Persistent segregation: spatial patterns and dynamics of residential segregation in Cape Town

Persistent Segregation

Spatial Patterns and Dynamics of Residential Segregation in Cape Town

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A thesis submitted for the degree of Doctor of Philosophy

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UNIVERSITY OF LONDON

Department of Geography
Birkbeck, University of London
London, February 2022

Statement of Originality

I, Jacobus Marthinus van Rooyen, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

The occurrence of urban segregation is a global phenomenon which is particularly stark in South Africa, where the policy of apartheid not only enforced the segregation of racial groups into dedicated urban areas, but also governed every aspect of life for more than four decades. As a result, more than twenty years into the post-apartheid era, the South African city remains strongly racially segregated. This is further aggravated by socio-economic inequalities akin to other cities in the Global South, with a high presence of informal settlements with sub-standards of living. While there is a wealth of literature on racial segregation in South Africa and an understanding of the interrelated nature of income and racial dimensions of segregation, the question of the extent in which residential segregation is being perpetuated by race or income in South African cities has not been explored quantitatively.

Taking the city of Cape Town as a study case, this thesis looks into this question using a combined methodological approach to explore residential segregation by race and income. The thesis explores the role of race and income inequalities in the persistence of residential segregation in Cape Town in a quantitative manner by using two complementary approaches. Spatial segregation indices were applied to measure and map varying segregation patterns throughout the study area. In addition, an agent-based model was developed to explore the dynamics of segregation and the underlying rules of interaction between individuals and groups which produce such segregated patterns. Findings suggest that, although segregation in Cape Town remains predominantly racial, income inequalities strongly contribute to the process as well as add complexity to the phenomenon. The thesis demonstrates that, while the segregation is a clear heritage of the apartheid's exclusion rules, the current process of residential segregation can only be fully understood by looking at the combined effect of race and income.

Acknowledgements

Firstly, l would like to thank my supervisor, Joana Barros, for her guidance, motivating me to undertake doctoral research and her continuous support throughout the development of this research project. I would also like to thank Vic Theunissen and Belinda Verster for instilling in me their infectious passion for urban studies and teaching me the fundamental values in developing sustainable urban habitats.

This work would not have been possible without the support and guidance from individuals at various institutions in South Africa. I would like to thank Helene Verhoef at Statistics South Africa for not only providing me with census and statistical data for Cape Town, but also for her continuous advice and guidance on the South African census. I would also like to thank the GIS team at the Strategic Development and Information department at the City of Cape Town council for assisting me with spatial data for Cape Town and frequently advising me on the urban infrastructure of the city.

The development of this research study was inspired by the work of various international researchers in urban studies, complexity science and agent-based simulation. I thank Susan Parnell at the University of Bristol and Charlotte Lemanski at the University of Cambridge for their work on cities of the Global South and urban inequality respectively. I am thankful to Mike Batty at the Centre for Advanced Spatial Analysis (University College London) and Luis Bettencourt at the Mansueto Institute for Urban Innovation (University of Chicago) for their pioneering work in urban complexity, a field I developed a great love for. I thank my good friend and neighbour, Johan van der Merwe, for his guidance in computer coding. Most of all, I thank my fellow researcher, Marcus Saraiva, for his endless advice and assistance in developing my agent-based model for Cape Town. I have not only gained knowledge and insight, but also a great friend.

Inspiration and courage for undertaking this PhD research project came from the life stories of Homer Hickham (Rocket Boys: A Memoir by former NASA engineer) and the late Bryce Courtenay (The Power of One). Inspiration for the subject of my research was gained from the hopes and dreams of Madiba (former South African president Nelson Mandela) to see a reconciled and united South Africa and from the filmography of Neill Blomkamp (District 9 and Elysium), accentuating the complex phenomena of social exclusion and economic inequality.

Finally, my deepest and most sincere gratitude goes to my parents, Koos and Baby van Rooyen, for their everlasting love and support and never failing to believe in me. I also thank my sisters, Hannely and Juliana for their endless support and I am most grateful to Asheley, for her love and encouragement.

I dedicate this thesis to my parents, the people of the Cape Flats and to Yeshua of Galilee, for giving me the faith to endure, the hope to succeed and the love to build lasting friendships on this journey.

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Chapter 1
Introduction

The occurrence of urban segregation is a global phenomenon which is particularly stark in South Africa, where the policy of apartheid not only enforced the segregation of racial groups into dedicated urban areas, but also governed every aspect of life for more than four decades (Smith, 1992; McDonald and Smith, 2004; Beinart et al., 2013; Dubow, 2014). As a result, the South African city remains strongly racially segregated more than twenty years into the post-apartheid era and urban space evidently shaped accordingly (van Rooyen and Lemanski, 2020). This is further aggravated by socio-economic inequalities akin to other cities in the Global South, with a high presence of informal settlements with sub-standards of living. Unlike townships, which refer to racially segregated and underdeveloped urban areas in the South African context, informal settlements are defined as unplanned settlements occupying land that has not been proclaimed as residential (The Housing Development Agency, 2013). The term “slums” is often used interchangeably with informal settlements (Huchzermeyer, 2010). Socio-economic segregation in the South African city remains a problem and is a predominant contemporary theme in urban studies (Turok, 2001; Pieterse, 2009; Musterd, 2020).

Research has been devoted to the influence of racial and economic exclusion of non-White population groups on spatial urban development patterns in South Africa (Saff, 2001; Turok, 2001; Lemanski, 2006a, 2007; Borel-Saladin and Crankshaw, 2009; Lemanski and Saff, 2010; Du Plessis and Boonzaaier, 2015). Urban segregation studies on South African cities predominantly focus on either the sociological aspects of segregation, studying racial and social polarisation as a result of historical or contemporary urban form (Davies, 1981; Lemon, 1991; Lemanski, 2006a; Beinart et al., 2013) or from a political viewpoint, analysing government involvement in the context of urban development and integration (Bickford-Smith, 1995; Pirie, 2007; Pieterse, 2009).

While there is a wealth of literature on racial segregation in South Africa and an understanding of the interrelated nature of income and racial dimensions of segregation, the question of the extent to which residential segregation is being perpetuated by race or income in South African cities has not been explored quantitatively. Even though quantitative analysis has been undertaken to study racial segregation patterns in most South African cities, including Cape Town (Rospabe and Selod, 2006; Parry and van Eeden, 2015), hardly any consideration has been given to the subject of income. Hence, the role income plays in the persistence of segregation in Cape Town is not sufficiently addressed in a quantitative manner.

It is essential that this subject is addressed, given the aspiration of the City of Cape Town council for a socio-economically integrated and inclusive society. These aims are reflected in the establishment of numerous post-apartheid policies to promote integrated development and address racial and economic disparity and related spatial segregation. Irvine (2012) highlighted that residential integration has been impeded by economic constraints that confine a large part of the Black African population to former townships, substantiating the notion that the problem of residential segregation might also be of an economic nature. This phenomenon has significant implications for policies with the objective of socio-economic integration.

Taking the city of Cape Town as a study case, this thesis looks into this question using a combined methodological approach to explore residential segregation by race and income. The role of race and income inequalities in the persistence of residential segregation in Cape Town is explored by using segregation indices to measure and map segregation patterns and an agent-based model to explore the dynamic rules producing such patterns. The main objective of this research project is to understand the role income plays, compared to race, in the persistence of segregation in Cape Town by unfolding the dynamics of both racial and socio-economic segregation and undertaking a comparative analysis of these subjects.

Findings suggest that, although segregation in Cape Town remains predominantly racial, income inequalities strongly contribute to the process as well as add complexity to the phenomenon. The thesis demonstrates that, while the segregation is a clear heritage of the apartheid's exclusion rules, the current process of residential segregation can only be fully understood by looking at the combined effect of race and income.

1.1 Thesis Outline

This thesis consists of two parts. Part I presents a review of literature on the phenomenon of urban segregation and the measurement and modelling of urban residential segregation.

The problem of persistent residential segregation presented, with particular focus on the South African context and more specifically the city of Cape Town. Part II presents the measurement and modelling of residential segregation in the study area of Cape Town and the methodology that was applied to undertake these measurement and modelling exercises.

1.1.1 Part I

Chapter 2 presents an introduction to the concept of segregation and the problem of persistent residential segregation in the urban environment. The occurrence of persistent segregation is then discussed in the context of the South African city and Cape Town, more specifically. The evolution of urban segregation in Cape Town and an overview of its contemporary urban form is presented with the intention of establishing the context in which the problem of persistent segregation in Cape Town has been studied as subject of this thesis.

A theoretical overview is provided in Chapter 3 of the measurement of segregation for enhancing the understanding of segregation patterns and trends. The chapter focusses on the development and advancement of methodologies for measuring segregation in a spatial manner.

Urban segregation is discussed from a complexity theory perspective in Chapter 4, introducing the complex nature of the phenomenon of persistent segregation. It presents a review of literature of the dynamic modelling of segregation and the methodology of agent-based modelling for studying the complexity of segregation. A conceptual overview is provided of agent-based modelling architecture and a methodological approach for model evaluation and implementation.

Chapter 5 presents the methodology applied in this thesis to firstly measure segregation in the study area of Cape Town and secondly model the dynamics of racial and socio-economic segregation in Cape Town. A discussion is included on the geographic context of the study and the spatial (geographic) and numerical (census) data that was applied in both the segregation measurement and modelling methodologies.

1.1.2 Part II

Chapter 6 presents the application of spatial segregation indices to measure three types of segregation in the study area of Cape Town: racial segregation, socio-economic segregation and socio-economic segregation by racial group.

The conceptual framework of an exploratory simulation model for Cape Town is introduced in Chapter 7. This is followed by the rationale and objectives of the three components to the model: the racial preference component, the income constraint component and the combined income-by-race component. Consequently, the development of the architecture and implementation framework of the model is presented for simulating household behaviour.

The evaluation that was undertaken to ensure accuracy of the model and that confidence is enhanced in both the development and functionality of the model is presented in Chapter 8. Model evaluation is undertaken through model verification and sensitivity analysis to establish the influence of the different parameters on the behaviour and output of the model.

Chapter 9 presents the empirical application of the simulation model, which was developed from the specifications of the conceptual framework introduced in Chapter 7 and includes a simulation exercise for each of the three components of the model. The aim of these simulation exercises is two-fold: to test some of the assumptions presented on persistent segregation in Cape Town and to serve as illustration of the potential of the model to explore various theories in terms of residential segregation relating to racial preference and income constraint in Cape Town.

The thesis is concluded in Chapter 10, providing a discussion of the contributions made by the research and the accomplishments of the objectives. This is followed by a discussion of the limitations of the study and suggestions on the future development of this research project.

PART 1

Urban Segregation and the City of Cape Town

Chapter 2
Urban Segregation and the South African City

The phenomenon of urban segregation is inherently a feature of the city and consequently a subject of study for almost a century. Initial studies of segregation as an urban problem can be traced back to the Chicago School of Sociology in the 1920's, with Park (1926) envisaging stages of immigrant settlement in a city (Vaughan and Arbaci, 2011). Although segregation in the urban context is broadly defined as the residential separation or organisation of population groups into various neighbourhoods (Kawachi and Berkman, 2003), the ambiguous understanding is cultivated of urban segregation as a problem in physical space only. Segregation is thus better defined as the occurrence whereby different groups of individuals are spatially separated from each other or isolated from different social groups in the urban environment (Feitosa, 2010).

White (1983, p. 1009) emphasised the necessity of understanding the meaning of segregation as either "sociological" (absence of interaction between social groups) or "geographic" (irregular distribution of social groups across physical space). It was noted that although a correlation might exist between sociological and geographic segregation, the occurrence of one type does not necessarily mean the presence of the other (ibid:1983). The drivers of segregation may also differ in nature and manifest varying consequences, related to the form and composition of a specific city and its historical and cultural context (Greenstein et al., 2000; Feitosa, 2010). Hence, it remains a challenge to quantify urban segregation and the socio-economic and spatial impact of urban segregation has been studied and debated for decades (e.g. Massey et al., 1987; Massey, 1990; Acevedo-Garcia and Lochner, 2003; Bayón and Saraví, 2013).

There is little consensus about the positive or negative consequences of ethnic (Clapham et al., 2012) and socio-economic (Klaesson and Öner, 2020) segregation. Authors have claimed that ethnic segregation is not inevitably a negative phenomenon and that the residents of ethnic concentrations may experience positive effects from the concentration of 'ethnic capital' and the promotion of ethnic entrepreneurship (Portes and Zhou, 1992; Portes and

Sensenbrenner, 1993; Borjas, 1998; Edin et al., 2003; Kloosterman and Rath, 2003; Cutler et al., 2008). However, this argument is contested as the physical separation of communities has frequently resulted in the social and economic exclusion of some population groups, which may inevitably lead to poverty and underdevelopment in the case of economic segregation (Feitosa et al., 2012).

Following on from the discussion above, the objective of this chapter is to introduce the issue of segregation and expand on the subject through discussion of segregation in the South African context and Cape Town, more specifically. In Section 2.1 the problem of segregation and some of the predominant issues relating to its occurrence is introduced by means of a discussion on causes and outcomes of segregation. This is followed by a contextualisation in Section 2.2 of racial and socio-economic segregation in the South African city and the attempts to address the problem (Section 2.3). Section 2.4 presents a discussion on segregation in the city of Cape Town and is accompanied by a presentation in Section 2.5 of studies which identified and analysed spatial segregation patterns in Cape Town.

2.1 The Problem of Segregation

The occurrence of residential segregation as an international phenomenon has been well documented (Sawhill, 1988; Van Grunsven, 1992; Paris, 1994; Telles, 1995; Turok, 2001; Pieterse, 2009; Nightingale, 2012; Musterd, 2020). General consensus exists among these authors that various factors, such as cultural, racial and religious differences or lifestyle choice not only cause residential segregation, but also serve to perpetuate it. Although the occurrence of segregation is often inadequately categorised merely as either forced or voluntary (Donaldson and Kotze, 2006), segregation is more complex and forced and voluntary segregation are argued to be predominantly interconnected (Reardon and Bischoff, 2011).

The most prominent form of forced segregation is caused by the overtly discriminating institutional forces of government policies and land use regulations, reinforcing racial and socio-economic residential exclusion (Beinart et al., 2013; van Ham and Manley, 2015; Henderson, 2017). The most extreme example remains the government-sanctioned separation of racial groups through the forced removal of non-Whites to residential locations disconnected from the White population by the apartheid regime in South Africa (Seekings and Nattrass, 2005; Beinart et al., 2013; Dubow, 2014). However, the persistence of inequality in the post-apartheid city is not only a consequence of separation of racial groups in the apartheid city, but also the subsequent socio-economic disparity between these groups. Pieterse (2004) pointed out that the physical separation of racial groups in the apartheid city resulted in a fragmented form, which in turn formed a foundation for the persistence of socio-economic segregation.

Socio-economic disparity in the urban residential environment is further enhanced by inequality in the labour market, resulting from low-skilled workers in segregated neighbourhoods being isolated from job opportunities (McDonald, 2008; Turok and Parnell, 2009; Emmenegger, 2012; Crankshaw, 2014). Economic inequality also affects the stability of neighbourhoods (Mare and Bruch, 2003) and the fact that spatial concentration of the urban poor frequently presents negative impacts on the wellbeing of the wider city and its inhabitants is globally advocated (Massey et al., 1987; Parnell, 1988; Sabatini et al., 2001; Turok and Watson, 2001; Pieterse, 2006; Sabatini, 2006). Feitosa (2010) argues that the occurrence of academic and policy debates on developing countries are increasing due to the negative consequences of poverty for urban residents and the inability of cities to promote socio-economic development.

Segregation is similarly driven in a more subtle manner through discrimination against urban residents with an economic or social disadvantage, either through economic restriction or the stereotyping of specific neighbourhoods (Bobo and Zubrinsky, 1996; Charles, 2003). The absence of affordable housing and social interaction thus result in the perpetuation of residential segregation. Socio-economic inequality may also persist through the subtle forces of estate markets and financial institutions marginalising the lower income inhabitants of the city (Donaldson and Kotze, 2006; Greenstein et al., 2000; Nightingale, 2012), which is evident in the privatisation of residential space through the development of gated communities (Lemanski, 2006b; Morgan, 2013).

Although voluntary segregation can entail the unprejudiced choice of certain people to live with their own kind, it can also mean that certain groups of people choose to live secluded from other groups. The dramatic increase in gated communities globally provides the most significant example (Lemanski, 2004; Polanska, 2010; Borsdorf et al., 2016; Bruinsma and Johnson, 2018). Various motivations exist for this emerging trend, such as the perception of guaranteed safety and security (Low, 2001; Lemanski, 2004; Bruinsma and Johnson, 2018) and a better lifestyle (Roitman, 2010) offered by such a privatised enclave. These perceptions are also stimulated through the marketing of real estate in such developments as natural, spacious and tranquil habitats away from the chaos of the city. Consequently, the demand is high and met by private developers who find these ventures highly profitable (Greenstein et al., 2000).

The occurrence of voluntary segregation where individuals of a certain group choose to live with each other rather than segregated from other groups is especially evident in the concentrated communities of cultural groups in large cities, such as the Jewish population in London (Donaldson and Kotze, 2006) and indirectly preserve social segregation (Clark, 1991; Clark and Ledwith, 2007; Schelling, 1969). Sabatini (2006) argues that although residential segregation can be negative, the development of such ethnic enclaves can be positive for preserving the culture of minority groups and in doing so enrich the cosmopolitan nature of the city. The author supported this view by highlighting the study of Qadeer (2005) on the importance of ethnic enclaves in Toronto's metropolitan area and how these clusters promote strong community organisations and social capital. These views were shared by Feitosa (2010), who stated that voluntary segregation in this manner is understandable rather than unfavourable.

Johnston et al. (2015) makes a strong case that 'segregation matters' and it is thus essential to consider the outcome of segregation. Although segregation may be seen as beneficial for some groups, a strong argument prevails that the outcome of segregation is predominantly negative. Williams and Collins (2001) suggested that a primary outcome of segregation is the differences in socio-economic status of racial groups, which in turn determines access to education and employment opportunities. The authors pointed out that residential segregation resulted in significantly segregated elementary and high schools in the United States and is a major cause of racial disparities in quality of education (Williams and Collins, 2001).

A further outcome of segregation and related residential isolation is the restriction to employment opportunities and consequently income levels, as was found with African Americans in the United States (Ahmed et al., 2007). For example, the White population in predominantly White neighbourhoods in Milwaukee, Wisconsin in the United States reflected a higher level of education and income levels, thank African Americans and Hispanics residing in their respective neighbourhoods (French, 2015).

