoTO, 2013) for the different suburbs. Where building structures and suburbs reflected mixed land uses, an average trip generation rate was calculated. In the preparation of the trip generations, it was assumed that the number of trips produced in a zone was equal to the number of trips attracted to a zone. Thus, a double constrained approach was adopted in the development of the trip generation as discussed in section 4.5.1.

There are standard trip purposes that are reflected in the census and National Household Travel Survey (NHTS) in South Africa. These were used to inform the trip purposes for this study. Therefore, three core trip purposes were defined based on earlier transport models and census data (Lombard, Cameron, Mokonyama, et al., 2007; TDA, 2012):

- Home-work- comprises of all work-related trips that originate and end at home;
- Home-education- comprises of all education-related trips (mainly tertiary, high school and primary) that originate from home and end at home;
- Home-other- comprises of all other trips (recreational, social, shopping, among others) that originate from home and end at home

As mentioned earlier, the METRONAMICA in its current state only utilises one endogenous mode while the current modelling exercise requires two endogenous modes. Therefore, to incorporate the two endogenous modes within the software limits, the initial trip matrix data was further segmented such that it reflected the trip purpose. Figure 5-9 shows the delineation of trip purposes by transport modes.

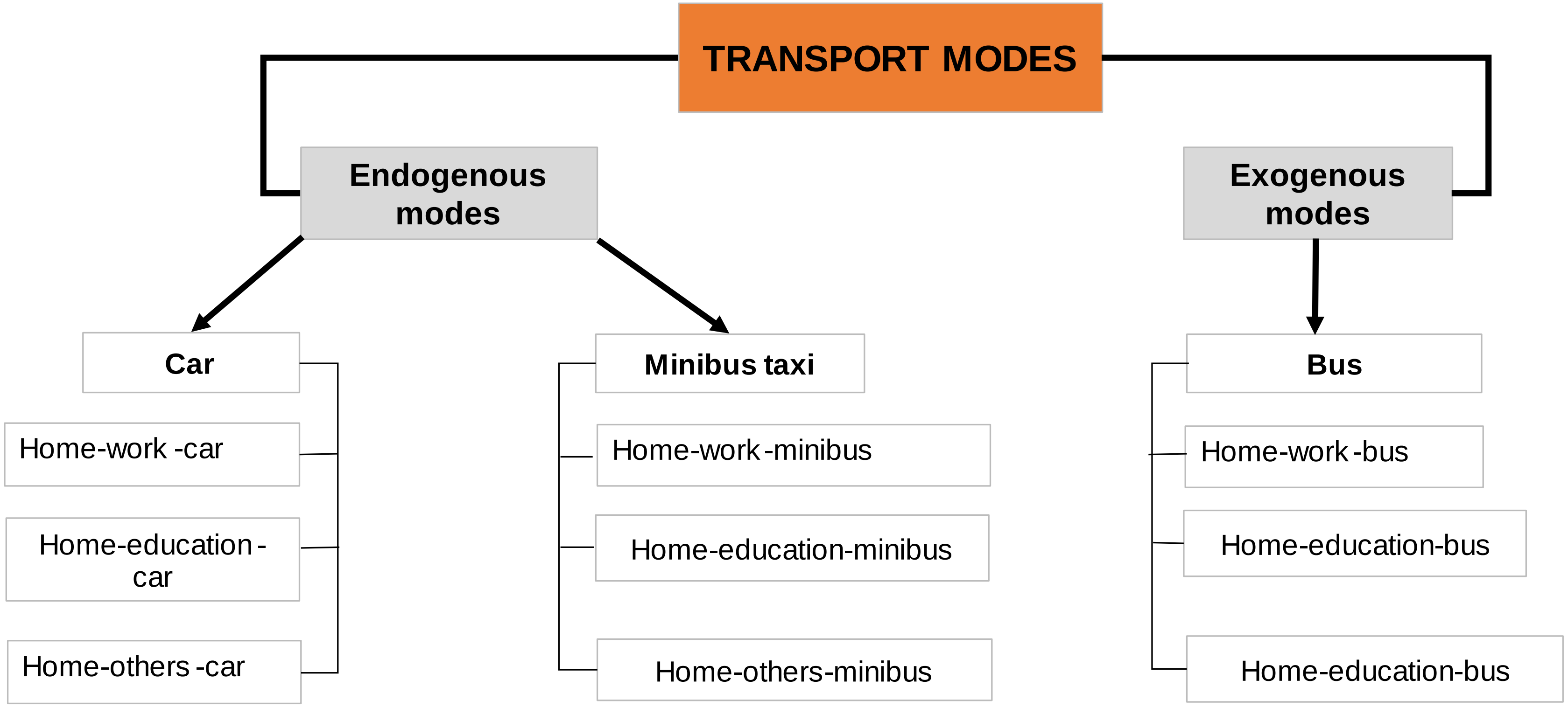


Figure 5-7: Delineation of trips by purpose by mode

5.5.2 Trip distribution matrices for each trip purpose for all transport modes

The trip distribution matrix is prepared for a representative hour for the morning peak and the rest of the day. The trip generation rates discussed in section 5.5.1 were used to calculate the trip distribution across all transport zones. The generalised cost of travel which represents the disutility to travel is normally calculated based on time, money, the distance among other attributes to determine the distribution of trips in the different zones (Ortuzar & Willumsen, 1994; RIKS, 2012). For this study to formulate the initial trip distribution, only the distance was used. This was used to calculate the impedance to travel hence distributing trips across the different origins and destinations. Hence, the friction of distance function formulation used in calculating the initial trip matrix is represented in the equation below.

$$F_{ij} = \frac{e^{-\delta D_{ij}}}{\sum_{i,j} e^{-\delta D_{ij}}} \tag{29}$$

where

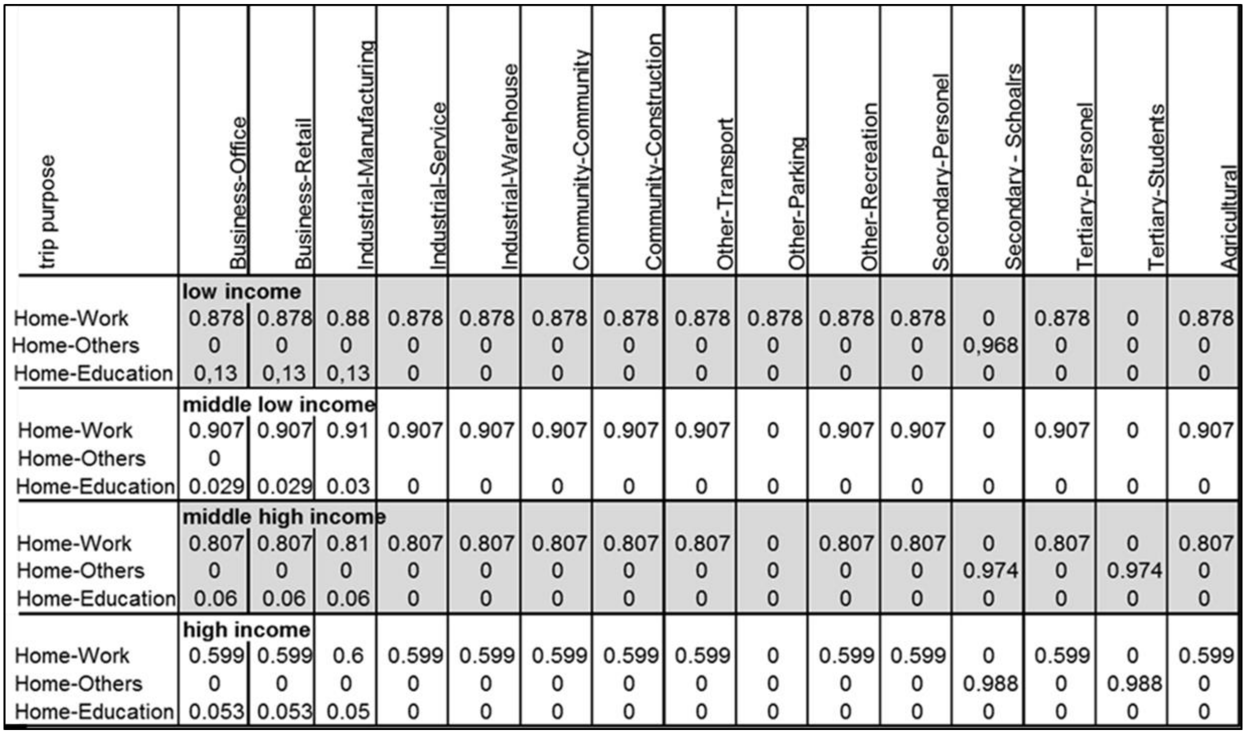
F_{ij} = is the friction of distance between zone *i* and zone *j*

D_{ij} = is the distance between zone *i* to zone *j*

δ = is a factor that expresses the disutility of travelling when the distance increases.

The City of Cape Town in the EMME model has calculated a set of disutility coefficients for different trip purposes and land uses for different income groups. These coefficients were adopted in the model paying attention to the residential land use category in section 5.5.2 (as discussed in the land use model data section) in each of the zones. Table 5-4 shows some of the coefficients that were used in the model.

Table 5-4: Coefficients adopted to distribute trips

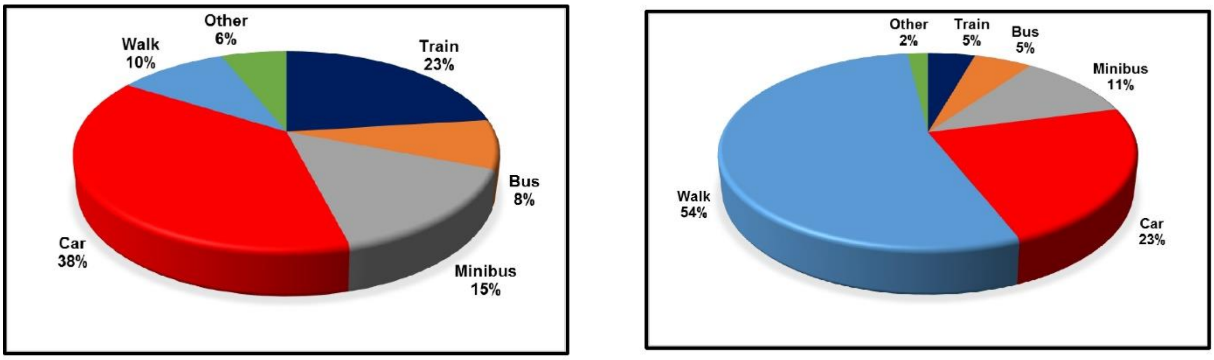


trip purpose	Business-Office	Business-Retail	Industrial-Manufacturing	Industrial-Service	Industrial-Warehouse	Community-Community	Community-Construction	Other-Transport	Other-Parking	Other-Recreation	Secondary-Personel	Secondary - Schoalrs	Tertiary-Personel	Tertiary-Students	Agricultural
	low income														
Home-Work	0.878	0.878	0.88	0.878	0.878	0.878	0.878	0.878	0.878	0.878	0.878	0	0.878	0	0.878
Home-Others	0	0	0	0	0	0	0	0	0	0	0	0,968	0	0	0
Home-Education	0,13	0,13	0,13	0	0	0	0	0	0	0	0	0	0	0	0
	middle low income														
Home-Work	0.907	0.907	0.91	0.907	0.907	0.907	0.907	0.907	0	0.907	0.907	0	0.907	0	0.907
Home-Others	0														
Home-Education	0.029	0.029	0.03	0	0	0	0	0	0	0	0	0	0	0	0
	middle high income														
Home-Work	0.807	0.807	0.81	0.807	0.807	0.807	0.807	0.807	0	0.807	0.807	0	0.807	0	0.807
Home-Others	0	0	0	0	0	0	0	0	0	0	0	0.974	0	0.974	0
Home-Education	0.06	0.06	0.06	0	0	0	0	0	0	0	0	0	0	0	0
	high income														
Home-Work	0.599	0.599	0.6	0.599	0.599	0.599	0.599	0.599	0	0.599	0.599	0	0.599	0	0.599
Home-Others	0	0	0	0	0	0	0	0	0	0	0	0.988	0	0.988	0
Home-Education	0.053	0.053	0.05	0	0	0	0	0	0	0	0	0	0	0	0

The data sets discussed so far are sufficient to set up the generic METRONAMICA-based land use transport model. However, given the uniqueness of the transport user context in Cape Town, modifications were made to the input data sets so that the land use transport model could reflect the transport structure in the city. Once the initial trip distribution matrix for different trip purposes was identified, they were delineated according to transport mode as shown in Figure 5-9. The modal splits implemented are discussed below.

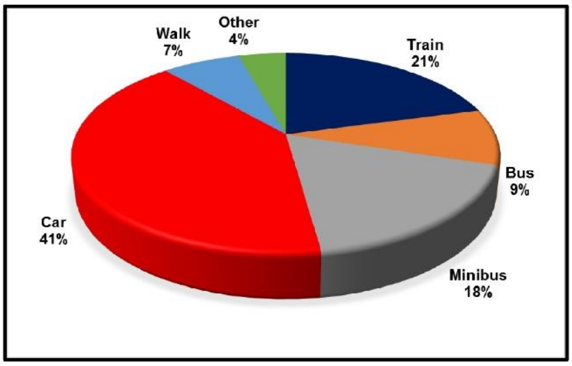
Modal Split

The OHS (1996, 1997) and the Census 1996 were used to identify the modal split for the different trip purpose for 1996 and 1997. Travel behaviour takes long periods to change (Behrens, Del Mistro, Lombard, et al., 2007; Del Mistro, Behrens, Lombard, et al., 2007; Behrens, Adjei, Covary, et al., 2015); given that, 1996 were assumed for 1995. These modal splits based on (Lombard, Cameron, Mokonyama, et al., 2007) were used to estimate the traffic flows for each suburb for the car, minibus taxi and bus. The modal split was disaggregated for every trip purpose. Figure 5-9 shows the overall modal split, modal split by trip purpose for education and work trips for 1996.



a) Overall modal split 1996

b) Education modal split 1996



c) Work modal split 1996

Source: Made by the author based on findings by Lombard, Cameron, Mokonyama, et al. (2007)

Figure 5-8: Overall Modal Split 1996

5.5.2.1 Private car matrices for 1995

The initial trip distribution matrix for private cars is a key component in the transport model. This determines the initial number of trips for a representative hour between origins and destinations for each trip purpose and travel period for the year 1995. Two sets of matrices for the morning peak and the rest of the day were prepared for each of the trip purposes for the private car; this resulted in a total of six matrices. Intrazonal trips were excluded in the study as they were assumed to take place within a zone and not from centroid to centroid. Further, they are also assumed to be over short distances hence non-motorised based.

5.5.2.2 Minibus taxi matrices for 1995

Like in the case of private cars, the minibus taxi mode is used to assign the initial number of trips between zone origins and destinations for each trip purpose and travel period for the year

1995. Two sets of matrices (morning peak and for the rest of the day) were required for each trip purpose and travel period. Earlier, it was mentioned that mode choice in Cape Town is highly correlated to income, minibus taxis are predominantly used by individuals who reside in low-income areas (Hitge & Vanderschuren, 2015). With regards to interzonal trips, a limited number of these were recorded in these zones. This is because one of the defining characteristics of these neighbourhoods is that there is a disparity between residential areas and job opportunities hence limited intrazonal work trips. A total of six matrices were estimated.

5.5.2.3 Bus matrices for 1995

An identical procedure as in the case of minibus taxis was followed to estimate the bus matrices. Intrazonal trips were excluded in the bus matrix. A total of six matrices were estimated for the bus.

5.6 Summary

This chapter discussed the datasets needed to set-up, calibrate and validate the METRONAMICA based land use transport model for Cape Town. The chapter also discussed the processes and methods used to prepare the dataset used to set up the model. The challenges encountered during data preparation and the methods used to overcome these challenges are also discussed. One of the important aspects in Chapter 5 was the discussion on the datasets needed to adapt the generic METRONAMICA transport model block to the Cape Town context. While previous applications (Aljoufie, Zuidgeest, Brussel, et al., 2013; Perez, Wickramasuriya, Forehead, et al., 2017) actively model private cars as the endogenous mode to assign trips onto the network, the Cape Town model uses a different approach. Instead, the private car and minibus taxi are utilised as endogenous modes. Due to transport informality characterised by the minibus taxi which serves the low-income and has a high intensity on the network, both private cars and minibus taxis are modelled as endogenous modes. This allows the transport model to accurately model the transport user system in the city. To incorporate the two modes, instead of having a trip distribution matrice for private cars only, the approach was to disaggregate the matrices by mode and by trip purpose to reflect the Cape Town user system. The datasets discussed are sufficient to adapt the transport model for the Cape Town case. The next chapter, therefore, discusses the steps involved in setting up the METRONAMICA land use transport model for the Cape Town Metropolitan Region (CTMR_LUT).

Chapter 6

Dynamic land use and transport modelling for Cape Town using METRONAMICA

6.1 Introduction

The preceding chapter discussed the processes and methods used to prepare the data to set up, calibrate and validate the land use transport model. This chapter begins a discussion on modelling land use and transport interaction in Cape Town and its influence on urban change. The hope is that the methodology developed in this chapter will aid in better understanding the spatiotemporal influences of land use and transport in the city and how this shapes the urban landscape. The modelling strategy has the potential to facilitate the development of urban policies that can address issues of access, spatial mismatch, transport affordability, among other issues that emerged in Chapter 1. A dynamic CA-based land use transport model developed within the METRONAMICA framework as discussed in Chapter 4 is introduced. The METRONAMICA framework is amenable to modelling and simulating spatially distributed land use changes and the competition for space between various land uses as it utilises cellular automata modelling. This makes it suitable to answer the research questions developed for this research.

Thus far, the discussion has revealed that in addition to inefficiencies due to the apartheid legacy, post-apartheid South African cities face new challenges. The growing car ownership and low confidence in the public transport system (STATSSA, 2014) have resulted in congestion and other externalities. The current discourse on redressing apartheid spatial planning with an emphasis on land rights inequities acknowledges the role of urban land as it provides an opportunity for housing for the poor; who traditionally have been located in the outskirts. However, these policies might open a Pandora's box of competition between land for residential needs and commercial development. From a planning perspective, there are challenges in prioritising these land needs as they are both essential aspects. As the urban areas continue to grow, managing this growth is required to ensure that there is equality and equity in the way resources are allocated.

Policies that aim to address social exclusion, urban densities, access to employment inter alia have to consider land use and transport planning jointly as they are interrelated. Cervero (2013) asserts that integrated land use and transport should be at the core of planning in developing cities especially given the rapid rate of urbanisation. Rapid urbanisation as a phenomenon is experienced in Cape Town and is characterised by polarised growth of economic centres in the affluent suburbs and the exurban location of low-income residential areas away from economic activities and transport. As such, it might be beneficial to utilise integrated modelling approaches that can explore the mutual evolution of land uses and transport. However, there needs to be an acknowledgement of the spatial-temporal interaction and competition for space that might exist between the different land uses (Verburg and Overmars 2009).

6.2 Modelling scope

This study appreciates the myriad of problems within the Cape Town context such as congestion, the economics surrounding congestion and how it shapes mobility and accessibility and its influence on the spatial location of activities. However, modelling scope of this research is:

- The spatial-temporal dynamics relating to low-income, middle-income and high-income residential areas, informal settlements, manufacturing services and trade services. These land uses were identified to make up the main work-related origins and destinations in Cape Town and are dynamic land uses. This leaves out land uses such as recreational parks, utility infrastructure among other non-dynamic land uses. Further, the processes that influence the spatial location of these land uses are possible to capture in cellular automata models using interaction rules as these land uses respond to behaviours of surrounding land uses.
- While Cape Town has several modes of transport, only the transport dynamics related to private cars, minibus taxis, Golden Arrow and contracted buses are modelled. The private cars and minibus taxis are considered as the endogenous modes and have higher intensity on the network; hence, they are the only modes used to assign trips to the network. On the other hand, the bus is regarded as the exogenous mode; therefore, the impact of busses on congestion is not actively modelled as the bus trips are not assigned to the network.

- Though the trips by Metrorail and MyCiti Bus Rapid Transit are not included in the study, the temporal influence of their infrastructure such as the train lines, train stations, the BRT network is explored. This allows the model to evaluate the influence of transport infrastructure on the land use dynamics. The dynamics due to the BRT are introduced in 2010 as this was when the bus came into operation. In the case of the Metrorail, though rail trips help in reducing road capacity demand, this mode does not directly impact congestion on the road network and therefore not explicitly modelled. Additionally, since the model involves several model blocks which have many parameters that need to be calibrated, including many modes of transport would have increased the parameters that needed to be calibrated which would have made manual calibration of the model difficult.
- The calibration of the transport model does not necessarily aim to achieve the efficiency of individual road network links. Instead, the research takes a “stylised” approach by focusing on the whole road network where the focus is on achieving volume capacity ratios that are comparable to those obtained by the Cape Town’s EMME model.

6.3 Setting up the Cape Town Metropolitan Region Land Use Transport Model

This section discusses the various steps in setting up the Cape Town land use transport model using the datasets presented in Chapter 5.

6.3.1 The regional model set up

The first step was to set up the METRONAMICA multiple-layer application which includes the regional and the land use model blocks. The regional model specifies three sector types:

- Population sector – relates to the number of people.
- Economic sectors – considers the number of jobs.
- Area demands - specifies the land use demands.

The regional model captures the number of people (population), *informal settlements (*area demands*),* and the number of jobs in *Industry or manufacturing services; and Trade services* sectors*.* Table 2-1 described the type of land uses and services in each of the sectors. The assumption in the regional model is that all sectors compete for labour and economic activities based on the type of land uses that exist in the region. It is at this stage that the land use model and regional model are linked. The function land uses (defined in Table 5-2) are allocated to the different sectors as shown in Table 6-1.

Table 6-1: Land use functions linked to sector types

Land use functions	Sector type	Modelled sector
High Income Residential	Population	Population
Middle Income Residential	Population	Population
Low Income Residential	Population	Population
Informal Housing	Area	Informal Housing
Manufacturing Sector	Economic sector	Industry or manufacturing services
Trade and Services	Economic sector	Trade and services

6.3.2 Combining the transport model and land use model

After setting up the regional model, it is integrated with the transport model. Given that the METRONAMICA software package used in the present study does not have a built-in transport model; the transport model was introduced exogenously. The resulting model is a land use and transport model for the Cape Town Metropolitan Region (CTMR_LUT). An extract of the user interface of the CTMR_LUT model which shows the linkage between the land use, regional and transport model is shown in Figure 6-1.

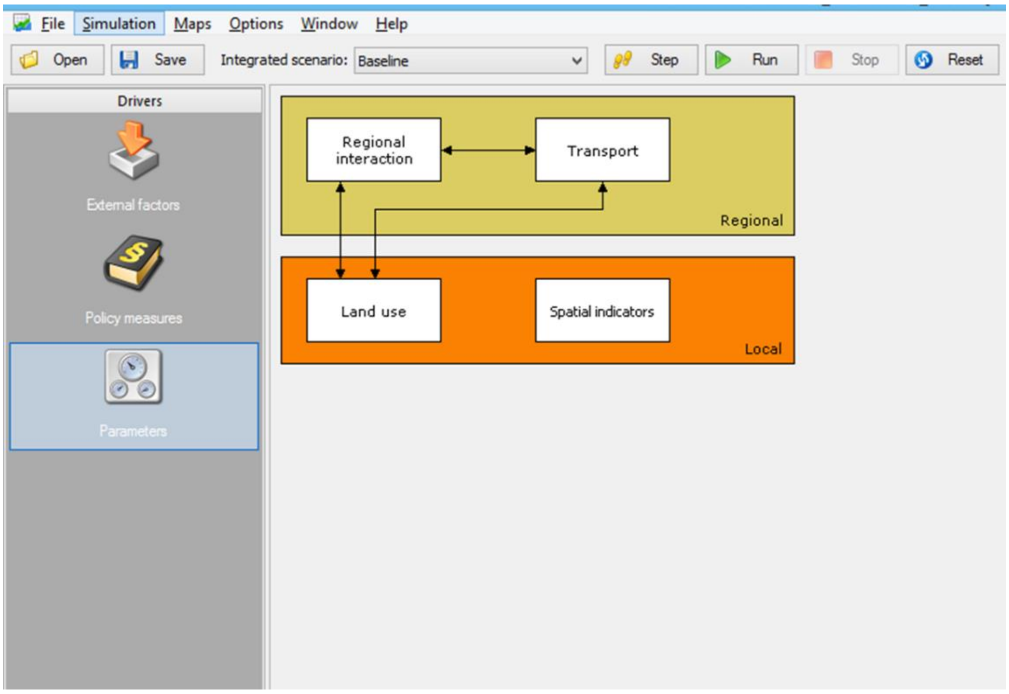


Figure 6-1: The user interface of the land use transport model

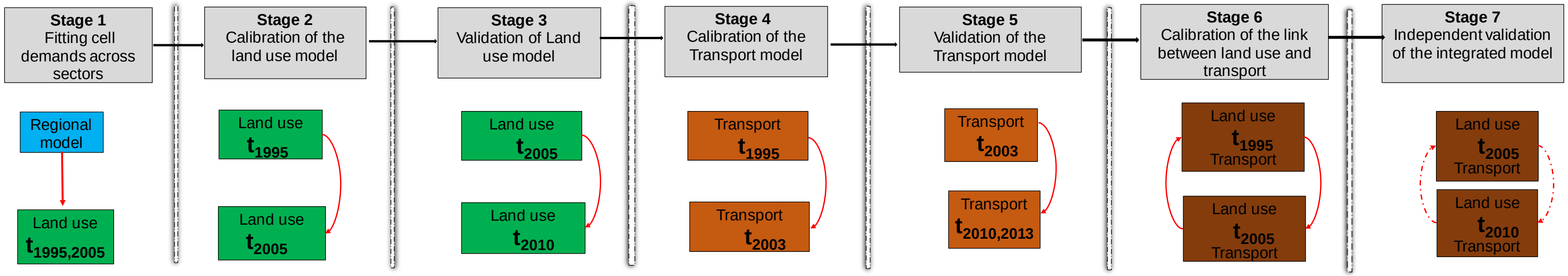
6.4 Calibration of the Cape Town land use transport model (CTMR_LUT)

After setting up the model, the calibration and validation exercises were carried out. Independently, the land use model has a minimum of 144 parameters including neighbourhood rules of land use pairs. On the other hand; two parameters; constant growth of density and the minimum density for each economic sector need to be calibrated in the regional model. This is a total of 6 parameters for this model block. In the transport model block, the parameters in each component of the four-step model also need calibration. Because of the numerous parameters that need to be calibrated, this makes the calibration process complex. A manual and sequential calibration approach was implemented to calibrate and validate the model after Abraham (2000). The period 1995- 2005 was used for calibration and 2005-2013 were used for validation. The CTMR_LUT model is an integrated model, hence, the calibration process was two-pronged:

- Firstly, a piecewise strategy where the parameters of the sub-models were calibrated separately was implemented. This involved the calibration of the individual models independently. The regional model was calibrated to obtain land use demands that were transferred to the land use model. After that, the land use model was then calibrated, and finally, the transport model was calibrated.

- In the second stage, the calibration focused on the parameters that linked the various model blocks. The focus was on the calibration of the zonal accessibility which links the land use and the transport model blocks.

The advantage of this approach is that observed data can be utilised to assess the calibration of the land use demands simulated by the regional model for 2005. Additionally, this procedure allowed the calibration problem to be divided into smaller pieces which were less overwhelming and made it easier to isolate issues during the calibration exercise. The calibration and validation procedure for the CTMR_LUT model is presented in Figure 6-2.



solid arrows represent the dynamics actively modelled at each stage
doted arrows represent the feedback loops between land use and transport

Figure 6-2: Sequential calibration and validation of CTMR_LUT model

6.4.1 Stage 1 Calibration of the regional model

As mentioned earlier (section 4.3), the regional model dictates the land use demands which are passed on to the land use model. Considering that the Cape Town metropolitan area was modelled as one region, only two parameters that influence the competition for labour within the regional model block were calibrated; *constant growth of density and the minimum density*. The constant growth of density determines the productivity of each sector and the minimum density looks at the number of people per land use (RIKS, 2012). For each of the sectors, the constant growth and the minimum density were calibrated to determine the activities per sector. The calibration of these two parameters was heavily dependent on the data relating to each sector as discussed in section 5.3. Once the parameters were set, the assessment of the calibration results considered the following aspects:

- The extent to which the regional model could simulate the correct land use demands for each function land use (goodness of fit).
- The extent to which the model can simulate the population and activities per sector compared to the actual data.

6.4.1.1 Calibration of the regional model: fitting land use demands

The regional model was simulated from 1995 to 2005. The calibration procedure for this model block focused on fitting the land use demands across all the different sectors which would then be used in the CA model as discussed in section 4.3. This was dependent on the calibration of the minimum density parameters and the contribution of each land use function to the economic sector. One aspect that continues to come up is the issue of low urban land use densities in Cape Town (Watson & Turok, 2001; Palmer, Brown-Luthango, & Berrisford, 2011). Initially, the calibration of the minimum density parameter focused on achieving minimum density values comparable to those reported for Cape Town for 2005, while allocating the right land use demands to each land use function. However, since the land use map for 2005 was available, land use demands simulated by the model for each function land use for 2005 were compared to the 2005 real map. Once the comparison showed relatively similar land use the calibration was considered successful.

6.4.1.2 Calibrating the activities per sector in 2005

The second stage in the calibration of the regional model was to evaluate the simulation of the activities per sector relative to the actual activities per sector. The focus was on allocating the different land use activities to the various sectors by determining the contribution of each function land use to the sectors.

6.4.2 Stage 2 Calibration of the land use model

The calibration period of the land use model block in the CTMR_LUT model was 10 years starting from 1995 to 2005. The calibration procedure of the land use model is discussed in the next sections.

6.4.2.1 Observed land use changes

The calibration started with obtaining a simulated map for 2005 that resembled the observed 2005 land use map. A manual calibration approach was adopted which involved a series of stages. The first stage in the calibration of the land use model was to ascertain the relationship between different land uses. Several land use models use the neighbourhood effect as a factor that influences land use changes (Verburg & Overmars, 2009; van Delden, Stuczynski, Ciaian, et al., 2010). Therefore, testing for the presence of the neighbourhood effect to determine the spatial relationship between the different land uses was a key step. This is especially crucial as setting the correct neighbourhood rules plays a pivotal role in ensuring that the model simulations are similar to observed land use patterns. This is even more important in the case of CA models where model outcomes are sensitive to transition rules (Verburg, de Nijs, van Eck, et al., 2004). Chapter 2, which discussed the spatial structure of the Cape Town landscape provided insights into the structure, spatial relationship and transitions between different land uses. Though this approach does not provide neighbourhood parameters for calibrating the land use models like the enrichment factors as discussed in Verburg, de Nijs, van Eck, et al. (2004) and van Vliet, Naus, van Lammeren, et al. (2013) the spatial metrics of Chapter 2 provided insight on the Cape Town landscape structure and the land use and neighbourhood preferences for the different land uses. Further, the results from this chapter provided a basis on which to determine the hierarchy of land uses, which helped in setting the initial neighbourhood rules.

6.4.2.2 Manual calibration of the drivers of land use

The calibration of land use models typically involves many parameters. This is linked to the presence of several drivers that influence land use change, as discussed in section 3.6.1. Land use models try to simulate urban dynamics in the urban system which are due to natural processes in the urban environment and human influences. These processes are primarily captured at the neighbourhood level. In that regard, it was essential to calibrate the neighbourhood rules first before any other drivers were calibrated. The calibration procedure has been discussed in section 4.6.2. In sequential order the calibration process focused on the following aspects:

- Setting the neighbourhood rules to explain the interaction of different land use pairs;
- Defining the accessibility parameters of each of the function land uses;
- Determining the suitability which plays a role in the potential of a land use to occupy a cell;
- Defining the zoning or policy-related drivers which potentially influence the location of land uses;
- Determining the random perturbation term which controls the degree of scattering of the land use patterns (White & Engelen, 2003).

6.4.2.3 Calibration of the neighbourhood rules

In setting up the neighbourhood rules, one important aspect where consistency is important was in determining the scale of the influence function or the weighting parameter $\boldsymbol{w_{z,y,d}}$ defined in equation 5. The weighting parameter which reflects the attraction and repulsion and the ease which land uses persist or are easily converted ranged between -2000 and 2000. The repulsion was measured from 0 to -2000 while the attraction was measured from 0 to 2000. The first step was to set the hierarchy of different land uses; this aided in establishing the extent to which land uses persisted in their location or the degree of conversion of land uses. In the second stage, interactions between the different land uses were identified; the focus was on establishing the attraction and repulsion effect of land use pairs. Section 2.4 which discussed spatial metrics helped in this stage of the calibration process, in particular identifying land uses that persisted in their locations for long periods of time.

.

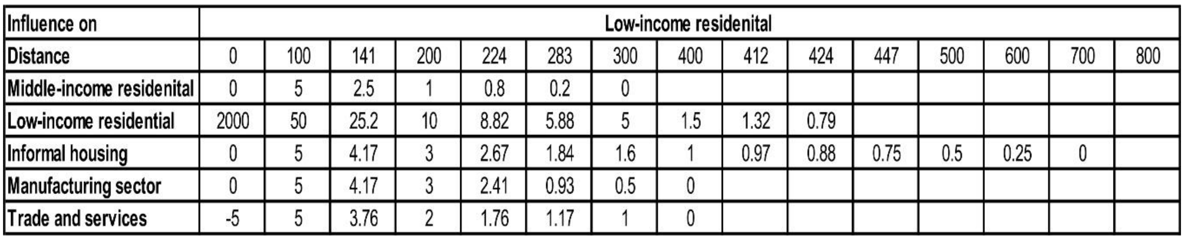
During the calibration, the neighbourhood rules were introduced for one land use pair at a time, and the model was simulated from 1995 until the end of the calibration period (2005). The simulated map was compared to the 2005 actual map using the map comparison techniques discussed in section 4.6. Noteworthy is that in land use models, not all land use pair combinations create land use dynamics that add value in explaining land use change. Hence, only a few neighbourhood rules between land use pairs were introduced. This approach is consistent with other studies White & Engelen (2003); Fertner, Jørgensen & Nielsen (2007) and Wickramasuriya et al. (2009). Therefore, the neighbourhood rules were first introduced between land use pairs with noticeable interactions such as:

- Medium-income residential areas and trade and service.
- Medium-income residential and manufacturing.
- Low-income residential and manufacturing.
- Low-income residential and informal settlements.

This was followed by the introduction of neighbourhood rules relating to the conversion of vacant land uses to function land uses. Finally, neighbourhood rules between feature land uses and some function land uses were then introduced. With the introduction of new rules to the model, some model behaviour aspects that were working would be disturbed requiring the neighbourhood rules to be revisited and fine-tuned. The approach has been suggested by other scholars White & Engelen (2003). At every stage of the calibration, the introduction of new neighbourhood rules resulted in a change in the behaviour and model dynamics. Hence, the simulated model results were continuously evaluated by comparing the simulated map of 2005 to the real map of 2005.