The concentration of poverty and lack of access to education and employment opportunities, as a result of racial residential segregation, is also accompanied by health disparities and limited access to medical care (White and Borrell, 2011). Health outcomes of ethnic residential segregation have been explored by various studies, such as the spread of infectious diseases such as tuberculosis (Acevedo-Garcia, 2000), the effect segregation has on weight status in adults (Chang, 2006) and poor mental health as a result of anxiety and depression (Lee, 2009). Contributors to disparities in the use of healthcare are often found to be racial and ethnic differences in health insurance status, education and income (Gaskin et al., 2012).

The high rate of crime experienced by segregated communities, which is detrimental to their physical and social well-being (Krivo et al., 2009), is another result of segregation and ultimately a consequence of poverty. Light and Thomas (2019) applied a combination of race-specific homicide, socio-economic and demographic data for 103 US metropolitan areas between 1970 and 2010 to study consequences of segregation that cause criminal behaviour. The authors found that racial segregation not only increases the risk of homicide among Black communities and decreases this risk among Whites, but also that a decline in racial segregation since 1970 resulted in a decrease in the homicide gap between Blacks and Whites (Light and Thomas, 2019).

2.2 Segregation in South Africa

The phenomenon of segregation in the South African city has been studied for more than six decades. Van Schoor (1951) was one of the first researchers to publish work on the origin and development of segregation in South Africa, dating back to Dutch occupation of the Cape in the 17th century. The author contributed significantly to research in the areas of lack of non-White land ownership, racial discrimination and prejudice through labour. Perhaps the most significant contribution was the realisation that the country's history and related path dependence needs to be understood to strive for unity and consequently the abolishment of persistent oppression of certain population and income groups.

In order to formulate a better understanding of the entrenched nature of segregation in South Africa, it is important to recognise the initial processes of urban segregation by race in the South African city and how this evolved over time to manifest disparity not only by race, but also socio-economically. The classification of the country's population by race played a significant role in the formulation of policies and mechanisms that were specific to these racial groups and would perpetuate inequality for decades to come. It is thus essential to commence the discussion of persistent segregation in South Africa by defining these racial groups.

2.2.1 The Classification of Race

The overtly racist approach of classifying the population of South Africa by race has defined the citizenship and social status of the population since 1657, when this classification was first made by the colonial authorities as part of enumerating the inhabitants of the colonies (Sáenz et al., 2015). When considering the subjects of race and socio-economic class in South Africa, a strong relationship manifested between the allocation of economic opportunities and resources and the "boundaries marking perceived social, cultural and physical difference" (Binns et al., 2000, p. 3). Racial classification thus played a pivotal role in the way political and economic rights were defined by the State (Zuberi and Khalfani, 1999). For example, only White citizens had the political power to vote, enjoyed state security and had access to the most preferable and skilled employment opportunities. The initial classification was that of 'Black', 'White' and 'Coloured', with 'Indian or Asians' added at a later stage and as a separate category.

The Black African population of South Africa forms the majority of the country's total population. Although this population group is classified as Black or African in general, there are linguistic and cultural differences. The Black African population is officially divided into ten ethnic groups (Smith, 1992), such as the Sotho, Zulu and Xhosa groups for example.

South Africa's Coloured population is a predominantly mixed race group concentrated in the Cape region and originated from a combination of various ethnic backgrounds, including Black, White, Khoisan, Griqua, Chinese and Malay (Buchanan and Hurwitz, 1950). Khoisan is a term devised as compound description of the Khoikhoi (nomadic pastoral agricultural tribe, also named Hottentots by the Dutch) and the San (hunter-gatherers, also named Bushmen by Europeans) tribes (Elphick and Giliomee, 1979). The Griquas are culturally and racially mixed and descended from intermarriages and relationships between the European inhabitants of the Cape Colony and the Khoi living there (Ross, 1976).

Being of European descent, the White population of South Africa is predominantly of Dutch, German, French and English heritage (Keegan, 1997). The 'Indian or Asian' population of South Africa are descendants of the indigenous people from Asia and especially the cities of Madras and Calcutta (Thompson, 2014) on the Indian sub-continent (Christopher, 2005a).

Although the parliament of the post-apartheid South African government repealed the Population Registration Act in 1991 (Republic of South Africa, 1991), it's racial categorisation remained in surveys and censuses as means to measure the eradication of apartheid's legacy and yet it reinforces this legacy. Hence, the most recent South African census of 2011 still reflects the population classification of Black African, Coloured, Indian or Asian and White (Statistics South Africa, 2012).

When the subject of segregation is considered in the South African context, apartheid is often presented as origin to the narrative. Alternatively, it is argued that the 'segregation' policy at the beginning of the twentieth century was the precursor and framework to which apartheid was developed (Dubow, 1989). However, the first manifestation of residential segregationist practices in the country dates back to the Dutch colonial settlement in the Cape in 1652 (Christopher, 1989a; Guelke, 1989; Beinart et al., 2013).

What the segregation and apartheid phases do provide is clear evidence of the persistence of segregation ever since the colonial era. The colonial, segregation and apartheid phases were significant in terms of urban development policy and were highlighted as the initiation of the driving forces of persistent racial and economic segregation in South Africa (Davies, 1981). It is therefore important to historically contextualise, in light of the three mentioned phases, the development of both racial and socio-economic segregation in the country.

2.2.2 Colonial Era

The colonial period spanned from the arrival of the first European settlers in the Cape in 1652, until the early years after the Act of Union was signed in 1910 (Davies, 1981; Lemon, 1991). Even though it is claimed that the Dutch East India Company aimed to establish a location for shipping supplies and not a town at the southern tip of Africa (Cook, 1991), the small settlement in the Cape expanded as the population of Dutch settlers increased. British rule of the Cape Colony (also known as the Cape of Good Hope) commenced in 1806, with British occupation of the Colony of Natal following in 1843 (Davies, 1981). The Dutch farmers (later known as Boers) fled British colonialism and established the independent republics of the Transvaal and Orange Free State to the north of South Africa (ibid:1981). These republics also became British colonies in 1902 (see Figure 2.1).

Figure 2.1: Map of Four British Colonies in South Africa in 1902 (Htonl, 2011)

The four colonial administrations reflected varying and divergent policies for the enforcement of segregation between the White colonialists and the other racial groups in the country (Christopher, 1990). Two predominant trends of legislation promoting racial disparity were highlighted: regulations applicable to the indigenous Black African population of all four colonies and regulations affecting the people of mixed race origin and Asian migrants and applicable to the three colonies outside of the Cape of Good Hope (Christopher, 1988). The following provides a brief overview of segregationist approaches to the racial groups of each of the four colonies:

In studying the level of segregation between racial groups in South Africa (1911-1985), Christopher (1992) came to the conclusion that the legacy of colonial segregation practices has persisted and is reflected in higher levels of early 20th century urban segregation in South Africa. The varying segregation policies of the four colonies resulted in different levels of segregation between them, as different racial groups were effectively treated and restricted differently. Nonetheless, the White population controlled social and economic relations in society through racial segregation, such as the prohibition of trade by the Indian population in Natal (Lemon, 1990). This control included the appropriation of land, prohibition of non-White property ownership and restriction of access to economic opportunities (Davies, 1981), which resulted in the development of income disparity between the White and disenfranchised racial groups in the colonial era.

2.2.3 Segregation Era

The union of the four colonies in 1910 consolidated the White population's power over the state, but also resulted in the strengthening of control over the Black population (Thompson, 2014). Such control was systematically enforced through segregationist legislation and commenced with the implementation of the Native Land Act of 1913 (Union of South Africa, 1913), which became known as the "cornerstone of territorial segregation" (Beinart et al., 2013). The main objective was supposedly to maintain the 'balance' in land occupation and ownership between the Europeans (Whites) and Natives (Black Africans) (Evans, 2015). However, this balance is disputed, given the fact that this act allocated only 7% of the total land in South Africa to the Black African population and also prohibited them from owning land outside of these designated areas (Hall, 2014).

Racial segregation in the urban environment intensified with the establishment of the Natives (Urban Areas) Act of 1923 (Union of South Africa, 1923). This legislation required that local urban authorities establish Black African residential areas at the urban periphery, control population influx to these areas and also to control the movement of Black Africans into the urban areas by means of a pass law (Harrison, 1992). Forcing Black Africans to carry a 'pass' document (see Figure 2.2), which stipulates where they are allowed to move meant that they were restricted to where they could work, which was "underpinning a system of cheap labour" (Shear, 2013, p. 207) and progressing income inequality.

Figure 2.2: Black African Pass Inspection (South African History Online, 2019a)

This legislation was only aimed at controlling Black settlements and control over the Coloured and Indian settlements was still differing between cities (Saff, 1998). However, the Asiatics Land Tenure and Indian Preservation Act of 1946 (Union of South Africa, 1946) resulted in the restriction of Indian integration into White settlements. The Indian communities were significantly affected economically as a result of their trade and employment opportunities being limited (Maharaj, 2014). As if positioned in the shadow of the notorious Group Areas Act to come, limited research expanded on the economic implications of the act of 1946, apart from highlighting that Asian ownership and occupation of land was restricted to areas segregated from the urban environment (Christopher, 1992). Although no legal controls existed over the Coloured population in the segregation era (Davies, 1981), these communities were still subject to hostile discrimination in the housing market in this era (Christopher, 2001a).

In contrast, the White population flourished economically during the segregation era. Firstly, it is evident from the discussion in this section that land appropriation allowed for the designation of prime land to White owners. Secondly, the restriction of non-White racial groups to specific residential areas established concentrated sources of cheap labour and control over the movement of those population groups. Further economic advantage was maintained by the White government by restricting the trade opportunities of other racial groups, especially the commercial threat the Indian communities posed (Maharaj, 2014).

2.2.4 Apartheid Era

In 1948 the notorious system of apartheid was established whereby racial segregation in the country was most aggressively enforced through legislation (Christie and Collins, 1982). Apartheid planning approached city form as a structure for social and spatial control (Davies, 1981). The architects of apartheid suggested it would be a system to promote equal development (Asmal et al., 1997), but development between racial groups were extremely unequal. The apartheid era was effectively a continuation of the segregation era, perpetuating racial separation and economic disparity (Maylam, 1995). What made apartheid unique was not only the fact that it was introduced and maintained by a minority group and at a time when the world was abolishing racist policies after the Second World War (South African History Online, 2019b). It also comprised of a range of legislative strategies that controlled every aspect of the lives of non-White citizens, from education and employment to health services, transport and social interaction (Beinart et al., 2013).

The first significant law of the apartheid era was the Population Registration Act of 1950 (Union of South Africa, 1950a), which established the compulsory racial classification of South Africa's population and introduced identity cards specifying an individual's race. Individuals were often classified only by appearance, resulting in families being separated when members were classified into different races (Goldin, 1987). This occurrence was further exacerbated by the prohibition of inter-racial relationships (Dubois and Muller, 2017).

The subsequent and notorious Group Areas Act of 1950 (Union of South Africa, 1950b) was extensive legislation assigning and forcefully moving racial groups to designated 'group areas' (racial zones) in the urban environment and controlling their interaction (Clark and Worger, 2016). Figure 2.3 provides an example of measures that were taken to stipulate that certain areas are only accessible to White people during that period. The designated group areas the racial groups were forcefully removed to were also separated by buffer zones such as railway lines and open land in the interest of minimising interaction and entrenching racial hierarchies by allocating preferential urban space to reflect the socio-political importance of the White population (Lemon, 1991; Musterd, 2020).

Figure 2.3: Enforcement of Racially Designated Areas (Getty Images, n.d.)

The Group Areas Act was also the first official legislation to address the Coloured and Indian population and apart from forcefully relocating them to separate designated areas, separate amenities were established between them and the Black African communities (see Figure 2.4). Lester (1998) argued that the Coloured and Indian communities were in fact most affected by the Group Areas Act, as Black African segregation mostly occurred in the segregation (pre-apartheid) era.

Figure 2.4: Prohibited Use of Public Facilities by Certain Racial Groups (UWC Robben Island Mayibuye Archives, n.d.)

The continuity and direct relation between the three phases (colonial, segregation and apartheid) had a profound effect on the formation of the South African city and governmental restriction of racial mixing was “the essence of the apartheid policy” (Giliomee and Schlemmer, 1989, p. 87). It is thus argued that the subject of residential segregation, dominating work on South African urban policy, was only one dimension of the government’s aspiration of total control over lower-class urban Black Africans (Maylam, 1995). This review of urban segregation research reflects the complexity of a number of segregationist mechanisms employed over decades, which will have a lasting effect on both the form of the post-apartheid South African city and the persistence of racial and income disparity.

2.2.5 The Outcome of Segregation in the South African City

Similar to segregation in the United States, the outcome of segregation in South Africa had a far-reaching effect, in terms of education, employment and health. A major provision of the apartheid regime’s Bantu Education Act of 1953 (Union of South Africa, 1953) was the enforcement of racially-separated educational institutions and facilities. Hence, the requirement of Black African students to attend their nearest schools was directly related to racial segregationist practices, rather than geographic location. Like African American schools in the United States (Franklin, 2004), limited funding to non-White schools resulted in overcrowded classrooms and also affected the quality of teachers and learning materials (Jansen, 1990). The most extreme segregationist practice in Black African education was a 1974 decree that forced all Black African schools to use both Afrikaans and English as language mediums of instruction, with the former being the language of the architects of apartheid (Mhlauli et al., 2015).

Segregation in the South African city also had a multi-faceted effect on employment. Firstly, Black African communities experience physical access to employment opportunities to be challenging, as a result of being forcefully removed to remote residential locations by segregationist regimes, and long journeys and expensive commuting fees are common (Rospabe and Selod, 2006). This is a result of these communities being forcefully moved by the segregationist regimes to the least desirable locations furthest from the city centres. In contrast, the most segregated cities in the United States, such as Chicago and Detroit, reflect African American neighbourhoods relatively close to the city centres. Focussing on Cape Town, the authors pointed out that this “physical disconnection or spatial mismatch” does not affect all population groups equally and that the White and Indian/Asian population reside close to employment locations, with Coloured and Black African communities much further away (Rospabe and Selod, 2006, p. 269). The poor quality of education of Black Africans and their restriction to low skilled jobs also resulted in much lower wage earnings than the White population or even the Coloured and Indian/Asian population (Burger and Jafta, 2006).

Since colonization and persistent socio-economic restrictions, discrimination in health care supply was experienced (Charasse-Pouélé and Fournier, 2006). Brauns and Stanton (2016) emphasized that racism and prejudice manifested itself in every aspect of health in apartheid South Africa. This included strict segregation of health care facilities, severe underspending on Black African health care (resulting in overcrowded and unhygienic facilities), a disregard by public health policies of diseases that affect Black African people primarily and also the denial of basic services to Black African communities, such as clean water and sanitation. Similarly, the role residential segregation may play in the epidemiology of tuberculosis (TB) in the United States was studied as a significant issue, given the fact that a concentration of TB cases is evident among ethnic minorities (Acevedo-Garcia, 2000).

Although the focus throughout Section 2.2 is predominantly on the subject of racial legislation and related spatial segregation in the urban environment, it is acknowledged that a deeper understanding of racial residential segregation in the South African city would be acquired through further exploration of urban development forces and principles which established it, as suggested by Parnell and Mabin (1995). The authors highlight two interrelated themes for consideration: Firstly, the creation of local government in the early twentieth century and the contribution of urban administration in shaping urban society deserves consideration. In the attempt of improving health and water supply and reducing fire risk, urban officials formulated the ill-conceived methodologies of defining different groups in the South African urban population and attempted to segregate them, more for the purpose of simplifying administrative undertakings. Secondly, the influence of modernism as framework for urban management and intervention needs to be understood. Parnell and Mabin (1995) examines how modernist urban planners influenced the shaping of the racially segregated South African city and argue that modernist thinking and planning "lent itself to apartheid" (Parnell and Mabin, 1995, p. 55).

2.3 The Integrated South African City Agenda

With the gradual collapse of Apartheid in the 1980s, its termination in 1994 and the transition of South Africa to a democratic country in 1994, South African urban research focussed predominantly on the anticipated post-apartheid city and the potential decrease in persistent racial and socio-economic segregation. Studies included the examination of residential segregation and potential integration in the post-apartheid South Africa (Hart, 1989; Smith, 1992), the critical analysis of the apartheid city and propositions for assisting the transition period (Swilling and Humphries, 1992) and also the assessment of the impact of apartheid what obstacles it might hold for establishing the post-apartheid city (Smith, 1992). General consensus was that the transition from the segregated apartheid city to an integrated post-apartheid city would pose a tremendous challenge to the new democratic government (Smith, 1992; Harrison et al., 2003; Christopher, 2005a; Harrison et al., 2008).

This section considers the initiatives that were undertaken by the South African government to address the legacy of apartheid in the South African city and provides an assessment of the effectiveness of these programmes.

2.3.1 Post-Apartheid Planning

In 1994, Nelson Mandela became the first president of the new democratic country, but inherited a deeply divided nation with a weak economy (Dubois and Muller, 2017). As seen in the previous section, apartheid city management was characterised by a "complex process of functional inclusion, spatial separation and political exclusion" (Swilling et al., 1991, p. 175). In addition, the official repeal of segregationist legislation, resulted in a dramatic increase in urbanisation and consequently growing informal settlements and urban poverty. Turok (2012) estimated that 53% of the population was urbanised by 1996 and figures from Statistics South Africa (2006) showed that 2.9 million Black Africans migrated between 1992 and 1996, with the likelihood of this migration being predominantly to urban areas (Palmer et al., 2017).

The effectiveness of the post-1994 state would thus depend on how it challenges racial control systems and overcomes structural inequality (Palmer et al., 2017). With the main aim of eradicating apartheid's spatial planning legacy (Musterd, 2020) the government formulated urban planning policies with the intention to promote socio-economic inclusion and establish integrated residential development (Parnell and Pieterse, 1999). Consequently, the years following 1994 witnessed significant legislative change, focussing on most aspects of society.

With the implementation of the Reconstruction and Development Programme (RDP) in 1994 (African National Congress, 1994) the government's focus was on addressing inequalities and inefficiency in the urban environment and to develop democratic, non-racial and more sustainable cities. The RDP was intended as an encompassing policy for social and economic transformation to resolve urban and rural poverty and also segregation through the redistribution of resources to finance public service provision (Turok, 1995). At a urban level, this intention reflected the aspiration for a more compact and higher density urban environment with mixed land use and an integrated transport system (Todes, 2006).

However, Watson (2002, p. 72) pointed out that the popularity of the RDP was "short lived", despite general consensus on the programme. Problematic implementation was the main reason, due to a lack of capacity in drafting the business plans of the programme, related policies being incoherent (Rapoo, 1996) and opposing ideologies of agencies such as the World Bank and Development Bank of South Africa (Marais, 1998). Nonetheless, the RDP identified the requirement for new legislation for development planning, resulting in the formulation of two significant post-apartheid pieces of local government legislation.

Firstly, the Development Facilitation Act (DFA) of 1995 (Republic of South Africa, 1995) was implemented in an attempt to accelerate land development projects. However, it bypassed municipal decision-making on urban planning projects and thus partially reflected a "statement of mistrust" (Duminy et al., 2020, p. 43) in local government capability to implement suitable urban development procedures. Secondly, the Local Government Transition Amendment Act of 1996 (Republic of South Africa, 1996a) required municipalities to develop integrated development plans (IDPs) to strategize integrated urban development (Watson, 2002). The IDP is still an essential procedure for local government to promote public participation in social and economic development (Harrison, 2006). However, Duminy et al. (2020) makes a valid point in suggesting that the IDP tends to be approached by municipalities as compliance procedure, rather than an effective tool for integrated development. This is evident in the way IDPs differ in quality between municipalities, with some reflecting only the minimum content required.

The emphasis on economic growth replaced the focus on redistribution with the government development agenda moving away from the RDP and adopting the Growth, Employment and Redistribution (GEAR) strategy (Republic of South Africa, 1996b). GEAR intended to encourage rapid economic growth and employment and also address poverty and income inequality through private sector investment and easing trade barriers. However, the country "embraced wholehearted integration into the neoliberal global economic system" through trade reform and tariff reductions (Pieterse, 2009, p. 1). In addition, intrinsic contradictions were noted between the social democratic architecture of the RDP and the neo-liberal macro-economic GEAR strategy that replaced it (Pillay et al., 2006). The aspiration of growth through distribution was heavily contested from the start by neoliberal business views and privatisation endeavours (Marais, 1998). Because of these conflicting development policy agendas on socio-economic integration, integrated planning at both a national and urban scale was very difficult to achieve (Watson, 2002).

The establishment of the Urban Development Framework of 1997 (Republic of South Africa, 1997) was the first attempt of a policy that is concerned explicitly with urban issues, such as residential segregation (Republic of South Africa, 1997). It predominantly focussed on the advantages of urban areas for social and economic development and specified an ambitious vision of urban settlements that are "spatially and socio-economically integrated, free of racial and gender discrimination and segregation" (Republic of South Africa, 1997, p. 7). The UDF also stipulated that overcoming the entrenched patterns of the apartheid city is a "central prerequisite for meeting these challenges" of urban integration and efficient infrastructure maintenance (Republic of South Africa, 1997, p. 11). However, the UDF failed due to insufficient coordination between government spheres, weak spatial planning mechanisms to promote spatial change (Pieterse, 2003) and lack of clear direction for implementation (Harrison et al., 2008).

Despite the promotion of the so-called integrated urban agenda, specific goals and strategies to achieve these goals were absent, resulting in the plethora of policies not being complimented by specific action (Watson, 2003a; Duminy et al., 2020). It was argued that a variety of legislation existed at the urban level, but the potential for coherent urban transformation was restricted by the absence of an overall urban plan (Lemon, 1998; Williams, 2000). For example, while the UDF promoted more compact spatial development, the 2003 National Spatial Development Perspective (The Presidency, Republic of South Africa, 2003) presented spatial guidelines for public infrastructure investment and the 2009 National Urban Development Framework (NUDF Steering Committee, 2009) aimed at strengthening the capacity of towns and cities to support growth and sustainability.

Most recent planning legislation development witnessed the implementation of the National Development Plan 2030 (NDP) (National Planning Commission, 2012), with the predominant aim of reducing inequality and elimination poverty by 2030. This strategy set goals to address persistent urban-related problems, such as fragmented urban form, spatial segregation and income inequality and also emphasized the inefficiencies of the state housing system, whereby housing delivery occurs away from areas of economic opportunity (Duminy et al., 2020). The NDP also highlighted informal upgrading as key element of a robust, integrated and efficient planning system (National Planning Commission, 2012).

The post-apartheid government also initiated a process of land reform in South Africa to reduce inequality by allowing farm workers to own farms and for previously unemployed individuals to participate in the economic growth of the country (Torstensson, 1994). The three main areas of the land reform process concerns land restitution, land tenure reform and land redistribution (Deininger, 1999). While restitution entails the financial compensation of individuals that were forcefully removed from their land, tenure reform is the process of identifying the right of individuals to own land. Land redistribution is a means of securing land occupation for marginalised communities through the purchasing of land from owners by the government.

However, very few changes in terms of the form and location of settlements have changed in reality, despite this clear shift in policy (Harrison, 2014). The Spatial Planning and Land

Use Management Act (SPLUMA) (South Africa, 2013) only came into operation in 2015, replacing the Development Facilitation Act. The main aim is not only to provide a framework for spatial planning and land use management, but more importantly to rectify the inefficiency of the DFA and direct the functionality of land-use management back to local government.

Apart from physical planning reform, the post-apartheid government implemented affirmative action legislation to promote employment equity in South Africa, especially among marginalised racial groups. Although affirmative action is an international concept and first termed in the United States in 1961 (Anderson, 2004), it was only applied in the late 1990's in South Africa. Two significant pieces of legislation that were established in this regard were the Employment Equity Act of 1998 (South African Government, 1998) and the Broad-based Black Economic Empowerment Act of 2003 (South African Government, 2003), with the latter urging employers by law to employ groups that were previously disenfranchised. The Black Economic Empowerment (BEE) strategy is one of the most significant transformative policies since the end of the apartheid regime and focussed on the promotion of Black individuals into professional positions in the economy (Bhorat et al., 2014). Furthermore, the transfer of economic asset ownership to Black African citizens was also a priority, given the prior restriction of such ownership by the apartheid government.

As the new ruling party in South Africa, the ANC (African National Congress) also developed the National Health Plan for South Africa with the help of the World Health Organisation (WHO) and the United Nations Children's Fund (UNICEF) (African National Congress et al., 1994). The National Health Plan outlined its aspirations for the right to health care for all citizens, especially the vulnerable and poor, and placed the responsibility for providing such health care with the state to ensure a decentralised and democratic health care service at national level (Baker, 2010). However, governmental focus shifted from health care to economic development in 1996 with GEAR, as was the case with the RDP.

2.3.2 Post-Apartheid Segregation in the South African City

Despite the abundance of legislative reform, post-apartheid cities are as "segregated, fragmented and unequal as they were at the dawn of political liberation" (Pieterse, 2004, p. 82). Even though this observation was made prior to more recent changes in urban planning policy, Harrison (2014) shared this view in observing that very little physical change in urban form is visible. It is thus important to understand the drivers of persistent segregation and ultimately the legacies of segregation in the South African city.

Due to the incoherent application of economic strategies that were developed to undo apartheid urban segregation, socio-economic segregation persisted in the South African city. Slow economic development and the failure to reduce income disparities were two of the main factors constraining residential integration (Christopher, 2001b). In the early post-apartheid years, the government's urban land restitution programme (restoring property rights to individuals who lost it under apartheid legislation) was delayed and residential integration was left to market forces, with sporadic incidents of land invasion (ibid:2001c). Consequently, the majority of the very poor Black African population was unable to acquire properties in White residential areas.

Various shortcomings of the land reform programme and related constraints was also identified by Hall (2004a). Not only was progress slow regarding the redistribution of commercial agricultural land by 2015, but restitution also had minimum impact on land ownership patterns, given the fact that most rural claims have not been settled and the majority of urban land claims have been settled through cash compensation. Law enforcement for the protection of farm occupants' rights proved to be inefficient and no proactive procedure was in place for the provision of land ownership to farm dwellers. Land reform budgets and grants also proved to be inadequate, compared to the high and escalating price of land. It was argued that although land reform provides an opportunity to rectify the prejudices of apartheid and related racial inequalities, a focus shift in land policy from the rural poor to emerging Black African commercial farmers resulted in a pursuit of limited commercial farmland deracialisation rather than agricultural restructuring (Hall, 2004b).

Strong opposition to land reform is also experienced from large farmers, with a reluctance to integrated poorer neighbouring Black African farms into a farming community that would be more racially integrated (Ntsebeza and Hall, 2007). Lahiff (2007) argued that the market-led agricultural reform concept of 'willing buyer, willing seller' failed, as it only benefits White land owners and a minority of richer Black African entrepreneurs rather than the poor marginalised majority.

Two types of resistance, in terms of property rights, have been highlighted when a planning legislation approach is applied to resolve a legacy of dispossession and spatial segregation (Berrisford, 2011). Firstly, promoting investment in areas that were previously deprived by limiting the application of unused development rights in areas that are better resourced will result in the owners of these rights to claim compensation from the government. Secondly, where land is being developed for low-income housing neighbouring landowners are challenging these developments on the basis that enjoyment of their property will be reduced.

The White minority is not only developing and cultivating land that was acquired through dispossession, but also establishing legal restrictions on Black African land ownership (Zenker, 2014) and access to 'White-only' services. Although indirect, the similar practice of redlining was established in the US whereby mortgage lenders and insurance providers would restrict their services to certain applicants, often based on the racial characteristics of their neighbourhood (Krieger et al., 2020). This strategy was also extended to retail where a practice of spatial discrimination by retailers resulted in specific areas not being served, based on ethnic-minority composition (D'Rozario and Williams, 2005). Berrisford (2011) argued that the establishment of zoning-based planning legislation in the South African context intensified inequality in land ownership, by stipulating land use and development rights that are applicable to White-owned land and thus increasing its monetary value.

Bhorat et al. (2009) studied the changing levels of household income inequality in the first decade of South African democracy (1995-2005) and identified the drivers of these inequality changes. Examined income sources (wages, self-employment, state grants, capital income and private pensions) showed that wage income was the largest contributor to income inequality and was also increasing over time. It was found that this occurrence was directly influenced by the labour market, with highly skilled employees earning high wages and lower or unskilled workers either earning a poor salary or are unemployed. Although all South Africans experienced growth in income, White and Coloured individuals experienced the largest increases in income, with Black Africans and Asians experiencing little change in income for the same period. Income inequality in the urban areas were also significantly higher than in rural South Africa. Bhorat et al. (2009) also highlighted that migration of low-skilled individuals from the rural areas to the cities was a major contributor, with these migrants restricted to either low paying employment or the informal sector.

Similar findings reflected persistent and increased income inequality in South Africa, when the economic, political and social mechanisms were studied as drivers of 'inequality traps' (Pellicer et al., 2011). The inequality trap (Bourguignon et al., 2007) is a situation where a certain group of individuals is constantly disadvantaged with respect to another group. Economically, the labour market was key to understanding persistent segregation in terms of perpetual unemployment and low wages among the poor in South Africa. Politically, inequality may have been driven by the lack of influence the poor population have on policy formulation. Socially, the author highlighted institutionalised racial segregation through apartheid, creating an environment for persistent racial inequality. Pellicer et al. (2011) argued that the social mechanism for exclusion in the South African context was not zoning regulations, income barriers or the housing market, but rather a system of racial segregation that kept Black Africans (predominantly) from good residential areas.

The labour market in South Africa was also discovered to be "largely stratified by race" (Gradin, 2018, p. 555) as part of the legacy of both colonialism and apartheid, with access to employment being the predominant source of racial inequality. The high rate of urbanisation after apartheid resulted in escalating unemployment levels, among Black Africans especially, with an economy not geared towards the employment of lower skilled individuals (Kingdon and Knight, 2007). Tangri and Southall (2008, p. 699) highlighted that the South African government provoked controversy around BEE through the cautious manner in which it was implemented, due to the fact that it predominantly benefited "politically-connected individuals" rather than the disadvantaged majority and also because the White minority still dominated the corporate sector. The BEE process was not only criticised by Black African businesses for the slow pace at which White domination of the corporate sector was reduced, but also by labour for the enrichment of a some senior ANC members (Tangri and Southall, 2008).

The issue of racial inequality in the labour market is further perpetuated through the distribution of jobs and the previous regime withholding skilled or semi-skilled employment from Black Africans. A certain level of desegregation in this regard is occurring (Mariotti, 2012), although this was prompted by a shortage of White employees resulting from further upskilling of Whites. Physical access to employment opportunities is persistently restricted for a majority of the non-White labour force of South Africa, given the removal of non-White groups to the urban periphery during apartheid (Rospabe and Selod, 2006).

In turn, the issue of limited access to employment as a result of occupational distribution is mainly influenced by educational disparity, as outlines in Section 2.2.5. Hoogeveen and Ozler (2005) observed that the earning return on education only increased for Black Africans with higher levels of education, but inequality is still increasing due to the small increase in educational grants for Black Africans. Gradín (2013) concurred by finding that the only decrease in income inequality is found where Black African individuals with better education and higher skilled occupations are reducing the inequality gap, especially due to the fact that Black Africans were most restricted to proper education and better employment opportunities (Gradín, 2013). The Coloured and Indian/Asian communities should not be overlooked. Although their standards of education were better than those of the Black African community, it still fell short of the much higher standards of White education (Salisbury, 2016).

Spaull (2015) pointed out that the legacy of apartheid and related correlation between education and wealth not only meant that poorer students perform worse, but also that White schools continuously progress well and Black African schools remain dysfunctional. Consequently, the poor quality of education that these students receive “helps drive an intergenerational cycle of poverty where children inherit the social standing of their parents or caregivers, irrespective of their own abilities or effort” (Spaull, 2015, p. 34). Burger and Jafta (2006) argued that the persistent difference in quality of education will ensure that the legacy of apartheid remains a significant influence on labour market outcomes. This is evident in the racial gaps in the labour market - a result of the difference in attained education (van der Berg, 2007).

Affordable housing provision has the potential to serve as a tool of integration and addressing the inadequate spatial layout of the South African city (Gunter and Manuel, 2020). However, housing policy in South Africa moved its focus from housing delivery to eradicating informal settlements by 2014. By blaming illegal foreign immigration for the growth of informal settlements attention has been diverted from the internal dynamics that are perpetuating and increasing urban disparity (Huchzermeyer, 2005). Racial segregation is also propagated through the provision of low-cost housing predominantly on the periphery of the city and often where non-White groups were forcefully removed to in the apartheid era (Hamann and Horn, 2015; Malala, 2019).

The occurrence of desegregation in the South African city in the 1990's reflected specific trends and characteristics that were highlighted by various studies (e.g. Beavon, 1998; Kotze and Donaldson, 1998; Horn, 2002; Prinsloo and Cloete, 2002; Saff, 1994, 2002; Hamann and Horn, 2015). However, segregation was perpetuated through these developments. Inner-city desegregation progressed noticeably faster than within the predominantly White suburbs. This may be due to the availability of affordable tenure (Lemon and Clifford, 2005; Graham, 2007). Saff (1994) noted that these new inner-city residents were predominantly the younger and upwardly mobile Black Africans, preferring these areas rather than predominantly White suburbs. However, it was argued that in newly formed ghettos formed in the inner urban areas with the White population subsequently moving away to more affluent urban fringe developments (Jurgens et al., 2003; Christopher, 2005a). Prinsloo and Cloete (2002) found that Black African home buyers prefer residential neighbourhoods closer to or in the same areas as existing Black African settlements, which in turn promotes monoracial neighbourhoods

Even though progress has been made to eradicate the legacy of apartheid, it is widely argued that social segregation and exclusion persists (Turok, 2001; Tomlinson et al., 2003; Watson, 2003b; Lemanski, 2006b) and that socio-economic class segregation increased substantially in the post-apartheid city (Saff, 1998; Seekings, 2000; Horn and Ngcobo, 2003). Seekings (2000) highlighted the slow pace at which racial integration occurs, due to the fact that race and socio-economic class intersect extensively but "are no longer coterminous" (2000b, p. 834). The author suggests that this is evident in the decline of interracial inequality, while intra-racial inequality increased as a result of upward mobility enjoyed by many Black Africans, while the majority of the Black African population remains poor.

It is argued that gentrification appeared as an urban process in South Africa in the post-apartheid era, but that these changes in the spatial formation of city centres were viewed as urban regeneration (McDonald and Smith, 2004). This is evident in South African cities adopting the North American concept of Business Improvement Districts (BID), which resulted in the infiltration of neoliberal principles into the context of post-apartheid planning, such as public-private partnerships and entrepreneurialism (Didier et al., 2013). The BID is broadly defined as a specified urban area in which property and business owners fund enhanced security for the particular area through additional taxes or duties (Han et al., 2017; Houstoun, 2003; Steel and Symes, 2005). In this context, with a political shift towards a neoliberal approach to economic development, the focus of urban development in the country moved away from government-led redistribution towards a market-driven approach to transformation, as discussed in Section 2.3.1. Consequently, urban development initiatives, in the contemporary context of neoliberal globalization, underwent extensive transformation in the post-apartheid era.

Similar to other international occurrences, the foundation of wealth and its accumulation for certain groups of society in South Africa have been established not only through racial labour market discrimination, but also capital dispossession (Terreblanche, 2002). Such discrimination and also intergenerational wealth (predominantly transferred through inheritance) enforces the legacy of apartheid segregation and wealth inequality in South African (Chatterjee, 2019). Intergenerational wealth transfer in the US was found to be significant in the accumulation of wealth and potentially more important than life savings (Gale and Scholz, 1994), while the increase of inherited wealth in the UK between 1896 and 2018 was highlighted by Atkinson (2018). In the South African context, the apartheid government supported strategies for capital accumulation such as the concentration of White-owned capital and thus deliberately structuring wealth inequality along racial lines (O'Meara, 1997). In turn, these wealth accumulation strategies formed the foundation of inequalities in health (Coovadia et al., 2009) and education (Chisholm, 2012) and thus perpetuates these disparities.