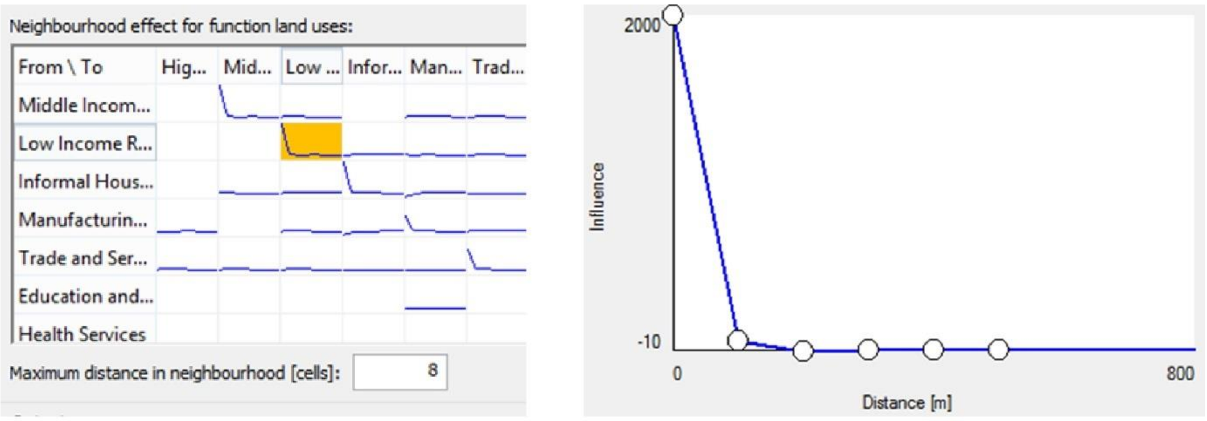
Table 6-2 presents the neighbourhood rules derived for low- income residential areas paired with other land uses. The relationship shows that low-income residential areas prefer to locate close to other low-income residential and grow in large patches normally separated by roads. The influence parameter $W_{z,y,d}$, for low income at distance 0 is set to 2000 showing that low- income housing persists in their location and hence cannot be easily converted. Once they occupy a location, conversion to other land uses is difficult. A full set of the derived neighbourhood rules applied in the model are presented in Appendix A.

Table 6-2: Influence on low-income residential



Influence on	Low-income residenital														
Distance	0	100	141	200	224	283	300	400	412	424	447	500	600	700	800
Middle-income residenital	0	5	2.5	1	0.8	0.2	0								
Low-income residential	2000	50	25.2	10	8.82	5.88	5	1.5	1.32	0.79					
Informal housing	0	5	4.17	3	2.67	1.84	1.6	1	0.97	0.88	0.75	0.5	0.25	0	
Manufacturing sector	0	5	4.17	3	2.41	0.93	0.5	0							
Trade and services	-5	5	3.76	2	1.76	1.17	1	0							

Figure 6-3a shows the matrix for all CA rules introduced for all function land uses while Figure 6-3b shows the influence function for low-income residential on other low-income residential areas.



Maximum distance in neighbourhood [cells]: 8

a) Matrix of CA rules

b) Influence of low income on other low income

Figure 6-3: Matrix of CA rules and the influence function for low income on low income

6.4.2.4 Calibration of the accessibility parameter

Once the neighbourhood rules provided realistic land use relationships, the accessibility parameter was introduced for each of the land uses. Two aspects were considered at this stage; the network weight and the distance decay parameter for function land uses. The network weight parameter determines the importance of a link type to a land use while the distance decay parameter determines the desirability of a location for particular land uses; this is well discussed in section 4.4.2. Table 6-3 shows the final parameters in the calibration of accessibility for low and middle-income residential areas.

Table 6-3: Accessibility parameters for low-income residential areas

Infrastructure type	Distance decay (Cells)	Weight
Freeway	-10	1
Main road	15	0.8
Secondary and primary arterials	15	1
Train lines	1	0
Train stations	20	0.5

These parameters were manually calibrated based on the location of land uses relative to the transport network as observed in the1995 and 2005 maps. The parameters provided in Table 6-3 gave a good representation of the location of the different land uses relative to the different transport related infrastructures. These parameters also resulted in realistic land use patterns. The parameters indicate that low-income residential areas tend to locate in areas properly serviced by main roads, secondary and primary arterial. On the other hand, freeways discourage low-income residential areas from locating in their vicinity. The implicit accessibility discussed in section 4.4.2 also needed to be calibrated for all function land uses. The parameter was calibrated to 1 thus ensuring that all function land uses were accessible in spite of the road network structure or the presence of an impassable land use.

6.4.2.5 Introduction of suitability and zoning

Zoning and suitability represent the policy and physical constraints respectively on the land use dynamics. In the context of Cape Town, the structure of the urban environment is influenced by the historical planning structure and post-apartheid urban planning policies. This makes zoning an important driver of land use change. The suitability layer presented in Figure 5-3 was adopted for the calibration period 1995 to 2005. On the other hand, the zoning maps for all function land use maps up to 2010 presented in Figure 5-4 are used. In the case of informal settlements, no zoning maps were introduced as these are illegal structures which sometimes locate in restricted areas.

6.4.2.6 Random perturbation

The last parameter to be calibrated was the random perturbation term $\boldsymbol{r_{k,i}}$ presented in equation 4 which introduces randomness, and the scatter of land use patterns while controlling the density and the location of new land use clusters. The calibration of this parameter was determined by two things; the land use patterns produced by the model, and the level of zoning introduced in the model. The urban patterns at the end of the calibration period were assessed using the fractal dimension. Once the fractal dimension for the simulated map was close to the real land use map for the same period, the random parameter was considered calibrated.

The default parameter setting 0.5 was used as the initial parameter value to calibrate the model. The land use patterns produced by the model determined whether a new $r_{k,i}$ parameter should be introduced and whether it would be higher or lower than the previous one. The observations made based on the simulation with $r_{k,i}$= 0.5 indicated a clustering of land uses with land use allocation patterns that were uncharacteristic of the Cape Town landscape. The next parameter introduced was $r_{k,i}$= 0.6. This parameter produced more realistic land use patterns. However, the fractal dimension indicated that the landscape structure produced by the model simulation was not close to the fractal dimension from the observed 2005 land use map. The final parameter adapted in the model was $r_{k,i} =$ 0.7, the generated land use patterns were close to the 2005 land use map. The results are presented in Table 7-7. Given that zoning was an important driver in the model, a high perturbation parameter would allow the model to simulate unpredictable land use changes. Hence, 0.7 was an appropriate parameter given the land use patterns that the model produced. The calibration results based on this parameter which relate to the process accuracy of the model are presented in Chapter 7.

6.4.2.7 Assessment of the calibration results

The methods employed to assess the calibration of the land use models have been discussed earlier in section 4.6. These methods are implemented in this research to evaluate the calibration of the model. This entailed determining the goodness of fit, the process accuracy as well as the predictive accuracy of the model. The Kappa statistic and its variant discussed in section 4.7 were implemented to assess the goodness of fit and the predictive accuracy.

The results of the model for the calibration (1995-2005) results were assessed by looking at the following aspects:

- The goodness of fit [land use changes compared to the simulated land use changes map for 2005].
- The real change [the observed land use patterns at the beginning of the calibration period (1995) was compared to the simulated land use changes for the same period (2005)]
- The performance of the model against a Random Constraint Match (RCM) model which is used as a benchmark for assessment. A reference map is created in the model by randomly allocating land uses over the actual land use map with the class sizes accurately distributed (Hagen-Zanker & Lajoie, 2008).

Additionally, the fractal dimension calculated in FRAGSTAT (McGarigal, Cushman, Neel, et al., 2002) utilised in Chapter 2 was implemented to evaluate the process accuracy of the model. Visual interpretation was also used to interpret the growth and spatial patterns of the simulated and observed land use changes. These aspects have been discussed in section 4.6. Finally, the Map Comparison Kit (Hagen, 2008) was used to derive the statistics used to assess the calibration of the model. Figure 6-4 and 6-5 provide maps that were utilised to evaluate the model results.

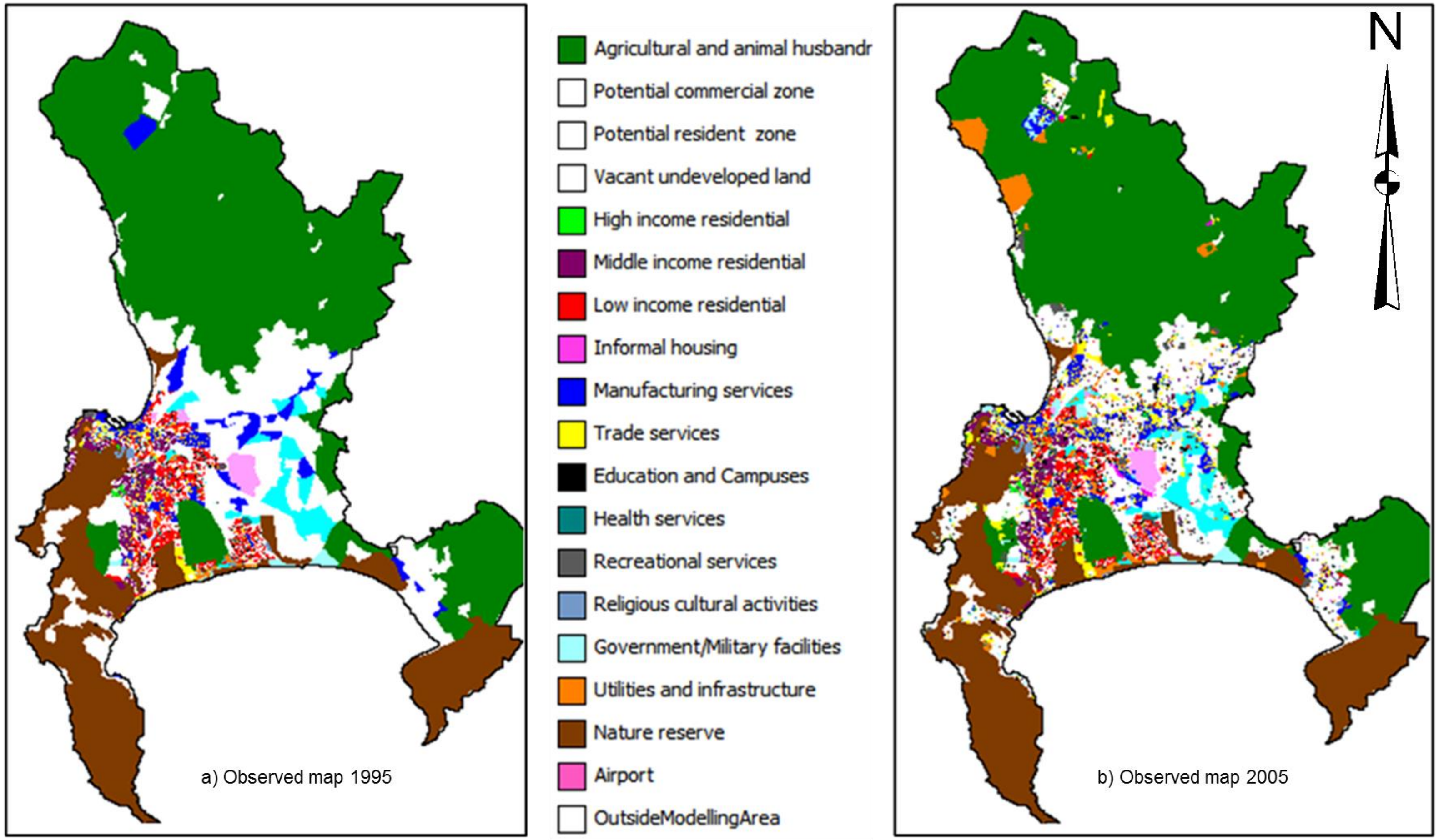


Figure 6-4: Real 1995 and 2005 land use maps

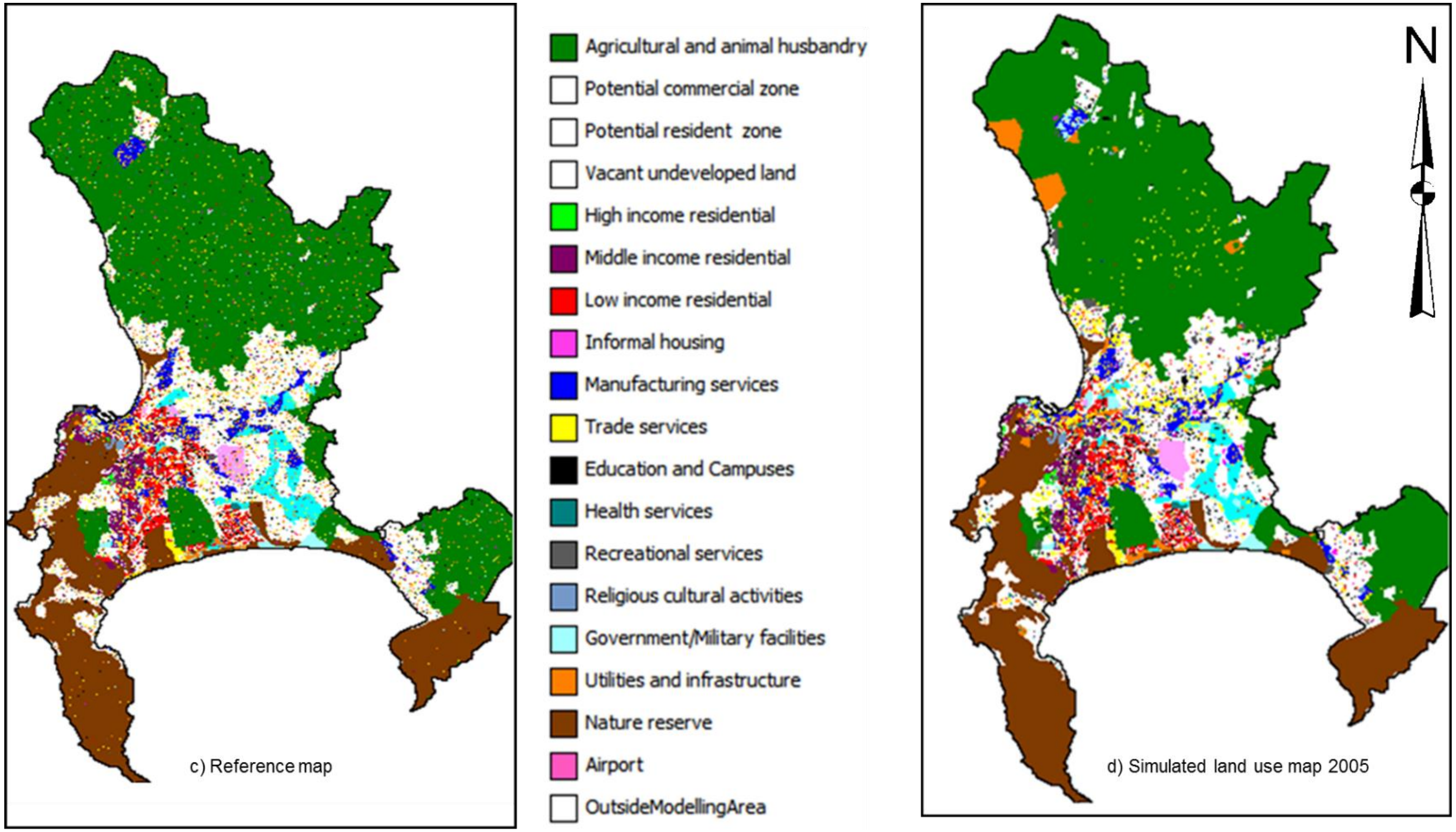


Figure 6-5: Reference map and simulated land use map for 2005

6.4.3 Stage 3 Independent validation of the land use model

The validation period for the land use model was 5 years from 2005-2010. The 2010 land use map was used as the validation dataset as it was not implemented in the calibration. The focus during the validation was to evaluate the process and predictive accuracy of the model by comparing the simulated and actual land use map in 2010. The fractal dimension and variations of the Kappa statistics are used to assess the predictive and process accuracy of the model. This approach is similar to that carried out in Stage 2 in section 6.4.2. The validation of the model also helped to evaluate the performance of the model when simulated for an extended period. This is an important exercise as it provides information on whether the model can be used for forecasting and exploratory policies. Noteworthy is that at this stage, the temporal dynamics of transport are still not explored in the simulation.

6.4.4 Stage 4 Calibration of the transport model

The transport model operationalised in METRONAMICA is a dynamic four-step model as discussed in Chapter 4. The calibration period for the transport model was 1995 -2008. A stage-wise calibration process was applied to calibrate the different components of the model; this entailed calibrating the sub-blocks within the model individually. While the land use dynamics are not yet explored in the independent calibration of the transport model, the 1995 map was utilised as an input in the transport model. This is because the land uses provided the initial land use activities within the transport model in the form of origins and destinations. Figure 6-6 shows the sequential calibration of the transport model block.

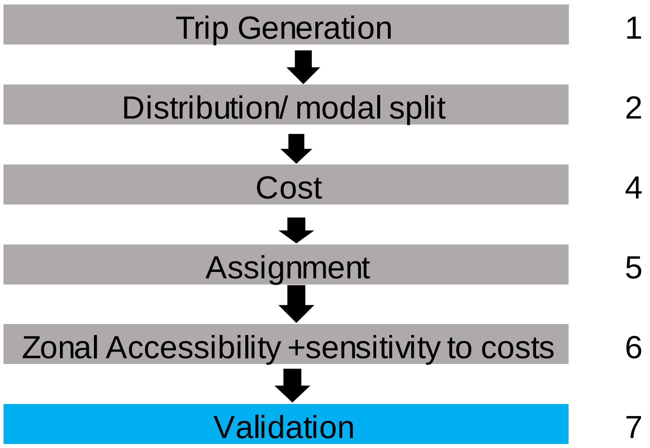


Figure 6-6: Sequential Calibration of the METRONAMICA transport model

During the calibration, the first stage was to establish whether some of the parameters within the several model blocks could be derived from previous studies. The following parameters: costs per kilometre, parking costs and mobility growth were established from historical data, such as the census data, travel survey as discussed in section 5.4. Once these parameters were set, they were not changed during the calibration process. The parameters that were calibrated are briefly discussed in the next sections.

6.4.4.1 Parameters relating to the production and attraction

a) *Activity weight*

This parameter is essential in determining the number of activities in each transport zone and is based on the land uses within that zone. During the calibration, residential land uses, manufacturing services, trade services and educational institutions were given the highest activity weight as they form the main trip origins and destinations. The activity weight was also calibrated for the different levels of urbanisation. Some of the calibrated parameters are given in Table 6-4.

Table 6-4: Activity weight per land use

Activity	**Weight**
Population	1
Industry/Manufacturing	1
Trade and services	1
Informal settlement	1
Education and Campuses	1.5
Health services	0.85
Recreational facilities	0.1

b) Urbanisation classes (uc)

This parameter relates to the density of transport activities in the different transport zones. This helped in differentiating low activity generating zones mainly rural zones and the urban areas. Three urbanisation classes were used high, medium and low urbanisation levels. Depending on the land uses, areas that are more urbanised produce and attract more trips and this was reflected in the calibration of this parameter. During the calibration, only the lower limit of the activity density in an urbanisation class was set to show the urbanisation level in each zone where higher values indicated that the zone was more developed and zero represented rural areas. Once urbanisation classes were set, these were constant throughout the calibration. Table 6-5 shows the lower bounds of the activity densities in each urbanisation class used in the model.

Table 6-5: Activity densities per urbanisation class

Urbanisation class	Activities / cell
High	150
Medium	50
Low	0

c) *Trip generation rates*

Several sources were used to inform the magnitudes of the trip generation rates (Onderwater, 2015; Onderwater & McKune, 2016). Noteworthy is that these studies provided a starting point with regards to the magnitude of the trip generation rates. For some transport zones, the trip generation rates needed to be readjusted depending on the density and type of land uses found in the transport zones as explained in section 5.5.2. The parameters used in the model are presented in Table 5-4.

d) *Origin-destination weight* (ω^p)

This parameter is used to balance the number of trip destinations and origins for each trip purpose. The parameter was calibrated for both the morning peak and the rest of the day for all the trip purposes. Additionally, the weighting in the calibration of this parameter was dependent on the trip purpose. Therefore, in the morning peak, work trips were given larger weights compared to recreational or social trips. To balance the origins and destinations the origin-destination weight (ω^p) was set to 0.5. Table 6-6 shows the calibrated parameters for productions and attractions.

Table 6-6: Daily distribution of trips

	Home-based-work	**Home-based-education**	**Home-based-other**
O-D weight	0.5	0.5	0.5
Morning peak	0.9	0.9	0.4
Rest of the day	0.1	0.1	0.6

e) *Cargo mode equivalent* (E_{truck})

This parameter considers the share of cargo relative to cars on the road network. Cape Town metropolitan has a high cargo mode share on the road network, and this has an impact on congestion (TCT, 2015). The calibration of this parameter was a trial and error process until a suitable parameter which allocated a share of cargo trips on the network was identified.

f) Mobility growth factor (G^p)

The National Household Travel Survey, the Census data and employment outlook data were used as the main sources to inform on the mobility growth for different trip purposes. This was based on the projections of unemployment over the period which helped in deducing whether there is an increase or decrease in work trips. Additionally, the increase in car ownership was also used to determine mobility growth for private cars for different trip purposes. Mobility growth associated with education trips and recreational trips was assumed to be constant over time.

6.4.4.2 Parameters relating to the distribution and modal split

This is where the Furness iteration in the model is carried out to calculate the trip origin and destination matrix. Two key parameters were calibrated, the cost sensitivity and distribution inertia.

a) Sensitivity to cost per activity

This parameter determines the allocation of transport costs to different trip purposes by reflecting on whether people are more sensitive to spending money on leisure trips compared to work-related trips. The sensitivity to cost was calibrated for all trip purposes. The general assumption in the calibration of this parameter was that low-income people are more sensitive to costs related to leisure trips compared to high-income individuals. Further, people are less sensitive to the costs associated with work and education trips compared to recreational activities. Though the calibration of this parameter was iterative and mainly trial and error, previous M-LUT applications such as Xplorah for Puerto Rico and the information from the NHTS were invaluable in the formulation of the assumptions made during the calibration of this parameter. This parameter influences the allocation of land uses; hence it was also revisited during the calibration of the zonal accessibility parameter.

b) Distribution inertia

In Chapter 4, the dynamic transport model implemented in the M-LUT was introduced. The important aspect was the calculation of the trip distribution matrix where three aspects were considered important; (1) the responsive distribution, (2) inertia distribution and (3) the inertia factor ρ^{p}. As mentioned earlier (section 4.5.2), the distribution inertia parameter reflects the extent to which trip distribution in the current time step relies on the previous time step. This shows the responsiveness of people to a change in the generalised cost among other issues. To calibrate this parameter, it was assumed that behaviour is habitual following (Ouellette & Wood, 1998; Gärling & Axhausen, 2003). Further, to determine whether inertia was a factor in the Cape Town context, travel behaviour change studies for Cape Town (Behrens, Del Mistro, Lombard, et al., 2007; Del Mistro, Behrens, Lombard, et al., 2007; Behrens, Adjei, Covary, et al., 2015) were used where findings generally suggested that people did not change their behaviour in the short term. Therefore, the inertia factor was added in the calibration and was also given a higher weighting compared to the responsive distribution factor, showing that the previous behaviour contributed to the current travel patterns. Work and education trips were given a higher inertia value compared to social and recreational trips. The inertia factor is given by ρ^{p} as in equation 22 while the responsive distribution factor μ^{p} for trip purpose p, is given by:

$$\mu^{p} = 1 - \rho^{p} \qquad (30)$$

The inertia and responsive distribution parameters are calculated for different trip purposes. Given that there was no prior data relating to the responsiveness of people to behaviour change the calibration of this parameter was iterative. Table 6-7 shows the inertia factors ρ; used to calculate the responsive distribution μ for all trip purposes.

Table 6-7: Trip distribution parameters

Trip purpose	Responsive distribution factor μ	Inertia factor ρ
Work	0.4	0.6
Education	0.4	0.6
Other	0.6	0.4

6.4.4.3 Parameters relating to cost

The decision to make a trip among individuals is based on travel time, distance, costs, parking costs among others depending on the mode of transport used. These aspects are considered when individuals decide on the type of mode and the route they choose to participate in different activities. Some parameters could not be derived from previous studies or existing datasets, for these parameters, they were set to zero, and where possible they were estimated. The different cost parameters are discussed in the next sections.

a) Aversion costs and costs per km

Aversion costs express the unwillingness of people to use a transport mode. In Cape Town, there is a high correlation between mode choice and income (Hitge & Vanderschuren, 2015). This parameter was crucial during the calibration of the transport model. On the other hand, the cost per kilometre was guided by the minibus taxi fares and the cost of fuel.

After calibrating these parameters, the transport model simulations were evaluated at two-time steps, 2003 and 2008. Three metrics were assessed:

- Trip generation for work and education trips in 2003 reported by Lombard, Cameron, Mokonyama, et al. (2007);
- Modal split in 2003 reported by Lombard, Cameron, Mokonyama, et al. (2007);
- Average trips distances for private cars in 2008 reported in Comprehensive Integrated Transport Plan (TDA, 2012).

6.4.5 Stage 5 Validation of the transport model

One of the aims of this research is to apply a land use transport model for exploratory policy scenarios in Cape Town, in that regard, validating the model is a crucial step. The validation period was from 2008-2013. The City of Cape Town currently uses the EMME model for integrated land use transport planning. Therefore, the validation procedure implemented in this study compared the CTMR_LUT model simulations in 2013 to the EMME model output. This approach has been implemented by other scholars, Pfaffenbichler, Emberger & Shepherd (2008) to evaluate the performance of MARS land use transport model against UrbanSim (Waddell, 2002) and MEPLAN (Hunt, 1994). The validation of the model focuses on the simulation of the overall Volume-to-Capacity (V/C) ratios, which is an indicator of congestion on the Cape Town network compared to the EMME model. The focus was on comparing the maximum congestion levels as per the EMME model to those simulated by the model as an indicator of relative model performance. Where possible, the road network link comparison was carried out mainly focusing on the most congested road network links. The validation results were assessed by comparing the congestion levels simulated by the model in 2013 and those generated Cape Town’s EMME model.

6.4.6 Stage 6 Calibration of the feedback between land use and transport

The core thrust of integrating land use and transport is based on the notion that there is a symbiotic relationship that exists between land use and transport (Wegener & Fürst, 1999; Abraham, 2000; Wegener, 2004; Aljoufie, Zuidgeest, Brussel, et al., 2013; Acheampong & Silva, 2015). In the calibration of land use-transport interaction models, it is essential to identify the relational feedbacks that exist between these two sub-systems, either from land use to the transport component or vice versa. Within the METRONAMICA modelling framework, the feedback between land use and transport is represented in the zonal accessibility as discussed earlier in section 4.5.4. Hence, the calibration procedure entailed finding the minimum zonal accessibility that led to an allocation of land uses that resemble observed land use patterns (RIKS, 2012). In calibrating the link between land use and transport, the sensitivity to cost parameter was also revisited as this parameter is essential in allocating land uses to transport zones for different trip purposes. Several zonal accessibility parameters were evaluated during the calibration to determine the minimum parameter to utilise in the model. The minimum zonal accessibility was determined based on the extent to which each zonal parameter affected the dynamics developed within the land use model, especially the influence of zonal accessibility on known land use relationships.

The discussion in Chapter 2 provided a starting point in evaluating the zonal accessibility. The general observation made in Chapter 2 was that middle-income residential areas were found close to trade services while low-income residential areas are located in the peripheries away from employment centres. Therefore, in the validation of the model, suburbs with low-income residential areas are expected to have low zonal accessibility scores when evaluated in relation to suburbs with trade services and manufacturing. A good calibration of this parameter should corroborate this finding.

In the discussion of zonal accessibility, it is essential to assess how it differs across land uses and the potential relationships that might exist. For example, trade services rely on residential housing for labour. Hence it is plausible that the zonal accessibility of these land uses would be interdependent. Again, this relationship should be observable in the visual interpretation of zonal accessibility of the different land uses. The final zonal accessibility parameter that produced land use patterns with a good fit to the observed 2005 land use map was 0.7. From the definition of zonal accessibility provided in section 4.5.4, land uses with a zonal accessibility score less than 0.7 are assumed to be less accessible. This value was adopted as the final parameter for the calibration and validation period of the transport model. Further, this zonal accessibility parameter was also adopted for exploratory policy scenarios.

6.4.7 Stage 7 Independent validation of the integrated model

The simulation results were evaluated by checking the predictive and process accuracy of the model (as discussed in section 4.6) using the 2010 simulated and observed 2010 land use maps. The most critical parameter in the integrated model is the zonal accessibility as it provides the link between the land use and the transport model. Therefore, validation of the integrated model considered assessing the predictive accuracy and process accuracy of the model after the introduction of the link between land use and transport was introduced. As discussed in section 4.6.1, the Random Constraint Match (RCM) was implemented as a benchmark on which to assess the model. Additionally, the visual interpretation of the zonal accessibility maps was carried out to understand the spatial location of land uses and the zonal accessibility for the different suburbs.

6.5 Summary

This chapter presented the methods that were utilised and developed in this thesis. For METRONAMICA to reflect the Cape Town transport user system, the private car and minibus taxi modes were explicitly modelled as endogenous modes of transport. The most important aspect of this chapter was the discussion on the calibration and validation of the model.

A stage-wise sequential calibration procedure was adopted to calibrate the model. This is an acceptable method which has been implemented in other studies Abraham (2000) and Aljoufie, Zuidgeest, Brussel, et al. (2013) to calibrate integrated models. The approach entails individually calibrating the sub-model blocks of the integrated mode. This approach was also useful in the calibration of the integrated model as identifying model blocks that needed to be revisited was straightforward. This is because behaviours of the individual blocks and responses to a change in parameters were observed in the calibration of individual model blocks.

Before identifying the final model which best explained the land use transport dynamics in Cape Town, several model simulations were carried out. For each of the model simulations, the goodness of fit, predictive and process accuracy of the model in the context of the land use model were assessed. The Kappa statistics and its variants along with the fractal dimension were used to assess the calibration and validation results. The chapter discussed the calibration of the link between the land use and the transport model blocks which is represented by the zonal accessibility parameter. The calibration of the zonal accessibility parameter involved simulating the model based on a series of zonal accessibility parameters until an optimal parameter which produced realistic land use patterns was identified.

Though the drivers were introduced one at a time during calibration, the process was not straightforward. The calibration of each parameter resulted in changes in other dimensions of the model that were well calibrated. For instance, the calibration of the neighbourhood rules between residential areas and trades services; these land use pairs had to be revisited several times as they affected the land use dynamics very often. However, because it was essential not to over calibrate the model, after several calibration attempts, some drivers were not revisited. A decision was made to ensure that the calibration procedure balanced the process and predictive accuracy of the model; this approach obviates model overfitting. Once the calibration and validation of individual blocks were satisfactory, the analysis focused on the assessment of the predictive, process and goodness of fit of the integrated model. The results from the calibration and validation of the individual blocks and the integrated model form the basis of the discussion in the next chapter. These results also guide the decision on whether the model performs well enough to be used for policy scenario analysis.

Chapter 7

Calibration and validation results

7.1 Introduction

This chapter discusses the results pertaining to the calibration and validation of the model (CTMR_LUT) implemented in this research. For ease of reference and consistency, the results are presented and discussed in the same order in which the calibration and validation exercise was carried out in Chapter 6. Section 7.2 discusses the analyses of the calibration of the regional model, while section 7.3 details the results from the calibration of the land use model. Section 7.4 continues the discussion on the land use model by presenting and discussing the validation results of the land use model. The discussion on the transport model commences in section 7.5, where the calibration results are discussed followed by the validation of the transport model in section 7.6. Section 7.7 discusses the calibration results of the link between the land use and transport model. The results from the independent validation of the integrated model are presented in section 7.8. The chapter concludes by summarising the results (section 7.9) and briefly discussing the implications of the results (section 7.10) on the applicability of the model for exploratory scenarios in Cape Town.

7.2 Stage 1 Calibrating the regional model

The evaluation of the regional model results entails comparing the simulated land use demands for 2005 and the observed land use demands for 2005. Table 7-1 shows the simulation results of the regional model.

Table 7-1: Regional Model calibration results in 2005

Land Use	Simulated cell counts 2005	Actual cell counts 2005	Cell count error	% Error
High-income residential	223	213	10	4.695
Middle-income residential	3,667	3,674	-7	-0.191
Low-income residential	5,886	5,872	14	0.238
Informal settlements	365	365	0	0.000
Manufacturing Services	5,186	5,182	4	0.077
Trade and Services	6,239	6,293	-54	-0.858
	Underestimation		-33	

Previous calibrations attempts (Shahumyan, White, Twumasi, et al., 2009) of the regional model have attained estimation errors as high as 9.14%. The Cape Town model results show 4.7% as the highest estimation error. Based on these results, the model could generally simulate land use demands. Specifically, the model performed well in simulating the middle-income residential and manufacturing services. The estimation errors show an underestimation of land use cell demands for the middle-income residential and trade services; and an overestimation by the model for high-income residential, low-income residential and manufacturing services. Overall, the discrepancy in the estimation of dynamic land use demands is 33 cells.

The calibration process of the regional model also assessed the extent to which the model could simulate the activities per sector. The results are presented in Table 7-2.

Table 7-2: Comparison of the number of people/ activities

	2005	2005	
Sector	**Actual**	**Simulated**	**% Error**
Population	3,368,892	3,369,110	-0.006
Industry or manufacturing services	300,000	296,253	1.265
Trade and Services	720,728	818,212	-11.914

Based on the results, there is a good fit between the model simulation and actual activities per sector and the population for Cape Town in 2005. Though the model performed well in simulating the population and the number of jobs in the industry or manufacturing services sector, Table 7-2 shows that the model overestimated the number of jobs in Trade and services sector by approximately 11%. The overestimation might be attributed to the reclassification of the employment sectors, which might have led to some Trade and Services jobs to be reported in a formal sector, yet they fall under informal.

The general observation regarding the land use cell demands and the activities per sector for 2005 is that the model performs relatively well. However, from both Table 7-1 and 7-2, it is clear that the model prediction error for the different land uses and sectors is erratic. The error in prediction is relatively low for some land uses and high for others. This indicates that it was difficult to simultaneously find parameters for both the constant growth in density and minimum density that could accurately determine the land use demands and activity growth. However, since the overall prediction errors result in relatively small over and under-estimations of both land use demands and total activity, the calibration of the regional model was considered successful.

7.3 Stage 2 Results from the calibration of the land use model

The calibration of the model was a cyclical process with several model simulations; as presented in fig 6-2 and discussed in section 6.4.2; this section only presents the results from the best-calibrated model identified in the simulations. The methods implemented in assessing the goodness of fit, process and predictive accuracy of the model are discussed in section 4.6 following Brown et al. (2005), Hagen-Zanker & Lajoie (2008) and van Vliet et al. (2013).

7.3.1 Goodness of fit of the model using 2005 real data and 2005 simulated map

As mentioned earlier, the model was simulated to mimic land use changes between 1995 and 2005. Different variations of the Kappa statistic were implemented to assess the model results. These are presented in Table 7-3. At this stage, only the calibration of the land use model without the linkage to the transport model was carried out. Hence the results only report on the findings of the calibration of the land use model block.

Table 7-3: Assessing the calibration results

	Cape Town Model (2005 simulated vs 2005 observed)	Real Change (2005 vs 1995)	Random Constraint Match
Kappa	0.903	0.868	0.792
Fuzzy Kappa	0.929	0.882	0.832
Kappa Simulation	0.580	0.000	-0.001
Fuzzy Kappa Simulation	0.616	0.000	-0.001

The results presented in Table 7-3 show that the Kappa statistics for the model is close to 1 indicating a high similarity between the simulated and actual land use map for 2005. Given that land uses such as residential areas tend to persist in their locations, this is not a surprising finding. However, the Kappa statistic does not account for land use persistence thereby does not give a good indicator of the predictive capabilities of the model. Another approach was implemented to determine the predictive accuracy capabilities of the model. This entails focusing on the ability of the model to simulate and predict actual land use transitions.

7.3.2 Predictive accuracy of the model

The predictive accuracy of the model cannot be determined without providing a benchmark on which to compare the model results. As described in section 4.6, the Random Constraint Match is a potential benchmark on which to assess the model results. From Table 7-3 presented earlier, the results indicate that the Cape Town model has a high Kappa and Fuzzy Kappa (FK) indicating a high degree of similarity between the observed and simulated maps. However, the reference model also scores a high FK value, implying that the simulated model is not providing more information compared to the reference model.