Numerous problems in the South African healthcare system also enforce the apartheid legacy in which the provision of healthcare was very fragmented and discriminatory between the different racial groups of the country (Baker, 2010). Although the post-apartheid government have set numerous goals to improve the quality of healthcare systems and related service delivery, as discussed in Section 2.3.1, several persistent issues are highlighted by Maphumulo and Bhengu (2019). The unequal distribution of healthcare professionals between the public and private sectors in South Africa results in prolonged waiting times due to a shortage of human resources. A shortage of medicine and medical equipment is also experienced at the healthcare facilities of poorer areas. Furthermore, public healthcare facilities also exhibited poor hygiene, poor infection control measures and poor equipment maintenance (Dunjwa, 2016)

This section has provided an overview of the most essential pieces of legislation that were implemented in the aspiration to eradicate the legacy of the apartheid regime. More importantly, it highlights the inefficiencies and challenges of programmes to successfully promote racial and income integration in the South African city and the legacy that constrains effective propagation of segregation adopted from the past. The following section will focus on the chosen study area of Cape Town and the persistence of segregation in the oldest city in South Africa.

2.4 Persistent Segregation in Cape Town

Further to the discussion in the previous two sections on segregation in the context of South Africa, this section focusses on segregation in the city of Cape Town. Section 2.4.1 discusses the initial occurrence of segregation in Cape Town and its progression to the apartheid era. This is followed by a discussion in Section 2.4.2 of segregation in the post-apartheid era and the legislative efforts undertaken to address the perpetuation of segregation in Cape Town. Finally, contributing factors to segregation in the contemporary city of Cape Town is discussed in Section 2.4.3.

2.4.1 The Foundation of Segregation in Cape Town

Thompson (2014) suggested that many scholars of South African urbanism are of European descent and ethnocentric assumptions are prevalent regarding the non-existence of pre-colonial urban trends and segregation in Cape Town. This is evident in the dispute regarding the high degree of colonial segregation (Bickford-Smith, 1995), when it was argued that colonial Cape Town reflected a racially mixed residential composition and is “unique amongst South African towns in the extent to which it was racially integrated” (Welsh, 1971, p. 174). Similarly, Christopher (1992, p. 567) stated that the Cape Colony pursued a “colour-blind policy related to the qualified franchise” and residential segregation depended mainly on class and wealth, but then mentions that this results in the poor being non-White. Nonetheless, scholars argued that the apartheid era was rooted firmly in a colonial foundation (Maylam, 1995; Robinson, 1996) and that the Cape Colony became a “complex, racially stratified society” within the first decade (Thompson, 2014, p. 33).

Although the segregation era resulted in increased racial discrimination against the Black African population of Cape Town, through relocation to the urban fringe and movement control through pass laws (as discussed in Section 2.2.3), it was only with the apartheid regime that circumstances profoundly changed for all non-White citizens of the city. The differentiation of group areas under the Group Areas Act of 1950 (Union of South Africa, 1950b) ensured that it is illegal for any individual to reside outside of the area that was designated for that person's specific racial group (Crankshaw, 2012). However, 'grey areas' (residential areas of illegal racial integration) existed in the suburbs of Woodstock, Observatory and Salt River and were predominantly unaffected by the Group Areas Act (Elder, 1990).

While the White population remained in the most desirable and well-located (in terms of employment and commercial opportunities) Northern and Southern suburbs, the non-White communities were forcefully removed from these designated White areas (see Figure 2.5), such as District Six, Sea Point, Wynberg and Simon's Town (Western, 1981; Hart, 1988; Field, 2001).

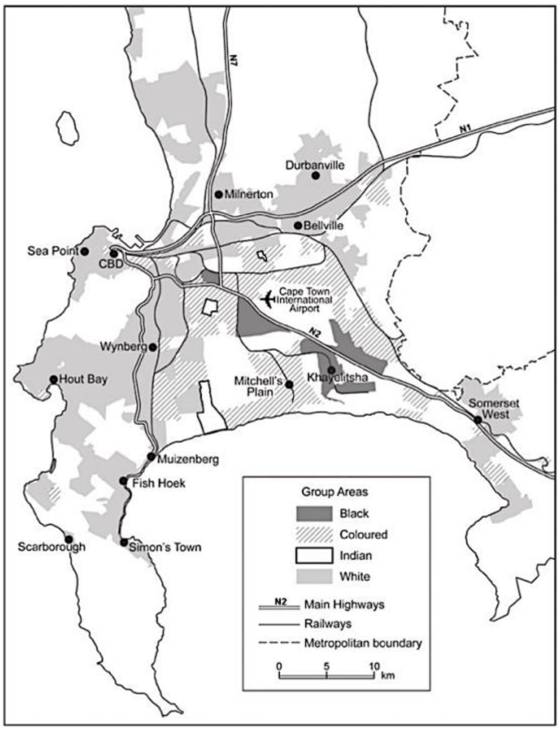


Figure 2.5: Group Areas During the Apartheid Era (Crankshaw, 2012)

Housing was provided to the low-income Black African communities, resulting in a significant racial separation between the Coloured (Mitchell's Plain) and Black African (Khayelitsha) areas in the 'Cape Flats' and the White neighbourhoods of the Northern and Southern suburbs (Crankshaw, 2012). These group areas were also purposefully segregated by rail and open land buffer zones and racial mixing was prohibited (Giliomee and Schlemmer, 1989). Similar to the other cities in South Africa, the removal of specific racial groups to designated areas in Cape Town and the restriction of their movement by law formed the basis of the complexity of persistent racial and socio-economic segregation experienced in Cape Town to this day (Christopher, 2005a; Lemon, 1991; Mabin, 1992; Maylam, 1995).

The Group Areas Act was perceived to be a failure, as it increased racial tension in the city rather than 'avoiding conflict' between racial groups – the general justification used by the apartheid regime for separating communities racially (Western, 1982). Nonetheless, the forced removal of large communities from their homes was successful and although the Cape Town city council was very opposed to the Act (Western, 1981) an estimated 150 000 residents were moved to public housing townships (Wilkinson, 2000). The manner in which the three most important structural components of the city (housing, employment and transport) were controlled to promote the White minority and to the disadvantage of the Black African majority (Dewar, 1995) resulted in the city of Cape Town reflecting residential development patterns characterised by persistent socio-economic segregation and physical fragmentation.

Focus on the subject of racial segregation in Cape Town was expanded through research on its persistence over time, from the colonial to apartheid and post-apartheid eras (Western, 1981; Cook, 1991; Saff, 1998), given the fact that Cape Town remains the most segregated city in South Africa regardless of its racial diversity. Further studies were formulated around the perpetuation of socio-economic segregation in post-apartheid Cape Town and the subject of restricted access to employment and economic opportunities as a consequence of the segregation of racial groups historically and the strategies of residential exclusion (Rospabe and Selod, 2006; Lemanski and Saff, 2010).

2.4.2 Post-Apartheid Segregation in Cape Town

There was general consensus among various stake holders in Cape Town in the early 1990s that the city had spatial problems that needed to be addressed, outlined mainly as transport access issues, a requirement for urban integration, environment concerns due to urban sprawl and urban quality concerns (Watson, 2003b). The local authority in Cape Town desired to rethink the spatial planning of the city, recognising the importance of restructuring the fragmented urban form and creating a more equitable and inclusive city (Turok and Watson, 2001). This resulted in the formulation of the Metropolitan Spatial Development Framework (MSDF) (CMC, 1996). Acknowledging the occurrence of inequality, the MSDF proposed the use of well-located vacant land to house poor households, linking neighbourhoods through nodes (key areas lacking socio-economic opportunity) and corridors and promoting mixed use and higher density residential and retail developments.

However, the MSDF was criticised for being a stagnant approach to future development of the city (Turok and Watson, 2001). This was evident in the fact that the MSDF presented a vision of spatial development for the city, without any proposal on how this will be achieved. It was further argued that the 'spatial problems' not only persisted a decade later but also intensified (Watson, 2003b). Thus, despite the significance of legislative intervention, post-apartheid Cape Town remained extremely polarised, dominated by centrally located (predominantly White) wealthy suburbs and economic nodes, alongside (predominantly Black African) overcrowded and destitute settlements at the fringes of the city (Christopher, 2000; Turok and Watson, 2001). Turok (2001) emphasized that even though basic services are being extended to the segregated township areas, the nature of social and economic development varies drastically across the city.

It was proposed that, although excluded socially and spatially from the wider city, the construction of new multi-racial and state-subsided settlements at the urban fringe could provide alternative areas for desegregation (Oldfield, 2000, 2004a; Lemanski, 2006c). However, such a strategy would effectively perpetuate the problem of social and spatial separation and inadequate access to employment and commercial opportunities. The fact that most low-income public housing developments are undertaken on low-cost land at the periphery of the city also propagates the legacy of income inequality and thus effectively racial inequality (Seekings, 2010a). Turok and Watson (2001) also argued that trends in development are not promoting urban integration, but rather reinforcing fragmentation and spatial division.

This sentiment was widely shared in the belief that the apartheid city's racial exclusion was replaced by the post-apartheid city's division of class (Seekings and Nattrass, 2005; Pirie, 2007; Leibbrandt et al., 2009; Seekings, 2010b; Bray et al., 2011). Although residential movement patterns were noticeable in Cape Town, especially Black African middle-class households moving into former White suburbs (Saff, 1994, 1998) and poor Black African households moving into former White inner-city areas (Morris, 1999; Seekings, 2000) these patterns are more orientated to class- rather than race-based residential mobility. This is emphasized by the 'flight' of White residents from the inner-city, indicating a new phenomenon of class-based segregation and not the termination of segregation per se.

Geyer and Mohammed (2016) suggested that while class-based segregation is replacing racial segregation in South Africa, it is linked to "hypersegregation" (2016, p. 35) occurring simultaneously. Hypersegregation refers to the condition whereby poor neighbourhoods become economically and racially more homogenous due to upwardly mobile middle class residents migrating out (Massey and Denton, 1993). Geyer and Mohammed (2016) argued that rich neighbourhoods concurrently become economically homogenous, segregated from poor neighbourhoods and indirectly heterogeneous as a result of in-migration of upwardly mobile resident from poor neighbourhoods.

The authors undertook an analysis to establish whether hypersegregation and class-based segregation is occurring in Cape Town and found significant clusters of neighbourhoods reflecting both these characteristics between 2001 and 2011 (see Figure 2.6).

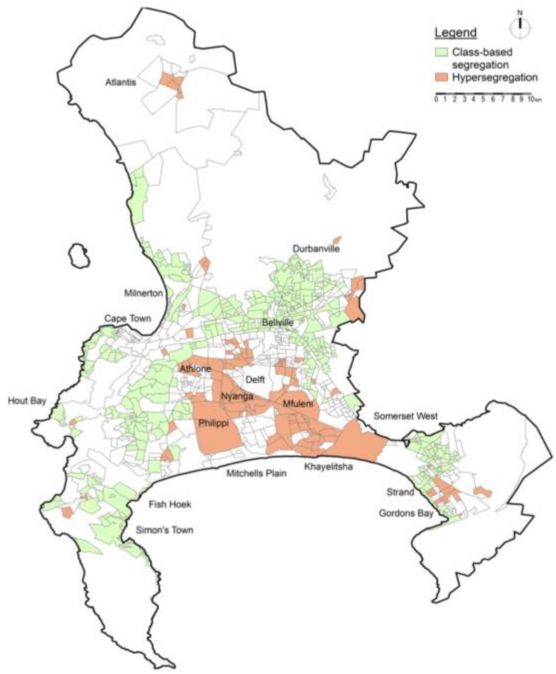


Figure 2.6: Neighbourhoods of Class-based and Hypersegregation in Cape Town in 2011 (Geyer and Mohammed, 2016)

The spatially segregated nature of metropolitan Cape Town was highlighted (see Figure 2.7), with low to very low poverty neighbourhoods located to the northern and south-western suburbs and extreme poverty concentrated to the south-eastern neighbourhoods. Geyer and Mohammed (2016) also found that spatial segregation of neighbourhoods with different poverty levels also became more ingrained between 2001 and 2011, with extreme poverty increasing to the southern parts of Cape Town. In contrast, poverty levels decreased noticeably in the northern, south-western and south-eastern suburbs of Cape Town as a result of upwardly mobile households migrating in from poorer neighbourhoods.

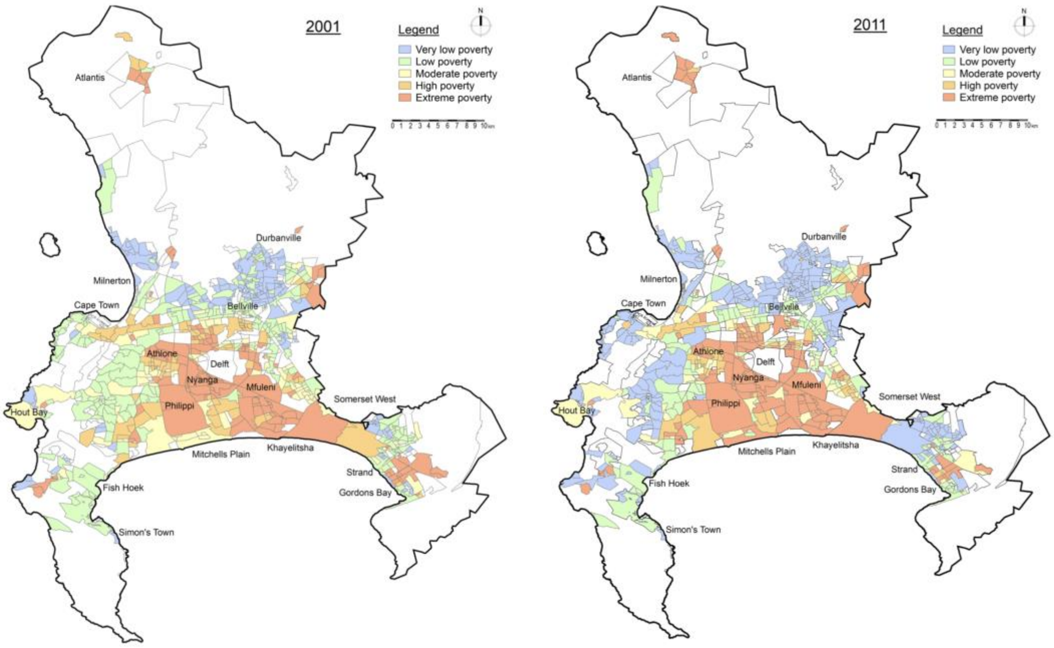


Figure 2.7: Neighbourhood Poverty Levels in Cape Town, 2001 & 2011 (Geyer and Mohammed, 2016)

Geyer and Mohammed (2016) argued that although increasing racial diversity is observed in formerly White higher income neighbourhoods, these neighbourhoods are becoming more homogenous economically with poorer neighbourhoods increasingly more heterogenous in terms of occupation and income and resulting "in the formation of socio-spatially fragmented city as segregated and exclusive as during the apartheid era" (Geyer and Mohammed, 2016, p. 37). Hypersegregation is thus a result of concentration of cumulative problems like persistent unemployment, low education levels and dependence on welfare (Lemanski, 2007; Seekings, 2007) and similar theme to Crankshaw's (2012) research on workforce polarisation between the professional middle class and low-skilled and unemployed under class in Cape Town.

Seekings (2010a) found that less racial integration occurred in the cheaper neighbourhoods of the post-apartheid city, but that economic reasons are insufficient in Cape Town, as segregation persists similarly between poor Black African and poor Coloured communities.

A number of reasons were presented, including the allocation of public housing to specific mono-racial informal settlement, continuous immigration into the predominantly Black African informal settlements and also the result of upward income mobility. Monoracial neighbourhoods also persisted in Cape Town regardless of internal class differences, such as the gated communities for Black African teachers and other higher income families within Khayelitsha, which is predominantly Black African and also higher income Coloured households either their current homes or developing larger dwellings within their current neighbourhoods (Seekings, 2010a). Seekings (2010a, p. 12) suggested that the main reason is most likely a combination of “economic constraint and social preference”.

Apart from lower to middle-class private residential developments providing the prospect for racial integration, such as Summer Greens (Broadbridge, 2001), the state also aimed to generate racially mixed neighbourhoods, such as the Black and Coloured suburb of Delft (Oldfield, 2004) and Westlake (Lemanski, 2006). In contrast, desegregated areas were found in middle-class suburbs where there was “in-migration of Blacks of an income status equal to or higher than those (Whites) moving out” and White residents accepted the Black households (Saff, 1994, p. 382).

Another phenomenon that received attention in Cape Town was the concept of ‘spatial deracialization’ of certain neighbourhoods. This occurred where Black informal settlements invaded White residential areas and changed the racial composition or diversity of that area, but remain “functionally excluded” from all the facilities in that area and remain segregated as a community (Saff, 1998, p. 70). These neighbourhoods were thus considered as deracialised (rather than desegregated), because “no cross-group social integration occurred” (Lemanski, 2006b, p. 401).

The most notable examples are the establishments of Imizamo Yethu (see Figure 2.8a) and Masiphumelele (see Figure 2.8b) towards the south of the city in the Cape Peninsula and Marconi Beam in the north of Cape Town (Saff, 1998). During the political transition phase after apartheid a small number of these informal settlements emerged within the boundaries of wealthy White neighbourhoods in Cape Town (Saff, 1994, 1998) and were able to remain.


a)


b)

Figure 2.8: a) Imizamo Yethu in Hout Bay and b) Masiphumelele (Miller, 2018)

It was suggested that urban planners aim to encourage deracialised space, as it allows for Black households to reside in White areas and alter the mono-racial dynamics of that urban space without having to allow these Black inhabitants access to local services and facilities (Lemanski, 2006a). Subsequently, it is questioned: 1) whether classifying a neighbourhood as desegregated is a superficial phrase implying racial integration, which actually disguises social segregation and 2) whether assumptions are accurate regarding urban policies of desegregation facilitating social integration too (Lemanski, 2006a). Seekings (2010a) stated that deracialization also occur in upper classes, but that it is limited to those classes and due to the acceptance of the upper-class status of non-White residents, regardless of their race.

However, certain neighbourhoods in Cape Town were significantly desegregated and it was proposed that this occurs due to the housing tenure of these neighbourhoods (Crankshaw, 2012). Thus, neighbourhoods with predominantly smaller and cheaper apartment developments present a rapid turnover in residents since they are largely rental properties and provide for the opportunity of racial desegregation. The central business district (CBD) of Cape Town and neighbourhoods of Greenpoint, Sea Point, Observatory, Mowbray, Brooklyn and Maitland are shown as examples (see Figure 2.9). The suburbs also reflected desegregated neighbourhoods along railway lines, to Heathfield in the southern suburbs and Bellville CBD in the northern suburbs (ibid:855). Nonetheless, Crankshaw (2012) pointed out that these higher levels of desegregation only occur in formerly Whites-only neighbourhoods that are either adjacent to or surrounded by formerly Coloured-only neighbourhoods, while the core of these suburbs remain mostly segregated.