However, using the Kappa Simulation (KS) and the Fuzzy Kappa Simulation (FKS), it is possible to account for land use persistence and land use transitions in the model. This helps in delineating the performance of the Cape Town model and the RCM. The results in Table 7-3 show that the FKS and KS for the Cape Town model are lower than the Kappa and FK scores reported earlier. This indicates that the high similarity reported through the FK and Kappa can be attributed to the model simulating more land use persistence relative to actual land use changes. Though the KS and FKS are lower compared to the FK and Kappa statistics, the scores are still greater than zero showing that the Cape Town model can simulate land use changes. Further, the FKS and KS results show that the Cape Town model still outperforms the Random Constraint Match (RCM). More importantly, the KS and FKS results for the Cape Town model are 0.580 and 0.616 respectively while for the RCM both the KS and FKS are below zero. Therefore, the Cape Town model has some predictive accuracy compared to the RCM.

It was also important to consider how the Cape Town model performs in simulating individual land uses. Table 7-4 and 7-5 show the FK and KS respectively for individual land uses for the Cape Town model and the RCM.

Table 7-4: Categorical Fuzzy Kappa calibration results for function land uses

Fuzzy Kappa	**Real change (2005 vs 1995)**	**Cape Town Model (real 2005 vs simulated 2005)**	**Random Constraint Match**
High-income residential	0.859	0.801	0.771
Middle-income residential	0.908	0.907	0.874
Low-income residential	0.905	0.885	0.858
Informal housing	0.005	0.058	0.023
Manufacturing services	0.803	0.873	0.806
Trade services	0.376	0.589	0.368

Table 7-5: Kappa Simulation results for function land uses

	Cape Town Model (real 2005 vs simulated 2005)	**Random Constraint Match**
Overall Kappa Simulation	0.616	0.001
High-income residential	0.104	0.000
Middle-income residential	0.212	-0.002
Low-income residential	0.252	0.000
Informal housing	0.005	-0.001
Manufacturing services	0.524	0.011
Trade services	0.234	0.002

As expected, the FK scores reported in Table 7-4 for all dynamic land uses are relatively high except for informal settlements which has a low FK score. Again, this might reflect the simulation of land use persistence especially persistence of residential land uses in some locations. However, in the case of manufacturing services and trade services, the high FK value is encouraging as these land uses respond to market forces which might influence their location. To verify the plausibility of these findings, the KS was used to account for land use persistence, results presented in Table 7-5. As expected, the KS scores for both models are lower than the computed FK scores for the individual land uses. While the scores are lower than FK scores, the KS scores for the simulated model are above zero. This indicates the capability of the model to simulate land use changes for individual land uses whereas for the RCM they are below zero. This is an expected finding as the RCM does not predict land use transitions.

However, the KS score for informal settlements and high-income residential areas are the lowest indicating that the model struggles to reproduce land use changes for these land uses. The low KS for trade services can be attributed to the fact that trade services went through significant changes which makes it difficult for the model to predict land use changes accurately. Other authors, Pontius, Huffaker & Denman (2004) indicated that when land uses undergo significant changes, it becomes more challenging to simulate their related land use changes. This might explain the difficulties in simulating the land use changes relating to trades and services.

Another step in the assessment was to disaggregate the KS into $K_{transloc}$ and $K_{transition}$ to explain the nature of simulation errors in the model. For ease of reference, the results presented in Table 7-6 show all the Kappa statistics variants used in the model.

Table 7-6: Assessing the ability of the model to simulate land use locations and transition

	Cape Town Model (2005 simulated vs. 2005 observed)	**Random Constraint Match**
Fuzzy Kappa	0.929	0.832
Fuzzy Kappa Simulation	0.616	0.001
Kappa	0.903	0.792
Kappa Simulation	0.580	0.001
$K_{TransLoc}$	**0.709**	**-0.001**
$K_{Transition}$	**0.862**	**0.704**

The results show that for both the model and the benchmark, the $K_{transloc}$ is less than 1 indicating that the model is not simulating all land use transitions in their right locations. However, for the Cape Town model, the $K_{transloc}$ is 0.709 which is well above 0 and close to 1 compared to the RCM model. This shows that the model can simulate land use locations better compared to the RCM.

Additionally, the $K_{transition}$ for the model is higher compared to the RCM indicating that the model can simulate class transitions better than the RCM model.

7.3.3 Visual interpretation

Visual interpretation can be used together with statistical methods to evaluate the calibration of land use models. For visual interpretation analysis, function land uses were evaluated to compare how the simulated changes differed from real changes from 1995-2005. Figure 7-1 presents a visual interpretation for manufacturing and middle- income residential areas while Appendix C shows the visual interpretation of other function land uses. A comparison of real change and simulated change shows that for both middle-income and manufacturing services, the patterns of changes are similar. Informal settlements show the largest deviation between the simulated changes and reality. This finding is consistent with the observation based on the predictive accuracy of the model (presented earlier in Tables 7-5 and 7-6) where the behaviour of informal settlements was challenging to simulate. Additionally, though trade and services reported low scores for Kappa and its variants, there are similarities between simulated land use change patterns and those observed in reality. While the visual interpretation shows similarities between observed and simulated patterns of change, the location of these changes is not entirely accurate, which explains the low Kappa simulation scores.

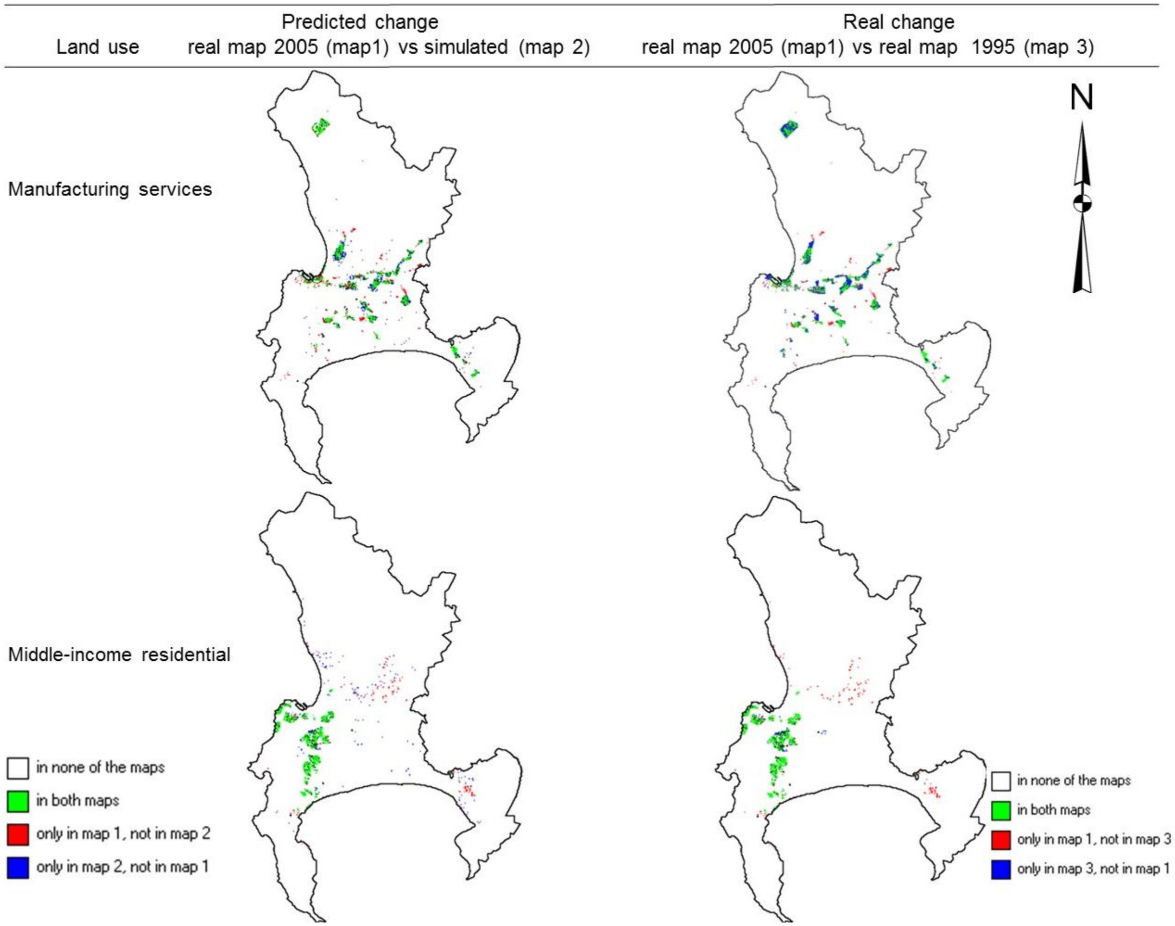


Figure 7-1: Simulated and real land use patterns per land use category

7.3.4 Process accuracy

As mentioned in section 6.4.3, the fractal dimension can be applied to evaluate the process accuracy of the model. The fractal dimension was calculated using FRAGSTAT (McGarigal, Cushman, Neel, et al., 2002) focusing on dynamically modelled land uses. The aim when using the fractal dimension as a process accuracy check is to assess whether the landscape patterns generated by the model are similar to those observed in reality. The closer the results of the simulated fractal dimension are to the fractal dimension based on the actual landscape, the more acceptable the model. The results are presented in Table 7-7.

Table 7-7: Fractal dimensions of housing for observed and simulated land use maps

land use maps	fractal dimension
Real map 1995	1.0325
Real map 2005	1.0315
Simulated map 2005	1.0269

The results show that the fractal dimension calculated based on the 2005 simulated map is close to the fractal dimension of the actual land use map. There is a 0.005 deviation in the fractal dimension between the simulated map and the real map. This is comparable to other studies van Vliet, Naus, van Lammeren, et al. (2013) who report a 0.008 deviation. This is an encouraging finding as it indicates that the model simulates land use patterns that are consistent with reality. Further, this also suggests that the neighbourhood rules developed are suitable for Cape Town model as they generated realistic land use patterns.

7.4 Stage 3 Results from the validation of the land use model

The calibration of the model was a period from 1995 -2005, while the validation period was from 2005-2010. Since the 2010 data point was not used for calibration, and independent validation of the land use model could be carried out. Like in the calibration stage, the validation procedure entailed looking at the goodness of fit, process and predictive accuracy of the model. The RCM is used as a benchmark on which to compare the validation results.

7.4.1 Predictive accuracy

Variations of the Kappa statistics utilised to evaluate the predictive accuracy of the model for the validation period (2010) are presented in Tables 7-8 and 7-9.

Table 7-8: Variations of the Kappa statistic results for the model

	Cape Town Model (2010 simulated vs 2010 observed)	**Random Constraint Match**
Kappa	0.849	0.797
Fuzzy Kappa	0.881	0.840
Fuzzy Kappa Simulation	0.325	-0.004
Kappa Simulation	0.293	-0.001
KTransLoc	0.544	-0.002
KTransition	0.538	0.530

Table 7-9: Kappa simulation for function land uses

Kappa Simulation	**Cape Town Model (2010 simulated vs 2010 observed)**	**Random Constraint Match**
High income residential	0.136	-0.001
Middle income residential	0.163	0.001
Low income residential	0.143	0.003
Informal housing	0.002	0.009
Manufacturing services	0.119	-0.002
Trade services	0.284	0.000

Table 7-8 and 7-9 compare the results from the Cape Town model and the Random Constraint Match. The Kappa and FK statistics for the model are very high and close to 1, which shows a high degree of similarity between the actual and simulated maps for 2010. However, the high similarity could be an indication of the model simulating land use persistence and not land use transitions as the RCM also has a high Kappa score. After accounting for land use persistence, the results show that the KS and FKS are lower than the FK and Kappa which indicates that along with land use changes, the model also simulates land use persistence. Though the KS and FKS are lower, they are above zero and outperform the RCM indicating that the model simulates land use transitions better than the benchmark.

From Table 7-9, the KS scores of the individual land uses for the model are above 0. However, the results show that the model struggles with simulating informal settlements as the KS value is very close to zero. Encouragingly, for all land uses, the KS for the model still outperforms the benchmark. Additionally, looking at the $Kt_{ransitions}$ and $K_{transLoc}$ the results show that for the Cape Town model, both the $K_{transitions}$ and $K_{transLoc}$ are above zero compared to the RCM model. This shows that the model yields better results when simulating land use transitions and their locations compared to the RCM model.

7.4.2 Process accuracy

To asses the process accuracy of the model for the validation period, the fractal dimension was implemented. The results are presented in Table 7-10.

Table 7-10: Measure of process accuracy

land use maps	fractal dimension
Real map 2005	1.032
Real map 2010	1.031
Simulated map 2010	1.027

The results indicate that the structure of the landscape simulated by the model in 2010 is relatively similar to the 2010 real map as there is a 1% difference between the fractal dimensions. Further comparison of the 2005 real map and 2010 simulated map shows high similarity in the landscape structure. This is consistent with the findings in Chapter 2 where the results showed that the Cape Town landscape in 2010 was very similar to 2005. This result suggests that the neighbourhood rules generated in the calibration period (1995-2005) could also be used to determine the land use patterns during the validation period (2005-2010) which is a good indication of the calibration of the model. Based on these results, it was concluded that the calibration and validation of the land use model block were successful and the next stage was to calibrate the transport model block.

7.5 Stage 4 Results from the calibration of the transport model

Thus far the discussion centred around the calibration results of the regional and land use model blocks. This section discusses the calibration of the transport model for the period 1995 to 2003.

7.5.1 Trip generation

The assessment for the trip generation was carried out for all the zones by looking at the number of work and education trips predicted by the model in 2003. The model simulations were compared to the observed trips as reported National Household Travel Survey, this is based on findings by Lombard, Cameron, Mokonyama, et al. (2007). Further, only the results for bus, taxi and car are reported as they are the only modes of transport utilised in the model. The total number of work and education trips predicted by the model for 2003 are 626, 854 and 321,707 respectively while the NHTS survey metropolitan reports for 2003 show that the observed work and education trips are 637,235 and 317, 609 respectively. This represents a 98.37% prediction accuracy for the work trips and a 98.73% prediction accuracy for the educational trips. This shows that the model slightly underpredicted work trips and overpredicted education trips. Based on the results, most of these trips are morning peak trips, this is consistent with the time when work and education trips occur. Compared to similar applications of METRONAMICA (Aljoufie, Zuidgeest, Brussel, et al., 2013) the Cape Town model performs well in predicting the number of trips generated as the estimation is 98.73% compared to 92.5% for the Jeddah model. The results also indicate that Mitchells Plain, Retreat, Athlone, Nyanga, Bellville are some of the main trip origins by bus, this parallels findings in the City of Cape Town's integrated plan.

7.5.2 Comparison of the trip generation for selected trips origins

The number of trips predicted by the model is compared to those reported in the 2004/05 Current Public Transport Record (CPTR) (TDA, 2012) for Cape Town. This was done for the bus mode for three suburbs that were recorded among the highest trip generators in the morning peak. The results presented in Table 7-11 show that the model slightly overestimates the number of trips for Mitchells Plain while the overestimation is relatively high for Bellville and Hanover Park showing estimation errors ranging between 0.08% and 23.4%. Other studies (Aljoufie, Zuidgeest, Brussel, et al., 2013) have reported estimation errors ranging from 12.3% to 18.2% in estimating the number of trips. The Cape Town estimation errors are slightly higher compared to Aljoufie, Zuidgeest, Brussel et al. (2013) however, the lowest estimation error is 0.08% for the Cape Town model compared to 12.3% for the Jeddah case. Based on these results and the performance of the model relative to similar models, the trip generation simulated by the model is acceptable.

Table 7-11: Simulated and reported trip generations

Origin	Simulated	Observed	Error	% Error
Bellville	2,579	2,465	114	4.64
Hanover Park	1,629	1,320	309	23.41
Mitchells Plain	21,729	21,712	18	0.08

7.5.3 Modal split

The modal split for all trips simulated by the model was compared to modal split in the NHTS for Cape Town, the results are presented in Figure 7-2. The model predicts cars as the mode with the highest mode share followed by minibus taxis this is similar to the pattern observed in the NHTS (2003). However, the model underpredicts car trips by 17% and overpredicts the minibus taxi trips by 3%. In the case of private cars, the low prediction might be attributed to the underestimation of the number of people who use private cars for intrazonal trips which were not accounted for in the data preparation. However, based on the results, the modal split calibration of the model was successful and comparable to reality. This is a good indication of the performance of the model.

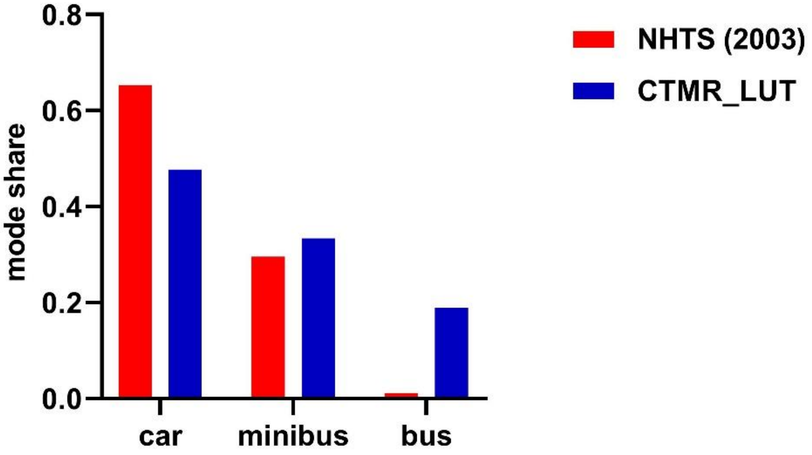


Figure 7-2: Comparison of the modal split between the Cape Town model and the NHTS (2003)

7.5.4 Average trip distance

The 2008 average trip distance for private car mode is 17.5km (TDA, 2012) compared to 14.3km as simulated by the model. This shows that the model underestimates the distance by around 24%. One potential explanation for the shorter average distances could be related to the exclusion of intrazonal trips. In reality as well as Cape Town's EMME model, the trip length of intra-zonal trips is positive whereas in the CTMR_LUT they are assumed to be zero. Additionally, the average distance calculated by the model is for car and minibus taxis as they were modelled jointly. Minibus taxis have many pick-ups and drop-offs along a route especially along "mature" corridors such as the Main Road South of the city and Voortrekker corridor; this might also help to explain the low average trip distance simulated by the model.

7.6 Stage 5 Results from the of the validation of the transport model

This section presents the results from the validation of the transport model. The discussion focuses on the comparison of the Cape Town model to the EMME model which is utilised as a benchmark.

7.6.1 Simulated congestion levels versus EMME model outputs

This section makes a comparison between the congestion levels simulated by the EMME model for 2013 and the CTMR_LUT model. The CTMR_LUT model simulates 2.44 as the maximum V/C ratio while the EMME model simulates 4.28 as the maximum V/C ratio. This indicates that within the EMME model, the city experiences heavy congestion on the network compared to the CTMR-LUT model. This is an acceptable finding as the EMME model utilises all road-based modes of transport in assigning trips onto the network whereas the CTMR_LUT assigns trips based on the private cars and minibus taxis. While this is a positive outcome of the model simulation, the key element in comparing congestion levels is to assess whether the model can predict congestion on the network in locations similar to the EMME model. More importantly, similar to the EMME model, the CTMR_LUT model managed to simulate congestion on road network links such as Voortrekker, Rhodes Drive on the M3 and Marine Drive among other links which were also identified as problematic links in the EMME model. The overall finding is that the CTMR-LUT simulations are comparable to the benchmark indicating as good validation of the CTMR-LUT model. Figure 7-3 shows the difference in congestion between the two models for a selected section of the network. Appendix F shows the congestion levels on the whole network for the EMME model and the CTMR-LUT model.

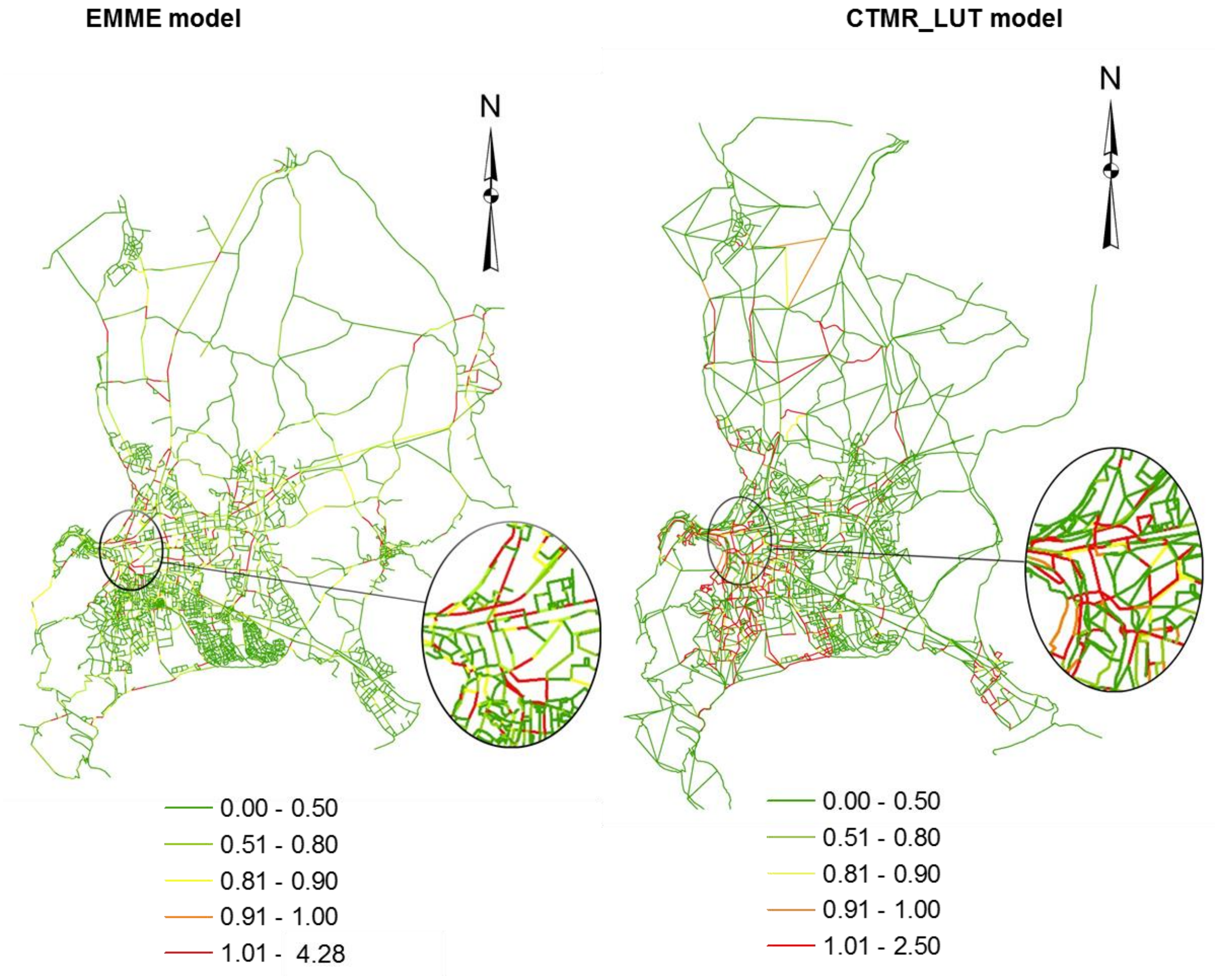


Figure 7-3: Congestion as simulated by the CTMR-LUT model and EMME model respectively

7.7 Stage 6 Results from the calibration of zonal accessibility

In stage 6, the link between the land use and transport models was introduced. Visual interpretation using the Map Comparison Kit was implemented to assess the model results. This entailed assessing the zonal accessibility maps generated by the model for high, middle and low-income residential areas for 1995, 2000 and 2005. Figures 7-4 through to 7-6 show the zonal accessibility for these function land uses while Appendix D shows the numerical zonal accessibility scores. The aim is to assess the change in zonal accessibility for low-income, middle-income and high-income residential areas. The expected outcome is that the spatial relationships identified in Chapter 2 would be observed in the visual interpretation of zonal accessibility. This ties the discussion in the present chapter to the analyses carried out in Chapter 2. As a reminder, in section 6.4.6, the calibrated zonal accessibility parameter was 0.7, which implies that any zone that scores below this threshold is considered to have poor access. The zonal accessibility represents the extent to which activities can be accessed from different activity zones. The discussion on the zonal accessibility entails identifying zones which are less accessible (with zonal accessibility scores below 0.7) and link these findings to the results in Chapter 2.

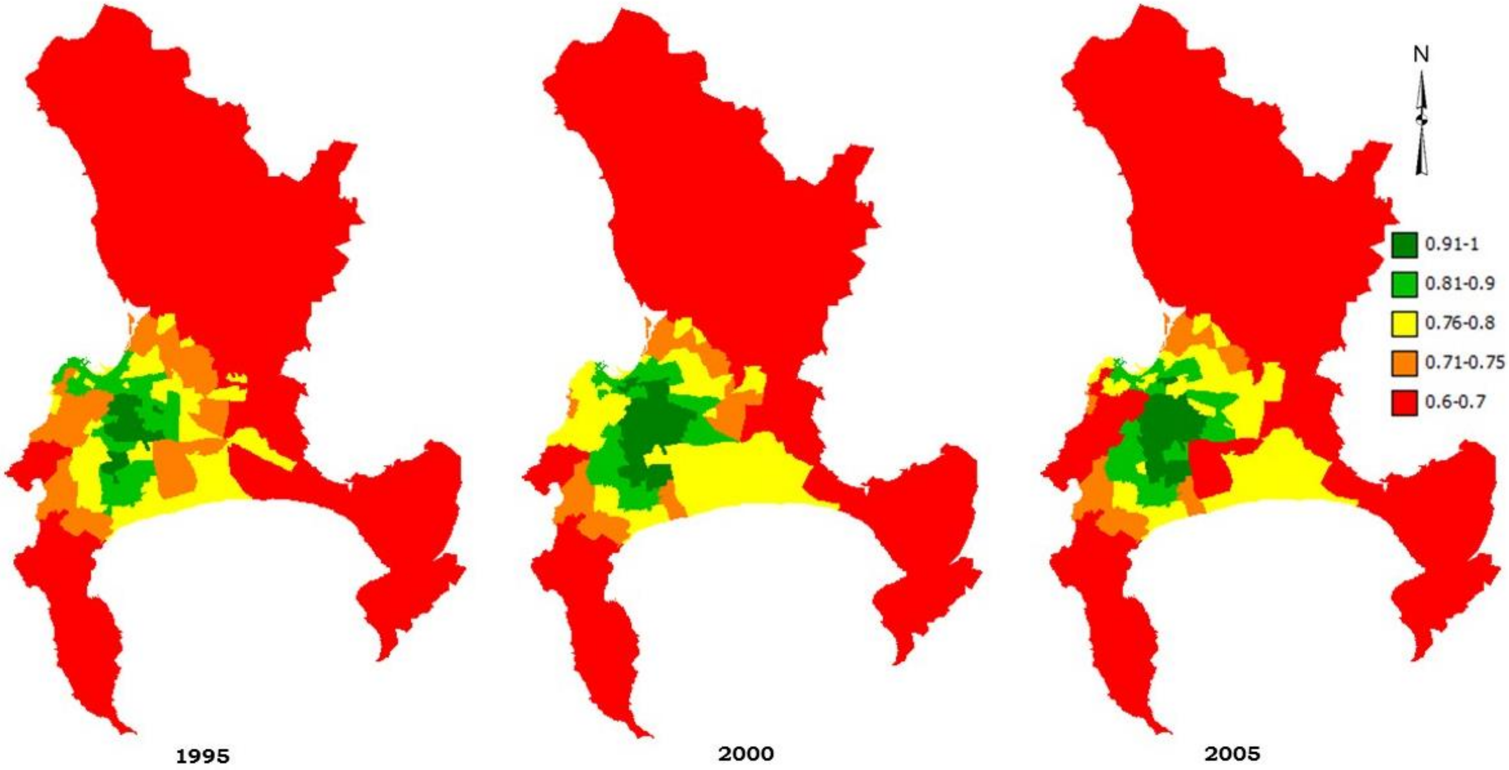


Figure 7-4: High-income zonal accessibility

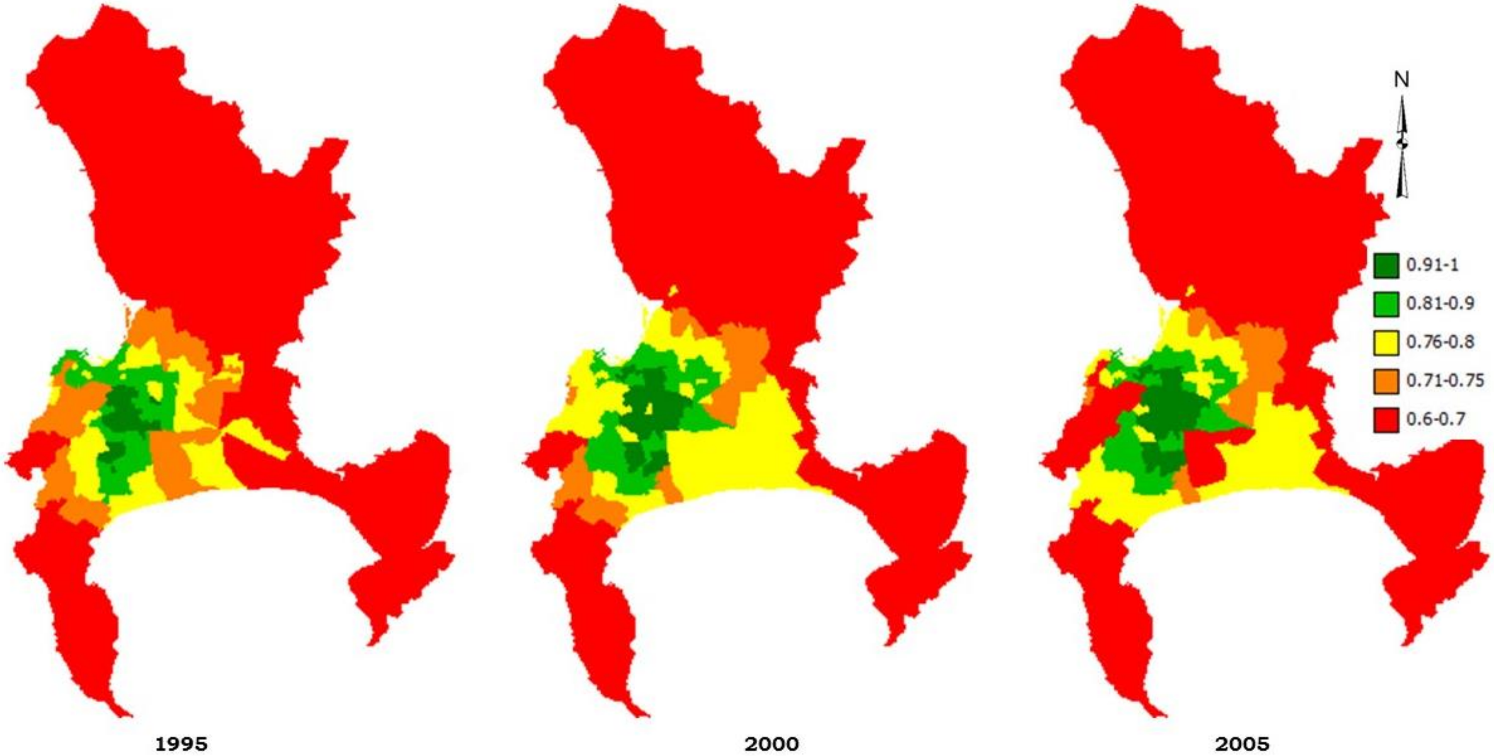


Figure 7-5: Middle-income zonal accessibility

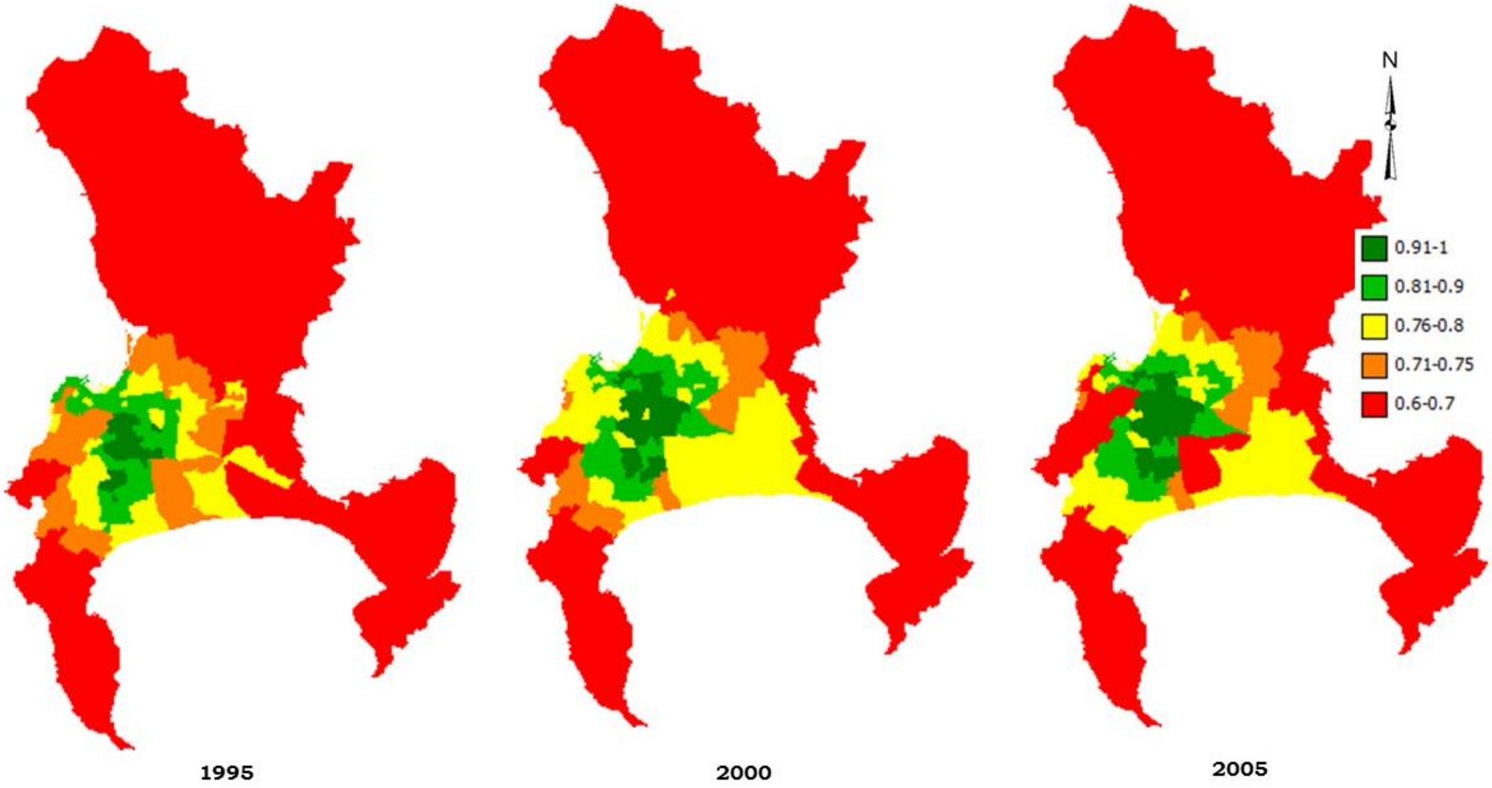


Figure 7-6: Low-income zonal accessibility

The maps presented in Figure 7-4 show the change in zonal accessibility for high-income residential areas between 1995 and 2005. Visual interpretation of the maps shows that the zonal accessibility has improved between 1995 and 2000. However, it has remained constant between 2000 and 2005 as there are no significant differences between the two zonal accessibility maps. This can be attributed to the fact that there are new high-income residential areas continue to locate in already existing high-income residential areas. This explains the similarities in the zonal accessibility scores for this land use.

For middle-income residential areas, presented in Figure 7-5, the results indicate that zonal accessibility is high and has remained constant in transport zones such as Kenilworth, Claremont, Gardens, Pinelands, Mowbray (locations shown in Appendix E) for 1995, 2000 and 2005. This can be explained by the presence of interdependent mixed land uses in these neighbourhoods which influences the zonal accessibility. Further, these zones are along primary and secondary arterials which offer local accessibility and facilitate zonal accessibility. This might be a possible explanation for the high zonal accessibility scores. Overall, the zonal accessibility for middle-income residential areas has improved between 1995 and 2005.

The results in Figure 7-6 show that in 1995, low-income residential areas such as Mitchells Plain and Gugulethu have zonal accessibility scores close to 0.6. This shows that these zones are relatively inaccessible compared to other areas. This can be explained by the network connectivity for these areas and the residential zoning laws implemented during apartheid South Africa. This acted as an impediment to mobility as low-income residential areas located in the peripheries with limited access to transport thus limiting accessibility. While a slight improvement is observed in 2000 and 2005 for some low-income areas with a change in zonal accessibility from the 0.71-0.75 band to the 0.76-0.80, the overall pattern suggests that low-income neighbourhoods have poor access to economic centres. These findings are consistent with the analysis in Chapter 2 where low-income dwellers were found to have limited access to employment and other services.

7.8 Stage 7 Results from the independent validation of the integrated model

The literature review in this research discussed the link between land use and transport and their combined influence on the urban environment. The model utilised in this research captures the link between land use and transport through the zonal accessibility. The validation of the integrated model focused on the predictive and process accuracy of the model once the link between the land use and transport model was introduced. Table 7-12 reports and compares the model results with and without the link between the land use and transport model.

7.8.1 Goodness of fit of the integrated model

To evaluate the goodness of fit of the model after integrating the land use and transport model, the actual and simulated land use maps of 2005 and 2010 are compared. Table 7-12 presents the results.

Table 7-12: Goodness of fit of the Integrated model

	Cape Town model			Random Constraint March
	without transport	with transport	with transport	
	2005	2005	2010	2010
Kappa	0.903	0.934	0.849	0.797
Kappa Simulation	0.580	0.688	0.293	-0.001
Fuzzy Kappa	0.929	0.950	0.881	0.840
Fuzzy Kappa Simulation	0.616	0.704	0.325	-0.003

The results in Table 7-12 show that the Kappa and FK scores for all models for both the calibration (2005) and validation (2010) are close to 1. More importantly, there are apparent differences in the Kappa statistic and its variants between the model simulations with and without the link to the transport model for 2005 and 2010. For example, after accounting for land use persistence for the calibration period (1995-2005), the KS increased from 0.580 to 0.6884 while the FKS increased from 0.616 to 0.703. It is evident that there is an improvement in the Kappa statistics and its variants for the calibration period, which shows that the introduction of the link between land use and transport adds value in explaining urban dynamics. Given that linking land use and transport helps in understanding urban dynamics, from here on, only the results from the simulation that includes the link between land use and transport are reported and compared to the RCM. Noteworthy is that there is a slight decline in the model performance during the validation period. This is expected as the predictive accuracy of the model becomes limited over time and is even more difficult when there are more land use changes to predict over time, this notion is supported by other studies (Haase, Lautenbach, & Seppelt, 2010).

7.8.2 Predictive accuracy of the integrated model

The results from Table 7-13 indicate that the CTMR-LUT outperforms the benchmark. Further, both the KS (0.2927) and FKS (0.3251) are above zero, this indicates that the model does simulate land use changes. Conversely, the results for the RCM show that this model does not simulate any land use changes as the KS and FKS scores are below zero. This is expected as the RCM does not simulate any land use change. To further evaluate the predictive accuracy of the model, the nature of errors in the model are assessed. This is done by disaggregating the Kappa and KS scores as shown in Table 7-13

Table 7-13: Nature of errors in the model

	Cape Town model (with transport) 2010	**Random Constraint Match (2010)**	**Actual change**
Kappa	0.849	0.797	0.853
Kappa Histogram	0.932	1.000	1.000
Kappa Location	0.911	0.798	0.922
Kappa Simulation	0.293	-0.001	0.000
Ktransition	0.538	0.530	N/A
KtransLoc	0.544	-0.001	N/A

The results show that the number of cells per land use in the RCM is equal to the number of cells in the 2010 real map. This is related to the way the reference map is calculated in the RCM. Conversely, for the Cape Town model, the cell counts per land use is not equal to 1. This finding is consistent with the results from the calibration of the land use demands from the regional model as discussed in section 7.1. The regional model underestimates the number of function cell demands by 33 cells; additionally, there is an increase in feature cells which are not accounted for in the simulated maps but accounted for in the actual land use maps. This is a potential explanation for the kappa histogram that is less than 1. Additionally, the Kappa location for all models is less than 1 suggesting that the errors in the Cape Town model are a combination of an underestimation of cell demands and the poor location of land use transitions.

Compared to the RCM, the $K_{transLoc}$ and $K_{transition}$ for the Cape Town model are above zero while the $K_{transition}$ for the RCM is zero. This is expected as the RCM does not simulate land use transitions. Overall, the Cape Town model explains the class transition and the location of the class transition better than the RCM model. Noteworthy is that high Kappa Simulation scores do not necessarily indicate a good model. Therefore, it is essential to evaluate the merits of the model using other assessment methods. The process accuracy of the model was also evaluated to assess whether the landscape patterns simulated by the model are comparable to reality.

7.8.3 Process accuracy of the integrated model

Evaluating the process accuracy of the model was two-pronged. The first part looked at landscape complexity by using the fractal dimension. The second part considered the evaluation of the zonal accessibility for different land uses and compared the results to the findings in Chapter 2. Table 7-14 shows the results for the fractal dimension based on the real maps of 2005 and 2010 and those simulated by the model for the same time steps.

Table 7-14: Urban pattern analysis as a measure of process accuracy.

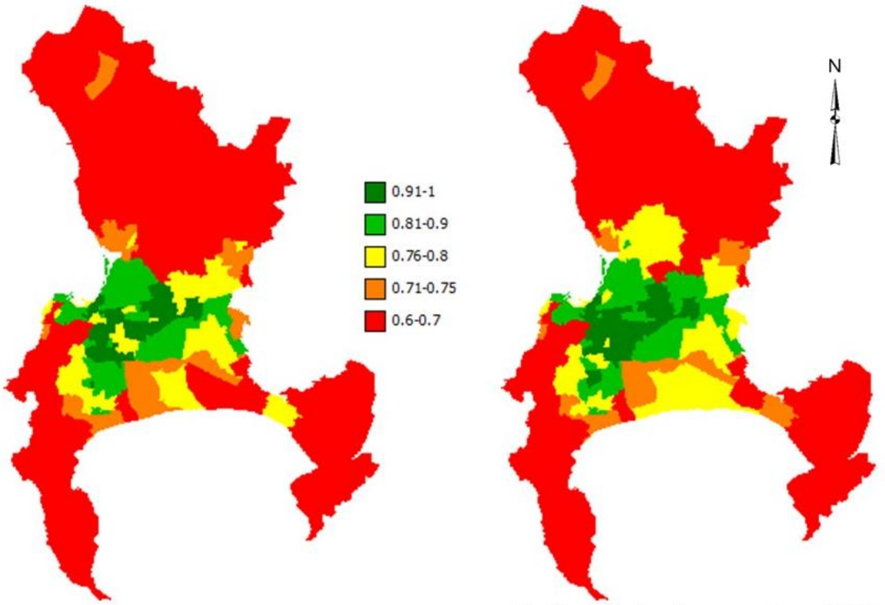
land use maps	fractal dimension
Real map 2005	1.032
Real map 2010	1.031
Simulated with transport 2005	1.026
Simulated map with transport 2010	1.027

The results show that the fractal dimension measured from the simulated maps for 2005 and 2010 are close to the fractal dimension calculated based on the actual 2005 and 2010 land use maps. There is a 1% difference between the fractal dimension calculated based on the simulated map and real map showing that the land use patterns simulated by the Cape Town model are comparable to reality. This is a relatively small difference, based on the results, it was concluded that the introduction of a link between the land use and transport model improved the ability of the model to simulate land use patterns.

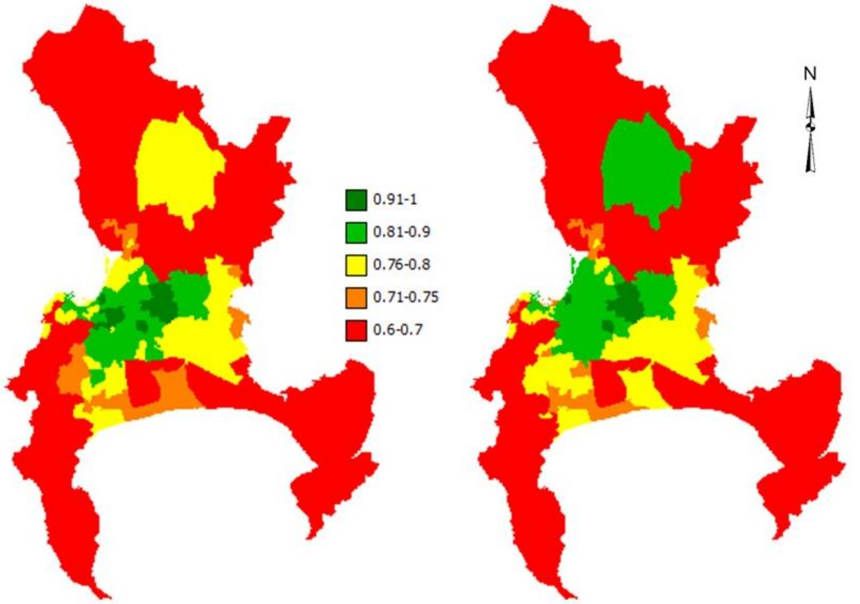
7.8.3.1 Process accuracy using visual interpretation of zonal accessibility

The zonal accessibility for the model is assessed for the validation period (2005-2010) to add another layer in assessing the process accuracy of the model. This continues the discussion started in Chapter 2 where an evaluation of the location of centres of economic activities relative to residential areas was carried out. In this case, the zonal accessibility of manufacturing services and trade services is explained relative to the locations of low-income and middle-income residential areas. The key is to look at areas where manufacturing services and trade services have high zonal accessibility scores; inferences are made regarding residential areas located in those areas.

Figure 7-7 shows the change in zonal accessibility for trade services and manufacturing services for 2005 and 2010. The visual interpretation shows that manufacturing services have registered the most substantial improvement in zonal accessibility between the two periods. There is an improvement in zonal accessibility for manufacturing services in areas with low-income residential areas. The zonal accessibility score ranges for Khayelitsha and Mitchells Plain has increased from the range 0.71-0.75 to 0.76-0.80 showing that manufacturing services are becoming more accessible to people in these suburbs.



a) Manufacturing services 2005 **b) Manufacturing services 2010**



c) Trade services 2005 **d) Trade services 2010**

Figure 7-7: Comparison of Zonal accessibility

As expected, the zonal accessibility for trade and services is low for transport zones that have low-income housing such as Khayelitsha, Philippi and Mitchells Plain. For areas like Mowbray even though they have a share of low-income housing, the zonal accessibility for trade and services is relatively high as it is located along a “mature” corridor where there is sufficient access to trade and services. Further, Mowbray has mixed land uses which explains the high zonal accessibility values. Also, trade and services have high zonal accessibility for high and middle-income zones like Pinelands and Claremont. This can be attributed to a mixture of housing and employment generating centres which influence the zonal accessibility of trade services in these areas.

Interestingly, the zonal accessibility for manufacturing for all neighbourhoods is above the minimum threshold. However, over the years, the zonal accessibility score has decreased for some transport zones. This is expected as there has been a loss of productivity that has led to closures of some companies in the manufacturing sector. Overall, the behaviour of the model concerning the zonal accessibility outputs can be explained and is related to the spatial location of each residential category relative to economic centres. Further local knowledge and ground truth relating to suburbs like Claremont, Mowbray, Pinelands, Mitchells Plain and Khayelitsha also suggest that the model can simulate the dynamics that lead to land use change. This indicates that the model has relatively good process accuracy.

It was also essential to evaluate the zonal accessibility for manufacturing services and trades and services for the validation period (2010). The results presented in Figure 7-8, highlights some examples of low, middle and high-income residential areas and the Cape Town CBD.

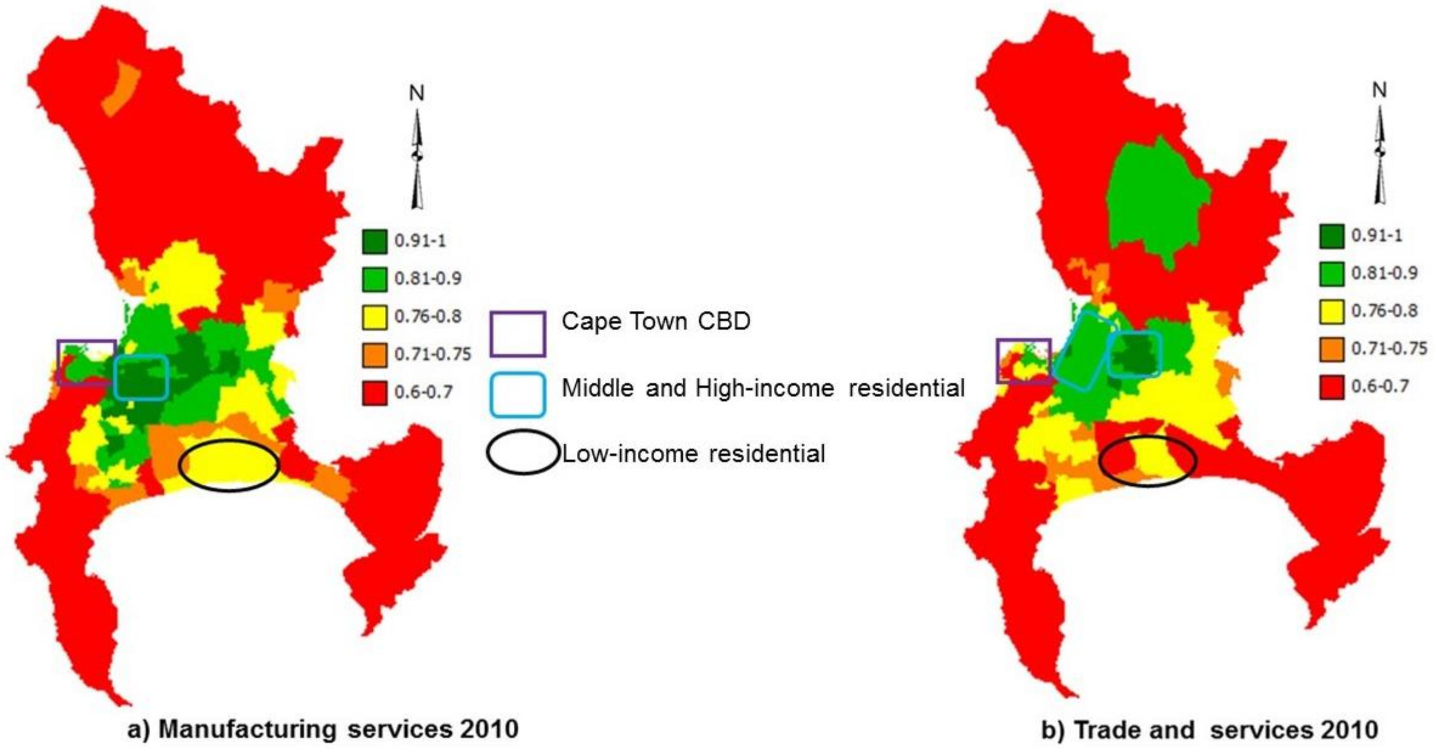


Figure 7-8: Zonal accessibility for 2010

The results are explained relative to residential areas highlighted in the figure. The results indicate that the zonal accessibility score for manufacturing services and trades services are between 0.6 and 0.75 for Khayelitsha and Mitchells Plain showing that some households in these suburbs are inaccessible. Noteworthy is that these areas are predominantly low-income and are key trip origins; these are highlighted in Figure 7-8 (in black). This trend was observed in Chapter 2 where low-income residential housing was generally located away from employment centres. On the other hand, the zonal accessibility scores for manufacturing services and trade services in middle-income residential are between 0.76 and 1 with the bulk of these areas having a zonal accessibility score above 0.80. This indicates that medium-residential areas are generally accessible.

As expected, areas like Claremont, Rondebosch, Milnerton and Durbanville, which are predominantly middle and high-income residential areas as marked in Figure 7-8 (in blue) have high accessibility scores. Additionally, there is an increase in the zonal accessibility for Milnerton, Bellville, and Durbanville. This finding is consistent with efforts by the City to densify these areas in the recent past. Further, there has also been an increase in high density mixed land uses in these areas. Again, this finding is consistent with the spatial patterns found in Chapter 2 where middle and high-income residential areas were seen to locate in areas close to economic activities. Though areas with low-income residential areas were observed to have lower zonal accessibility scores compared to high and middle-income residential areas, the general observation is that zonal accessibility for most areas has improved between 2005 and 2010 which parallels the city's efforts through policy.

7.9 Summary of results

This chapter reported on the findings from the calibration and validation of the different model blocks. The land use model was calibrated to mimic land use changes between 1995 and 2005 and validated for the period 2005-2010. On the other hand, the transport model was calibrated to represent transport conditions in 2003 and 2008 and validated from 2008 to 2013. The results from the individual model blocks and the integrated model were discussed.

The results from the land use model were evaluated using the different variations of the Kappa statistics by assessing the predictive accuracy of the model. Further, the process accuracy of the model was evaluated using the fractal dimension which is used to characterize landscape complexity. While variations of the Kappa statistic are useful tools for model assessment, the use of visual interpretation also provided insights into the land use change patterns generated by the model. The FK and Kappa statistics for the model were close to 1 for both the calibration and validation periods. However, given the weakness of the FK and Kappa statistics in assessing the performance of the model, the RCM model was introduced as a benchmark on which to compare the model performance. The results show that the CTMR-LUT consistently outperforms the benchmark for both the calibration and validation period. This is an indication that the model explains land use changes better than the benchmark.

In order to account for land use persistence, the KS and the FKS were introduced as well to assess the model performance. Both the KS and FKS were above zero for the calibration and validation showing that the model could simulate land use changes. This indicates that the model has some predictive accuracy. This finding is consistent for the independent land use model and when the link (zonal accessibility) between the transport and land use models was introduced. The integration between the land use and transport model (results presented in Table 7-12 and 7-13) produced better results with the KS and FKS increasing from 0.580 to 0.688 and 0.616 to 0.704 respectively for the calibration period. The improvement in the KS and FKS shows that the integration of the transport and land use model improves the ability of the model to predict land use dynamics.

Another encouraging finding is that the introduction of the land use and transport link (Table 7-12) resulted in high KS and FKS 0.688 and 0.704 compared to the statistics without the link between the land use and transport model. This was also the case for the Kappa and FK which increased to 0.934 and 0.950 respectively with the introduction of the link between the land use and transport models. This suggests that the high Kappa and FK values reported are not predominantly from simulating persistence but show that the model does indeed simulate land use changes. Additionally, the KS and FKS of the benchmark are below zero which is expected as this model does not simulate any land use changes.

In addition to predictive accuracy, it was essential to assess whether the land use model could correctly predict land use transitions and the location of the transitions. This was done by disaggregating the KS into $K_{transition}$ and the $K_{transloc}$. The results from the calibration (Table 7-6) show that the $K_{transition}$ and the $K_{transloc}$ are relatively high and close to 1. This is an encouraging finding as it shows that the model has some predictive accuracy. However, given that the $Kt_{ransloc}$ is below 1 it shows that there are issues with the model in predicting the exact locations for the land use changes. In the context of Cape Town, the landscape has changed significantly which makes the prediction of these changes difficult.

Since the assessment of the calibration results showed that the integration of land use and transport improved the performance of the model, the validation results only considered the model simulations based on the simulation with the integration between the land use and transport models. As presented in Table 7-13, the KS and FKS for the CTMR_LUT were 0.293 and 0.325 respectively compared to the RCM model statistics which are below zero. Compared to the RCM, the Cape Town model has better predictive accuracy and can predict land use changes better as the KS and FKS are above zero in the validation period.

Over the validation period, all variations of the Kappa statistics have decreased as shown in Table 7-13. However, the CTMR_LUT model consistently outperforms the benchmark. While the model is a good fit in explaining the urban dynamics in Cape Town, an assessment of the FK s shows that the model underperformed in the simulation of informal settlements and trade services. This can be attributed to an expansion in informal settlements between 1993 and 2010 (from 50 in 1993 to 230 by 2010) due to rural-urban migration which resulted in a drastic change in the urban composition. This represents over 400% increase in the land space occupied by informal settlements which potentially makes it difficult to simulate their temporal growth and dynamics thereof. This characteristic has been observed in other land use models were significant land use transitions challenge the ability of models to accurately simulate land use changes (Pontius, Huffaker & Denman, 2004). Additionally, the behaviour of informal settlements is highly erratic and heavily depends on human decisions and is unregulated; hence formulating neighbourhood rules that sufficiently explain their growth and dynamics is a challenging exercise.

Evaluating the process accuracy of land use models is essential especially when the model is applied in policy evaluation and assessment. Assessing the process accuracy entailed evaluating whether the land use patterns simulated by the model were comparable to reality. The fractal dimension indicated that the land use patterns simulated by the model are similar to observed land use patterns. This finding also suggests that the neighbourhood rules generated in the calibration of the model could replicate observed land use patterns.

While the results from the calibration and validation show that the model performs well on various predictive and process accuracy checks, several limitations were observed. For instance, the goodness of fit of the model especially its ability to predict individual land use changes showed that the model struggled with predicting informal settlements. The model performed as well as the RCM in its prediction of informal settlements. As mentioned earlier, informal settlements formation is unpredictable by nature this might explain the challenges encountered in capturing their behaviour. Further, informal settlements are strongly influenced by the housing market which is complex and has many actors, this constraint the prediction of their dynamics and morphogenesis. This explanation is supported by Manson (2007) who argues that the predictive accuracy of simulated land use changes is limited by the uncertainty that is related to the behaviour of individuals within urban ecosystems.

In the case of trade and services, they are very dynamic and highly driven by market forces and are also dependent on the behaviour of other land uses such as residential areas. This makes it difficult to predict the associated land use changes. While the visual interpretation shows realistic land use change (Appendix C) - an indication of a good calibration, the results do show that the model does not predict the exact locations for some land uses especially for trade and services. The behaviour of economic centres offering trade and services is influenced by policy among other drivers which influences their location. This made it difficult to generate neighbourhood rules that could accurately capture the role of policy and individual decision-makers who are profit-seeking for this land use.

Overall the results are acceptable; however, like other land use transport models, during the calibration process, it was clear that the Cape Town model was complex to calibrate due to the various factors in the urban environment. This issue points to the fact that land use change is a complex process which makes the models implemented to detect the process;

complex as well. This is mainly related to the interconnectedness and interdependency between urban ecosystems. This has been cited to as an issue in simulating and accurately predicting land use changes (Liu, Hull, Batistella, et al., 2013; Meyfroidt, Lambin, Erb, et al., 2013)(Liu, Hull, Batistella, et al., 2013; Meyfroidt, Lambin, Erb, et al., 2013). In the present study, this was mostly identified, in the calibration of the neighbourhood rules of the following land use pairs: (1) informal settlements and low-income residential (2) middle-income residential and trade and services. With regards to trade services and middle-income, these land uses are interdependent as middle-income supplies labour to trade and services and are found close to each other in the city. The fine-tuning of this rule consistently resulted in significant changes in the land use dynamics. For low income-income housing and informal settlements, the change in the behaviour of low-income housing due to other land uses influenced the location of informal settlements. Moreover, the influence of human behaviour and decision making which is inherent in informal settlements compounded the unpredictability and complexity of this land use which limited the ability of the model to simulate the location of this land use correctly.

Regarding the transport model, the model could predict the overall trip generation for work and education trips over the calibration period 1995 to 2008. The calibration of the transport model was staged and relied on the availability of data. This resulted in the use of different time points to assess the calibration results for the land use and transport model. The simulation of transport conditions until 2003 showed that there was a 2% deviation of simulated trip generation from the actual values indicating that the model could simulate transport conditions in 2003. While the model could predict the modal split hierarchies, the results indicate that the model struggled to predict the modal split magnitudes that are close to those reported in the NHTS data. However, the model did well in predicting the modal split for minibus taxis. This result may signal the need for more data to help in the calibration of the trip distribution model block especially the inclusion of intrazonal trips.

The comparison of the congestion levels indicates that the maximum V/C ratios predicted in the CTMR-LUT model were lower than those reported in the EMME model. This was expected as only the private car and minibus taxi were used to estimate the congestion level in the CTMR_LUT model while EMME utilised all road-based modes. Similar to the EMME model, the CTMR-LUT could predict congestion on problematic links such as Voortrekker, Rhodes Drive on the M3 and Marine Drive. This is a good indicator of the performance of the model.

7.10 Implications of model results

One of the objectives of this research is to apply a land use transport model for exploratory policy scenarios in Cape Town. This section discusses the results in the context of the applicability of the model for exploratory policy scenarios. This section provides insights into the implications of the results and the methods utilised to assess the model. Inferences are made on whether the model is appropriate for exploratory policy scenarios in Cape Town.

The validation of models should be done in the context of the intended use of the model. Additionally, the validation exercise should not be construed as a test of how good the model is but as an assessment of the extent to which the model meets a minimum criterion (Jakeman, Letcher, & Norton, 2005; Houet, Aguejdad, Doukari, et al., 2016). As such, identifying a benchmark on which to compare the model is an essential aspect during the validation exercise especially when a model is intended to act as an advisory tool. The assessment of the calibration and validation results for this research entailed comparing the model results against a benchmark. The Random Constraint Match was adopted as a benchmark to assess the land use model results. The results from the calibration and validation exercises of the land use model block showed that the Cape Town land use model consistently outperformed the benchmark based on the comparison of the Kappa statistics and its variants; results presented in Tables 7-4, 7-4, 7-5, 7-6, 7-8, 7-9, 7-12 and 7-13.

On the other hand, the transport model was evaluated based on various metrics. Firstly, during the calibration, there was a comparison of the number of trips generated by the model to those from previous transport studies in Cape Town. Secondly, the main origins and destinations simulated by the model were also compared to those reported by the City. The results suggest that the parameters utilised in the model were reasonable and could generate transport conditions that were comparable to reality. For the validation of the transport model, the congestion patterns simulated by the CTMR_LUT were compared to those generated by the EMME model which-a land use transport modelling framework utilised by the City of Cape Town. The congestion conditions from the CTMR_LUT model could be explained and related to those from the EMME model. Based on the methods implemented to assess the model, the conclusion is that the model could simulate land use patterns and transport conditions that are relatable to reality.

The model evaluation also considered the integrated model by focusing on the zonal accessibility scores simulated by the model for different suburbs. The aim was to assess the accessibility patterns generated by the model and compare them to known land use patterns as cited by various authors (Turok, 2001; Palmer, Brown-Luthango, & Berrisford, 2011; Turok, 2011a) and to the findings presented in Chapter 2 of this thesis. The results indicated that the spatial patterns simulated by the model were comparable to those of the city's urban landscape between 1995 and 2010. Specifically, the zonal accessibility patterns indicate that low-income residential areas have poor access to economic activities compared to their middle and high- income counterparts. This finding is consistent with the results in Chapter 2. Concerning the model performance, this is an encouraging finding as it indicates that the neighbourhood rules and transport parameters utilised in the model could capture the land use and transport dynamics for the city's landscape.

Additionally, it was also essential to evaluate whether changing the model parameters to adapt them for exploratory scenarios would influence the performance of the model. The observation after changing some model parameters (results in section 8.3) was that the Cape Town model still outperformed the benchmark. This is an indication that if need be, it is possible to change model parameters to fit policy interventions without influencing the performance of the model relative to a benchmark.

The third objective of this research is to formulate a set of policy strategies that may provide insight into the impacts of policy interventions on urban change in Cape Town. The methods implemented for model appraisal provided insight into whether the model could be used for its intended purpose thereby fulfilling recommendations by Jakeman, Letcher & Norton (2005) and Houet, Aguejdad, Doukari, et al. (2016). Based on the results from the various assessment measures, what is clear is that the model developed in this exercise consistently performed well against the different benchmarks that were utilised. Therefore, in conclusion, the land use transport model developed for the Cape Town metropolitan region can be utilised for “what if” exploratory scenarios discussed in the next chapter.

Chapter 8

Assessing the impacts of alternative urban development approaches

8.1 Introduction

Themes that continue to emerge with regards to Cape Town include the peripheral location of low-income housing, expensive access to transport and its infrastructure, inefficient urban densities, residential informality, congestion among others. Despite several policies being put forward to ‘unlock’ low-income housing in strategic areas as well as reviving the inner city, the low rates of return on investment have limited the uptake of some of the policy incentives. This has perpetuated the marginalisation and, the exurban location of low-income housing as land acquisitions for the residential units and property development are relatively affordable in peripheries (Herron, 2017). This trend has continued even though compact growth strategies are more attractive as they are associated with low transport expenditure; potentially as low as 10% of income compared to 14% of income under sprawl developments (Palmer, Brown-Luthango, & Berrisford, 2011). For Cape Town to address its urban issues, urban policies need to acknowledge the dynamic interactions and synergies that exist between the different aspects of the urban environment. This is an avenue through which the city can uplift itself and progress on a path that addresses issues of equity, social exclusion and ensure the integration of all social groups.

This chapter implements the dynamic model developed in this research. Firstly, a discussion on some of the transport and land use development strategies implemented in Cape Town is carried out to provide a context on how the land interventions implemented in this chapter fit into the current urban planning context in the city. Further, understanding the transport and land uses development approaches implemented in Cape Town aids in understanding the drivers that need more attention in formulating the exploratory policy scenarios.

8.2 Transport and Spatial development trends in Cape Town

In 2006 Pieterse (2006) wrote that "…the more the state acts on the city with all of its 'good' intentions, the more it seemingly stays trapped in its apartheid form if not identity. Eleven years after political liberation, there is an undeniable gap between policy intent and outcome suggesting that a powerful ghostly hand of segregation intertwined with inequality is at work". This statement still rings true over two decades since South Africa gained its independence. While there has been progress in changing the spatial structure of Cape Town, Chapter 2 revealed that the city is lagging in solving urban issues. A background of land use and transport strategies that have been pursued by the City of Cape Town is discussed to identify the urban change drivers that the city has focused on through these strategies:

- New Urbanism
- Corridors and nodes
- Bus Rapid Transit
- Transit-oriented development

Below, each of the transport and land use strategies is briefly discussed, focusing on aspects that relate to redressing segregation, congestion, transport accessibility, affordability and social exclusion. This will help in identifying the drivers that are vital in setting up the policy scenarios.

8.2.1 New Urbanism

New urbanism encourages land use diversity which encourages social interaction in neighbourhoods while promoting non-motorised transport; this typically results in a decrease in environmental degradation (Robert, 1996). The Cape Town Foreshore Freeway Precinct is one such project grounded in new urbanism. This was viewed as a potential avenue to solve some of Cape Town's urban problems. After several proposal evaluations and deliberations with private stakeholders, the project was abandoned. However, one of the criticisms raised before the abandonment of the project was that the winning project bid did not propose to 'unlock' a significant number of low-income units within the precinct. Some scholars, including Watson (2018) (cited in Accelerate Cape Town, 2018), indicated that the 450 low-income residential units proposed in the bid were more of a symbolic effort to "appease" proponents of housing inclusivity in the CBD instead of being motivated by the urgent need to address social and economic imbalances

8.2.2 Nodes and corridors

Post-apartheid spatial planning in South Africa focuses on development along nodes and corridors (Todes, 2005). In Cape Town, the Spatial Development Framework focuses on urban growth near growing centres of economic activities and along established transport routes and infrastructure. The main focus is on the densification of transport corridors to facilitate access to employment opportunities. The Cape Town Spatial Development Framework (CTSDF) discussed in section 3.4 focuses on four main corridors:

- The main road from Simon's Town to Cape Town also known as the west corridor.
- The southern corridor which links the Claremont area, the Cape Town metro in the South East and Somerset West.
- The eastern corridor which links Khayelitsha and Mitchells Plain to Bellville.
- The urban core corridor which links the Cape Town CBD to Bellville along Voortrekker roads (TDA, 2012).

Further, the Cape Town Integrated Transport Plan (CTITP) complements the CTSDF as it seeks to understand trip productions and attractions on corridors for better transport planning (TDA, 2012). However, despite land use developments along these corridors, they are still characterised by low residential densities which conflict with the need to improve access to employment as per CTSDF.

The Built Environment Performance Plan

The Built Environment Performance Plan was developed to address issues of urban densities along specific corridors. It charts how Cape Town aims to use public transport to transform the city's spatial structure to ensure a more compact, inclusive, efficient and sustainable urban form. In the BEPP, locations within the city that will facilitate restructuring and integration are identified. The strategy considers:

- Linking Khayelitsha and Kuils River through the metro rail.
- Linking the metro-south east and the Cape Town CBD with by improving road-based public transport on this corridor.

- Linking the Bellville, Maitland, Parow, Goodwood and Salt River CBDs with the Cape Town CBD via the Voortrekker Road corridor (TDA, 2018).

8.2.3 Transit-oriented development (TOD)

TOD in Cape Town is envisaged to address issues of spatial inequality, transport affordability, urban sprawl through the integration of public transport and land uses (CoCT, 2016). One of the interventions in the CTSDF is to pursue land use intensifications that focus on transit-oriented development; this is closely related to the corridor and nodes urban development strategy discussed in section 8.2.2. Urban development strategies like the Comprehensive Integrated Transport Plan (ITP), Spatial Development Framework (SDF) and a Densification Strategy (DS) detail the TOD frameworks the City hopes to pursue (TDA, 2012, 2017a). The following aspects within the TOD strategy resonate with the present study:

- Locating affordable housing in accessible locations.
- Integrated land use and transport strategies that allow for corridor development which in turn supports public transport.
- Precinct planning that focuses on the integration of transport facilities and land use developments in the surrounding areas.
- New developments that have mixed land uses that are inclusive, well-located.

Three main corridors are identified as integration zones which can potentially serve to restructure the city. These include:

- The Metro South East also referred to as the Metro South-East Integration Zone (MSEIZ), this also comprises of a corridor that links the city centre.
- The Voortrekker Road Voortrekker Road Corridor Integration Zone (VRCIZ) which mainly focuses on the Cape Town CBD and Bellville.
- The Blue Downs corridor which links the Metro South East and Bellville (TDA, 2017b). It also considers the Blue Downs Rail link.

The idea is that these corridors would:

- Provide affordable opportunities by public transport to restructure the urban form following the principles of TOD.
- Provide an opportunity to diversify and intensify land uses.

- Entail infrastructure improvements and urban development projects.
- Have the capacity to link economic opportunities and mono-use settlement patterns.

The strategies above attest to the dedication to pursue land use and transport policies aimed at restructuring the city. Noteworthy is that historically marginalised suburbs are highlighted as they stand to benefit from integration and restructuring as this improves the prospects of access to economic activities for the low-income cohort.