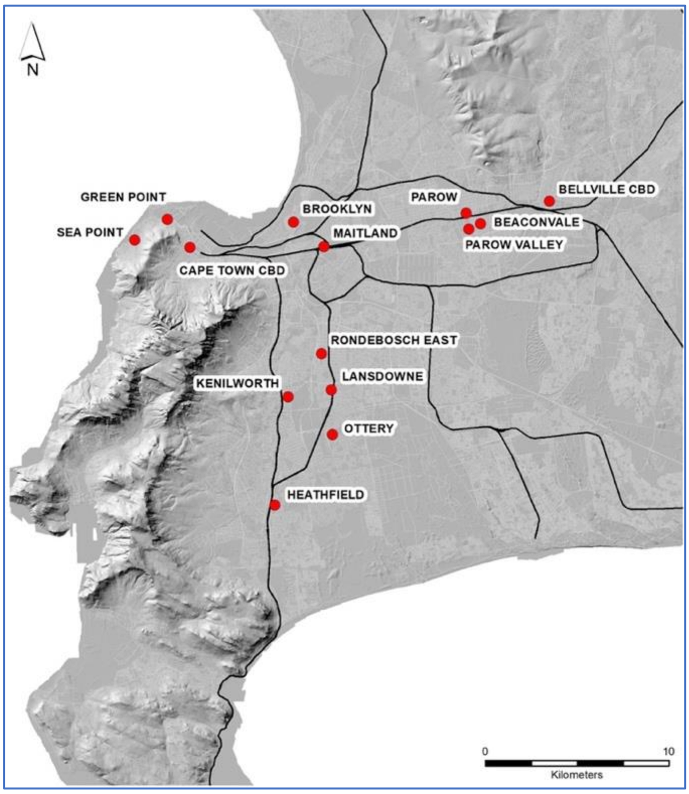


Figure 2.9: Desegregated Neighbourhoods of Cape Town (©esri)

The discussion on Cape Town in this section reflects the findings of Seekings (2010a), that the South African city remains significantly segregated and mostly by class, but racially too. The author also points out that studies suggest the link between these inequalities and neoliberal policy, regarding infrastructure, housing and services (ibid:2010a).

2.4.3 Segregation in the Contemporary City

Scholars maintain that Cape Town's addition to the global economy has intensified inequality inherited from the colonial and apartheid eras, due to the global demand and foreign investment for professional services and tourism, while the manufacturing industry and related lower skilled employment declined dramatically (Crankshaw, 2012). Consequently, division widened between the affluent White suburbs and the poor Black African townships and market forces reinforced spatial divisions rather than promote urban integration (Turok, 2001; Jenkins and Wilkinson, 2002; Robins, 2002). Higher skilled and higher paid employment are dominated by Whites, resulting in "significant socio-economic polarization based on race" (Lemanski, 2007, p. 457).

However, Crankshaw (2012) contested these views by studying the relationship between deindustrialization and racial inequality in Cape Town and suggesting that the decline in manufacturing employment and increased service-sector employment did not result in workforce polarisation, between high and low income and skills. The author found that there was growth in the upskilling of the employed workforce, with a contrasting low growth in employment of low-income and -skill jobs. Thus, due to population growth and migration to Cape Town, inequality increased as a result of increased Black African unemployment. Crankshaw (2012) also stated that not only Whites benefitted from upskilling, but that Black African employment increased in high-income professional jobs.

Nonetheless, Pieterse (2009) shared the sentiment of widening socio-economic division by pointing out that "the over-riding feature of South African cities is unsurprisingly economic" with economic disparity that has "grown dramatically over the past two decades" (2009:1). The following statement on the South African city is very much applicable to Cape Town also: "Extreme income inequality is translated into spatial segregation through the 'sorting' process of the housing market" and "replaced the administrative processes of racial separation under apartheid" (Turok, 2012, p. 42). Thus, poor households can't afford to buy or rent properties in well-located and –serviced areas and are forced to live in their current areas with poor quality infrastructure and services. This is evident in the low residential mobility of low-income households in Cape Town, where households tend to stay in the same type of income areas if they do move (Haferburg, 2003).

The adoption of BID's or CID's (City Improvement Districts in the South African context), discussed in Section 2.3.2, in Cape Town is also viewed as a direct result of the development of a national neoliberal government (Michel, 2013). The privatised governance in Cape Town through CID's (Miraftab, 2007; Peyroux, 2006) was a direct result of high levels of crime in the urban environment (McDonald and Smith, 2004; Lemanski and Saff, 2010; Samara, 2010).

However, physical consequences were evident as a result of Cape Town’s newly developed CID’s and Visser and Kotze (2008) highlighted three distinct changes in the CBD.

Firstly, upper-class residential areas increased dramatically and resulted in the development of an inner-city service economy and rental increases (Pirie, 2007). Secondly, the office space construction resumed in central Cape Town and resulted in the establishment of a new financial district with a convention centre and exclusive hotels and apartments (Pirie, 2007). Thirdly, the service economy of the city evolved from an administrative and legal nature to a private sector and commercial orientation (Visser and Kotze, 2008). In summary, the ‘classical’ form of socio-economic displacement in the early stages of the post-apartheid era gave way to a second phase of conceptualising spatial change in the gentrified urban environment as regeneration (Visser and Kotze, 2008).

The governance of the downtown CID’s in Cape Town from a social and spatial perspective is suggested to reflect neoliberal urban development strategies and highlights the “persistence of exclusionary citizenship and the right to the city” (Miraftab, 2007, p. 617). This view was widely supported by the belief that the privatisation of public space is discriminatory towards certain social groups (Gulick, 1998; Wilkinson, 2004; Lemanski, 2007; Peyroux, 2008). Miraftab (2007, p. 16) also suggested that urban development dynamics have come full circle in the sense that contemporary urban renewal strategies: “What land was to the white colonizers, downtown real estate properties in the neoliberal era are to national and foreign investors”. Property owners in lower income areas cannot afford the fees related to Cape Town’s privatised CID services and as a result spatial and social disparity is intensified. The ambition for global economic integration thus progressed in Cape Town, but at the expense of racial and income integration (Slater et al., 2004; Lees, 2007; Miraftab, 2007).

Harrison et al. (2003) supported this argument by pointing out that although the conceptual aspiration of globalisation is to promote integration and enhance connectivity, urban fragmentation is a core result and evident in the Cape Town CID’s. Within this neoliberal urban environment, significant spatial outcomes were unmistakable in the “elite enclaves” (see Figure 2.10) and “commodified collective spaces” of the upper-income South African suburb (Huchzermeyer, 2011, p. 249).

Figure 2.10: Gated Community (Silvertree Security Estate) in Cape Town (Image Captured: 2009, © Google 2018)

The ongoing development of gated communities perpetuates social stratification, economic disparity and fragmenting of the urban form internationally, as found in Cape Town for example (Lemon, 1991; Turok, 2001; Lemanski and Saff, 2010). In addition, it also poses challenges in terms of maintaining social interaction and cohesion between urban inhabitants. The choice of certain residents to live separately from others was also studied as a perpetuating factor of socio-economic segregation and Lemanski (2004) highlighted the fear of crime in post-apartheid Cape Town as a predominant cause of segregation by more affluent groups through gated developments

It is thus evident that contradicting results took shape from Cape Town's 'global city objective', with the neoliberal transformation of certain neighbourhoods in the city through increasing private investment and in contrast the exclusion of disadvantaged neighbourhoods from such developments (Gibb, 2007). Lemanski (2007) also questioned the global aspiration of cities in the Global South, such as Cape Town, through the regeneration of the city centre, while socio-economic disparity requires intervention, especially in the poor communities at the fringes of the gentrifying CBD of Cape Town. Apart from the CID concept, the inequalities of basic service provision in the urban environment is another prominent example of the perpetuation of segregation as a consequence of neoliberal privatisation (Alexander, 2010; Atkinson, 2007).

2.5 Patterns of Segregation in Cape Town

The occurrence and patterns of residential segregation in Cape Town have been studied for more than three decades to understand how this phenomenon changed over the colonial, segregation, apartheid and post-apartheid eras. Figure 2.11 presents a timeline of these political eras (discussed in Chapter 2) and the occurrence of each census that was studied in relation to segregation in these eras. However, all these studies (e.g. Christopher, 1988, 1989a, 2001a; Rospabe and Selod, 2006; Parry and van Eeden, 2015) omitted the censuses of 1918, 1926, 1931 and 1941 (only enumerating the White population) and the censuses of 1946 and 1980 (occurring too close to the censuses of 1951 and 1985). Consequently, they are excluded from the timeline in Figure 2.11.

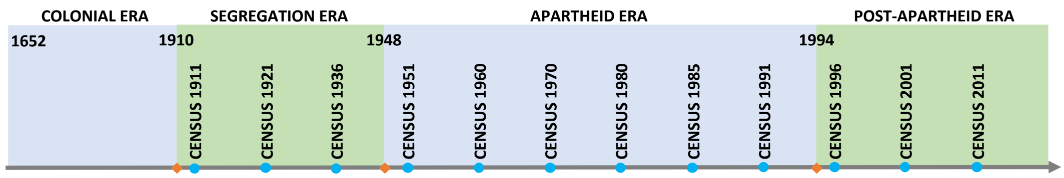


Figure 2.11: Timeline of Political Eras and Census Enumeration Considered

Christopher (1988) discovered that the Black African and Coloured population in Cape Town were less segregated compared to other South African cities by 1911. However, when studying segregation in Cape Town between 1911 and 1985 the author found that segregation was significantly high between most racial groups by 1985, with segregation between Black African and all other groups the highest for all relevant census years (Christopher, 1989b). When racial segregation between the census years of 1951 and 1996 was studied by Christopher (2001a), segregation between the White population and all other racial groups intensified as a result of apartheid. This was also the case for segregation between the Coloured and Indian/Asian Groups in Cape Town, even though segregation was lowest between these two groups for all census years between 1951 and 1996 when compared to other racial groups.

Rospabe and Selod (2006) studied the 1996 census data for Cape Town's urban area to assess racial segregation levels between the city's Black African, Coloured, Indian/Asian and White population groups. Significantly high segregation levels were evident between the Black population group and all other groups. In contrast, segregation was found to be lowest between the Coloured and Indian/Asian group. These trends are broadly similar to the findings of Christopher (2001a) for Cape Town.

Parry and Van Eeden (2015) extended the study of segregation levels in Cape Town by measuring racial segregation with the census data of 1991 to 2011. It was found that although segregation decreased for all racial between 1991 and 2011, segregation between the White and Black African group was still very high. Compared to the city of Johannesburg, it was also found that the White population in Cape Town is more segregated. In addition, clear patterns of low racial diversity are evident in the neighbourhoods of Khayelithsha and Nyanga in Cape Town, which are both former Black African settlements. The same was found for the suburbs of Atlantis and Mitchell's Plain in Cape Town, which were both demarcated Coloured areas and still reflect a dominant Coloured population (Parry and van Eeden, 2015). The rate of racial integration also slowed down in Cape Town between 1996 and 2011.

Although the phenomenon of segregation was prevalent in the findings of the discussed researchers, a degree of integration was also detected. Another remarkable occurrence of urban integration during apartheid was the desegregation of Hillbrow, an inner-city neighbourhood of Johannesburg (Morris, 1994). Historically, Hillbrow had a large Black African population in the 1950s until a majority of non-White citizens were removed, in accordance with the Group Areas Act of 1950 (Union of South Africa, 1950b), from the centre of Johannesburg a decade later. However, a national political and economic crisis in the 1970s resulted in a shortage of state housing in the Black African group areas and forced these communities to migrate into the inner-city of Johannesburg. This housing shortage and the surplus of accommodation in the inner-city also resulted in the migration of Coloured and Indian communities to Hillbrow (Morris, 1994). The government was forced to accept the racial integration of this area, due to a lack of financial capacity to orchestrate mass evictions and also that the occurrence of migration solved the Coloured and Indian housing problem.

Saff (1994) pointed out that the dimension of class (rather than race) would become more prominent in post-apartheid South Africa, "with access to urban space based on wealth rather than racial criteria becoming the defining characteristic of South Africa's cities" (Saff, 1994, p. 377). This phenomenon was evident in the city of Durban where racial desegregation occurred, since the repeal of the Group Areas Act in 1991, in suburbs that were predominantly White previously. Kichin (2002) examined the migration of Black African households from townships into the suburbs of Durban, which suggested to the author that race is "no longer the most important defining basis of analysis" within the city itself, excluding informal settlements and townships (Kitchin, 2002, p. 1). However, Kichin (2002) acknowledged that although race does not appear to be a defining characteristic of segregation in the South African city anymore, the non-White majority of South Africans would remain segregated from the rest of the more affluent urban areas.

2.6 Summary

This chapter introduced the problem of segregation and related issues in the urban setting, followed by a contextualisation of racial and socio-economic segregation in the South African context and more specifically the case study of Cape Town. Finally, a discussion is provided on the findings of segregation measurements that were undertaken for Cape Town at various time frames across the different eras of segregation that were presented in this chapter.

Segregation in the South African city originated as a measure of racial separation and control and it is evident that the classification of the population by race was key to the initiation of three consecutive eras of segregation. The systematic separation of racial groups during the colonial and segregation eras escalated dramatically with the initiation of apartheid and the forced removal of all non-White communities from newly designated White urban areas. Decades of racial segregation not only shaped the South African urban environment, but also evolved into socio-economic inequality and posed an immense challenge for post-apartheid planning and the aspiration for integrated cities.

Although it was suggested that Cape Town was a racially mixed establishment with 'colour-blind' policies from the beginning, racial disparity occurred since the colonial era. It was argued that the population of Cape Town was segregated by class and wealth rather than race, but it was evident that the poor were also non-White. During the segregation era in Cape Town discrimination against the Black African population resulted in the relocation of these communities to less-desirable areas at the fringes of the city. Apartheid resulted in the legalised removal of all non-White racial groups to these fringes of Cape Town with limited access to economic opportunities, which perpetuated income inequality.

Segregation persisted in the post-apartheid city of Cape Town as a result of various dynamics determining the distribution of different racial and income groups. Apart from the provision of low-income public housing in previously segregated neighbourhoods perpetuating segregation, the low level of income in these areas limited the opportunity of upward mobility. Poorer areas are thus found to be racially less diverse, while former White upper-income neighbourhoods become racially more diverse due to an influx of more affluent non-White households. Further socio-economic polarisation occurred with an increase in middle- to upper-income gated communities and city improvement districts. Hence, the initial segregation of race in Cape Town evolved over time to include socio-economic disparity.

More critical to this thesis, racial and socio-economic segregation are inherently related, with the occurrence of racial segregation often the foundation of income disparity. However, the relationship between race and income as drivers of persistent segregation are seldom explored quantitatively. Studies are predominantly devoted to the subject of race rather than income levels in the South African context and the measurement of socio-economic segregation remains a significant challenge.

The following chapter discusses the measurement of segregation and related methodologies, which will be applied to measure racial and socio-economic segregation in the city of Cape Town.

Chapter 3

Measurement of Residential Segregation

Residential segregation has been studied since the 1920s and despite being a persistent phenomenon, segregation presents significant and complex problems to the potential for population groups to interact and have equal access to amenities and economic opportunities. Consequently, the measurement of residential segregation in the urban environment has been studied and applied for more than half a century, due to the negative impact of segregation on the cohesive development of urban societies and integrated infrastructure. Since the 1950s urban segregation research focussed on the continuous development of segregation indices as a useful methodology to better understand and further study the degree of segregation in urban areas (Feitosa et al., 2007).

Following the discussion of racial and socio-economic segregation in South Africa and especially Cape Town, this chapter discusses the measurement of residential segregation and the indices applied in this thesis to analyse the spatial distribution of both racial and income groups in Cape Town and better understand the role the subjects of race and income play in the persistence of segregation in the city. The objective of this chapter is firstly to introduce the subject and development of segregation measurement and secondly to discuss the spatial measurement of segregation in more detail and introduce the indices that area applied in this thesis to measure racial and socio-economic segregation in Cape Town.

The chapter is composed of three sections. Section 3.1 provides background to the initial development and implementation of segregation measurements. Section 3.2 focuses on the dimensions or variation in spatial distribution of residential segregation. Finally, a discussion is provided in Section 3.3 on segregation measurements that were undertaken in the South African context and the indices that were applied.

3.1 Background

The measurement of urban segregation has been deliberated and debated since the 1940's and resulted in a series of studies applying different methods, articles assessing these methods and proposals from researchers on measures to capture the different dimensions of segregation (Bell, 1954; Duncan and Duncan, 1955a; Morgan, 1975; Jakubs, 1981; Sakoda, 1981; Massey and Denton, 1988; Wong, 1993; Reardon and O'Sullivan, 2004) . In the mid-1950s the first measures focussing on the distinction between two population groups (Bell, 1954; Duncan and Duncan, 1955a) was established and resulted in the proposal of a subsequent array of segregation indices to capture segregation between numerous groups (Morgan, 1975; Sakoda, 1981).

The work of Duncan and Duncan (1955a) was deemed as the "first systematic analysis and critique of segregation indices" (Reardon and Firebaugh, 2002, p. 34) and emphasized the shortcoming of segregation measures in terms of conceptualising segregation. Duncan and Duncan (1955a) iterated that some proposed segregation indices have mathematical properties of which their supporters are unaware of and which result in interpretation issues and consequently questionable empirical work until 1955. Consequently, Duncan and Duncan (1955a) demonstrated that their index of dissimilarity (*D*) contained most of the information found in other existing indices, which resulted in the index of dissimilarity being applied as standard segregation measure for more than two decades. The dissimilarity index measures how the population composition of a locality differs on average from the composition of the whole study area.

Bell (1954) undertook an examination of the logic of the Shevky-Williams index of isolation (Shevky and Williams, 1949), which measures the level of residential relationship of individuals within the same group and was also used to compare isolation of different groups from each other in the same city. As a result of this study, Bell (1954) proposed a probability model which estimates the probable interaction between members of the same cultural group and another model estimating the probable interaction between members of different groups. Bell (1954) concluded that a major advantage of the probability model is that it provides for the direct interpretation of scores at any point of the spectrum (from none to complete segregation). However, despite the author presenting a number of indices to measure exposure/isolation, focus at that time was mainly on comparing segregation between cities and consequently the dissimilarity index of Duncan and Duncan (1955a).

Cortese et al. (1976) published a critique of the index of dissimilarity (*D*) in which four major objections were stipulated. Firstly, it was stated that "evenness" in distribution is not as useful as "randomness" as the opposite of segregation (1976:631). Secondly, it was found that *D* is affected by variation in the proportion of a minority in a population, which prevents inter-city comparison. Thirdly, *D* is affected by the size of the area of analysis, in terms of number of households. Finally, the interpretation of *D* as percentage of non-Whites who need to change residence to ensure even minority distribution throughout the city (Duncan and Duncan, 1955a) was identified as misleading, as replacement of the relocated minority was not considered.

This critique by Cortese et al. (1976) resulted in renewed interest in the measurement of segregation and the late 1970's witnessed a number of publications on proposed new measures (Taeuber and Taeuber, 1976; Van Valey and Roof, 1976; Jakubs, 1977, 1981; O'Connell, 1977; Steinnes, 1977; Winship, 1977; Massey, 1978, 1981). Segregation studies in the 1970's also began to focus on multi-group dynamics and related problems, including the segregation of ethnic and social classes (Feitosa et al., 2007). These studies were undertaken by means of a proposed new generation of segregation indices (Morgan, 1975; Sakoda, 1981; Reardon and Firebaugh, 2002), "generalizing versions of existing two-group measures" (Feitosa et al., 2007, p. 301) to measure multi-group segregation dynamics.

In the 1980's two developments in the measurement of segregation were deemed as important advancements (Reardon and Firebaugh, 2002). Firstly, James and Taeuber (1985) developed a set of criteria, derived from a set of principles that clarify the definition of segregation, to assess segregation measures against and used these criteria to demonstrate that related indices in empirical studies may behave quite differently under specific circumstances. The second development which was highlighted by Reardon and Firebaugh (2002) was by Massey and Denton (1988) and concerned the conceptual classification of segregation indices into five dimensions in order to provide clarity on the concept of segregation. As the dimensions of segregation will be considered throughout this chapter, the following section discusses the development of these dimensions in further detail.

3.2 Dimensions of Residential Segregation

Massey and Denton (1988, p. 282) argued that the field of segregation studies was "in a state of theoretical and methodological disarray" at the time, with various definitions and measures of segregation being promoted by different researchers. In the interest of establishing order, Massey and Denton (1988) evaluated 20 measures of residential segregation and undertook a conceptual classification of these indices, together with a study of how each index would correspond to each of five specified variations of spatial distribution: *evenness*, *exposure*, *concentration*, *centralization* and *clustering:*

- *Evenness* relates to the distribution of population groups, where minority members for example may be unequally distributed and "overrepresented in some areas and underrepresented in others" (Massey and Denton, 1988, p. 283).
- *Exposure* focuses on the degree of potential interaction between members of minority and majority population groups sharing the same residential area.
- *Concentration* reflects the relative quantity of physical space occupied by a group, as a minority group may be concentrated spatially and occupy less space than a majority group.
- *Centralisation* measures the extent to which a certain population group might be located to the centre of an urban area.
- *Clustering* is relevant to areas of a specific population group that are closely grouped to form a large adjoining society or scattered throughout an urban environment.

The following sections further discuss the two dimensions of evenness and exposure/isolation, as they are relevant to this thesis and studied in the measurement of racial and socio-economic segregation in Cape Town. The indices Massey and Denton (1988) have identified for each of these dimensions are also explored, although these particular (aspatial) versions of the indices are not applied in this thesis.

3.2.1 Evenness

Massey and Denton (1988, p. 283) emphasized that measurement of the evenness dimension of segregation is not undertaken in an "absolute sense" but scaled rather in relation to another relevant group. A high level of evenness and low degree of segregation is experienced when all the areal units in the study area reflect the same relative amount of minority and majority individuals as the study area or city as a whole. In contrast, it is found that the level of evenness is low and segregation at a higher degree when individuals from a majority group and those from a minority group don't share the same residential area.

The measurement of evenness is undertaken mostly by application of the Index of Dissimilarity. Massey and Denton (1988, p. 284) stated that James and Taeuber (1985) defined the index of dissimilarity as a method for measuring the "departure from evenness by taking the weighted mean absolute deviation of every unit's minority proportion from the city's minority proportion, and expressing this quantity as a proportion of its theoretical maximum".

The following is one formula for the dissimilarity index (Forest, 2005):

$$D = \frac{1}{2}\sum_{i=1}^{n}\left|\frac{w_i}{W_T} - \frac{b_i}{B_T}\right| \tag{1}$$

where *n* is the number of census tracts/spatial units, w_i is the the number of Whites in tract *i*, WT is the total number of Whites in the whole city, b_i is the number of Blacks in census tract *i* and *BT* is the total number of Blacks in the city.

Hence, it measures a percentage of the population of a certain minority group that needs to change where they reside in each neighbourhood to reflect the same percentage of that group overall in the whole urban area (Iceland and Weinberg, 2002). The index score will range from 0 for complete integration to 1.0 for complete segregation. As seen in the reconstructed graph (see Figure 3.1) from Duncan and Duncan (1955a), the dissimilarity index can also be derived from the Lorenz curve. The cumulative percentage of a minority group X can be plotted against the cumulative percentage of a majority group Y across areal units and the minority percentage is ordered from smallest to largest. D reflects the maximum vertical distance between the diagonal line of evenness and the curve for the above.

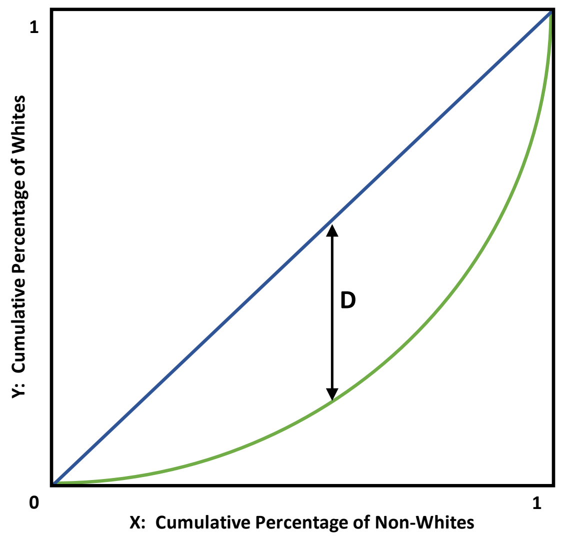


Figure 3.1: Dissimilarity Index Derived from Lorenz Curve

The Information Theory Index (*H*) is a second measure of residential unevenness, which was proposed originally by Theil and Finizza (1971), when it was applied as measure of segregation in schools. It measures the departure from evenness by measuring each unit's departure from the racial "entropy" of the city as a whole. Hence, the information theory index relies on what is known as 'Theil's entropy index' (Theil, 1967) (a measure of diversity) and compares the entropy of the whole study area to the entropy of localities.

The entropy of the city is effectively the extent in diversity of ethnicity and presented as:

$$E = (P)\, log\left[\frac{1}{P}\right] + (1 - P)\, log\left[\frac{1}{1 - P}\right] \tag{2}$$

With the related entropy of an aerial unit as:

$$E_i = (p_i)\, log\left[\frac{1}{p_i}\right] + (1 - p_i)\, log\left[\frac{1}{1 - p_i}\right] \tag{3}$$

where *P* is the proportion of the city's minority population and p_i is the proportion of the areal unit's minority population

Massey and Denton (1988, p. 285) described the information theory index (*H*) as "the weighted average deviation of each unit's entropy from the city-wide entropy, expressed as a fraction of the city's total entropy" and presented he city's entropy as:

$$H = \sum_{i=1}^{n} \left[\frac{t_i(E - E_i)}{ET} \right] \tag{4}$$

As was the case with the dissimilarity index, the entropy index also varies between 0 (with all areas reflecting the same composition as the whole city) and 1.0 (where all areas only contain one population group). However, Massey and Denton (1988) found that it differs from the other two indices in the sense that it fails according to the compositional invariance criterion specified by James and Taeuber (1985). This is mainly due to the fact that its value is partially determined by the relative amount of minority group members.

3.2.2 Exposure/Isolation

Exposure, as a dimension of segregation, was distinguished as important by Bell (1954). The dimension of exposure in a residential area was identified as "the degree of potential contact, or the possibility of interaction, between minority and majority group members within geographic areas of a city" (Massey and Denton, 1988, p. 287). Indices of exposures would thus measure the level of physical interaction between members of minority and majority population groups, in relation to the sharing of common residential space. The focus of exposure is largely on the measurement of how the average minority or majority group individual experiences segregation.

Massey and Denton (1988) stated that exposure and evenness are quite distinct conceptually, regardless of the interrelatedness of the two measures, as exposure is to a large degree dependent on the size of the groups being compared and evenness not. The example was provided of minority group members being evenly distributed across residential areas of a city, but still experiencing a low degree of exposure to the members of majority groups if these minority members are a large percentage of the city.

In contrast, the individuals from minority groups will experience much higher levels of exposure to the majority if they are a small percentage, regardless of what the evenness dimension reflects. Residential exposure is studied by the two interrelated measures of interaction and isolation (Massey and Denton, 1988). Subsequently, both indices reflect the likelihood of a minority group individual sharing an aerial unit with an individual from a majority group or with another minority group individual.

Also known as the interaction index, exposure measures the degree to which minority group (X) individuals are exposed to individuals from a majority group (Y). The index is effectively the minority-weighted average of the majority proportion of each areal/spatial unit (Massey and Denton, 1988). The equation was designated by Lieberson (1981) as follows:

$$xP^*y = \sum_{i=1}^{n} \left[\frac{x_i}{X}\right]\left[\frac{y_i}{t_i}\right] \tag{5}$$

where x_i, y_i and t_i are the numbers of *X* group members, *Y* group members and the population as a whole of unit *i*, respectively. *X* reflects the number of *X* members in the whole city.

The isolation index measures the degree to which the members of a minority group are exposed only to each other, rather than to the individuals of other groups (Massey and Denton, 1988). Hence, it is calculated as "the minority-weighted average of each unit's minority proportion" (Massey and Denton, 1988, p. 288):

$$xP^*x = \sum_{i=1}^{n} \left[\left[\frac{x_i}{X}\right]\left[\frac{x_i}{t_i}\right]\right] \tag{6}$$

Both the exposure and isolation indices also vary between 0 and 1.0. Thus, a lower figure of exposure and a higher figure for isolation will both indicate a high degree of segregation. The exposure indices representing the exposure of minority group members to majority group members will be equal to the exposure of majority to minority group members, but only in the instance where the two groups consist of the same proportion of the population. Massey and Denton (1988, p. 288) pointed out that the exposure index is "asymmetric" due to its "compositional dependence" and as a result *xP*y* will not be equal to *yP*x*.

It should be reiterated that the indices of exposure and isolation are "inversely related" (Noguera et al., 2015). Hence, exposure refers to the level of possible contact between a member of a certain population group and the members of another population group and isolation refers to the level of possible contact between a member of one population group to the rest of the members of that same group.

Considering the dimensions of segregation, Massey and Denton (1988) reiterated that population groups might be segregated from each other in different ways, which correspond to various combinations of the five dimensions of spatial distribution. Massey and Denton (1988, p. 309) thus emphasized that residential segregation is multi-dimensional and doesn't arise from a single process, but rather from a "complex interplay of many different social and economic prosses that generate various constellations of outcomes interpreted as segregation". Consequently, the authors suggested that segregation should rather be measured with a combination of indices and not only one, due to its multi-dimensional nature and also that spatial distribution should be recognised as separate dimensions and measured directly with their relevant indices.

White (1983) also pointed out that all measures of residential segregation to date did not consider the spatial relationship of land parcels and this finding inspired further development of measures that would be able to capture the spatial dimension of segregation (Jakubs, 1981; Morgan, 1983; White, 1983; Morrill, 1991; Wong, 1993; Wong, 1998; Reardon and O'Sullivan, 2004). In undertaking an assessment of the work of Massey and Denton (1988), Reardon and O'Sullivan (2004) argued that segregation has no aspatial dimension and the authors suggested that the measurement of residential segregation patterns and trends has been restricted by spatial patterns of population distribution and census tracts not being taken into account.

Segregation could effectively be seen as a degree to which members of different groups inhabit or experience different social environments (Reardon and O'Sullivan, 2004). "A measure of segregation, then, requires that we (1) define the social environment of each individual, and (2) quantify the extent to which these social environments differ across individuals" (2004, pp. 122–123). Consequently, Reardon and O'Sullivan (2004) highlighted two major problems of aspatial segregation measures: the checkerboard problem – not taking the spatial relationship of geographic parcels into account (White, 1983; Morrill, 1991) and the modifiable areal unit problem (MAUP), named by Openshaw and Taylor (1979) – the effect on aggregated data by spatial unit scales and related boundary conditions (Openshaw and Taylor, 1979; Wong, 1997). It was proposed that spatial segregation measures require a "redefinition of the social environment" (Reardon and O'Sullivan, 2004, p. 124) to minimise these two problems.

Further to the assessment of the work of Massey and Denton (1988), Reardon and O'Sullivan (2004) also suggested that the difference between the aspatial dimension of evenness and the spatial dimension of clustering is a result of the aggregation of data at different scales. The degree of evenness at one aggregation scale (such as census tracts) is strongly related to the degree of clustering at a lower level of aggregation (Reardon and O'Sullivan, 2004). Subsequent to these findings, Reardon and O'Sullivan (2004) suggested an alternative to the dimensions of residential segregation by Massey and Denton (1988). The authors argued that there are two main conceptual dimensions of spatial residential segregation: spatial exposure (or spatial isolation) and spatial evenness (or spatial clustering).

Spatial exposure refers to the degree at which members of one group encounter the members of another group (or their own group, in the case of spatial isolation) in their local area. Spatial evenness refers to the degree to which groups are comparably distributed in a residential area. The dimensions of centralisation and concentration were classified as subgroups of the newly generated evenness/clustering dimension. Reardon and O'Sullivan (2004) highlighted that spatial exposure is a measure of the environment experienced by individuals and thus depends partially on the general racial composition of the population in the studied area.

Feitosa (2010) supported this view in emphasizing the relevance of considering different dimensions and scales of segregation when analysing the impact of segregation. It was argued that the spatial concentration of a population group (dimension of evenness/clustering) might be positive, as it could assist in the preservation of the cultural identity of an ethnic group or promote the power of the urban poor socially and politically (Sabatini, 2006). However, social or cultural homogeneity (dimension of isolation/exposure) is inclined to promote issues such as lack of access to job opportunities and infrastructure of the poor and increased crime occurrence (Sabatini, 2006; Feitosa, 2010), especially at larger scales of segregation along the urban periphery.

Reardon and O'Sullivan (2004) constructed four patterns of individual (black and white) residential locations (see Figure 3.2) to visualise the distinction between spatial exposure and spatial evenness. The top two patterns show black and white households evenly distributed in space and thus have a high level of evenness and low level of clustering. However, there is a higher exposure of white-black households in the top right quadrant and a higher level of white isolation on the left. The bottom half of the figure reflects more clustering, but more or less the same degree of exposure than the corresponding distributions above. Reardon and O'Sullivan (2004) pointed out that the evenness and clustering dimensions of Massey and Denton (1988) are thus collated into a single dimension and that the exposure dimension remains unchanged, but now conceptualised as spatially explicit.

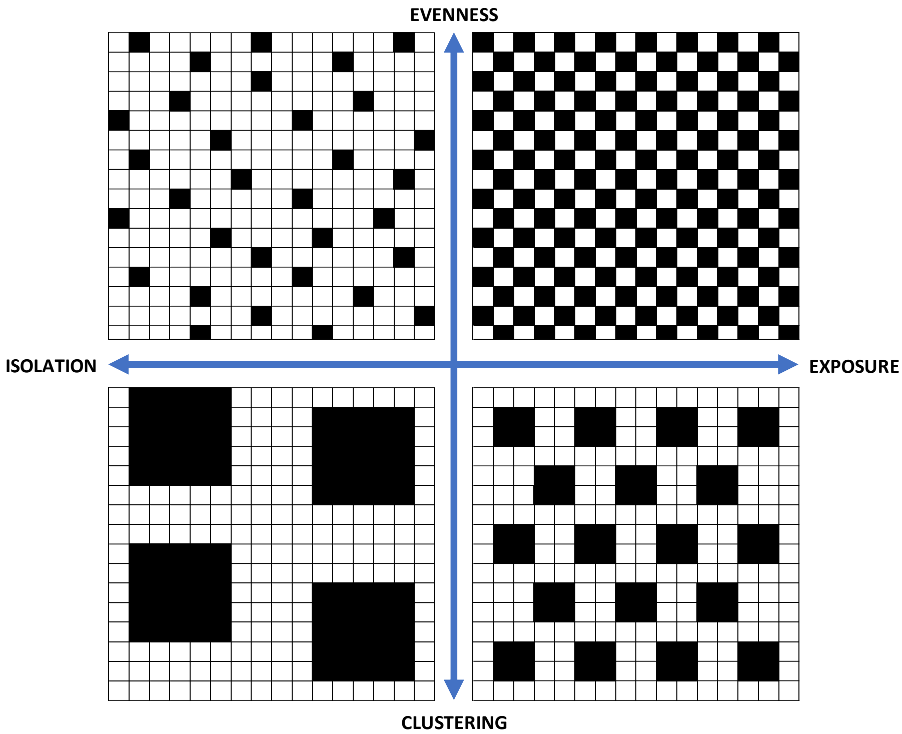


Figure 3.2: Dimension of Spatial Segregation (Reardon and O'Sullivan, 2004)

This resulted in Reardon and O'Sullivan (2004) establishing a general approach for the measurement of spatial segregation among multiple population groups, which will allow a researcher to stipulate any theoretically based definition of spatial proximity desired in the computation of segregation measures. This approach provided the authors with the basis to develop the following indices: a *general spatial exposure/isolation index*, a *set of general multi-group spatial evenness/clustering indices* (*spatial information theory index*), a *spatial relative diversity index* and a *spatial dissimilarity index.* More recent developments in the measurement of segregation, such as global and local spatial indices, have provided new approaches to studying indices of segregation (Barros and Feitosa, 2018). Consequently, it is possible to analyse spatial patterns of segregation and how it varies over geographic space (Lloyd and Shuttleworth, 2012) and also to explore the multi-scale characteristics of segregation (Reardon et al., 2008; Clark et al., 2015; Fowler, 2016).