8.3 The development of exploratory policy scenarios

As discussed above, most of the planning legislation and policy directives in Cape Town consider city restructuring to comprise promoting mixed land uses and high-density development along urban corridors. This was considered a viable response to addressing inefficient spatial patterns which are linked to high transport costs, especially for the low-income cohort. The exploratory scenarios considered in this research focus on land use and transport related changes and evaluate their influence on land use developments and transport through a set of indicators. The scenarios in this research are:

- Business as usual (BAU).
- Redressing of social exclusion (SE).
- The potential proliferation of informal settlements (PI).

The exploratory scenarios simulate the land use transport changes from 2010 to 2030. A set of assumptions made in simulating the scenarios are presented in Table 8-1. The storyline and rationale for each of the scenarios are discussed in sections 8.3.3 to 8.3.5.

Table 8-1: Exploratory scenarios and policy interventions

	Scenarios	Population	Spatial Development	Transport
Suggested policy interventions	**Business as usual (BAU)**	• Assumes the continuation of current population trends	• Assumes the continuation of current spatial trends	• BRT network from 2010 • Planned infrastructural development
	Redressing social exclusion (SE)	• Steady growth in population and jobs in all sectors • Increase in rural to urban migration	• Increase in the construction of low income housing in the Metro South East corridor and close to transport infrastructure • In situ upgrading of the informal settlements to low income residential • New centres of economic activities locate along the Metro South East corridor	• BRT network from 2010 • Road infrastructural development to link the Metro South East to the Cape Town CBD
	Proliferation of informal settlements (PI)	• Steady growth in population and jobs in all sectors • Increase in rural to urban migration	• Increase in the construction of low income housing in the peripheries • In situ upgrading of the informal settlements to low income residential • Centres of economic activities locate in the affluent suburbs • Revival of the Cape Town CBD	• BRT network from 2010 • Planned infrastructural development

8.3.1 Data for simulating exploratory scenarios

This section briefly introduces the data set that was used in simulating land use and transport changes in all the scenarios. The BAU scenario assumes that current population growth trends. On the other hand, the population projections provided in the Socio-Economic Profile (SEP) for Cape Town (Western Cape Government, 2017) were used for the steady growth of population up to 2030. The employment data outputs in the EMME 2013 model simulation were also used as inputs in the exploratory scenarios.

8.3.2 Modifying parameter values for scenarios

One of the issues that emerged in this research are inefficient urban development patterns and polarisation of centres of economic activities in the affluent suburbs. To effect change in the spatial development of the Cape Town urban landscape in the forecasting period, it is essential to modify some model parameters to allow for new urban development patterns. However, for the BAU scenarios, the parameters were not updated. The following adjustments were made to some model components and parameters for the SE and PI scenarios.

- Changing the parameters for the regional model to simulate new land use demands in the social exclusion and informal settlements scenarios from 2011 until 2030.
- Revisiting the neighbourhood rules between trade and services and manufacturing services to allow for the formation of more urban clusters from 2011 to 2030 in the social exclusion and informal settlements scenarios.
- Revisiting the neighbourhood rules for low income and trade and services to facilitate their interaction and coexistence adjacent to each other over short and also long distances from 2010 to 2030 in the social exclusion scenario.
- Adding the MyCiti bus network from 2010 to evaluate the transport impacts on land use in all scenarios.

In the regional model, the parameters that were modified are the constant growth of *density and the minimum density* to allow for the formation of high land use and activity densities. In the case of neighbourhood rules, the influence function of trade and services on itself was changed such that it had a long tail which allowed for larger clusters to form and for this land use to interact with other land uses over longer distances. For manufacturing services, the influence function of manufacturing services on itself was also changed such that the tail was slightly longer to allow for large clusters and interaction with land uses over relatively longer distances compared to the calibration and validation period. For the influence functions of trade and services on low income and low income on trade and services, they were changed to facilitate positive attraction and interaction between these two land uses over both short and long distances.

Regarding the perturbation parameter ($\boldsymbol{r_{k,i}}$), since this parameter controls for scattering and the formation of new clusters, it also needed to be revisited. Initially, the model was simulated until 2030, and the land use patterns were observed. Earlier in section 4.7.1, the discussion on process accuracy pointed out that urban processes are path dependent; hence certain urban patterns can be measured and observed. Instead of implementing the fractal dimension as in section 7.3.3, the correlation between cluster-size and frequency after Zipf (1949) can be utilised to assess land use development based on the model simulations. The log of the frequency of land use clusters is plotted against the log of the size of the clusters. The rationale with Zipf's law is that urban development is characterised by the formation of a few large land use clusters and many small land use clusters. Hence a plot of the relationship between the size of land use clusters and their frequency is expected to be log-linear. This approach has been implemented to evaluate the calibration and validation of dynamic land use models (White et al., 1997; White, 2006). The results in Figure 9-1 show that the CTMR_LUT simulated until 2030 can represent the cluster-size relationship, thus indicating urban development patterns that are realistic as they conform to the structures of most cities. This indicates a good calibration of the model, suggesting that the model can be confidently used to explore policy scenarios for Cape Town.

After changing the model parameters, the Cape Town model was simulated using the new neighbourhood rules until the end of the validation period 2010. The model simulations were assessed to evaluate the performance of the model before applying it for exploratory scenarios. This entailed evaluating whether historical land use patterns (1995-2010) could be simulated by the model after the parameters were changed. The simulated map in 2010 was compared to the RCM as described in section 6.4.2. Table 8-2 shows the Kappa statistics and its variants after the neighbourhood rules were modified to facilitate the simulation of the exploratory scenarios.

Table 8-2: Kappa statistics after changing some model parameters

	Base model neighbourhood rules	Adopted neighbourhood rules	Reference map 2010
	Cape Town Base model 2010 simulation	**Cape Town model 2010 simulation**	**Random Constraint Match**
Kappa	0.849	0.873	0.797
Fuzzy Kappa	0.881	0.842	0.84
Kappa Simulation	0.293	0.239	-0.001
Fuzzy Kappa Simulation	0.325	0.274	-0.003

Though the different Kappa scores have decreased, the results in Table 8-2 indicate that the Cape Town model still outperforms the benchmark after the neighbourhood rules were changed. This suggests that the model could still simulate land use changes that are comparable to reality and better than a random model. Therefore, the new neighbourhood rules were concluded to be appropriate for implementation in the forecasting period.

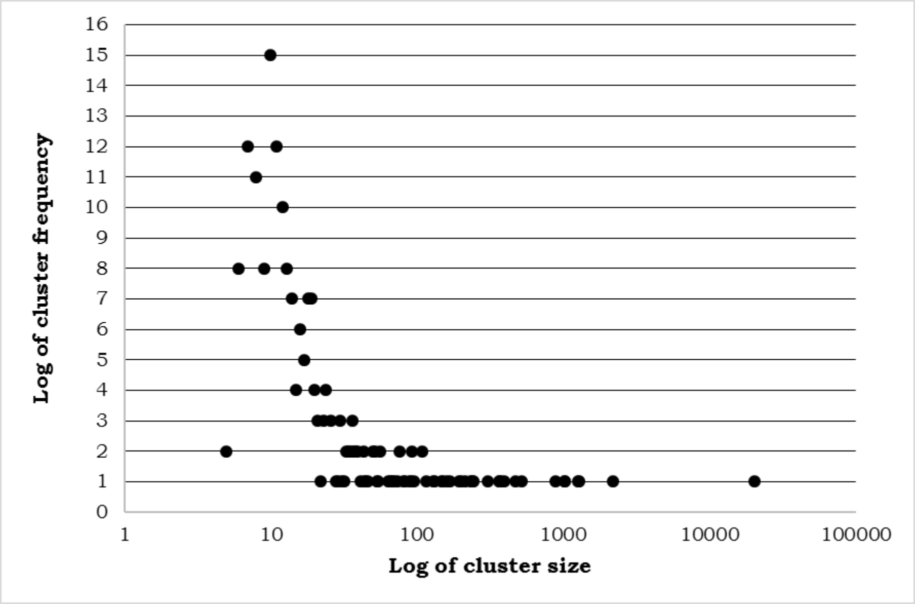


Figure 8-1: Cluster-size frequency of Cape Town in 2030 based simulated land use map

8.3.3 Business as usual (BAU)

This is the baseline case and considers a continuation of the status quo in the growth trajectory of land use and transport changes and the associated interactions from 1995 to 2010. The scenario includes the continuation of planning trends where low-income housing continues to locate in the peripheries and away from economic activities which perpetuate urban sprawl. Informal settlement growth is also unregulated; hence, they are expected to increase.

8.3.4 Redressing of social exclusion (SE)

There is a consensus that South African cities need to be restructured, specifically by redressing apartheid spatial planning to attain equitable, socially and economically inclusive cities. The Social Housing Regulatory Authority (SHRA) explains that restructuring in the South African context entails pursuing housing interventions that diverge from historical planning. This scenario considers ‘unlocking’ low-income housing in areas with fully developed transport infrastructure with access to economic opportunities. The scenario focuses on land use policy interventions within the integration zones as defined by the City of Cape Town (TDA, 2018) in the Built Environment Performance Plan. This scenario also reflects on the potential of land use and transport impacts of infilling vacant land close to areas with fully developed transport infrastructure. Chapter 2 revealed that urban development strategies implemented in Cape Town have resulted in sprawled growth of the city. Therefore, this scenario also considers compact growth or densification strategies where the focus is on the extensive development of the Metro South East Integration Zone (MSEIZ). This entails locating new low-income residential areas and employment generating land uses in this integration zone. A new zoning map was introduced in this scenario and this demarcated area earmarked for new developments and conservation areas from 2016. Additionally, in this scenario, there is strict protection of vulnerable flora, fauna and agricultural land.

The rationale for the scenario

An estimated 40% of Cape Town’s population lives within the Metro South East Integration Zone. Additionally, this area houses the most vulnerable individuals with low income and poor access to essential services which can be related to social exclusion (Herron, 2017; TDA, 2018). Hence, evaluating the land use and transport impacts based on this scenario might produce invaluable information with regards to policy on redressing social exclusion.

8.3.5 The proliferation of informal settlements (PI)

Informal settlements are a part of the urban fabric in Cape Town and their growth needs to be managed. Abbott & Douglas (2003) found that informal settlements were growing at a faster pace than the rate of provision of formal housing which reveals a shortage in the housing stock. Current discourse proposes that in situ upgrading of informal settlements might be a viable option to address the housing problem in the city (Misselhorn, 2008; Massey, 2015; Brown-Luthango, Reyes, & Gubevu, 2017). Therefore, this scenario considers the growth of informal settlements and predicts the new locations of informal settlements. Assuming that in situ upgrading takes place, it means these informal settlements would eventually become low-income housing. Identifying the locations where informal settlements are likely to develop is potentially useful for the implementation of proactive approaches to managing their growth. Given the organic nature and unpredictability of the growth of informal settlements, the aim is to evaluate the neighbourhood relations that attract new informal settlements. The hope is that this information provides additional knowledge in the prediction of informal settlement growth and locations in Cape Town. Noteworthy is that this scenario serves as an avenue to evaluate whether the new locations of informal settlements and the eventual in situ upgrading are in line with housing policy aimed at improving accessibility for the low-income.

The rationale for the scenario

Informal settlements are an urban phenomenon in South African cities, one that continues to tether South Africa to its historical past. Debates with regards to informal settlements (Turok, 2015; Turok, Budlender, & Visagie, 2017) suggest that informal settlements either provide opportunities or trap people in poverty. While policies such as the Breaking New Ground through the Upgrading of Informal Settlements Programme (UISP) are clear on the need to integrate informal settlements into the urban fabric (DoH, 2004), other authors (Misselhorn, 2008; Bradlow & Bolnick, 2011; Fitchett, 2014) argue that there is still ambivalence in policy with regards to the response on the growth of informal settlements. One of the suggested approaches is to prioritise in situ upgrading of informal settlements instead of relocation as this might lead to a loss of social networks by informal settlements dwellers. In a context where there is a preference of in situ upgrading, it would be interesting to identify whether these new locations allow for the integration of low-income housing to economic opportunities or whether these new locations perpetuate segregation in Cape Town.

8.4 Results from scenarios

This section presents the results of the explanatory scenario simulations. A framework that is used to assess the different policy interventions is presented.

8.4.1 Framework for assessing scenario results

This section discusses the methods that are implemented to assess the policy interventions. The scenario analysis aims to characterise and identify urban change emanating from different transport and land use policy interventions. One way of characterising and identifying urban change is through the development of indicators. This helps in identifying the different components within urban areas that drive change. The method implemented to assess the scenarios provides an opportunity to evaluate the impacts of the different intervention on the spatial structure of the landscape and transport related aspects. A set of indicators are developed for each intervention to characterise the urban landscape and transport conditions. The following aspects relate to the spatial expansion and urban patterns on the landscape:

- Spatial indicators to determine the spatial development of the city under different scenarios.
- The change in zonal accessibility for manufacturing and trade and services in relation to residential areas.

While the following discuss aspects that relate to transport mainly considering trip making:

- Average distance to locations with manufacturing and trade and services from the different residential categories. The analysis also considers the average commuting distance to economic centres from residential areas under different scenarios.
- Congestion under different scenarios. This entails extracting road network links on the different sections of the network and make a comparison of the traffic flow conditions.

8.4.2 Spatial indicators to determine urban patterns

Spatial metrics are implemented to understand the urban spatial patterns and to evaluate land development for different scenarios between 2010, 2020, 2025 and 2030. The fractal dimension, a measure of landscape complexity, previously discussed in section 7.3 is implemented to assess the Cape Town urban landscape. Additionally, the patch density is also added and has previously been applied in other studies to understand urban change and urbanisation (Weng, 2007; Deng, Wang, Hong, et al., 2009; Li, Peng, Yanxu, et al., 2017).

8.4.3 Overall spatial expansion for all scenarios

The scenarios utilised different drivers to influence the spatial patterns of land uses in Cape Town. The variations in land use developments and the resulting spatial structure of Cape Town in 2030 is presented in Figure 8-2. One common outcome in all the scenarios is the tendency of informal settlements to locate in the outskirts of low-income residential areas. The SE scenario (fig 8-2c) shows that low-income residential areas locate in the Metro South East Integration Zone (MSEIZ) as per the densification strategy implemented. This is mostly along the primary and secondary roads in the MSEIZ. Interestingly, though the intervention was aimed at ‘unlocking’ low-income housing and employment generating activities, middle-income residential development was also effectively directed into the MSEIZ. This resulted in mixed land uses on the corridor especially trade and services, low-income and middle-income housing. A similar observation was made along the BRT corridor where there was an increase in the development of commercial land use and residential areas. This resulted in mixed land uses along the corridor. The protection of agricultural land and curbing of urban sprawl limited the encroachment of urban land uses onto agricultural land. Interestingly, ‘unlocking’ manufacturing services under this intervention has not been successful as only a few new manufacturing services have been observed along the MSEIZ corridor in all scenarios. On the contrary, the PI scenario resulted in new manufacturing services locating close to low-income residential mainly in Khayelitsha and Gugulethu. This can potentially increase access to opportunities for the low-income cohort in these neighbourhoods.

On the other hand, the BAU (fig 8-2a) and PI (fig 8-2b), clearly resulted in the scattering of low-income housing across the metropolitan, especially towards the peripheries. In both scenarios, the informal settlements were observed to form into large clusters which show that informal settlements are likely to get bigger as opposed to forming in new locations. While informal settlements are mostly expanding in their locations, new informal settlement locations were observed to locate on previously vacant land close to manufacturing services and in some cases close to low-income housing.

Another observation in the simulation of land use patterns under the SE and PI scenarios was that though the low-income residential areas were growing, no significant urban expansion was observed. This was linked to the redevelopment of old buildings into new low and middle-income residential areas, especially around Mowbray and Observatory.

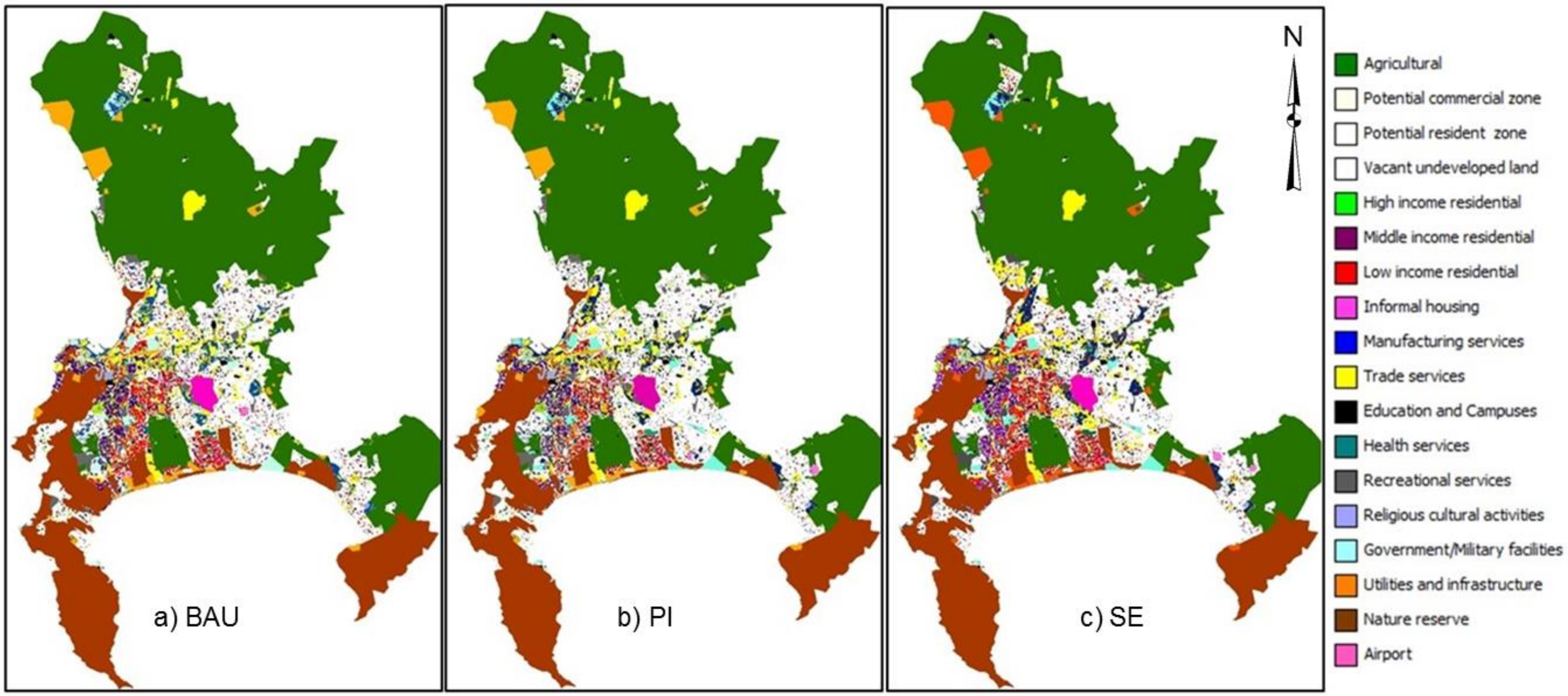


Figure 8-2: Land use simulations under the different scenarios

An evaluation of the urban clusters presented in Figure 8-3 suggests that the spatial patterns from the scenarios are broadly similar with the urban clusters mainly comprising of cluster sizes between 0-5 hectares. However, there are noticeable differences where there is high land use density in the MSEIZ corridor in areas like Gugulethu and Khayelitsha under the SE (fig 8-3c) scenario compared to the BAU (fig 8-3a) and PI (fig 8-3b) scenarios. This can be linked to the land use development strategies that focus on the high density and compact growth on the MSEIZ as shown in Figure 8-2c. Further, in the BAU scenario, there are smaller clusters sizes which are more isolated across the landscape showing the tendency of sprawl in this scenario, this is almost similar to the PI scenario.

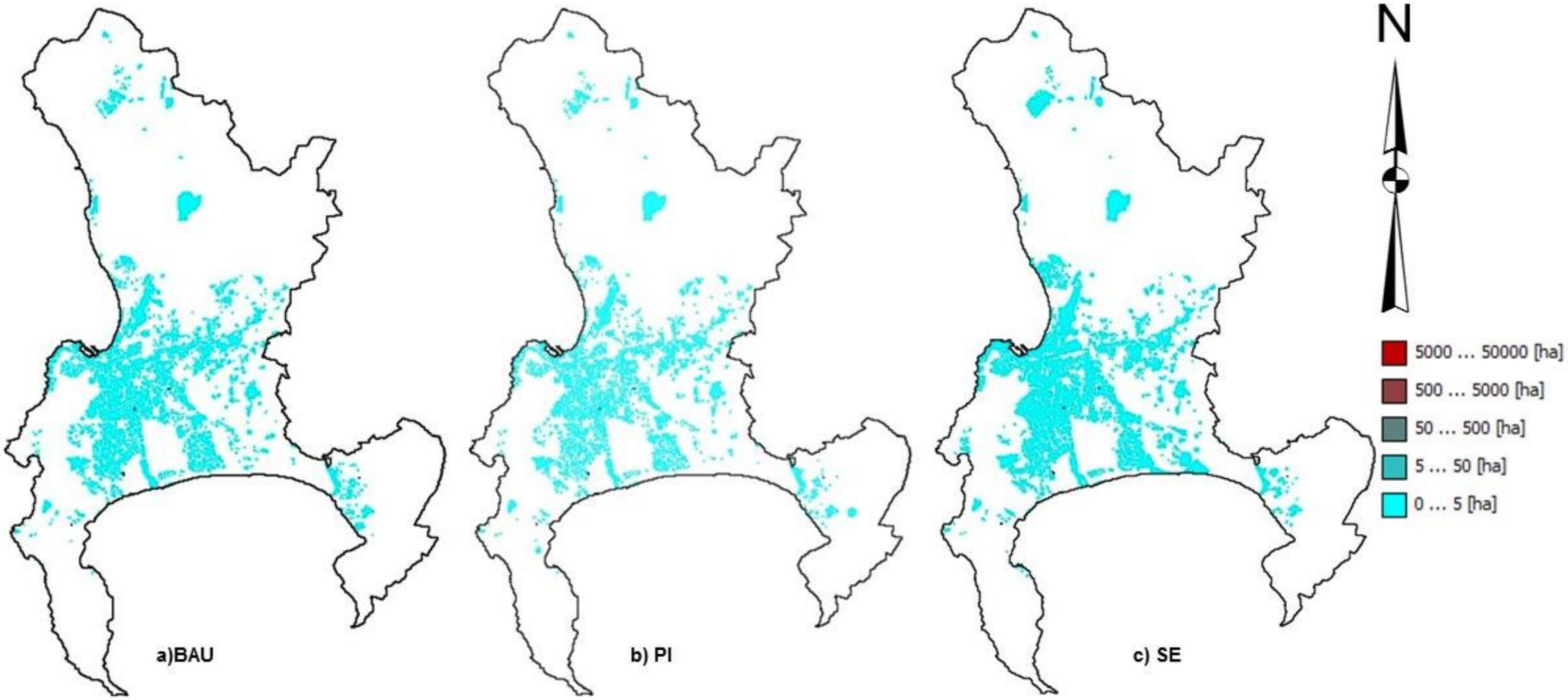


Figure 8-3: Urban clusters between the different scenarios

8.5.1 Comparison of spatial indicators across scenarios

8.4.3.1 Sprawl indicators for all scenarios

Figure 8-4 depicts the spatial changes simulated over 15 years by the model for Cape Town using two metrics, patch density (fig 8-4a) and fractal dimension (fig 8-4b). These metrics are linked to the urbanisation processes associated with each scenario. The results show that for all scenarios, the patch density (fig 8-4a) has decreased over the 15 years indicating that some land use patches are becoming connected. However, the changes are minimal as the slopes of all curves are very low. The PI scenario has the highest percentage decrease in patch density of 19%, while for the BAU and SE scenario the patch density has decreased by 10.9% and 5% respectively

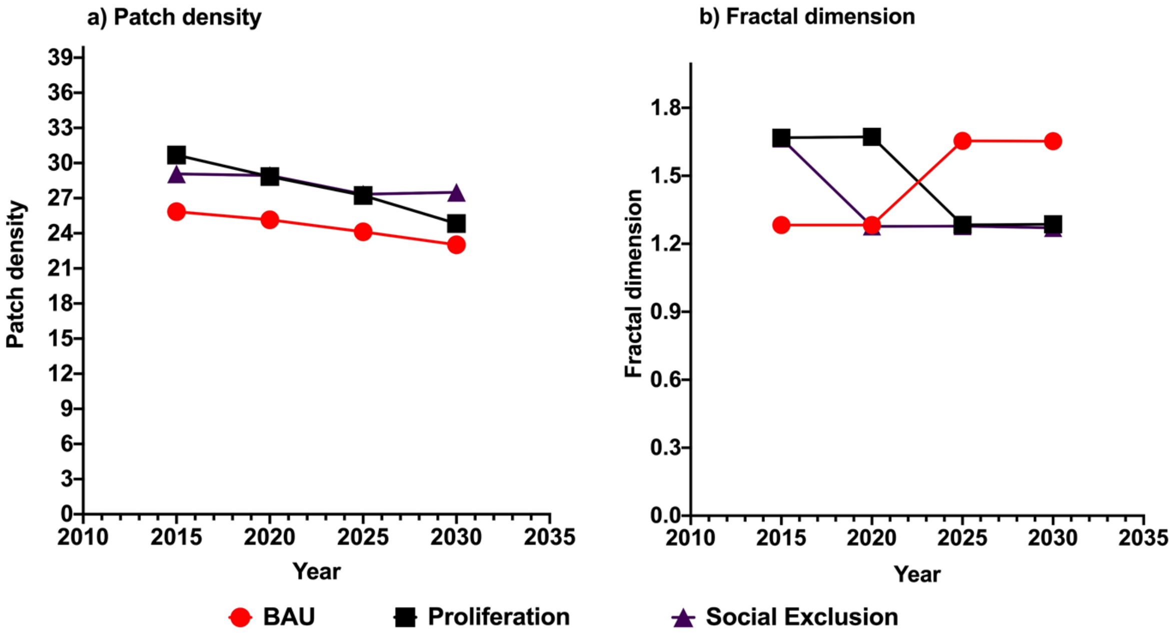


Figure 8-4: Urban sprawl measures

While the BAU scenario is characterised by sprawled growth as shown by the urban clusters in Figure 8-3a, the patch density has decreased (fig 8-4a) which reflects the potential effects of infilling in urban development. This is potentially due to the zoning introduced (UDZ tax incentive) to rejuvenate the urban core which might have resulted in the coalescing of some urban land uses (primarily commercial) due to infilling. This might also account for the reduction in patch density. Further, the growth of informal settlements into large patches adjacent to low-income housing results in continuous urban patches which influences the patch density. Interestingly, the fractal dimension for the BAU scenario has increased over the period indicating an increase in the complexity and landscape fragmentation; this can be linked to the sprawled nature of the landscape in this scenario.

As expected, the patch density in the SE scenario (fig 8-4a) has decreased as this scenario focused on land use development along the MSEIZ corridor which previously is characterised by low land use densities. The intensification of land use development on this corridor has resulted in the aggregation of previously isolated patches due to infilling of vacant land along the corridor and its surrounding areas. This is observable in the structure of urban clusters in this scenario (fig 8-3c) where the urban clusters are larger and compact. Expectedly, the spatial structures also represent a decrease in the fractal dimension (fig 8-4b) over the period which is indicative of a more regular and aggregated landscape due to the coalescing of land uses along the MSEIZ corridor. Since this scenario focused on compact growth characterised by infilling the coalescing of land use patches is expected which consequently decreases the patch density.

On the other hand, the PI scenario shows a high fractal dimension between 2015 and 2020. The depicted trend (fig 8-4b) indicates that the results from the policy intervention kick in after 2020 where the fractal dimension decreases and matches the downward trend depicted by the patch density in Figure 8-4a.

8.4.3.2 Comparison of zonal accessibility across all scenarios

Zonal accessibility was used to evaluate the ease with which different land uses can be reached. This section presents the zonal accessibility results and how the spatial-temporal change of the urban landscape in 2030 influences the accessibility to manufacturing and trades services from residential areas. By evaluating accessibility in 2030, a linkage is made between the role of policy interventions in solving issues of social exclusion and accessibility, themes that emerged in Chapters 1 and 2. A minimum zonal accessibility score of 0.7 (section 6.4.6) is used as a reference to assess the change in zonal accessibility to manufacturing and trade and services in 2030 for all scenarios. This is compared to the zonal accessibility in 2010 to assess the progress the city can potentially make in improving access under the different interventions. The zonal accessibility scores are interpreted to reflect the ease with which economic centres can be reached from all residential categories. Previously, the zonal accessibility trends observed in 2010 (figs 7-4 and 7-5) indicated that manufacturing and trade and services were more accessible to people in the middle and high-income suburbs whereas low-income residential areas had poor access to economic activities. Figures 8-5 and 8-6 provide a comparison for zonal accessibility for manufacturing and trade and services between 2010 and 2030 for all scenarios.

Relative to 2010, the BAU scenario depicts a deterioration in zonal accessibility implying a reduction in access to manufacturing services (fig 8-5) from low-income suburbs, especially in some sections of Khayelitsha. There is also a loss in zonal accessibility in the northern part where the zonal accessibility score has decreased from the 0.76-0.8 band to 0.71-0.75 band. This indicates that manufacturing services are becoming less accessible. While there has been a loss in zonal accessibility in some parts of the north, sections of Durbanville and Bellville have experienced an increase in accessibility to manufacturing services. This can be linked to the growth in manufacturing services in this area as depicted in Figure 8-2a. On the other hand, accessibility to manufacturing services in the eastern parts such as Somerset West has remained constant under the BAU and PI scenarios while there is a significant positive change under the SE scenario.

Though there is an emergence of new locations of manufacturing services in the Cape Flats for the low-income cohort under the PI scenario, this did not accrue into an increase in zonal accessibility. Possibly, the net gains in manufacturing activities were lower than the loss in manufacturing activities. Noteworthy is that the loss in accessibility to manufacturing services by the low-income cohort is greatest in the Cape flats under the SE scenario as compared to other scenarios. This scenario failed to stimulate sufficient growth in manufacturing services along the MSEIZ corridor. However, under this scenario, an increase in zonal accessibility was observed in the eastern part of the city with the accessibility to manufacturing services increasing from the 0.71-0.75 band up to values close to 0.8. Despite promoting economic activities on the MSEIZ corridor in the SE scenario, the accessibility to economic activities within the Cape Town CBD has consistently remained high in all scenarios. This suggests that the city centre will continue to be a key activity hub in the future. On the contrary, there has been a significant loss in accessibility to manufacturing services in some sections of Milnerton, Bloubergstrand mainly linked to a decline in productivity as depicted in this scenario as only a few new manufacturing services located in areas close to low-income housing in these zones.

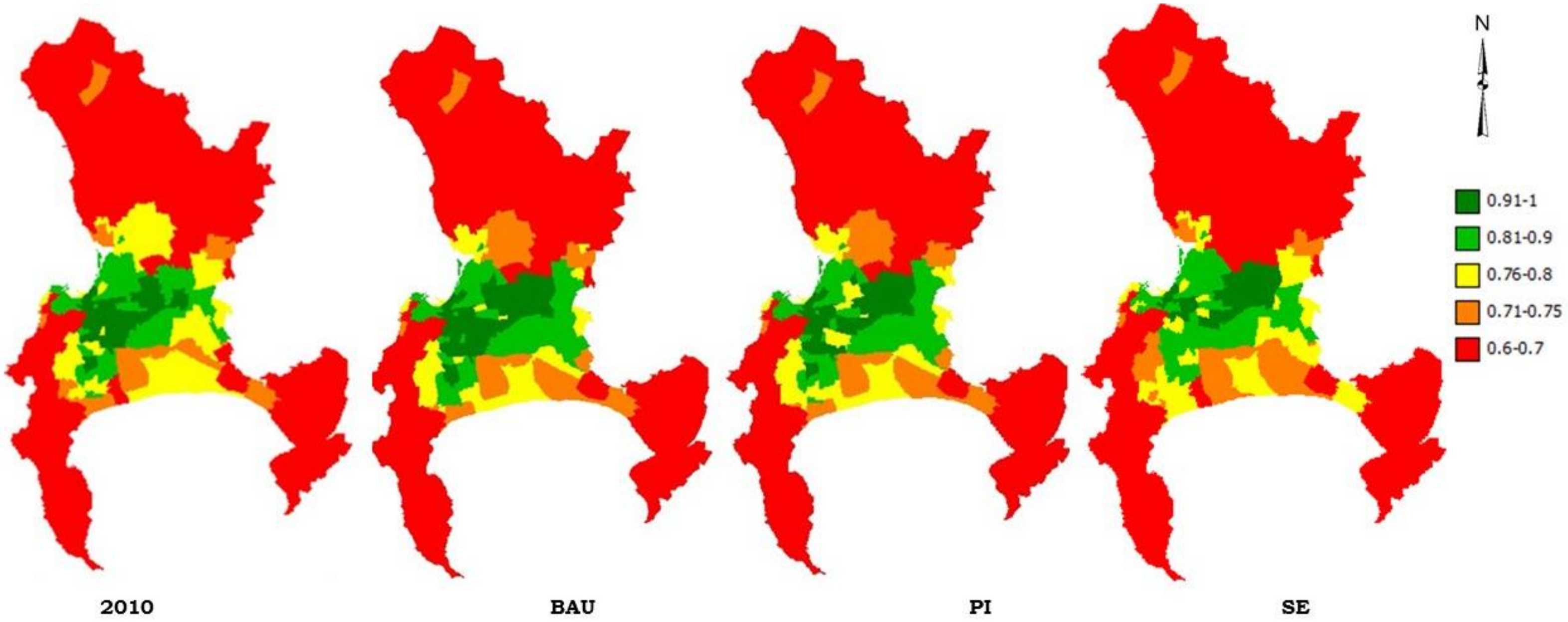


Figure 8-5: Zonal accessibility in 2030 for Manufacturing services across all scenarios

With regards to trade services (fig 8-6), as in the case of manufacturing services, the BAU scenario indicates a loss in zonal accessibility compared to the 2010 situation in the Cape Flats and the northern parts of the city. On the contrary, the zonal accessibility scores in the eastern parts remained low and below the minimum threshold of 0.7 for all scenarios. However, for the SE scenario, the zonal accessibility score for trade and services in the low-income suburbs such as Nyanga, Khayelitsha and Gugulethu has increased relative to the 2010 situation. This is linked to the growth in trades and services clusters in areas close to housing thus resulting in mixed land uses. This has potentially reduced the commuting distances hence improving access to trade and services from these zones especially those along the MSEIZ corridor.

Noteworthy is that in the SE scenario, the MSEIZ corridor attracted a significant share of low-income housing which is a vital aspect in the context of inclusion of previously marginalised groups. The general trend in this scenario is an improvement in zonal accessibility in some area where the zonal accessibility score has increased from below the minimum zonal accessibility threshold (0.60-0.70 band) to above the minimum threshold. Zones such as Mowbray, Observatory, Rosebank, Claremont and Rondebosch have consistently maintained high zonal accessibility scores for trade and services. For areas with middle and high-income residential areas, the zonal accessibility has remained high for all scenarios which shows that the implemented interventions did not result in a loss in accessibility for people in middle and high-income neighbourhoods.

Overall, significant changes are observed in the zonal accessibility patterns under the SE scenario. On the contrary, the zonal accessibility scores under the PI scenario for trades and services are relatively similar to 2010. Only a few changes were observed in zones such as Table View, Bloubergstrand and Milnerton which have a mixture of high-and middle-income residential areas.