The work of Reardon and O'Sullivan (2004) was explored by Feitosa et al. (2007) and provided a basis for the authors to develop further spatial indices of segregation. These spatial indices by Feitosa et al. (2007) and Barros and Feitosa (2018) are applied in this thesis to measure racial and socio-economic segregation in Cape Town, as will be shown in Chapter 6. These spatial indices of segregation were built on the notions "*locality*" and "*local population intensity*" (Feitosa et al., 2007, p. 302), as the authors hypothesise that an urban area has different *localities* where individuals reside and share experiences with neighbours. Feitosa et al. (2007) emphasized that the measurement of the intensity of these exchanges is a primary issue for studies of segregation and also believed that the intensity would vary in accordance with distance between population groups. The *local population intensity* expresses the characteristics of the population of a locality.

Each *locality* has a centre point or core, which is defined by an aerial unit's centroid and formulated around the idea that it indicates the central part of a borough as the place where its characteristics are most distinct. Hence, a study area would have many localities as areal units. Feitosa et al. (2007) make use of a kernel estimator (Silverman, 1986) to calculate the local population intensity of a locality, which is a function for the estimation of an attribute's intensity in different locations of a study area.

As reflected in Figure 3.3, the local population intensity of localities i and j is calculated by positioning the kernel estimator on the centroid of the spatial units of *i* and *j* and computing a weighted average of the population data (Feitosa et al., 2007). The weights are provided by the choice bandwidth (*bw*) parameter and distance decay function. Feitosa et al. (2007) emphasized the fact that a choice of function and bandwidth of a kernel estimator enables much flexibility for researchers in this field. Kernel functions include linear, polynomial, Gaussian (see Figure 3.3) and sigmoid types (Schölkopf et al., 1997). The kernel bandwidth is chosen in accordance with the geographic scale of the analysis of segregation and the use of different bandwidths for index computation allows for the studying of different scales of segregation.

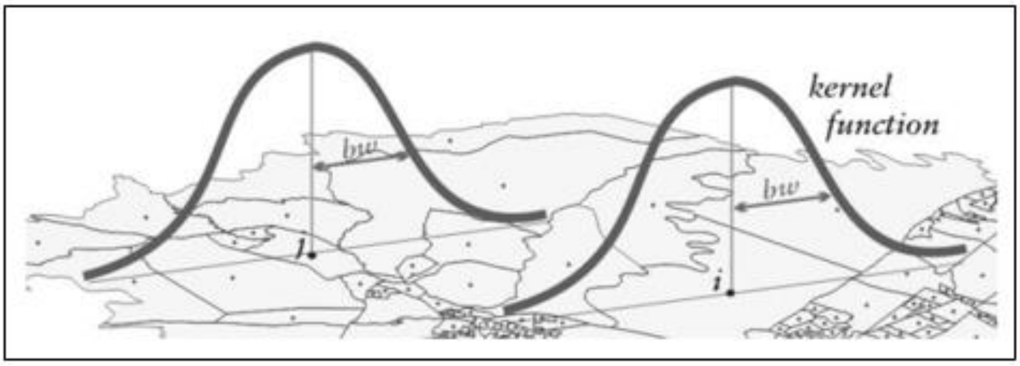


Figure 3.3: Gaussian Kernel Estimator (Feitosa et al., 2007)

Feitosa et al. (2007) suggested that local population intensity can be seen as a subtype of the composite population count (Wong, 2005). The authors defined the local population intensity as “a geographically-weighted population average that takes into account the distance between groups” (2007, pp. 303–304). It was also deemed useful to compare the local population intensity to the ‘population density of a local environment’ proposed by Reardon and O’Sullivan (2004). However, the measure of Reardon and O’Sullivan (2004) uses density values obtained from individual counts or aggregated estimation. In contrast, the local population intensity is the weighted average of population counts. Weighted counts (Feitosa et al., 2007) only depend on the spatial distribution of the population of a specific group in a neighbourhood, while weighted density (Reardon and O’Sullivan, 2004) rely on the distance between spatial units (spatial distribution) and also on the areas of the spatial units. Hence, the spatial unit sizes directly influence density-based measurements. Secondly, weighted density estimation measures are also not bounded like the weighted intensity counts, which always display an output from zero to one and is much easier to interpret.

Based on this concept of local population intensity, Feitosa et al. (2007) adapted spatial segregation indices from the measures of Reardon and O’Sullivan (2004):

i. *the generalized spatial dissimilarity index* $\check{\mathrm{D}}(m)$: measuring how each locality’s population differ from the composition of the population as a whole

ii. *the spatial exposure index* $\check{P}^{*}_{(m,n)}$: measuring the degree of potential contact between two different population groups

iii. *the spatial isolation index* $\check{Q}_{m}$: measuring the degree of potential contact between members of the same population group

For the purpose of applying spatial indices to a study, it is a requirement that the local population intensity of all the city's localities is calculated first. Feitosa et al. (2007) presents equation for the local population intensity of a locality as follows:

$$\check{L}_j = \sum_{j=1}^{J} k(N_j) \tag{7}$$

where N_j represents the total population in the areal unit *j*; *J* is the total number of areal units in the study area and *k* is the kernel estimator that estimates each areal unit's influence on the locality *j*.

The global generalised spatial dissimilarity index $\check{D}(m)$, proposed by Feitosa et al. (2007), is a method for measuring how the population for each census sub-place differ (averagely) from the whole population of the urban area as a whole. This index provides a spatial version of the index Sakoda (1981) developed, known as the generalised dissimilarity index *D*(*m*). The spatial version by Feitosa et al. (2007) of the generalised dissimilarity index considers localities for measurement, rather than aerial units. Thus, the segregation dimension of evenness/clustering can be captured by applying a set of population groups. The authors provided the following formula for the generalised spatial dissimilarity index:

$$\check{D}(m) = \sum_{j=1}^{J} \sum_{m=1}^{M} \frac{N_j}{2NI} \left| \check{\tau}_{jm} - \tau_m \right| \tag{8}$$

where

$$I = \sum_{m=1}^{M} \tau_m \, (1 - \tau_m) \tag{9}$$

and

$$\check{\tau}_{jm} = \frac{\check{L}_{jm}}{\check{L}_j} \tag{10}$$

In the first two equations above, N represents the total population of the city, N_j the total population of aerial unit *j*, τ_m the proportion of a certain group m in the city, $\check{\tau}_{jm}$ is the local proportion of population group *m* in the locality *j*, *J* represents the total number of areal units in a study area and M is the total number of population groups considered. In the third equation $\check{L}_{jm}$ represents the local population intesity of population group *m* in locality *j*.

The $\check{D}(m)$ index has a variation from 0 to 1, where 0 reflects a minimum degree of evenness and 1 a maximum degree. Feitosa et al. (2007) also emphasized the importance of recognising the difference between $D(m)$ and $\check{D}(m)$. The aspatial index $D(m)$ does not measure intensity across the boundaries of aerial *j* (discussed in the equation above). $D(m)$ makes use of the proportion of group n in areal unit *j* and not the local proportion $\check{\tau}_{jm}$ of the group *m* in the locality *j*, which is applied by the spatial $\check{D}(m)$. However, the spatial index $\check{D}(m)$ is sensitive to interaction at the local level and might therefor be much lower than the aspatial index when a multi-group area with ethnic homogeneous census areal units is considered.

The global spatial exposure index measures potential contact that may occur between two population groups in the sample area.

$$\check{P}^{*}_{(m,n)} = \sum_{j=1}^{J} \frac{N_{jm}}{N_m} \left(\frac{\check{L}_{jn}}{\check{L}_j} \right) \tag{11}$$

Where N_{jm} represents the total of population group m in areal unit *j*; N_m is the population of group m in the study area; $\check{L}_{jn}$ Is the local population intensity of group n in locality j and $\check{L}_j$ is the local population intensity of the locality *j*.

The index ranges from 0 (minimum exposure) to 1 (maximum exposure). This spatial version of the exposure index is also sensitive to the interaction of different groups across areal unit boundaries. Feitosa et al. (2007) noted that the outcome of the exposure and isolation indices is dependent on the composition of the city as a whole. The authors provide the example of the exposure index of group *m* to group *n* being higher usually when the proportion of group *n* in the city is high. In such a scenario the members of group *n* might rather interact with other groups. Hence, the exposure index is found to be asymmetrical, meaning the exposure index of group *m* to *n* will differ from the same index of group *n* to *m*. Feitosa et al. (2021) pointed out that absolute isolation and exposure indices, ranging between 0 and 1, are significantly dependent on the city-wide proportions of the studied groups and that such a dependency proves to be problematic for comparative studies.

The global spatial isolation index measures the potential contact that may occur between individuals who belong to the same population group. Feitosa et al. (2007) presented the following equation for the spatial isolation index:

$$\check{Q}_m = \sum_{j=1}^{J} \frac{N_{jm}}{N_m} \left(\frac{\check{L}_{jm}}{\check{L}_j} \right) \tag{12}$$

where N_{jm} represents the total of population group m in areal unit *j*; N_m is the population of group m in the study area; $\check{L}_{jm}$ is the local population intensity of group m in locality j and $\check{L}_j$ is the local population intensity of the locality *j.*

The index also ranges from 0 (minimum isolation) to 1 (maximum isolation).
In consideration of the fact that segregation varies spatially (Wong, 2002), especially in larger cities in which global segregation indices are not able to capture local segregation trends, Feitosa et al. (2007) proposed the decomposing of the global segregation indices to obtain local spatial indices. The local segregation indices will then indicate to what degree each locality makes a contribution to the global measure of segregation of the city. Hence, local indices are provided in a way suitable for mapping and visualising extents of segregation. Subsequently, the Local Dissimilarity Index, Local Spatial Exposure Index and Local Spatial Isolation Index were developed. The formula for the local spatial dissimilarity index is presented by Feitosa et al. (2007) as follows:

$$\check{d}_j(m) = \sum_{m=1}^{M} \frac{N_j}{2NI} \left| \check{\tau}_{jm} - \tau_m \right| \tag{13}$$

where the parameters for the equation reflects that of the equation for the generalized dissimilarity index

The local spatial exposure index of population group m to n is as follows:

$$\check{p}^*_{j(m,n)} = \frac{N_{jm}}{N_m}\left(\frac{\check{L}_{jn}}{\check{L}_j}\right) \tag{14}$$

where the parameters are the same as for the global spatial exposure index

In consideration of the local spatial exposure index, the local isolation index will effectively be as follows:

$$\check{q}^*_{j(m)} = \frac{N_{jm}}{N_m}\left(\frac{j(\check{L}_{jm})}{\check{L}_j}\right) \tag{15}$$

where $j(\check{L}_{jm})$ is the local population intensity of group m at the locality j

Johnston (2004) suggested that although the index of isolation is useful to study the level of segregation found between ethnic groups, there is one issue that needs solving in order for "cross-city comparison" (2004, p. 556) to be more significant. The absolute index of isolation discussed thus far assumes that ethnic groups are randomly distributed across the census areas of a city. If this was indeed the case, the larger a group is as percentage of the total population the larger its index of isolation would be - consequently the higher the probability that a member of the group will randomly interact with a member of another group.

Thus, Cutler et al. (1999) and Noden (2000) proposed that the formula (6) for the index of isolation should be adjusted as follows to take into consideration the relative size of an ethnic group:

$$MI_{ij} = I_i - \left(\frac{X_{ij}}{T_j}\right) \tag{16}$$

where MI_{ij} is the modified isolation index for the ethnic group *I* in census tract *j;* I_i is the index of isolation for the ethnic group *I,* X_{ij} is the total population of ethnic group *i* in census tract *j* and T_j is the total population of census tract *j.*

Following on from the four adapted spatial segregation indices by Feitosa et al. (2007), a study by Barros and Feitosa (2018) further contributed to the development of spatial segregation indices by testing and applying a global and local spatial version of the Information Theory Index *($\breve{H}$)* to the study areas of São Paulo and London.

The global index *($\breve{H}$)* relies on the Theil Theory of Information Index (Theil and Finizza, 1971) to compare the entropy of the whole study area (*E*) with the entropy of locality ($\breve{E}_j$) and is presented as follows:

$$\breve{H} = \sum_{j=1}^{J} \left[\frac{N_j\left(E - \breve{E}_j\right)}{EN} \right] \tag{17}$$

where

$$E = \sum_{m=1}^{M} (\tau_m) \ln\left(\frac{1}{\tau_m}\right) \tag{18}$$

$$\breve{E}_j = \sum_{m=1}^{M} (\check{\tau}_{jm}) \ln\left(\frac{1}{\check{\tau}_{jm}}\right) \tag{19}$$

where *J* is the total number of areal units in the study area, *M* the total number of population groups and *N* the total population in the study area. N_j is the total population in areal unit *j*, with τ_m the proportion of group *m* in the study area and $\check{\tau}_{jm}$ the local proportion of group *m* in locality *j*.

The global index *($\breve{H}$)* captures the average of the entropy of the localities and expresses it as a fraction of the entropy of the study area as a whole. It ranges from 0 (integration - all localities have the same entropy of the study area) to 1 (maximum segregation – all localities contain only one group). In turn, the local information theory index $\breve{h}_j$ presents a decomposition of the global index *($\breve{H}$)* and reflects the level of contribution each locality makes to the global indices:

$$\breve{h}_j = \frac{N_j\left(E - \breve{E}_j\right)}{EN} \tag{20}$$

where N_j is the total population in areal unit *j, N* the total population in the study area, *E* the entropy of the whole study area and $\breve{E}_j$ is the entropy of locality *j*.

The local information theory index $\breve{h}_j$ will present a negative value when the local entropy ($\breve{E}_j$) of locality *j* is greater than the global entropy (*E*)*,* indicating that local is more diverse than the study area as a whole. Positive values will reflect the opposite occurrence.

3.3 Application of Segregation Indices to South African Cities

The discussion on urban segregation in the South African city in Chapter 2 shed light on the fact that although urban segregation can be traced back to the colonial era, prior to the Union of South Africa in 1910, it was propagated through the segregation and apartheid eras that followed. Consequently, a comparison of the degree of racial segregation between the colonial, segregation, apartheid and post-apartheid eras has been a focus area of South African research since the 1980's (Parry and van Eeden, 2015).

Table 3.1 provides an overview of segregation measurement studies ranging from the first census in 1911 to the most recent census of 2011 and includes the indices applied to each study, the geographical extent of the study areas, the enumeration tract sizes and boundary conditions that were incorporated. However, all of these studies focussed on racial groups only. The racial groups of Black African, Coloured, Indian/Asian and White were used in all studies, even though the Coloured and Indian groups were combined in the 1911 census.

Table 3.1: South African Segregation Measurement Studies

Author/ Researcher	Census Year	Segregation Indices Applied	Geographic/Study Area Extent	Geographic Unit/Census Tract Size
(Christopher, 1988)	1911	Index of Dissimilarity & Index of Segregation	Various cities and towns, **incl. Cape Town**	-Enumeration areas (500-1000 people each) -Only towns > 2000 individuals
(Christopher, 1989a)	1985	Index of Dissimilarity	Various cities and towns, **incl. Cape Town**	-Urban areas grouped into magisterial districts
(Christopher, 1989b)		Index of Segregation	Cities and Towns by Provinces	-Urban numeration areas (average 697 persons per tract) Groups < 25 members in urban area excluded
(Christopher, 1990)	1911, 1921, 1936, 1951, 1960, 1970, 1985	Index of Segregation	Cities and Towns by Provinces	-Enumeration areas (600-1500 people each) -Towns < 1000 people & < 3 enumeration areas excluded
(Christopher, 1992)		Index of Dissimilarity	Cities and Towns by Provinces	-Enumeration areas of various sizes -Urban areas < 2000 people excluded
(Christopher, 1994)	1985, 1991	Index of Dissimilarity & Index of Segregation	Cities and Towns by Provinces	-Enumeration areas (3-1800 tracts per town). -Communities < 25 members city-wide excluded
(Christopher, 2001a)	1996	Index of Dissimilarity	Various cities and towns, **incl. Cape Town**	-Urban areas grouped into magisterial districts -Towns < 5000 individuals & racial groups < 2% of total were excluded
(Christopher, 2001b)		Index of Segregation	Various cities and towns, **incl. Cape Town**	-Enumeration areas (120-250 households/400-800 people)
(Christopher, 2001c)	1911, 1921, 1936, 1951, 1960, 1970, 1985, 1991, 1996	Index of Dissimilarity	Cities and Towns by Provinces	-Urban areas grouped as magisterial districts -Only towns > 2000 individuals
(Christopher, 2005a)	1996, 2001	Index of Segregation	Cities and Towns by Provinces	-Urban enumeration areas (avg. 673 people) grouped as magisterial districts for each city/town
(Christopher, 2005b)		Index of Dissimilarity	Cities and Towns by Provinces	-Urban enumeration areas (avg. 673 people) grouped as magisterial districts for each city/town
(Horn, 2005)	1991, 1996, 2001	Multi-ethnic spatial segregation index SD(m)	City of Pretoria	-Sub-place census area
(Rospabe and Selod, 2006)	1996	Index of Dissimilarity (1955)	**Cape Town**	-Enumeration areas
(Hamann and Horn, 2015)	1991, 2011	Multi-group segregation index D(m) & 'Interaction'/Exposure	City of Tshwane (Johannesburg)	-Sub-place census areas
(Parry and van Eeden, 2015)	1991, 1996, 2001, 2011	Index of Dissimilarity & Theil Index	**Cape Town** and Johannesburg	-'Fishnet' of grid cells (sizes vary: 1-8 square km)
(White et al., 2016)	1996, 2001, 2011	Index of Dissimilarity & Theil Index	Province of Gauteng	-Small Area Layer census tracts -Average 20 000 people per ward.
(Katumba et al., 2019)	2011	Spatial information theory index (H)	Province of Gauteng	-Sub-place census areas (total of 2579 areas)

An early segregation measurement study undertaken in the South African context was by Christopher (1988) and focussed on the 1911 census data. The author applied the index of dissimilarity (Duncan and Duncan, 1955a) and an adopted index of segregation (Duncan and Duncan, 1955b), which measures the level of segregation between a subgroup and the remainder of the population of the study area. Although segregation levels were discovered to differ between provinces, it was found that the Black African population was most segregated by 1911. The Black African and Coloured population in Cape Town were found to be less segregated compared to other South African cities.