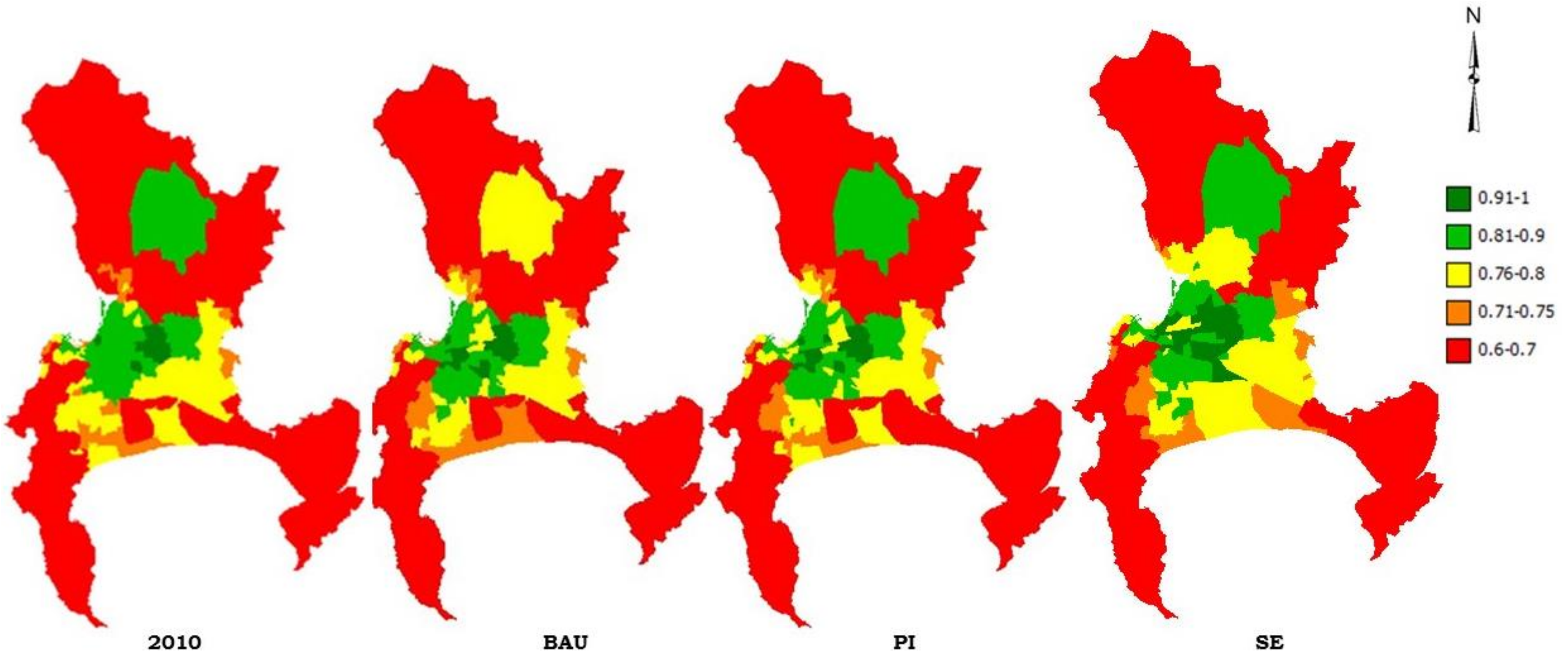


Figure 8-6: Zonal accessibility in 2030 for Trade and services across all scenarios

8.4.4 Transport indicators across the scenarios

This section analyses the distance to manufacturing and trade and services which are the main work trip destinations. Firstly, the analysis considers the aggregate distance to economic activities from individual residential categories and the average distance to economic centres from all residential areas. The analysis is then disaggregated to consider the distance from each residential category to manufacturing and trade and services separately. Additionally, the level of congestion is also reported for all scenarios.

8.4.4.1 Comparison of distance to economic centres (work trips only)

One key observation from the scenarios was that the average work commute distance decreased from 14.29km (simulated in 2010) to 9.42km and 8.51km in 2030 under the PI and SE scenario respectively. The BAU scenario was observed to have the longest work commute (13.40km) from all residential categories (Table 8-3) compared to all the other scenarios. Interestingly, the low-income cohort has significantly shorter commuting distances under the SE and PI scenarios compared to the BAU scenario. This indicates that with urban development intervention, it is possible to reduce the commuting distances for the low-income cohort. Additionally, the work commute for the low-income under the SE scenario is shorter than the residential average for all scenarios. This can be linked to the increase of trade and services in the low-income neighbourhoods under this scenario which has effectively reduced the commuting distances.

Table 8-3: Work trip commute distance to economic centres

	Land use	**Distance to centres of economic activities (km)**
BAU	High-income residential	14.72
	Middle- income residential	13.47
	Low-income residential	13.38
	Informal settlements	12.02
	Average distance	**13.40**
Proliferation	High-income	11.60
	Middle- income	9.17
	Low-income	6.85
	Informal settlements	10.05
	Average distance	**9.42**
Social Exclusion	High-income	11.36
	Middle- income	8.10
	Low-income	6.98
	Informal settlements	7.59
	Average distance	**8.51**

The overall distance to manufacturing and trade and services from each residential land use type between the different scenarios were also compared. This was linked to the spatial trends emanating from the different urban growth drivers implemented in each scenario. The results are presented in Figure 8-7.

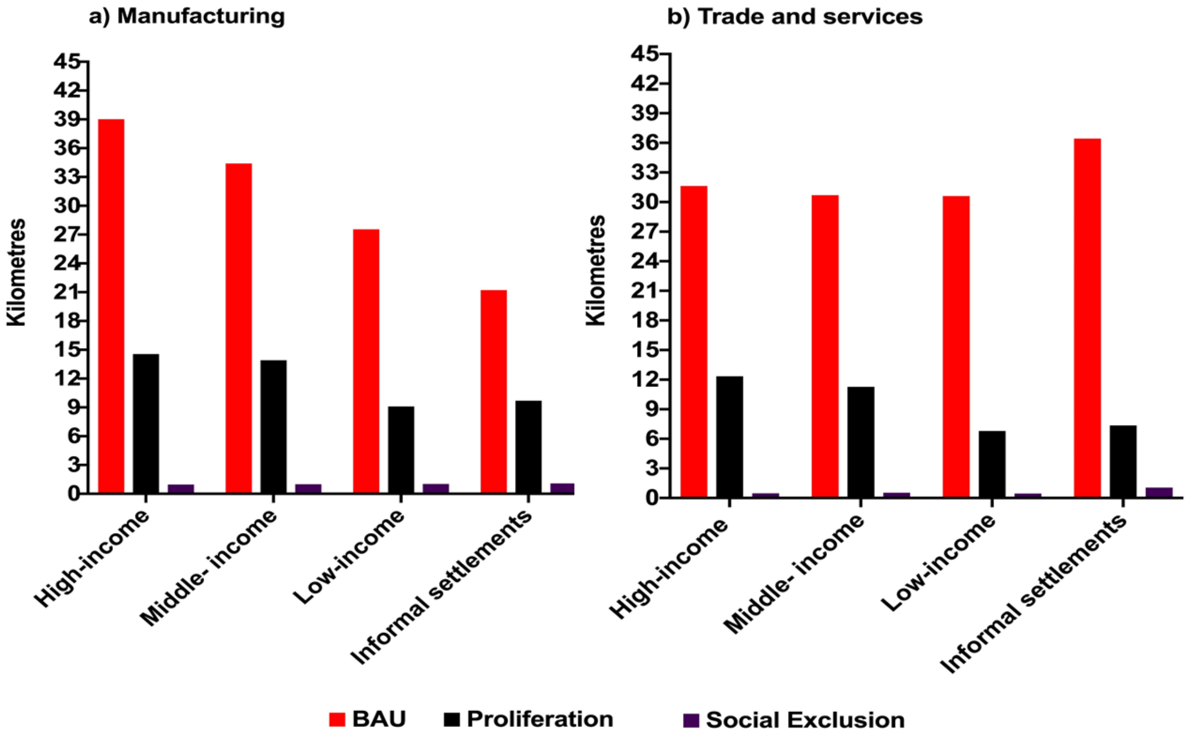


Figure 8-7: Average distance to economic centres from residential areas

As expected, the BAU scenario results in longer commuting distances to manufacturing and trade and services for all income groups with informal settlement dwellers having the longest distances to trade and services. On the other hand, shorter commuting distances (below 1km) are experienced under the SE scenario which might potentially result in easy access to both manufacturing and trades and services for all income groups. Further, the land use development intervention in the SE scenario resulted in mixed land uses of residential and economic activities which might have contributed to the low average commuting distances. This is an encouraging finding as the low-income cohort is located closer to economic activities in this scenario which is viewed as a viable solution to address issues of accessibility for this cohort.

8.4.4.2 Traffic flow conditions in Cape Town

This section discusses the traffic conditions simulated for all three scenarios. Where possible, the volume capacity ratios (V/C) are linked to the level of service (LOS) to evaluate the extent of congestion. Appendix G is used to relate V/C ratios and LOS for arterial roads after Roess et al. (1985). Firstly, the cumulative congestion of the whole network (fig 8-8) for all scenarios from 2010-2030 is discussed. The results show that there is an upward trend in congestion in all scenarios with the BAU scenario depicting the highest level of congestion in 2030. The increase in the gradient of the congestion curve under the BAU scenario suggests a worsening in congestion. This finding indicates that interventions to tackle congestion are needed as early as 2020. On the other hand, the rate of increase in congestion under the PI scenario is very low compared to the SE scenario which suggests that congestion might be easing off under the PI scenario.

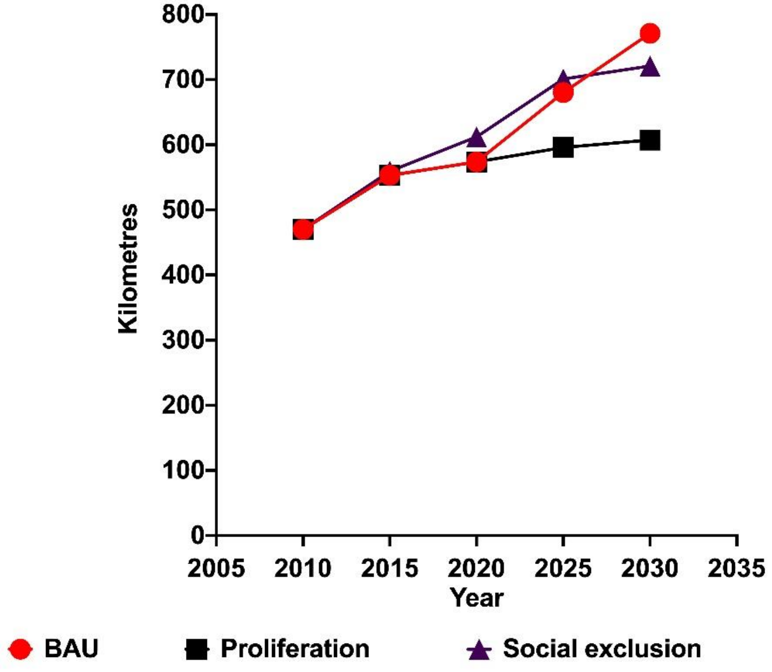


Figure 8-8: Cumulative congestion for all scenarios

To get a sense of congestion on some key links on the network, a local level analysis was carried out. The analyses focused on road conditions on selected links on the city's road network. The selected locations have been reported to have heavy congestion and needed congestion relief projects (TDA, 2018) or considered to be “mature” corridors according to the CITP (TCT, 2013). Further, the discussion focuses on Durbanville which is a key employment centre in Cape Town and hence it is essential to assess the change in road traffic conditions as the area attracts more activity. The road sections considered include:

- N2 close to Somerset West
- Vanguard Drive (M7) and Settlers Way (N2) near Pinelands
- Durbanville areas
- Voortrekker road and N1 in Maitland

Overall, the simulation results indicate severe congestion on the city’s road network in 2030. However, there are noticeable diiferences where some of the arterials in Somerset West (fig 8-9) suggest mixed traffic conditions with the V/C ratios ranging between 0.0-1.5. This shows that on some segments of the network, road users experience LOS A and on some segments LOS F is experienced. This suggests that without improvements (BAU) in land use and transport planning (fig 8-9a), in areas where congestion is already a problem, road traffic conditions will deteriorate. On the other hand, the PI (fig 8-9b) and SE (fig 8-9c) scenarios show a moderate decrease in congestion in the area, which is expected as these scenarios focused on land use development thus reducing the need to commute outside Somerset West. However, given that the change in congestion is minimal, this suggests that land use development did not effect significant changes in road traffic conditions indicating a need for both land use and transport interventions to alleviate congestion in this area.

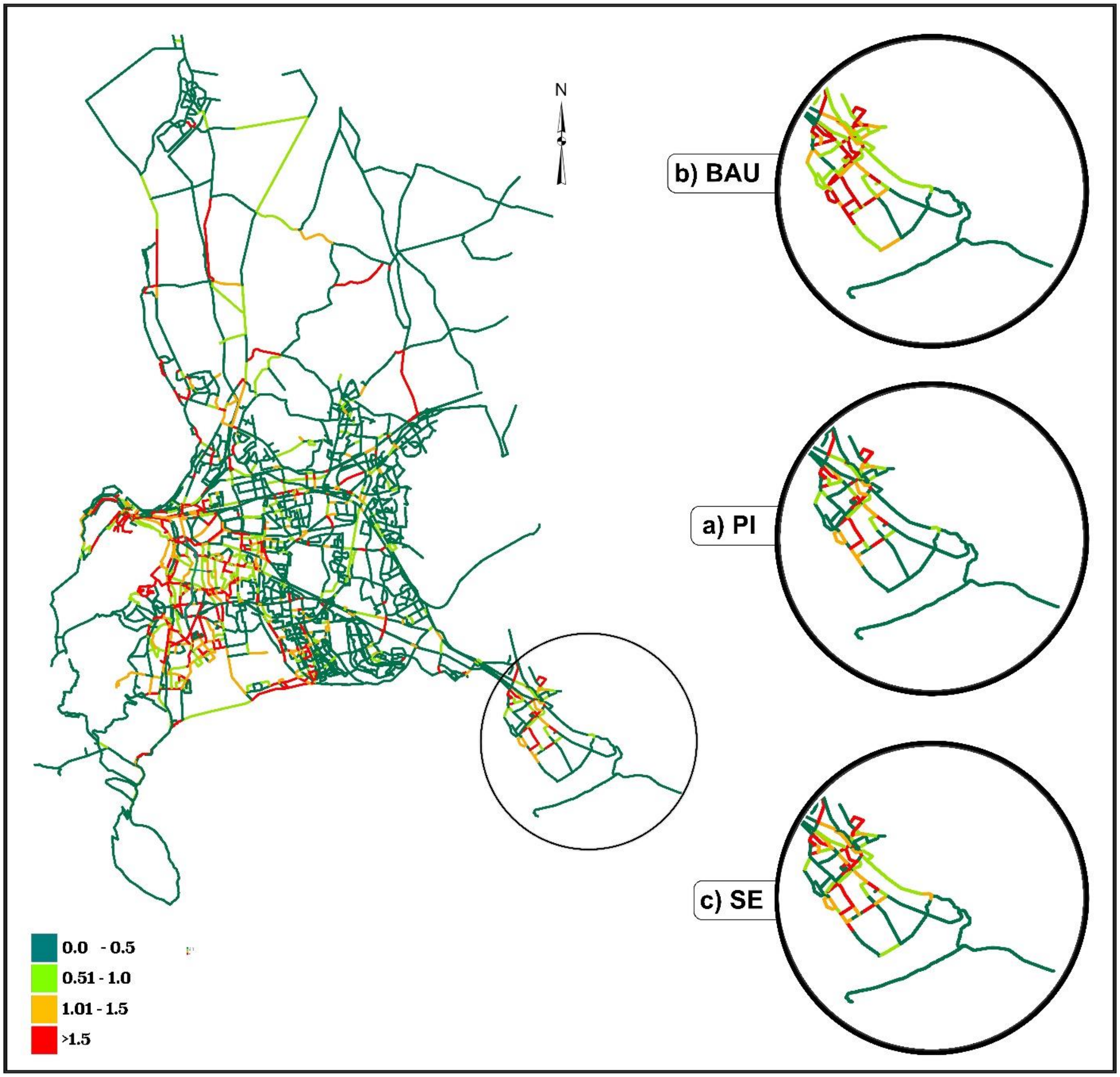


Figure 8-9: Traffic conditions N2 Somerset West

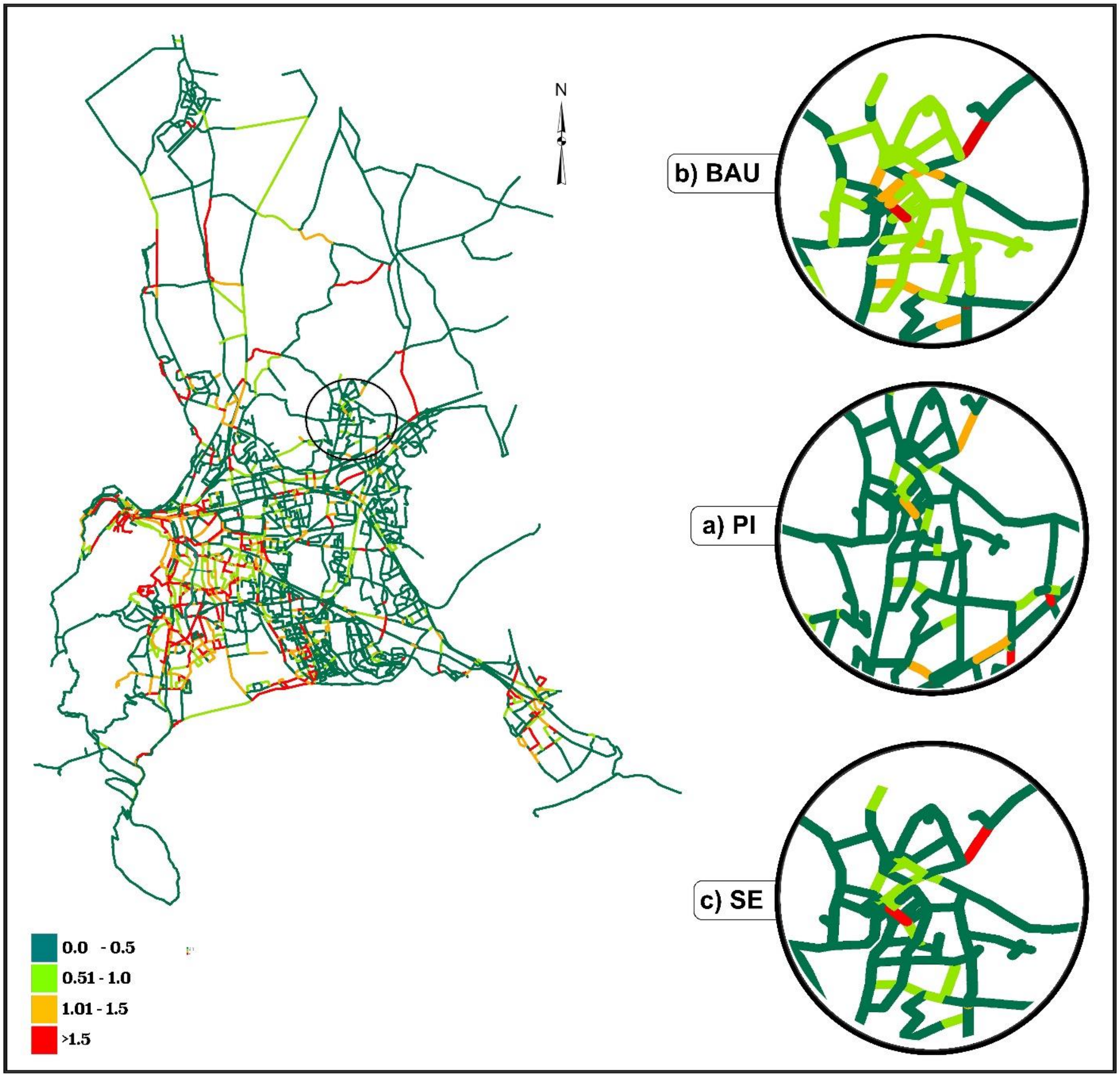


Figure 8-10: Traffic conditions Durbanville area

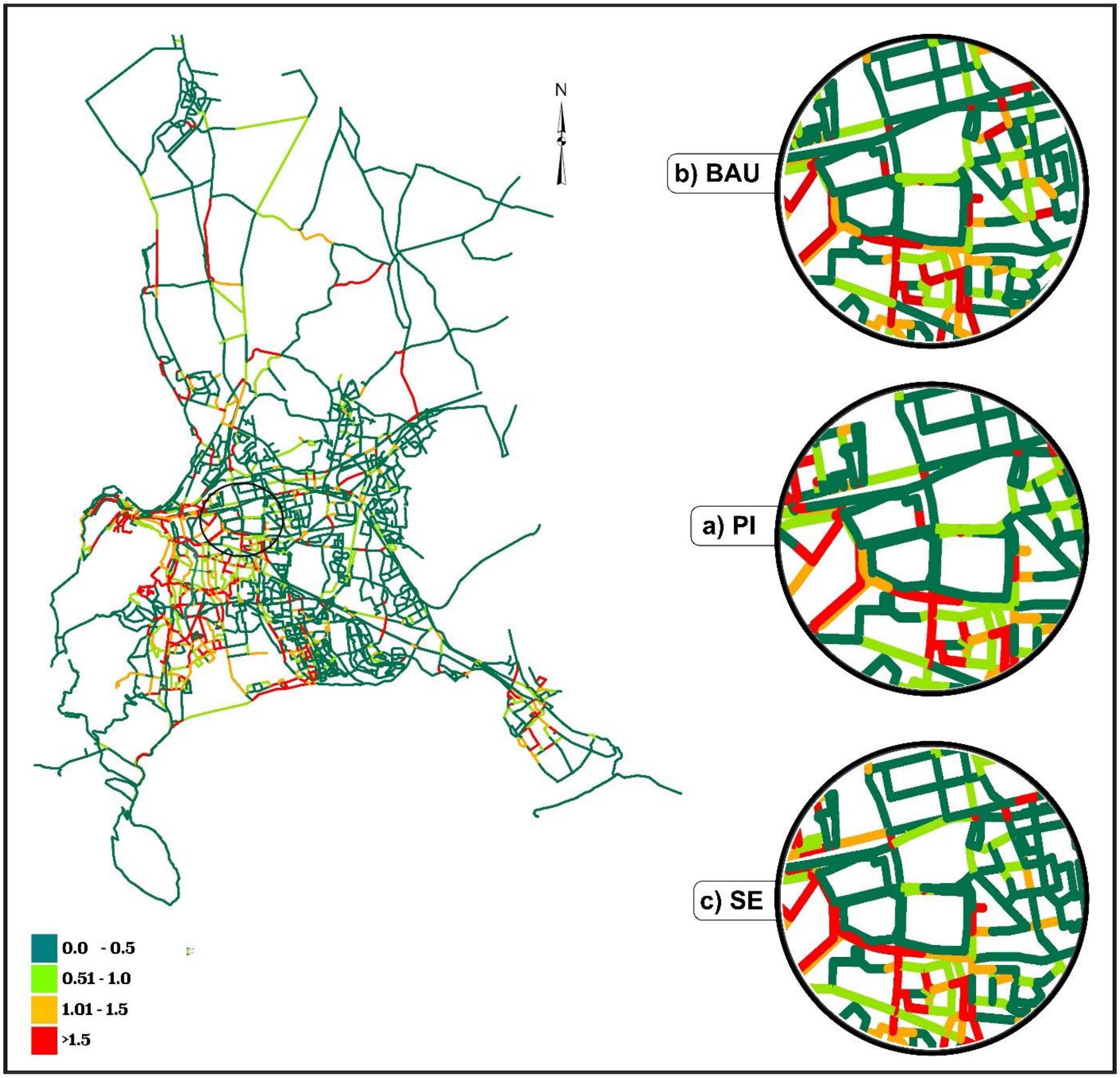


Figure 8-11: Congestion Vanguard Drive (M7) and Settlers Way

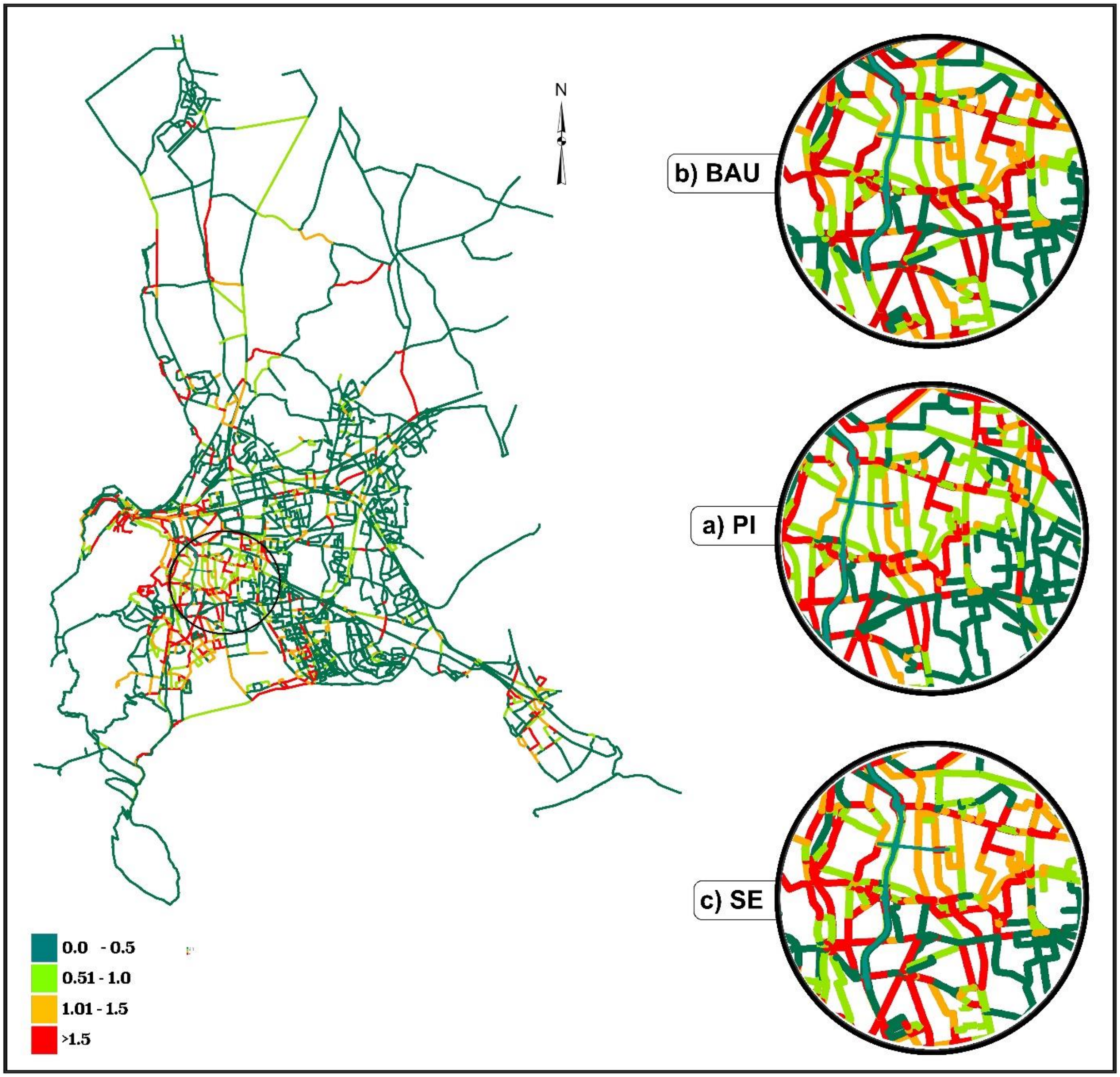


Figure 8-12: Traffic conditions parts of Voortrekker Road (R102) and N1

In areas like Durbanville (fig 8-10), where congestion is reported mainly for arterial roads, the BAU scenario (fig 8-10a), shows there is congestion on some links on the network with V/C ratios ranging between 0.5-1. For the section of Durbanville that was analysed, some segments have good traffic flow with Level of Service (LOS) A whereas on other sections; traffic conditions deteriorate to LOS D and E implying heavy congestion characterised by low travel speeds. Excessive growth in population and a boom in economic activities in this area might result in a worsening in traffic conditions where the LOS might deteriorate to level F. Interestingly, while there has been a growth in economic activity under the PI (fig 8-10b) and SE (fig 8-10c) scenarios, there is a significant improvement in transport conditions in this area. Some links experience V/C ratios below 0.5-representing LOS A where road users experience free-flow traffic. This could be linked to a reduction in commuting distances due to the presence of residential and employment generating land uses near each other hence a reduction in the use of the transport infrastructure over long distances.

Poor traffic flow is experienced on Vanguard Drive (M7) and Settlers Way on the N2 (fig 8-11) close to Pinelands in 2030 for all scenarios. Though there are some noted improvements on some segments of Settlers Way under the PI scenario, the general trend indicates that more intervention is needed to ease congestion if traffic conditions are to improve by 2030. In the SE scenario, the densification strategy effectively directed mixed-use developments to parts of Blue Downs which has contributed to an increase in congestion along Settlers Way on the N2.

The Voortrekker road (R102) in Maitland and the N1 close to the Koeberg interchange are some of the congestion hotspots in Cape Town especially during peak periods. This has resulted in peak period travel delays and therefore require interventions. The BAU scenario (fig 8-12a) indicates that congestion on these links will continue to be a problem in 2030. While the densification strategy implemented in the SE scenario resulted in mixed land use and effectively reduced commuting distances along the MSEIZ corridor to less than 1km (fig 8-12b), congestion has worsened on the Voortrekker corridor (fig 8-12c). Maitland which is an essential trip attractor in 2010 still experiences severe congestion in 2030 due to the intensification of land use development in the MSEIZ. This has increased the number of trips terminating in the area. What this suggests is that land use interventions alone are not sufficient; instead, land use interventions need to be accompanied by transport interventions to absorb traffic changes associated with land use development.

8.4.3.3 Comparison of modal split across scenarios

This section discusses the differences in modal split across the scenarios. This is especially important as it provides a better understanding of how land use and transport changes influence modal shift. This can also be used to provide insight into the influence of land use changes on mode choice decisions thus potentially useful in informing decisions on interventions that might have a positive impact on congestion. Figure 8-13 shows the shift in modal split for all scenarios.

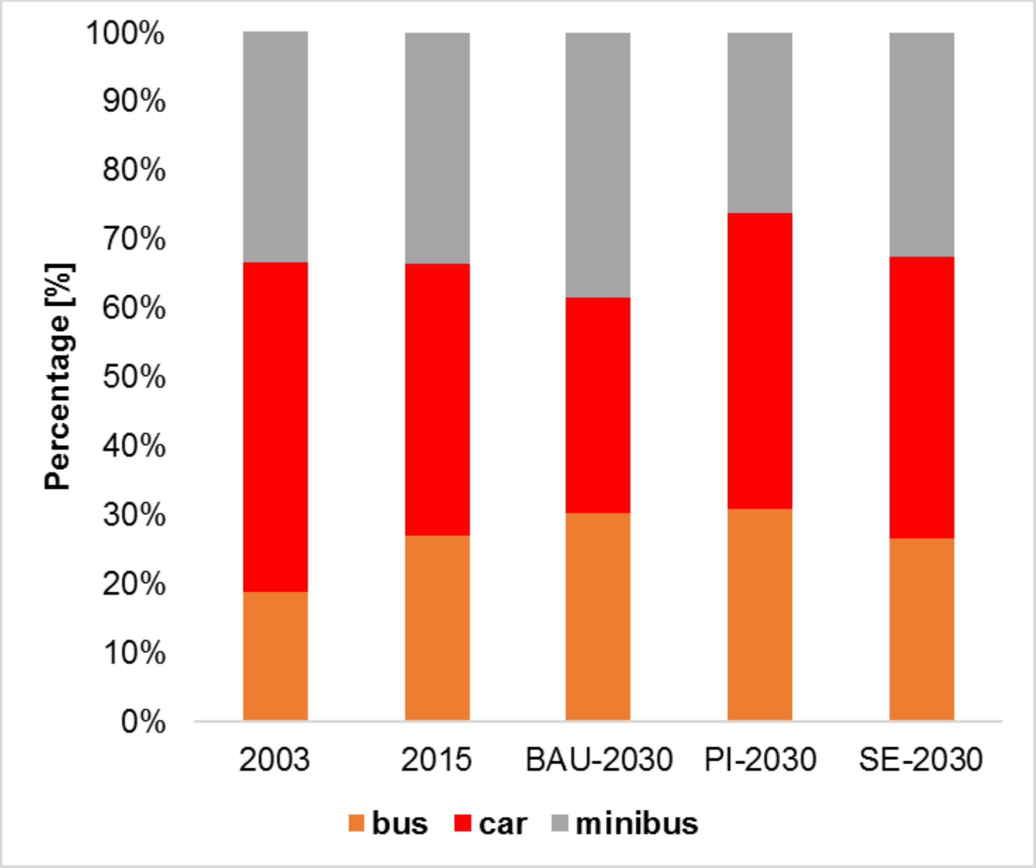


Figure 8-13: Change in modal split between scenarios

The results show a considerable modal split shift for all modes. The private car mode has the largest mode share for the PI and SE scenario while the minibus taxi has the largest mode share in the BAU scenario. Under the BAU scenario, the mode share loss for car relative to 2015 has resulted in an increase in mode share for both the minibus taxi and the bus. However, the minibus taxi has the biggest mode share gains compared to the bus. On the other hand, the PI scenario shows a decrease in the minibus taxi mode share compared to the 2015 modal split values with a mode share loss of 22.03%. The mode share loss is redistributed between the car (8.50%) and bus (14.86%). This results in the private car mode having the largest mode share of 43% under the PI scenario. Table 8-4 shows the percentage modal split shifts.

Table 8-4: Modal split shift relative to 2015 mode share

	BAU	**PI**	**SE**
bus	12.08%	14.86%	-1.55%
car	-20.64%	8.50%	3.45%
minibus	14.70%	-22.03%	-2.83%

Interestingly, the SE scenario experiences the lowest mode share shifts with both the minibus taxi and bus losing mode share of 1.55% and 2.83% respectively which is redistributed to the private car. This shows that, while the SE scenario intervention is aimed towards redressing the spatial location of residential areas relative to economic activities, it has minimal influence on mode choice decisions. Interestingly, the results also indicate that under the BAU scenario the minibus taxi overtakes the private car mode share. Overall, the results show a clear interaction of land use and transport and the potential influence on mode choice decisions.

8.5 Discussion of results

This chapter utilised the CTMR_LUT to explore the resulting spatial structures and transport conditions for Cape Town in 2030 based on different interventions. Several indicators which looked at urban expansion, accessibility, commuting distance and traffic conditions were utilised to assess the impacts of the suggested policy interventions. While the storylines focused mostly on land use development and its influence on transport, a transport component through the introduction of a BRT corridor which represents a transport network change was introduced to explore and understand the causality between land use and transport in influencing the spatiotemporal dynamics of the city.

The results from the BAU scenario suggest that the current land use and transport planning strategies are not viable if residential segregation and its accompanying social and economic social exclusion, long commuting distances, congestion among others are to be addressed. Specifically, the results suggest that in the absence of a comprehensive land use development policy, Cape Town’s urban expansion will be characterised by sprawl with the low-income cohort relegated to the peripheries of the city. Additionally, work commutes to trade services and manufacturing services were observed to be very long, above 30km, under the current trends while these distances could be halved with interventions. With land use interventions, the commuting distance to work for the low-income was observed to be shorter compared to other income groups, which suggests a change in the spatial relationship between the location of low-income housing and employment centres. This characteristic is also reflected in the change in zonal accessibility in some low-income residential areas where the zonal accessibility score increased to values above the minimum threshold of 0.7. Interventions that focused on land use intensification along the MSEIZ corridor mostly contributed to the change in the spatial relationship between low-income housing and economic centres. This resulted in mixed land uses mostly low-income, middle-income housing and trade and services. It was expected that with an increase in land use mix, the demand for travel would be very low as people could potentially walk to work. However, the intervention failed reduce congestion with some areas still experiencing an increase in congestion in 2030. Instead, there are sections of the N1 and Koeberg interchange where traffic congestion worsened. Nonetheless, a reduction in commuting distance from this intervention is a step in the right direction. Moreso, as the mixing of land use might be interpreted as the successful integration of land uses especially of low-income housing and trade and services thus redressing the economic exclusion of the low-income cohort.

While the simulations provided insight into potential land use development, questions emerged with regards to the type of strategies that need to be implemented to stimulate job opportunities in the manufacturing sector close to low-income residential; as they are a potential labour pool for this sector. For instance, the focus on intensive land use development on the integration corridor did not generate significant manufacturing activities. This brings to question whether there are underlying drivers that deter manufacturing services to locate in areas accessible to the low-income cohort. Nonetheless, targeted incentives are required to stimulate the growth of manufacturing services in low-income suburbs. The overall spatial trends and growth with regards to manufacturing show a slight decline in the sector which might explain the limited stimulation of this land use in the integration zone and the low-income residential suburbs. Unintendedly, interventions targeting the expansion of informal settlements resulted in the attraction of manufacturing services to low-income neighbourhoods. This suggests that with the right incentives, it is possible to craft policies that influence the population-employment interaction such that jobs follow people thereby potentially solving issues of access to employment for the marginalised.

Regarding informal settlements, while there needs to be clarity in policy, the results from the simulated land use changes suggest that in situ upgrading might be a viable option especially in cases where informal settlements located close to employment. One key aspect that is observed is that there are pull factors which stimulate the development of informal settlements close to low-income residential areas. Given the socio-economic demographics of informal settlement dwellers, besides the availability of land close to low-income residential areas; there is a possibility that the social drivers that attract informal settlements are mostly linked to the need to create and maintain social networks. Though not modelled in this research, the tendency of informal settlements to locate close to low-income housing might potentially signal a rampant increase in backyard shacks as opposed to informal settlements as people try to subsidise their income while filling a gap in the housing market. This is a potentially a concerning policy issue that needs to be addressed.

Although land use interventions are prominent in this research, the influence of transport infrastructure changes was also observed. Specifically, the introduction of a BRT corridor resulted in trade and services locating along this corridor which shows that transport does influence land use development. In response to land use densification on the MSEIZ corridor, the maximum congestion is lower in the SE and PI scenarios compared to the BAU scenario. Further, the results have indicated modal share shifts which have resulted in mode share redistribution to the bus and minibus taxi under the BAU and SE scenario. This is an encouraging finding in terms of land use interventions and their influence on transport. However the results still indicate that Cape Town has a long way to go as the private car has the largest mode share for the PI and SE. For local level improvement in congestion to be attained, there is a need to implement travel demand management strategies that motivate people to use other modes of transport.

Interestingly, the inclusion of the BRT corridor affected land use developments along the corridor which led to an increase in access through the reduction of commuting distance for all residential categories with the low-income cohort benefiting the most. While the results are encouraging, the results also suggest a lagged response in the influence of transport on land use. Juxtaposing this, an increase in land use activities in some parts, especially along the MSEIZ corridor, resulted in an increase in congestion on already congested roads. However, the response on the transport side due to land use development showed that the reduction in congestion was not instantaneous. Instead, changes became apparent after 2024 which shows a lagged response in people’s willingness to change their behaviour in car usage in the short-term. A valuable lesson that emerges especially from understanding the causality between land use and transport is that targeted interventions with regards to land use and transport can potentially result in positive outcomes that can steer spatial development along the path of inclusivity and equity.

8.6 Summary

The chapter presented three exploratory policy scenarios simulated within the CTMR_LUT model. The scenarios were simulated from 2010 until 2030 to demonstrate the effect of different policies on land use development and transport conditions. A set of spatial and transport indicators were used to evaluate the spatiotemporal changes of the Cape Town landscape due to land use and transport drivers. As the urban development challenges that the city face are already at a critical level, the scenarios only explored land use and transport conditions under the current growth trends and steady growth of population and employment. The results from the simulations provided insights on the role policy can play in solving some of the urban issues that the city currently grapples with. More importantly, the simulation results indicate that land use and transport interventions are needed in the city as early as 2020 as the traffic conditions are becoming dire. Further, the results show that the current planning strategies (BAU scenario) will widen the social exclusion gap resulting in the continuous marginalisation of the low-income cohort as it will continue to be difficult for them to access opportunities. While some of the simulation results paint a bleak picture of land use and transport conditions in Cape Town, interventions aimed at solving issues social exclusion and redressing the apartheid divide revealed that with targeted and clear policy interventions, it is possible over time to restructure Cape Town’s spatial structure to allow for integration, inclusivity and access to opportunities. Concerning informal settlements, in situ upgrading is a potentially viable option in some locations provided there is an understanding of the drivers of informal settlement morphology.

Though this exercise was aimed at evaluating the influence of policy interventions, lessons were also learnt. One of the objectives of this thesis was to generate a set of policy strategies to provide insights into the impacts of policy interventions on urban change. Through the different policy interventions, the interrelation between land use and transport and the causal effect thereof was revealed. The study managed to show that land use development influences transport and transport also influences land use change. This is a valuable lesson to planners as it points to the importance of coordinating land use and transport planning to aid in solving urban issues. Further, one of the lessons that flow from this exercise is the concept of lagging between land use interventions and transport changes. For instance, land use changes implemented in 2017 in the simulations were only observed to influence transport conditions in 2024. In terms of policy, this suggests that interventions aimed at tackling urban challenges should be implemented before the situation worsens. This is where land use transport modelling tools like the one utilised in this chapter become essential as they provide an opportunity to test policy interventions to facilitate proactive responses to urban challenges.

Finally, this chapter has also shown the that there is reciprocity in land use and transport as some of the land use changes resulted in significant modal share shifts. What this shows is that it is possible to use land use interventions as a tool to impact modal choice decisions which can potentially be useful in solving some of the transport problems.

Chapter 9

Synthesis

9.1 Introduction

The research described in this dissertation was motivated by the urban issues confronting South African cities. Specifically, the polarisation of economic activities in affluent suburbs, social exclusion, peripheral location of low-income residential areas, the growth in residential informality, low urban densities and congestion. In spite of various policy reforms, the country's cities continue to be mired in high public transport expenditure coupled with social and economic exclusion characterised by the exurban location of low-income housing thus marginalising the low-income cohort. The underlying reasons for these issues are complex. They are a combination of historical planning and current urban policies. In particular, the continuous location of low-income residential areas in the peripheries and the ambivalence of policy on how to address residential informality have exacerbated the country's urban challenges.

To understand the spatiotemporal dynamics of transport and land use interaction in Cape Town this research employed a dynamic land use transport model. The interaction between land use and transport over time was modelled to illuminate on the potential of land use and transport modelling to aid in planning. Three objectives guided this research. The first objective which was addressed in Chapter 2 sought to understand the growth trajectory and spatial structure of work-related trip origins and destinations focusing on residential, trade services and manufacturing service land use categories. The second objective, which was discussed from Chapters 4 to 7, introduced a CA-based land use and transport model to model urban dynamics in the City of Cape Town in the METRONAMICA framework. Calibration and validation focused on simulating land use and transport conditions from 1995-2005 and 2005-2010 respectively. The third objective, addressed in Chapter 8, applies the model for policy analysis by simulating exploratory policy interventions for the city from 2010 to 2030. The research objectives are revisited in section 9.2. This section also reflects on the research objectives and the extent to which this research has managed to address these objectives. The research findings linked to each research objective are also discussed in section 9.3. Section 9.4 concludes the chapter by detailing the research's contributions to knowledge.

9.2 Revisiting research objectives

A legacy of apartheid is that Cape Town's urban spatial patterns that are characterised by disparities between residential locations of low-income earners and centres of economic activities (Turok, 2001). Several policy reforms have been implemented to transform the urban environment and address these issues. However, there has been criticism that most of these policy reforms have not yielded significant results (Turok, 2011a). This research evaluated the spatial relationship between housing and centres of economic activities between 1995 and 2013 in Cape Town. A quantitative approach using spatial metrics was used to evaluate the growth trajectory of residential, commercial and manufacturing land uses. The results indicate slow progress in reconfiguring the spatial patterns to allow for integration and address issues of marginalisation. While there is progress in redressing spatial disparities and locating low-income residential areas closer to economic centres, policy interventions need to be more aggressive in incentivising private property developers to invest in low-income housing close to well-established transport infrastructure and centres of economic activities.

Though there is still debate on the progress the city has made, an evaluation of the temporal change of zonal accessibility for the different suburbs (section 7.6), revealed that between 1995 and 2010 there was an improvement in access to commercial and manufacturing services for the low-income cohort. The main finding that flows from this section is that compared to suburbs with low-income housing, middle and high-income suburbs consistently have higher zonal accessibility scores in relation to suburbs with employment generating activities. This finding aligns with the spatial configuration in the city where most middle and high-income suburbs have mixed land uses and are well located in relation to employment centres. By reflecting on the spatial and temporal location of residential land uses (Chapter 2) and evaluating the zonal accessibility of the different suburbs (sections 6.4.6 and 7.6), this research managed to address the first research objective which aimed to understand the spatial relationship between residential land uses and centres of economic activities.

The second objective aimed to calibrate and validate a land use transport model that could be utilised to understand urban change in Cape Town. A panoply of operational integrated land use and transport models have been utilised to understand urban change. While there are several operational land use transport models that have been reviewed, section 3.10 provides an overview of why METRONAMICA can be applied to the Cape Town context. The dynamic nature of METRONAMICA and its ability to model the competition for space through cellular automata made it a suitable tool. Additionally, the availability of METRONAMICA in terms of modelling support also made it an attractive tool to utilise in this thesis. Chapter 4 discussed the METRONAMICA modelling framework and provided details on the various model blocks and key linkages between sub-models. This introduced zonal accessibility which is a key component in understanding the dynamic interaction between land use and transport. This further established the appropriateness of METRONAMICA as a modelling tool. Chapter 5 introduced the different data sets that were used to set up the model, calibrate and validate it for Cape Town. Because of the uniqueness of the city's urban environment and transport user system, it was essential to tailor the model to the context. Therefore, the model implemented in this research deviates from the generic METRONAMICA applications (such as Aljoufie, Zuidgeest, Brussel, et al., 2013) where the private car was used to assign traffic on the network. Instead, in this research, private car and minibus taxis were used to assign trips on the network to reflect transport intensity due to these two modes and the transport user system in the city. Chapter 6 developed the methods used to calibrate, validate and assess the model.

During the calibration process, it was observed that linkages within and between model blocks rendered the calibration process complex. Therefore, a sequential stage wise calibration procedure after Abraham (2000) was implemented. This entailed calibrating the individual model blocks before the linkages were introduced. Once the behaviours of the individual model blocks were observed to be satisfactory, the linkage between the land use and transport model was then calibrated. The model assessment comprised of first comparing the model simulations based on the calibration of individual model blocks and finally the integrated model. The results indicated that the model performed better when the linkage between transport and the land use model was included. This revealed that within the Cape Town context, accessibility could be deployed to explain the symbiotic relationship between land use and transport. Though the calibration requirements of the model are complex, the resulting land use and transport conditions generated by the model indicate that it could simulate the land use and transport situation in the city for both the calibration and validation period. Through these steps, objective two was addressed.

Objective three focused on developing a set of policy strategies that could potentially provide insights into the impacts of policy interventions on urban change in the city. The concept of urbanisation was discussed in Chapter 3, specifically focusing on its influence on urban change in the context of developing countries. This helped in identifying the uniqueness of Cape Town with regards to its transport and land use issues and the potential to adopt tools implemented in other developing countries. This discussion concluded that the solutions to urban problems lie in land use and transport especially when the two systems are integrated. The review identified a gap in the implementation of integrated land use transport tools in Africa hence strengthening the need for this research and highlighting the potential contributions to African knowledge. Chapter 8 details the policy interventions that were developed for Cape Town to assess the effect of different urban development approaches. Further, the interventions also aided in identifying the potential drivers of urban change and how this knowledge can be used for proactive policies. Findings from this chapter indicate that land use and transport are linked and influence each other in shaping the urban form. However, time lags were observed between land use interventions and the response in transport indicators and vice versa. This is invaluable knowledge as it provides insights into the response of land use to changes in transport, thus providing timelines for land use policy to effect change. In that regard, this research has demonstrated the value of land use and transport tools – such as the one implemented in this study – in facilitating policy implementation and assessment particularly in a context of rapid change in the urban environment.

9.3 Research findings and implications for urban policy in Cape Town

This section discusses the key findings from the research. The main focus is on the research outputs with regards to the spatial association of residential land uses and centres of economic activities, informal settlements and congestion. The potential implications of these findings on urban land use and transport policy in the city are also examined.

9.3.1 On the spatial distribution of land uses

The current spatial patterns that exist in Cape Town are an outcome of historical land use and transport planning which led to the segregation of the black and coloured populations (Watson & Turok, 2001; Turok, 2011b; Brown-Luthango, Makanga, & Smit, 2012). However, post-apartheid planning has also perpetuated these trends. Results from this study show that between 1995-2013 – almost two decades – the spatial distribution of these land uses continued to trace apartheid spatial structures where the low-income cohort of mostly the black and coloured populations were segregated from economic opportunities. On the contrary, the middle and high-income earners continued to enjoy good and affordable access to economic centres and transport. While there has been slow progress in remedying the problem of social exclusion and the related spatial segregation, the results do indicate a shift in the spatial structures where there is some inclusion of the low-income cohort. Based on these findings, it is imperative to acknowledge that the urban issues in the city might require radical housing and urban development policy such that the historical urban development trends are not perpetuated.

Further, in addressing urban issues in the city, especially segregation, it is crucial to ensure that redressing does not dispossess one group to compensate the marginalised. In the Cape Town context, the results show that land use interventions on their own are not effective in mitigating urban issues. Instead, there needs to be complementarity with transport-related interventions. While it may be challenging to attain equality, it is possible to structure land use and transport policy along the path of equity. This research has shown a strong land use and transport link in Cape Town which can be used to understand urban dynamics. Therefore, implementing land use and transport interventions alongside each other can facilitate in achieving equity. In that regard, addressing urban change should consider the land use and transport system as dynamic and coherent systems. Additionally, to effectively address issues of inequality in the city it is essential to involve the public and private sectors as they are all stakeholders of urban change.

9.3.2 On informal settlements

The literature identified antithetical views with regards to informal settlements. On one side is the notion that informal settlements can, potentially, uplift people out of poverty and on the other hand the argument is that they lock the low-income cohort into poverty (Turok, 2015; Turok & Borel-Saladin, 2016). These arguments suggest that informal settlements have become an intrinsic component of the urban environment. In Cape Town, the prevalence of residential informality points to the failures of current housing policy in addressing housing backlogs. In situ upgrading of informal settlements has been suggested as a potential strategy to solve these backlogs while solving the issue of residential informality. Two key findings emerged from this research concerning informal settlements. First, in situ upgrading was found to be a viable option in the city when informal settlements are located in areas with easy access to economic centres. This allows dwellers to access employment thus uplifting people out of poverty.

Second, informal settlements were identified to be mostly located close to low-income residential areas thus suggesting a link between the socio-economic circumstances of informal settlement dwellers and low-income residents which then drives the location of informal settlements in these areas. Though this spatial location trend might allow for this cohort to maintain its social networks, in situ upgrading in these locations might not be a viable option as these areas are in the peripheries. This might perpetuate the relegation of the low-income cohort to the outskirts where there is limited access to economic activities and where transport becomes expensive. This finding brought questions on whether all the informal settlements simulated by the model are indeed informal settlements or backyard shacks especially those adjacent to low-income housing. This is a worrying finding given the prevalence of backyard shacking in some of the low-income suburbs of the city. What this suggests is that, like informal settlements, the issue of backyard shacks can potentially be a serious problem in Cape Town. It puts pressure on the utility service grids and this calls for an urgency in addressing the housing issue.

9.3.3 On congestion

One of the problems that motivated this research is the increase in congestion in Cape Town. The results in this thesis suggest that the city is already lagging in implementing interventions to tackle congestion. It was observed that traffic conditions continued to deteriorate up to 2030. For urban planning policy to address congestion, there needs to be a focus on changing the employment-housing relationship through more compact growth and mixing of housing and economic activities. This may facilitate affordable access to employment and help solve issues of economic segregation. While this might reduce the commuting distances to work, it is still crucial to invest in infrastructure that makes alternative modes like public transport, walking and cycling attractive thus “locking in” the benefits from improved spatial development. This is especially crucial if car users are to shift to public and non-motorised modes of transport. There are mixed results on the impacts of compact strategies on travel time and mode choice (Schwanen, Dijst, & Dieleman, 2004; Chhetri, Hoon, Chandra, et al., 2013), in Cape Town, it is clear that neighbourhoods that are close to economic activities and transport infrastructure benefit from improved travel times while those in the peripheries are disadvantaged. In that regards, there might be value for Cape Town to explore compact growth strategies.

9.3.4 On mode share

While the land use interventions in the study have managed to effect modal split shifts, the results also suggest that Cape Town has a long way to go as the private car still has a significant mode share. What this implies is that to solve issues of congestion in Cape Town there might be a need for a combination of spatial development supply side interventions that surgically target the improvement of the public transport infrastructure and the state of the public transport itself. This might motivate people to start using public transport.

9.4 Research contributions to knowledge

From the onset, the potential contributions of this research were bifurcated into practical and theoretical contributions. The practical contribution relates to the methodological aspects that were implemented in this research. On the other hand, the theoretical contribution speaks to the implications of the methodologies used in advancing land use and transport modelling in cities similar to Cape Town.

Among other applications, the METRONAMICA land use transport model has been applied to understand the urban change process (Shahumyan, Convery, & Casey, 2010; Aljoufie, Zuidgeest, Brussel, et al., 2013) and to support regional planning (Perez, Wickramasuriya, Forehead, et al., 2017). One common aspect in all these applications is how the transport model is operationalised. In these applications, the private car is defined as an endogenous mode and therefore used to assign trips onto the network. While this is a feasible approach in these contexts, the Cape Town context requires a different approach. The city has a complex transport user system where mode choice decisions are biased towards income. Furthermore, there is an additional transport mode in the form of the minibus taxi which also has high intensity thus competing for capacity on the network. Therefore, there is a need to reflect this in the way the transport model is operationalised relative to standard M-LUT applications. Consequently, the current research utilised two endogenous modes – private cars and minibus taxis – to assign traffic on the network. This allowed for a more accurate representation of the transport user system and transport intensity. Based on that, the methodological contribution of the thesis is that it provided a method to model transport within the METRONAMICA framework in a context where informal transport accounts for a significant proportion of transport infrastructure capacity demand.

Sustainable Development Goal 11 places emphasis on the need to create inclusive, resilient and sustainable cities. Closely related to this is Goal 10 which stresses the importance of reducing inequality within countries (UN, 2018). Both these issues resonate with Cape Town and South African story. It is becoming increasingly challenging to achieve these goals as rapid urbanisation can potentially exacerbate urban and residential informality (Cobbinah & Amoako, 2012; Hofmann, Taubenbock, & Werthmann, 2015; Inostroza, 2017). To respond to the potential impacts of rapid urbanisation it is essential to formulate urban planning policies that are proactive instead of reactive. While urban planning policies in South Africa are aware of the need for a clear and consistent policy with regards to informal settlements, their proliferation continues to be an issue in Cape Town. Proponents of informal settlement upgrading have proposed in situ upgrading as a potential solution to addressing residential informality (Misselhorn, 2008; Massey, 2015; Brown-Luthango, Reyes, & Gubevu, 2017). However, there is a need to understand whether in situ upgrading does not perpetuate inequality. Using an integrated LUT model, this study interrogated the viability of in situ upgrading of informal settlements in the locations they were simulated in the model. The results suggest that some locations that attract informal settlements are not suitable for in situ upgrading, while areas that are accessible to manufacturing services are good candidates for upgrading. It is against this background that the present research has contributed to research by identifying the drivers of informal settlement growth and the characteristics of locations suitable for in situ upgrading.

One of the exercises carried out in this research was to evaluate and trace the growth trajectory of urban land uses in Cape Town. The aim was to assess whether a change in the planning ideology from a politically zoning system to an economically and socially driven approach would untether the city from apartheid spatial planning structures. This was mainly done to redress issues of social exclusion and inequality among others. A land use development scenario that geared towards redressing social exclusion and inequality was developed. The main finding flowing from the land use scenario was that intentional and targeted land use development could help alleviate issues of economic and social exclusion. However, land use development also needs to be linked to transport interventions. In that regard, this research has contributed to knowledge especially within a developing world context in that it has shown the value that can accrue from implementing land use and transport modelling tools to assist in policy formulation and implementation especially where current discourse focuses on equity and inclusivity.

The interaction of household income and residential location has been extensively studied (Alonso, 1964; Guo & Bhat, 2007; Schirmer, Eggermond, & Axhausen, 2013). While these studies focus on the role of income in influencing residential location they indirectly shed light on income and its effect on the spatial structure of the urban environment. Put differently, household locations as determined by income influence urban dynamics. By delineating residential areas according to income, this research was able to calibrate the neighbourhood rules that explained housing locations based on their interactions with socio-economic variables. Incorporating socio-economic variables as drivers of urban change has been discussed as a potential avenue to improve the ability of the CA model to predict the complexity of urban change (Grimm, Grove, Pickett, et al., 2000; He, Okada, Zhang, et al., 2006; Mohammad, Sahebgharani, & Malekipour, 2013). Although attempts to incorporate socio-economic variables into CA have been cited (Engelen, White, Uljee, et al., 1995; He, Okada, Zhang, et al., 2006; Mohammad, Sahebgharani, & Malekipour, 2013), most of these models have integrated CA models with other models to capture socio-economic variables. As such, using income to represent residential land uses is a step towards identifying ways of incorporating socio-economic variables in the calibration of neighbourhood rules specific to different residential and income categories and how they influence urban change.

Chapter 10

Conclusion and recommendations

This chapter consists of four sections. The first part presents the conclusions that flow from this research, Section 10.2 discusses the limitations of this research. Section 10.3 discusses the possible transferability of the methods implemented in this research to cities similar to Cape Town. The chapter concludes by providing recommendations for future research directions in the city and South Africa in general.

10.1 Conclusion

This research implemented a dynamic land use and transport model to understand the urban dynamics due to land use and transport in Cape Town to aid in the development of proactive approaches to land use and transport planning. The model was implemented for forecasting to understand the influence of different policy interventions on the urban environment. While this research focused on Cape Town, South Africa's history has made its cities relics of apartheid planning. In that regard, the results from this research potentially resonate with most of the country's cities. The findings from this research suggest that attaining social inclusion, residential integration, addressing issues of residential informality, transport affordability and congestion in South African cities will require cohesion between land use and transport policy. Currently, the urban planning context in the country acknowledges that the integration of land use and transport is essential to address some of the urban issues, especially the impacts of apartheid spatial planning. However, the use of spatial decision support tools that are fully dynamic and integrate land use and transport while acknowledging the causality between land use and transport is still in its infancy. Transport modelling initiatives in South Africa commenced in the 1960s with the calibration of TRAMP and DELTRAN (Kane & Behrens, 2002) followed by the calibration of the EMME model in the early 1980s. Yet, the use of urban models to aid in policy formulation is still lagging. This research has clearly shown the value of such tools in forecasting land use and transport changes to guide in formulating proactive approaches to aid land use and transport planning. In that regard, SDS tools should be frequently utilised in the current planning discourse in the country's cities.

Concerning informal settlements, while there is consensus on the role of informal settlements in providing affordable housing, it is essential to manage their growth and potential influence on the provision of transport and other services. It has been argued that current policy is ambivalent on how to address the issue of informal settlements (Misselhorn, 2008; Bradlow & Bolnick, 2011; Fitchett, 2014), yet informal settlements are a potential powder keg as their dwellers experience high levels of unemployment and have limited access to transport and other services. Further, it is essential to acknowledge that high levels of unemployment in the city have resulted in a booming of an informal economy in some of the informal settlements thus providing employment and sources of income to their dwellers. Hence, policies that are aimed to address residential informality should be sensitive to the role of the informal economy in alleviating poverty among the marginalised groups. Proponents of informal settlement upgrading in South Africa advocate for in situ upgrading. However, this research has shown that there is no blanket approach to addressing the issue of residential informality. Instead, an approach that resonates with contextual realities would be more suitable as some locations may encourage sprawl and displace thriving businesses within the informal economy. This may be counter to the country's urban development strategies. It is also crucial to understand the drivers of the genesis of informal settlements in different cities as this provides an opportunity to ensure that upgrading does not exacerbate exclusion but instead fosters integration, inclusion and access to economic opportunities.

While Cape Town cannot be taken as representative of South Africa's cities that experience congestion, some lessons can be transferred to other cities. This research has alluded to congestion in the country's cities as a symptom of an inefficient and failing public transport system where car users remain captive to their private cars. This was especially clear in this study as the densification strategy along the Metro South East Integration Zone did not result in a significant change in congestion. This suggests that mitigating congestion in the country's cities requires coordination between land use development strategies and public transport improvement to ensure that it is attractive to car users. This is especially pertinent given the emergence of a new middle-income cohort which might increase motorisation.

10.2 Limitations of the study

During the calibration, it was clear that zoning was a key driver of land use change in the Cape Town context. However, the available zoning schemes were not consistent and in some cases difficult to interpret. This influenced the extent to which the model could simulate some of the locations of land use changes. During the modelling exercise, efforts were made to ensure that the zoning schemes were correctly interpreted using the available data. In spite of this limitation, the land use patterns simulated by the model for the calibration and validation period resemble reality which shows that the neighbourhood rules generated by the model and the zoning maps utilised could sufficiently simulate the land use dynamics.

Data paucity, especially of recent and historical time series data to use in the transport model was a problem. The insufficiency and sometimes lack of this data limited the extent to which the transport model could be calibrated, and the metrics used to assess the performance of the model at the validation stage. Additionally, this also limited the inferences on the performance of the transport model. To circumvent this issue and allow for independent validation of the model, the congestion outputs from the Cape Town's EMME model were used as a check for the general performance of the model. The overall simulated trip productions and attractions also aided in validating the model.

In the calculation of the initial trip matrix, only distance was used as an impedance to travel to distribute the trips to the different origins and destinations. This is a limited view in that impedance to travel can be due to several factors such as travel time and cost of transport. However, because there was limited data, only the distance attribute was used, and this reduced the number of assumptions made regarding the calculation of the initial trip distribution matrix.

The validation of models is a vital aspect as it helps in ascertaining the quality of the parameters set in the model. Land use and transport models intended for forecasting with the view for policy analysis need to be independently validated as it helps to assess the model performance when simulated over a long period. This entails using a dataset that was not used in the calibration of the model. For this research, though the land use and transport model blocks were validated independently, the process was not carried out at uniform time points. A staged validation procedure was implemented where the land use model was validated for 2010 and the transport model for 2013. The research could not identify any negative implications related to a staged validation on the overall performance of the model. Still, future research could investigate the implications of implementing such a validation approach.

10.3 Transferability of the research approach

Cape Town was used as a case city to understand urban dynamics relating to the interaction between land use and transport. Though the methods implemented in this thesis were explicitly developed for Cape Town, South Africa's cities share a history which has dictated spatial patterns especially the race and income spatial structure. In that regard, there is a potential for the neighbourhood rules generated in this model to be used as a starting point to calibrate a similar model for other cities in the country. This is especially possible given that income was used to delineate residential areas which are an important land use in the model as they influence the location of other land uses.

10.4 Recommendations on future research directions

This research has focused on understanding the land use and transport dynamics in Cape Town and how they influence the urban environment. Additionally, the research pointed to how urban models such as the one implemented in this research can play in guiding policy. The research considered the role of informal settlements in shaping the urban environment, the influence of land development on transport and the influence of transport on land use development among other issues. However, the research also highlighted areas that require further research:

- In this research, the location of informal settlements near low-income residential areas raised questions as to whether these are indeed informal settlements, or the model simulated the behaviour of backyard shacking. In that regard, it is critical to evaluate the spatial nature and prevalence of backyard shacks in low-income neighbourhoods. In addition to this, understanding what drives their growth and how they relate to low-income housing and informal settlements is important. It may be useful for future studies to combine high resolution satellite imagery and neural networks to accurately detect backyard shacking.
- The spatial structure of Cape Town is such that there are suburbs with mixed land uses and therefore these suburbs produce and attract trips simultaneously. This results in a significant number of intrazonal trips. In the current model, these are not accounted for on the network as they originate and terminate within the zone. In cases where the transport zones are large, these trips impact traffic intensity on some road network links. It would be interesting to understand the influence of land uses on intrazonal trips and the associated mode choice decisions. This is especially important in a context like Cape Town where land use and transport policy are undergoing a transition process where mixed land use development is viewed as a potential tool to transform the urban spatial structure.
- The Cape Town transport system is biased towards access to formal employment, yet the informal economy plays an integral role in Cape Town’s economy. While the discussion in this thesis only focused on access to formal employment, future

research should also consider economic activities within the informal economy and the influence on trip generation and the resulting congestion on the network.

- Sustainable Development Goal 11 notes the importance of an efficient transport network in facilitating sustainable development. In Cape Town, there are some road networks such as Voortrekker, Vanguard Drive and Settlers Way where road users experience travel speeds as low as 20km/hr during peak travel times thus representing a poor level of service on these links. While land use development is essential, this research has shown that on its own, land use development is not sufficient to mitigate congestion. Instead, there needs to be a joint effort with infrastructure development. Metrorail presents an opportunity to alleviate congestion. However, in its current state, the ridership mainly consists of low-income earners who are captive to public transport. Still, with proper investment in rail infrastructure, it is possible to increase the income diversity of Metrorail riders. Therefore, future research on integrating land use and transport modelling in the city should consider scenarios that evaluate the financial, economic and social benefits that might accrue from intensive investment in rail infrastructure so that it attracts more users.
- Traffic congestion in cities can result in both socio-economic and environmental impacts. This research did not consider these impacts. Future research should consider evaluating the socio-economic and environmental costs of congestion.
- Walking is a mode of transport that is sometimes overlooked in urban models, yet it is one of the most sustainable means of transport. It has a high mode share in developing countries. While the model implemented in this research does not consider walking, future research should consider it as a mode and evaluate the influence of pedestrian infrastructure on land use dynamics.
- The calibration of integrated models is an onerous task primarily when a manual calibration approach is implemented. Future research can consider an automatic calibration of the model for Cape Town and compare the calibration results based on these two approaches.
- A 100m by 100m cell size was utilised which is relatively small given that the whole Cape Town Metropolitan area was modelled. This made the calibration difficult. It is suggested that future research should consider increasing the cell size in the model.

The aspects that need to be addressed to facilitate future research include:

- It is pertinent for the City of Cape Town to have clear guidelines for collating data and complementarity between the different departments. This will ensure consistency in data which may potentially assist in addressing data related aspects that inhibit the proper calibration and validation of land use and transport models in the city.

- Collaboration between academia and government institutions responsible for planning is needed so that there can be a cross-pollination of knowledge from both spectrums. This might aid in better policy formulation and implementation.

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Related work

The following is research output that was produced during the course of the PhD and makes up part of Chapter 2 of the thesis

Journal articles

Tamuka Moyo, H.T. & Zuidgeest, M. 2018. Analyzing the temporal location of employment centers relative to residential areas in Cape Town: A spatial metrics approach. *Journal of Transport and Land Use*. 11(1):519–540.

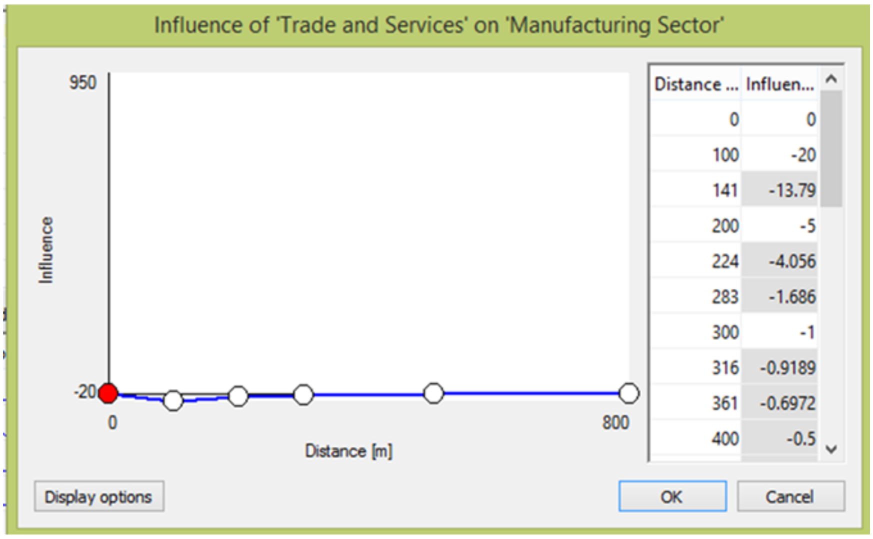
Conference presentations (Reviewed)

Tamuka Moyo, H.T. & Zuidgeest, M. 2017. Analyzing the temporal location of employment centers relative to residential areas in Cape Town: A spatial metrics approach. *2017 World Conference in Transport and Land Use, Brisbane, Australia*

Appendices

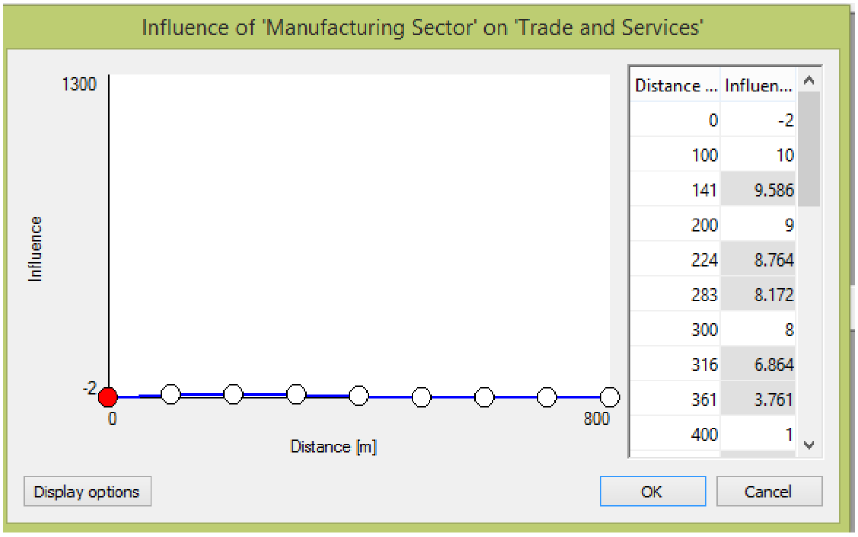
Appendix A: Neighbourhood influence rules used in the Cape Town model

a) Influence of trade and services on Manufacturing



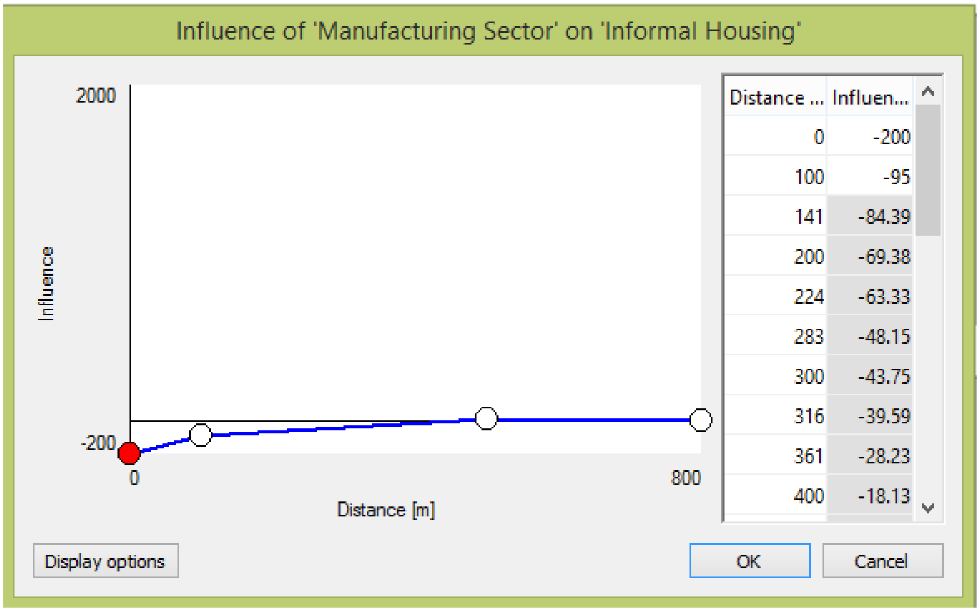
Distance ...	Influen...
0	0
100	-20
141	-13.79
200	-5
224	-4.056
283	-1.686
300	-1
316	-0.9189
361	-0.6972
400	-0.5

b) Manufacturing sector on trade and services



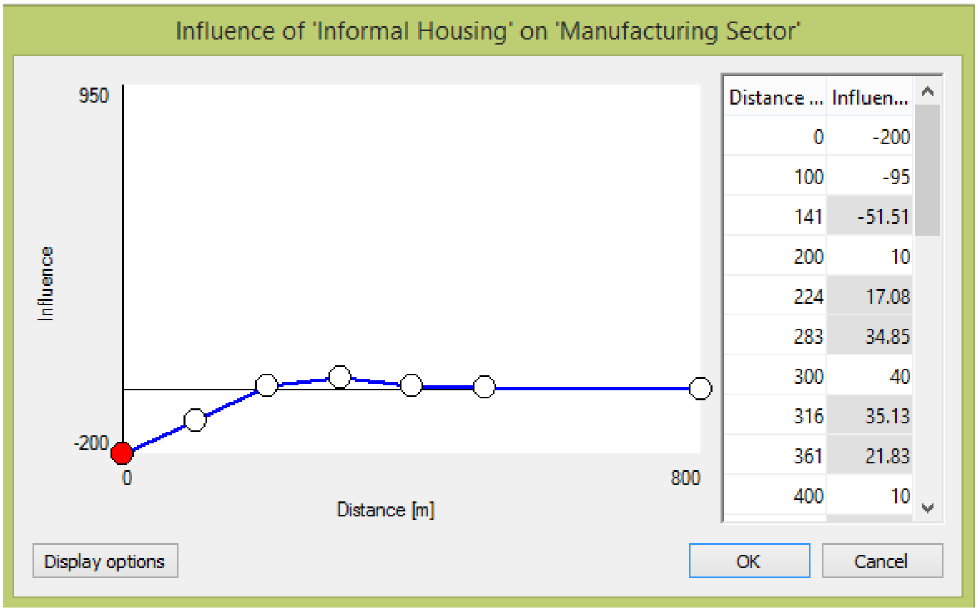
Distance ...	Influen...
0	-2
100	10
141	9.586
200	9
224	8.764
283	8.172
300	8
316	6.864
361	3.761
400	1

c) Influence of manufacturing sector on informal housing



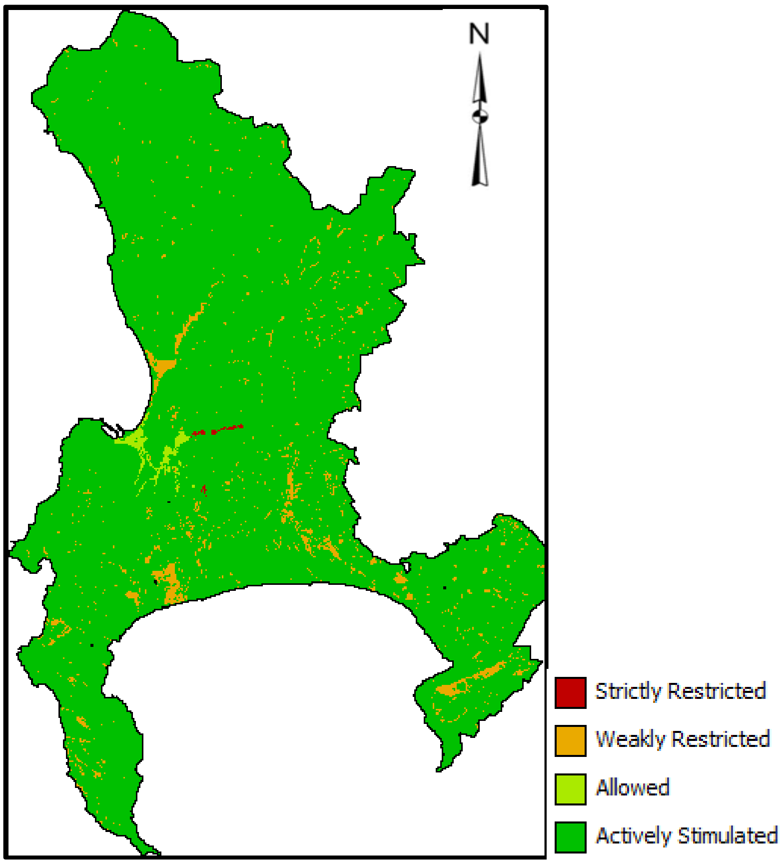
Distance ...	Influen...
0	-200
100	-95
141	-84.39
200	-69.38
224	-63.33
283	-48.15
300	-43.75
316	-39.59
361	-28.23
400	-18.13

d) Influence of informal housing on manufacturing sector

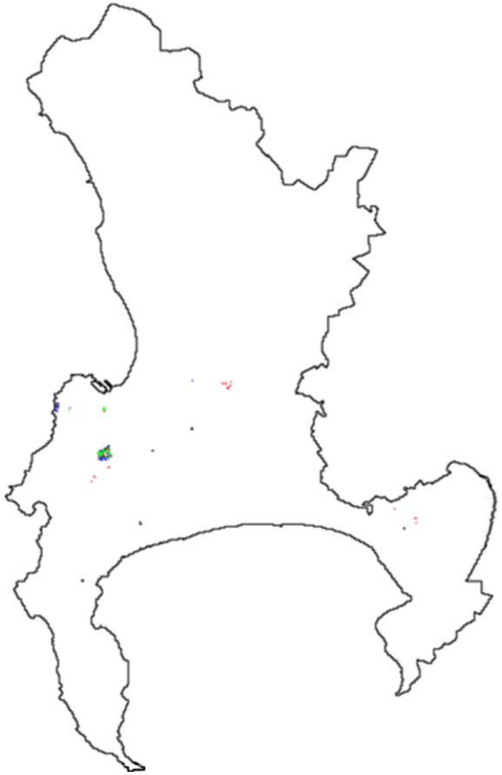
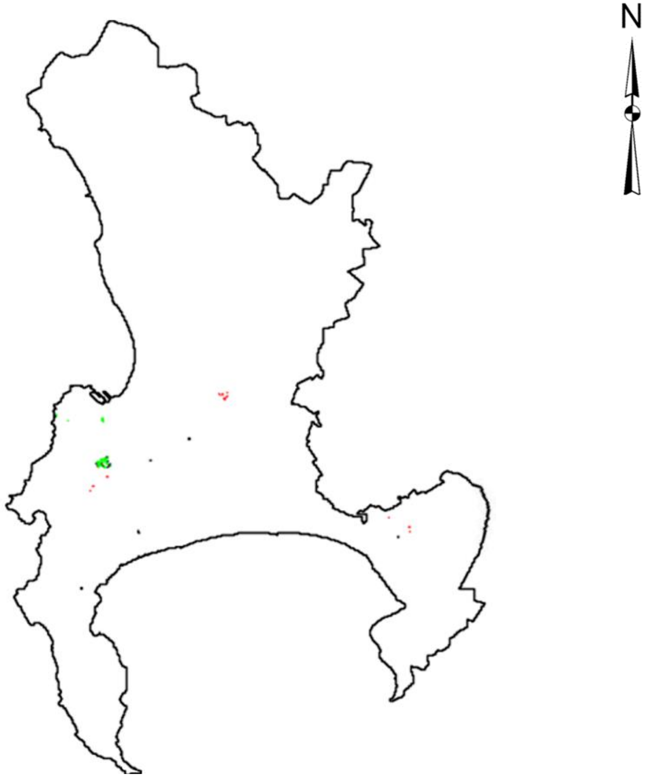


Distance ...	Influen...
0	-200
100	-95
141	-51.51
200	10
224	17.08
283	34.85
300	40
316	35.13
361	21.83
400	10

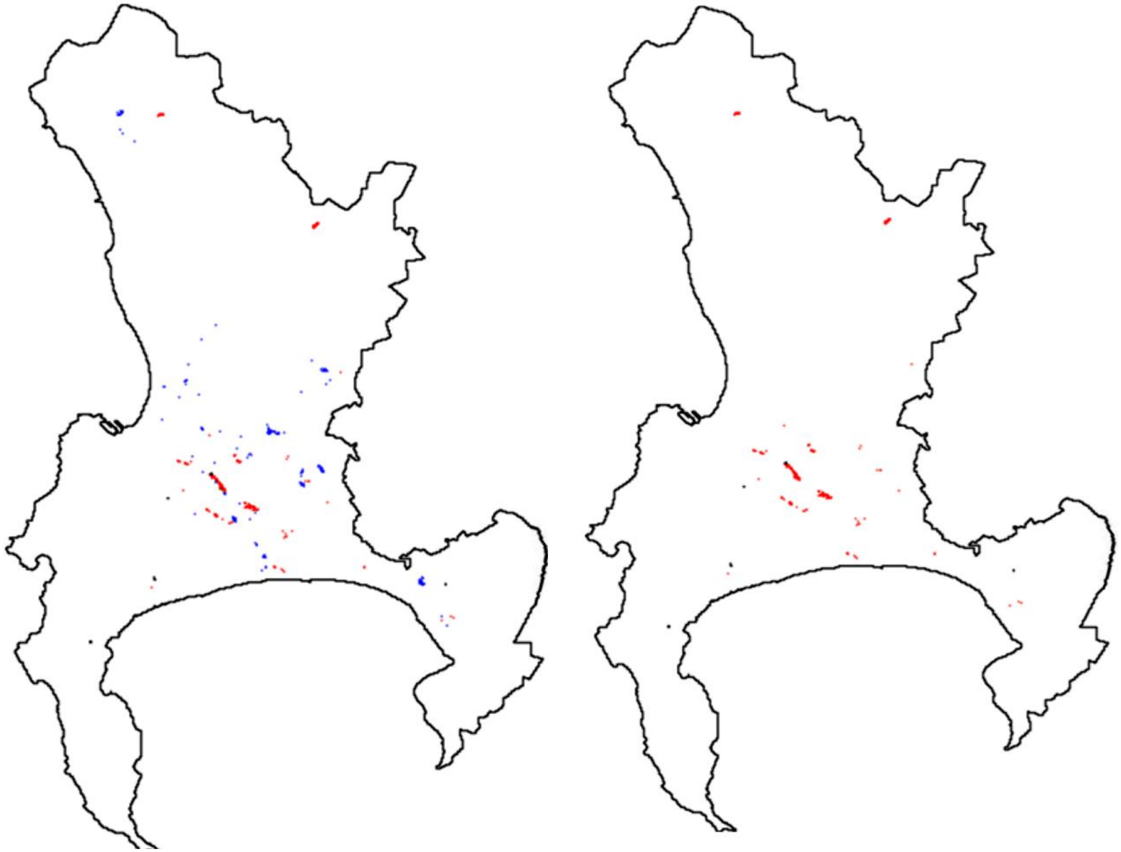
Appendix B: Flooding layer



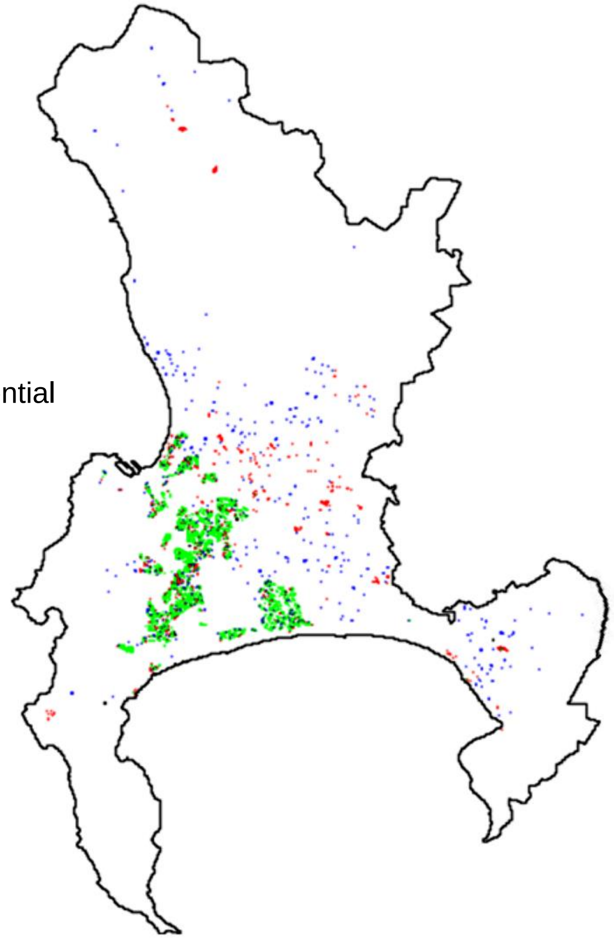
Appendix C :Visual interpretation for function land uses

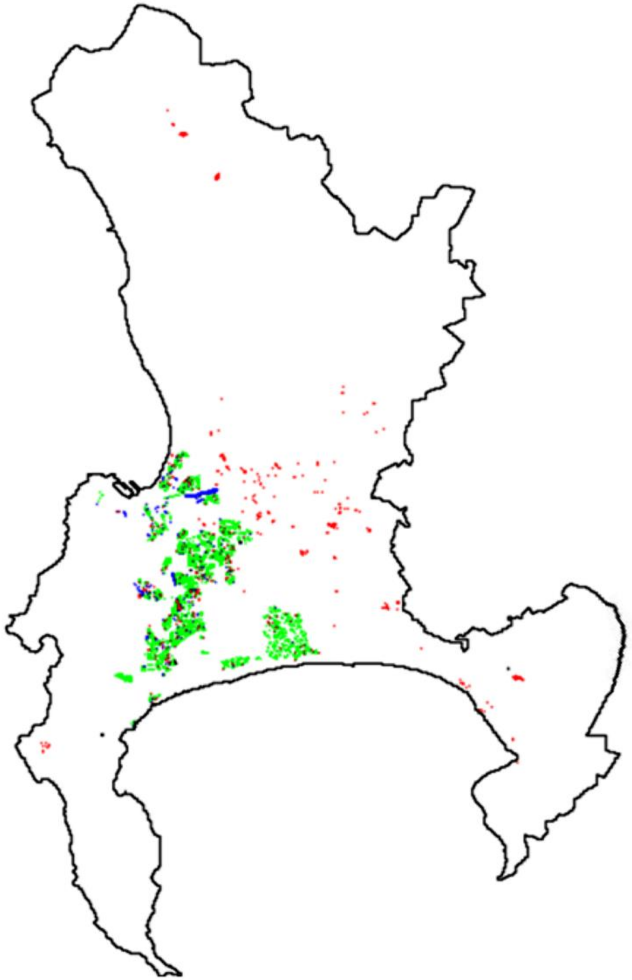
Land use	Predicted change real map 2005 (map1) vs simulated (map 2)	Real change real map 2005 (map1) vs real map 1995 (map 3)
High-income residential		

Informal settlements

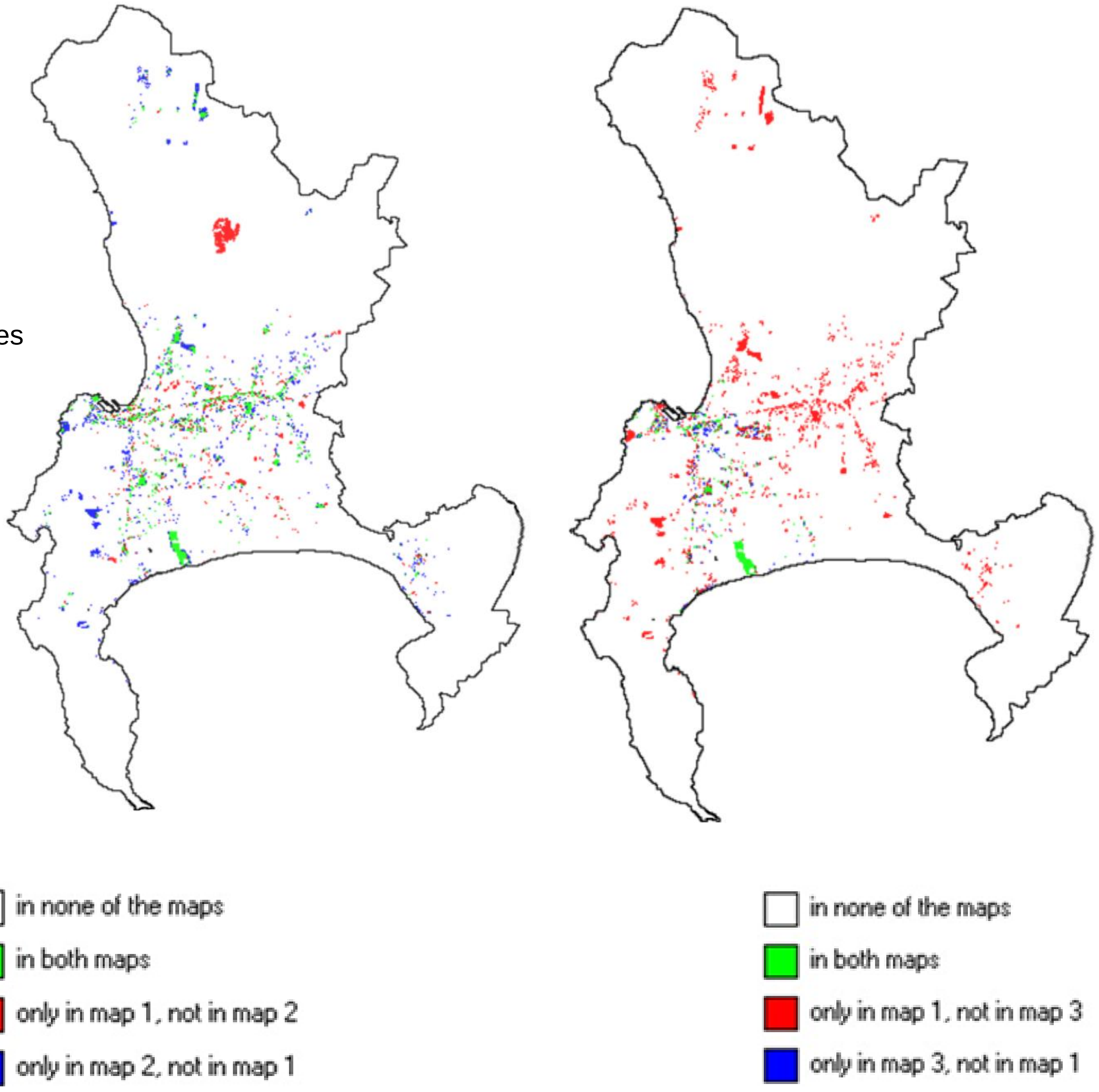


Low-income residential





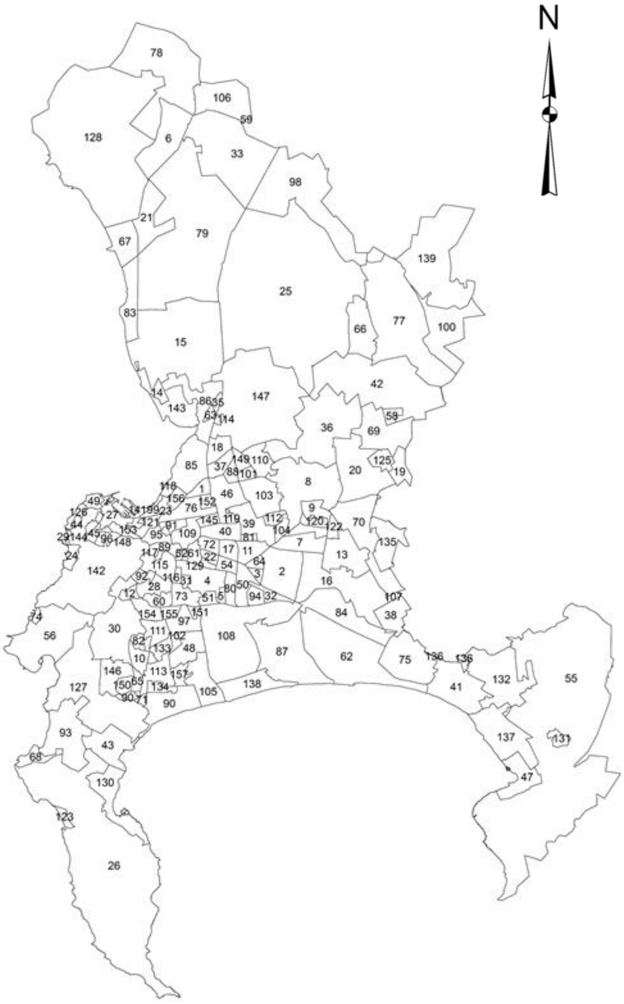
Trade and services



Appendix D: Zonal accessibility scores from the calibration period

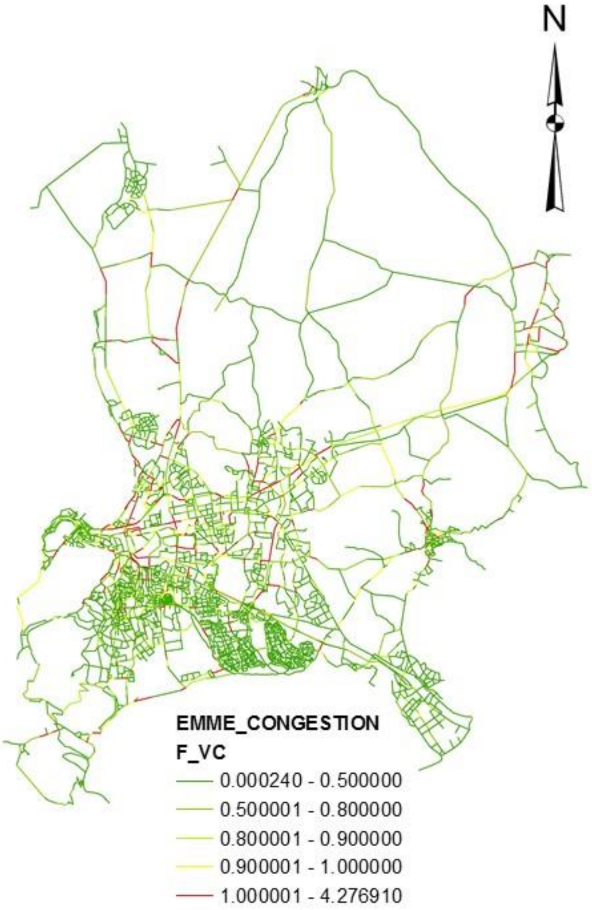
Zone	High income	Middle income	Low income	Informal settlements	Manufacturing services	Trade services
Acacia Park	0.78478	0.78259	0.78259	0.62365	0.77368	0.78418
Airport Industria	0.61648	0.61843	0.61843	0.60174	0.62479	0.60997
Athlone	0.61775	0.61591	0.61591	0.61088	0.60653	0.60868
Atlantis	0.99471	0.9874	0.9874	0.65781	0.95927	0.99972
Bellville	0.78999	0.78135	0.78135	0.63875	0.74016	0.76013
Cape Town City Centre	0.83278	0.83452	0.83452	0.62907	0.8452	0.84945
Claremont	0.78868	0.79036	0.79036	0.62896	0.78968	0.75531
Durbanville	0.9999	0.99108	0.99108	0.66269	0.95541	0.99801
Epping Industria	0.75906	0.76479	0.76479	0.62333	0.78119	0.72967
Gardens	0.65376	0.66113	0.66113	0.60872	0.68707	0.63783
Green Point	0.99013	0.98532	0.98532	0.65611	0.96671	0.99296
Guguletu	0.68239	0.67726	0.67726	0.61667	0.65211	0.66167
Kenilworth	0.63733	0.64005	0.64005	0.6058	0.64844	0.62627
Khayelitsha	0.72094	0.72721	0.72721	0.61703	0.74961	0.70895
Langa	0.88433	0.88589	0.88589	0.6375	0.89578	0.90069
Maitland	0.61408	0.61538	0.61538	0.60222	0.61906	0.60737
Milnerton	0.66293	0.66914	0.66914	0.61474	0.68975	0.64393
Milnerton Rural	0.72021	0.71469	0.71469	0.63585	0.69251	0.71964
Mitchells Plain	0.86548	0.86954	0.86954	0.63502	0.88405	0.85767
Mowbray	0.96877	0.95698	0.95698	0.66756	0.90745	0.95821
Newlands	0.67046	0.67305	0.67305	0.61066	0.68026	0.65629
Nyanga	0.91158	0.91035	0.91035	0.64411	0.90293	0.90029
Observatory	0.93257	0.93126	0.93126	0.64581	0.92687	0.93633
Parow	0.64946	0.65844	0.65844	0.60531	0.6913	0.6356
Parow Industrial	0.85863	0.85777	0.85777	0.63039	0.85839	0.87704
Philippi	0.68535	0.67927	0.67927	0.63399	0.65006	0.66332
Pinelands	0.62745	0.62854	0.62854	0.6101	0.63009	0.61464
Plumstead	0.88199	0.8708	0.8708	0.68744	0.82347	0.87035
Retreat	0.67924	0.67961	0.67961	0.6224	0.67583	0.65552
Rondebosch	0.75442	0.74788	0.74788	0.64436	0.71895	0.74204
Rondebosch East	0.60658	0.60795	0.60795	0.6006	0.61269	0.60331
Rosebank	0.98109	0.98444	0.98444	0.64838	1	0.99073
Salt River	0.84032	0.84119	0.84119	0.62932	0.84856	0.85785
Sea Point	0.69226	0.69917	0.69917	0.61301	0.72425	0.68086
Silver Mine	0.77977	0.77011	0.77011	0.65144	0.72636	0.75691
Silverstream Rd	0.9278	0.92343	0.92343	0.6525	0.90432	0.92052
Silvertown	0.76239	0.76896	0.76896	0.62073	0.79356	0.75494
Simon's Town	0.88727	0.88677	0.88677	0.6389	0.88653	0.8952
Somerset West	0.8947	0.88516	0.88516	0.65377	0.84291	0.87629
Southfield	0.84989	0.84386	0.84386	0.64342	0.81565	0.83139

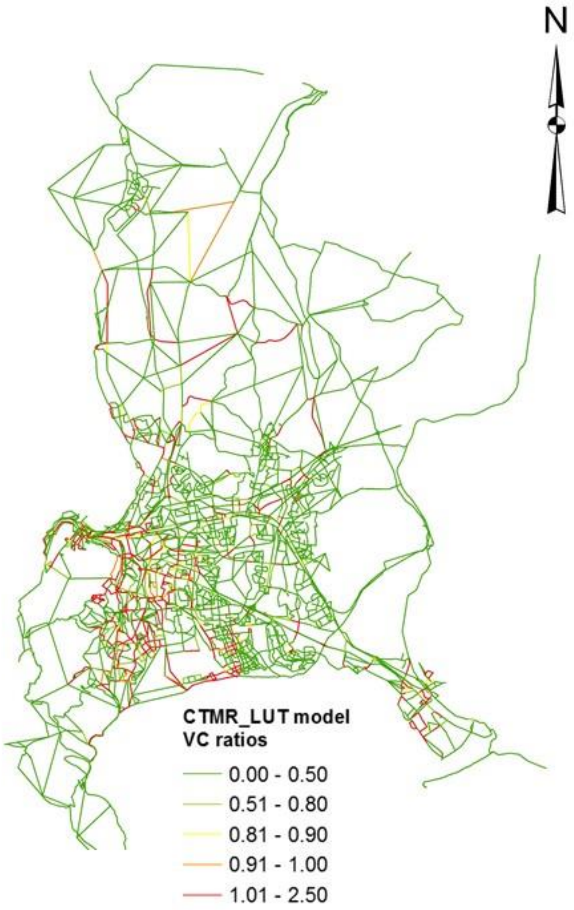
Appendix E: Location of Suburbs in Cape Town



1	Acacia Park
2	Airport
3	Airport Industria
4	Athlone
5	Athlone Industria
6	Atlantis
7	Belhar
8	Bellville
9	Bellville South
10	Bergvliet
11	Bishop Lavis
12	Bishopscourt
13	Blackheath
14	Bloubergstrand
15	Bloubergsvlei
16	Blue Downs
17	Bonteheuwel
18	Bothasig
19	Bottelary
20	Brackenfell
21	Brakfontein
22	Bridgetown
23	Brooklyn
24	Camps Bay
25	Cape Farms
26	Cape Point
27	Cape Town City Centre
28	Claremont
29	Clifton
30	Constantia
31	Crawford
32	Crossroads
33	Dassenberg
34	Diepriver
35	Dunoon
36	Durbanville
37	Edgemead
38	Eersterivier
39	Elsies River
40	Epping Industria
41	Firgrove
42	Fisantekraal
43	Fish Hoek
44	Fresnaye
45	Gardens
46	Goodwood
47	Gordons Bay
48	Grassy Park
49	Green Point
50	Guguletu
51	Hanover Park
52	Hazendal
53	Heathfield
54	Heideveld
55	Helderberg Rural
56	Hout Bay
58	Joostenberg Vlakte
59	Kalbaskraal
60	Kenilworth
61	Kewtown
62	Khayelitsha
63	Killarney
64	King David Country Club
65	Kirstenhof
66	Klipheuwel
67	Koeberg
68	Kommetjie
69	Kraaifontein
70	Kuils River
71	Lakeside
72	Langa
73	Lansdowne
74	Llandudno
75	Macassar
76	Maitland
77	Malmesbury Farms
78	Mamre
79	Mamre Rd & 304
80	Manenberg
81	Matroosfontein
82	Meadowridge
83	Melkbosstrand
84	Mfuleni
85	Milnerton
86	Milnerton Rural
87	Mitchells Plain
88	Monte Vista
89	Mowbray
90	Muizenberg
91	Ndabeni
92	Newlands
93	Noordhoek
94	Nyanga
95	Observatory
96	Oranjezicht
97	Ottery
98	Paardeberg
99	Paarden Eiland
100	Paarl Farms
101	Panorama
102	Parkwood
103	Parow
104	Parow Industrial
105	Pelikan Park
106	Pella
107	Penhill
108	Philippi
109	Pinelands
110	Plattekloof
111	Plumstead
112	Ravensmead
113	Retreat
114	Richwood
115	Rondebosch
116	Rondebosch East
117	Rosebank
118	Rugby
119	Ruyterwacht
120	Sacks Circle
121	Salt River
122	Sarepta
123	Scarborough
124	Schotschekloof
125	Scottsdene
126	Sea Point
127	Silver Mine
128	Silverstream Rd
129	Silvertown
130	Simon's Town
131	Sir Lowrys Pass
132	Somerset West
133	Southfield
134	Steenberg
135	Stellenbosch Farms
136	Stellenbosch Nu
137	Strand
138	Strandfontein
139	Swartland Nu
140	Sybrand Park
141	Table Bay Harbour
142	Table Mountain
143	Table View
144	Tamboerskloof
145	Thornton
146	Tokai
147	Tyger Valley
148	Vredehoek
149	Welgelegen
150	Westlake
151	Wetton
152	Wingfield
153	Woodstock
154	Wynberg
155	Youngsfield
156	Ysterplaat Airbase
157	Zeekoei Vlei
158	Zonnebloem

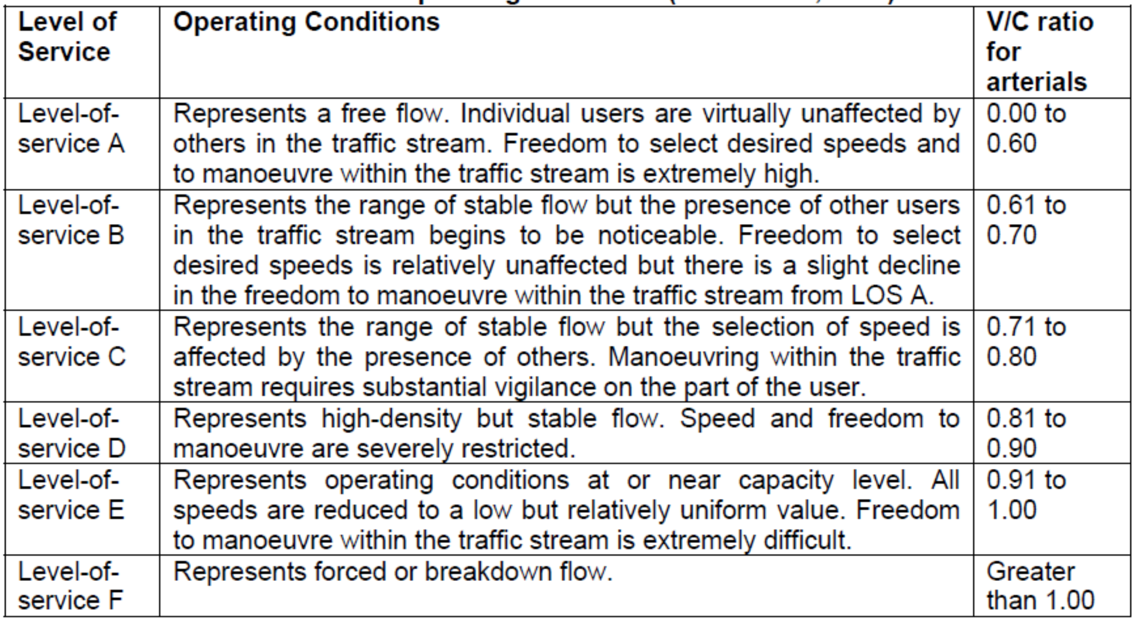
Appendix F: Congestion for CTMR_LUT and EMME model





Appendix G: Relationship between V/C ratio and Level of Service

Table 3: Levels of service with operating conditions (Roess et al, 1985)



Level of Service	Operating Conditions	V/C ratio for arterials
Level-of-service A	Represents a free flow. Individual users are virtually unaffected by others in the traffic stream. Freedom to select desired speeds and to manoeuvre within the traffic stream is extremely high.	0.00 to 0.60
Level-of-service B	Represents the range of stable flow but the presence of other users in the traffic stream begins to be noticeable. Freedom to select desired speeds is relatively unaffected but there is a slight decline in the freedom to manoeuvre within the traffic stream from LOS A.	0.61 to 0.70
Level-of-service C	Represents the range of stable flow but the selection of speed is affected by the presence of others. Manoeuvring within the traffic stream requires substantial vigilance on the part of the user.	0.71 to 0.80
Level-of-service D	Represents high-density but stable flow. Speed and freedom to manoeuvre are severely restricted.	0.81 to 0.90
Level-of-service E	Represents operating conditions at or near capacity level. All speeds are reduced to a low but relatively uniform value. Freedom to manoeuvre within the traffic stream is extremely difficult.	0.91 to 1.00
Level-of-service F	Represents forced or breakdown flow.	Greater than 1.00