In successive studies Christopher (Christopher, 1989b, 1989a, 1990, 1992, 1994, 2001a, 2001b, 2001c) applied the same segregation indices and presented a narrative of how racial segregation patterns changed across provinces in South Africa over the years since the colonial period, with the main aim of a comparative analysis for monitoring desegregation progress. Making use of data from Census 1911 to 1996 and then Census 1996 to Census 2001 (Christopher, 2005a, 2005b), change in segregation levels was measured. Although Black African and Coloured segregation decreased between 1911 and 1921, segregation levels for all racial groups increased significantly between 1921 and 1991, due to segregationist practices and policies. The White population remained most segregated of all racial groups from 1921 and although the Coloured population was least segregated between 1911 and 2001, a dramatic increase in segregation was noticeable between 1921 and 1991, with forced removal from designated White areas in the apartheid era further increasing this rate.

Black African-White segregation levels were significantly high already in 1911, with Black African - Indian/Asian segregation the highest of all groups from 1921, resulting from the forced segregation of Indian/Asian groups from the Black African areas to limit the business interests and prosperity of the Indian/Asian inhabitants. Segregation levels for Cape Town between 1911 and 1985 were significantly high between most groups by 1985, with segregation between Black African and all other groups the highest for all census years. Although Coloured-Asian segregation levels were lowest from 1911 to 1985, a significant increase is noticeable from 1960 (apartheid era).

A comparison of the second post-apartheid census of 2001 to the census of 1996 assessed the degree of racial integration that occurred in the towns and cities of South Africa 10 years after apartheid was abolished (Christopher, 2005a, 2005b). White segregation levels remained highest at a national level and reflect a slight decrease since 1991, with the Black African and Indian/Asian population also slightly less segregated. Only the Coloured population was found to reflect a significant decrease in segregation levels at a national level since 1991. The segregation between White and Black African remained highest by 2001.

Horn (2005) contended that the aspatial index of dissimilarity generally applied to measuring segregation is not an appropriate methodology for the quantitative measurement of segregation in “multi-ethnic, spatially complex, late-modern city” (Horn, 2005, p. 58) and undertook a comparative analysis of the aspatial and spatial versions of the dissimilarity index. Applying the multi-ethnic spatial segregation index SD(m) (Wong, 1998), the 1991-2001 census data for the city of Pretoria was used to measure change in multi-ethnic segregation. Although the values obtained for the aspatial dissimilarity index reflected a high level of segregation for all racial groups in 1991, a decrease was noticed for all groups by 1996. The multi-group segregation index reflected corresponding values but was found to be more refined. Significant integration of the Asian and Coloured groups was found, but also increased segregation between the African and White groups. Horn (2005) suggested that the SD(m) index is more robust, as it is able to reflect distinctive patterns between the four racial groups and integrates the spatial and aspatial dimensions of segregation. Further developments of this concept include the work of Reardon and O’Sullivan (2004), which Feitosa et al. (2007) built their work on and was discussed in Chapter 3 of this thesis.

Rospabe and Selod (2006) studied the 1996 census data for Cape Town’s urban area to assess racial segregation levels between the city’s Black African, Coloured, Asian and White population groups. The authors applied the two-group dissimilarity index (Duncan and Duncan, 1955b) to measure levels of segregation between the racial groups. Significantly high segregation levels were evident between the Black African population group and all other groups, but also between the Coloured and White groups. In contrast, segregation was found to be lowest between the Coloured and Indian/Asian group. These trends are broadly similar to the findings of Christopher (2001a) for Cape Town, although the results of Rospabe and Selod (2006) are generally lower.

Hamann and Horn (2015) analysed racial-residential desegregation in the city of Tshwane (Gauteng province) by applying the two-group dissimilarity index, the multi-group segregation index D(m) by Wong (1998) and the interaction and isolation indices by Massey and Denton (1988). Although the Indian/Asian and Coloured groups were most segregated from all other groups in 1991, both groups were least segregated to other groups in 2011. In contrast, segregation of the Black African and White groups increased from 1991. All groups had a comparatively low interaction level, with the White and Black African groups very isolated. Continued segregation also occurred by 2011 in most former non-White Group Areas (especially Black African) at the periphery of the city where the Black African population is still most isolated (Hamann and Horn, 2015). The authors concluded that although spatial patterns changed, racial residential segregation is persistent in the study area. The study area was also compared to Cape Town where the areas of wealth and of low-cost housing persisted in the same locations as in the past.

Parry and van Eeden (2015) used the census data of 1991 – 2011 for the four racial groups (Black African, Coloured, Indian/Asian, White) to measure racial residential segregation and diversity at various spatial scales for both the cities of Cape Town and Johannesburg. The authors applied the dissimilarity index and although it was found that segregation decreased between all groups from 1991 to 2011, White-Black African segregation in both cities (especially Cape Town) decreased little in comparison to the more significant decrease in White-Coloured and White-Indian/Asian segregation in both cities. The White population in Cape Town was also found to be more segregated from other groups in 2011 than the White population of Johannesburg. Diversity was then measured with Theil's index, which highlighted clear patterns of low racial diversity in the (predominantly Black African) areas of Khayelitsha and Nyanga in Cape Town and similarly the Coloured suburbs of Atlantis and Mitchell's Plain in Cape Town, which were both demarcated Coloured areas (Parry and van Eeden, 2015).

White et al. (2016) studied the 1996, 2001 and 2011 census data to assess change in the level of racial residential segregation in the province of Gauteng since the end of apartheid. The index of dissimilarity was applied to Gauteng, with the Theil's information theory index (H) Theil and Finizza (1971) applied across all provinces. The trend of segregation from 1996 to 2011 showed that although there was a steady decline in segregation of all population groups in Gauteng, segregation levels remained high especially between the Black African and White groups, confirming previous findings (Christopher, 2005a; Hamann and Horn, 2015; Parry and van Eeden, 2015). Residential segregation declined noticeably for all provinces between 1996 and 2011. In the City of Tshwane (north of Johannesburg), the most evident desegregation occurred mostly in inner-city and outlying areas (Hamann and Horn, 2015). White et al. (2016) suggested that examination is possible of the hypothesis that areas of enforced segregation under the Group Areas Act remained segregated, while integration might be more noticeable in White areas.

Katumba et al. (2019) also pointed out the shortcoming of aspatial segregation indices and applied the spatial information theory index (H) to study the spatial distribution of racial residential segregation of the four main racial groups in the Gauteng Province. It was found that segregation levels decreased with an increase in the size of the radius. It is thus evident that low segregation levels are detected at large scales, supporting previous findings, including those of Parry and van Eeden (2015).

Although knowledge was enhanced of the general extent and trends of racial segregation in South Africa, opportunity exists in three main areas to expand on past research. Firstly, previous studies concentrated mainly on the measurement of racial residential segregation and little consideration was given to studying segregation by income, even though it was suggested that a shift in policy focus should occur from racial segregation to socio-economic disparity (Hamann and Horn, 2015). It remains to be seen what the level of segregation is between racial groups and income groups, how spatial residential patterns would vary between racial and income distribution and also whether a relationship can be detected between the subjects of race and income. Secondly, aspatial segregation indices such as the index of dissimilarity were widely applied, due to ease of application and calculation to study segregation and only a few studies applied spatial indices (Horn, 2005; Katumba et al., 2019). Consequently, the spatial distribution of population groups beyond areal unit boundaries was hardly considered. Thirdly, the dissimilarity index also only allows for measurements between two groups at a time and does not take into account the multi-racial composition of the study area.

In this thesis, the measurement of segregation in Cape Town (see Chapter 6) expands on previous studies in these three areas. Not only is segregation measured by both race and income and a comparative analysis undertaken, but also in combination as income by race to explore whether further insight could be obtained from finer dynamics. The application of spatial segregation metrics allows for the segregation measurements in this thesis to be sensitive to the spatial distribution and relationship of racial and income groups beyond the areal census units that are applied. Finally, the generalised dissimilarity index is applied and is appropriate for the measurement of segregation of multiple groups.

3.4 Summary

This chapter discussed the measurement of segregation as methodology for enhancing the understanding of segregation patterns and trends. Although segregation indices were continuously studied and enhanced since the 1950s, limitations were identified in the application of aspatial segregation measurements. A spatial critique of the dimensions of segregation led to a discussion of the development of spatial segregation measurements. The spatial segregation indices adapted by Feitosa et al. (2007) and Barros and Feitosa (2018) is of particular importance to this thesis. The proposition of spatial global and local versions of traditional segregation indices provides for the potential of representing and analysing segregation at multiple scales and also visualising spatial patterns of segregation at various locations across the study area. The application of spatial segregation indices also minimises issues experienced with the modifiable areal unit problem (MAUP), as suggested by Reardon and O'Sullivan (2004).

In Chapter 6 both global and local spatial segregation indices are applied to the study area of Cape Town, allowing not only for the visualisation and analysis of segregation patterns and trends across the study area, but also enabling a better understanding of the role race and income play in the persistence of segregation in Cape Town.

The following chapter will discuss modelling techniques that are available to explore the spatial residential distribution patterns of population groups, especially the occurrence of residential segregation, and which will be applied in this thesis to explore the persistence of racial and income segregation in the study area of Cape Town.

Chapter 4
Modelling Urban Segregation

Models are defined as simplified and theoretical representations of real-world systems, such as the application of urban models that test urban theory and functionality in the form of computer simulations (Batty, 2009). The application of modelling techniques to study urban systems has been a traditional methodology for more than five decades. With an increase in computational power and related tools, highly-aggregated modelling was expanded through the introduction of individual or agent-based modelling techniques from the mid-twentieth century to study disaggregated and interrelated components of urban systems and represent them in a more heterogeneous manner (Marceau and Benenson, 2011). Subsequently, focus increased on the notion of structure emerging from bottom-up processes where global patterns are generated from the local actions and interactions of entities (agents).

The previous chapter presented methodologies for measuring residential segregation. These techniques include the spatial segregation indices that are applied in this thesis (see Chapter 6) to understand the role income plays, in comparison with race, in the persistence of segregation in Cape Town and also to explore and contrast the spatial relationship and segregation patterns of racial and income groups in the study area. While the measurement of segregation provides a static representation of segregation dimensions, the objective of constructing an agent-based model of the study area is to explore the complex dynamics of racial and socio-economic segregation and how these dynamics contribute to persistent residential segregation in Cape Town. Hence, this methodology provides a bottom-up approach to examine and formulate an understanding of how the racial preferences and economic constraints of individual households contribute to emergent aggregate patterns at a macro-scale.

This chapter provides a discussion of the methodological framework of agent-based modelling that is applied in this thesis to explore the complex dynamics of racial and socio-economic segregation in Cape Town and how these dynamics contribute to the persistence of residential segregation. Section 4.1 presents an overview of the approach to studying the complexity of cities and urban segregation. A discussion is presented in Section 4.2 on the subject of agent-based modelling and related architecture, as methodology for studying complex urban dynamics. Section 4.3 provides a focus on agent-based modelling of urban segregation and related methodologies and studies. Section 4.4 presents an overview of the model development process, with the focus on design, construction and evaluation. Finally, Section 4.5 provides justification for the application of agent-based modelling to study racial and income segregation in Cape Town.

4.1 The Complexity Theory Approach to Cities and Urban Segregation

It was suggested that "the only consensus among researchers is that there is no agreement about the specific definition of complexity" (Antunes and Gonzalez, 2015, p. 216). Johnson (2009, p. 1) argued that the science of complexity defines the "study of the phenomena which emerge from a collection of interacting objects." A system can thus be deemed as complex if it is composed of various interconnected parts, reflecting dynamic interactions that result in emergent behaviour (McDonald, 2009) and where the system as a whole is thus more than the sum of the parts.

Batty (2007) defines cities as systems that are highly complex, reflecting a combination of processes that lead to unexpected events and emergent arrangements not directly obvious from the components of their processes. Batty (2008, p. 769) goes on to point out that cities "are no longer regarded as disordered systems" and that a strong order exists beneath the diversity of the city's physical form (Batty, 2008, p. 769). Cities reflect systems of social organisation with numerous interdependent economic and infrastructural facets in a densely built environment managed by political and social establishments (Bettencourt, 2013). Some of the most significant challenges presented by cities and urbanisation to our understanding of social systems are rooted in the nature of cities as complex entities (Bettencourt, 2015).

It is argued that "tremendous potential" exists for analysts in the application of complexity theory to urban and regional studies and related interdisciplinary collaboration (Wilson, 2000, p. 2), especially due to the fact that these systems reflect complexity in the dependence between entities and cannot be successfully studied from a reductionist approach (Miller and Page, 2007; Feitosa, 2010). The suggestion is thus agreeable that the "complexity theories of cities" provide a single theoretical foundation to a variation of properties and phenomena in the urban context and also new insight (reflecting basic properties of complexity) to the understanding of cities (Portugali, 2012, p. 5). Among these properties of complex systems presented by the author in the urban context, the three concepts of non-linearity, emergence and self-organisation that are important to this thesis are highlighted below:

Firstly, the property of *non-linearity* is evident in cities, where the local interactions and behaviours of individual agents in an urban environment may affect the city as a whole more significantly than a larger unit, such as a planning department. Urban segregation is also a result of the occurrence of “non-linear interactions between many independent households that are able to generate unexpected and counter-intuitive global patterns” (Feitosa, 2010, p. 36). This argument is supported by the suggestion that the heterogeneity of agents promotes the non-linear dynamics and behaviour of systems (Mercure et al., 2016) and in the context of urban segregation various mechanisms influence residential decision-making.

Secondly, the phenomenon of *emergence* is highlighted in cities, where the local interactions between individuals result in properties that are only present or detected at a global city scale. In the context of urban segregation, for example, a significant level of ethnic or cultural segregation at a city-wide scale does not necessarily suggest significant segregative behaviour at a local individual level (Portugali, 2012). Emergence is, thus, an important concept that applies to urban segregation, as the structure emerging at a macro-level is a result of the micro-level interaction amongst a large number of individual entities (Schelling, 1971), such as households constantly choosing most desirable residential locations (Feitosa, 2010). Consequently, limiting the study of segregation as a complex system to only micro-level elements such as residential choice and mobility (Kronenberg and Carree, 2012) or macro-level structures such as spatial arrangement of different ethnic or social groups (White, 1983; Wong, 1998; Reardon and O’Sullivan, 2004) presents difficulty in truly understanding the system (Feitosa, 2010).

Self-organisation is another important concept of complexity, which can be understood as a dynamic process of adaption where the components of a system gather information from other components and their environment and respond accordingly without any central control or authority (Holland and Miller, 1991; Holland, 1996; Miller and Page, 2007; Feitosa, 2010). In the context of urban segregation, households may assess their neighbours and neighbourhoods and base residential decision-making on this information and consequently ‘self-organise’ to a more desirable location (Schelling, 1971; Benenson and Omer, 2001; Barros, 2004; Torrens and Nara, 2007; Benenson et al., 2009). Hegselmann (2017) suggested that segregation might also be unintentionally self-organised and void of discrimination.

Gilbert and Troitzsch (2005) emphasized that the only effective manner to study these complex properties of social urban systems is to develop a simulation model to simulate these dynamics. The most common application of simulation in the social sciences is to formulate an understanding in terms of social processes and mechanisms (Axelrod, 1997; Gilbert, 1998). Gilbert and Troitzsch (1999) suggested that three predominant periods/approaches have been identified over the last 50 years in the field of social simulation: macro-simulation, micro-simulation and agent-based modelling.

The macro-simulation approach of system dynamics was originally developed in the 1950's by Forrester (1958). Macro-simulations are generally constructed from sets of differential equations for the distribution prediction of population systems as all-inclusive function of other general factors. However, although system dynamics have been useful in the exploration of non-linearity of certain complex systems over a time period, it deals with aggregates instead of individual elements and consequently limits the possibility of modelling heterogeneity and more complex processes (Gilbert, 2008; Feitosa, 2010). The sentiment was shared by Ding et al. (2018), pointing out that system dynamics ignores the relationship between micro- and macro-behaviour and as a result it cannot explain the micro behaviours in a system and fully understand a complex system.

In contrast to system dynamics, microsimulation concerns the simulation of micro-behaviour of populations of individual agents over time (Orcutt, 1957). Gilbert (2008) suggested that an advantage of microsimulation is the fact that it starts from a real sample of agents, rather than from a hypothetical or randomly created set of agents. However, no communication or interactions exist between agents. Using the example of persons, Gilbert and Troitzsch (2005) surprisingly deemed the absence of interaction between individuals as an advantage of microsimulation. Although this methodology operates at the level of the individual to model local and global change, the capability of behavioural modelling is non-existent and modelling is also limited to one-directional effects such as policy impact on individuals (Crooks et al., 2018).

Agent-based modelling is a third modelling approach which rectifies the shortcomings of the previous techniques by not only facilitating the representation of individual units (agents), but also incorporating their decision-making and interaction with each other and their environment (Feitosa, 2010). The simulation of these interaction processes occurs at a micro-level, which allows for the exploration of the emergence of macro-structures from the bottom up, rather than top down (Miller and Page, 2007). Agent-based modelling offers the ability to generate individuals with numerous behaviours and attributes that can interact and move in geographic space, which is essential for developing toolkits to understand dynamical processes in geographical systems and especially the impact of the behavioural patterns of individuals (Crooks et al., 2018). Agent-based modelling thus presents a favourable approach to studying and understanding complex social systems, including the phenomenon of urban segregation.

4.2 Agent-Based Modelling

Agent-based modelling provides a computational approach to studying complex systems. Although agent-based systems have only been studied since the 1980's and specifically in the field of artificial intelligence, recognition was increasingly gained through research on complex social systems (Axelrod, 1997; Gilbert, 2004; Janssen, 2005; Abdou and Gilbert, 2009; Barros, 2012). From early on agent-based simulation was advocated as the foundation of a new and generative type of social science (Epstein and Axtell, 1996), which predominantly focusses on the simulation of interacting agents, which are boundedly rational and heterogeneous (Epstein, 2007). As a result, international research in social phenomena covered a wide range of subjects over the past couple of decades, including spatial settlement patterns (Dean et al., 1999), residential distribution (Benenson and Omer, 2001), rural-urban migration processes (Espíndola et al., 2006), crime prediction (Malleson and Evans, 2014) and urban segregation (Crooks, 2008; Benenson and Hatna, 2009; Alfasi et al., 2013; Aftika, 2014).

Axelrod and Tesfatsion (2006) outlined four main goals researchers in agent-based modelling aim for: *empirical understanding* of regularity development (standing ovations or trade networks), *normative understanding* in the evaluation of policy designs through modelling, *heuristic goals* of understanding causative processes in social systems and *methodological advancement* of tools and principles to enhance the study of social systems. In addition, a number of basic features also characterise agent-based models (Richiardi et al., 2006): Some models are technical in how they conducts time (continuous or discrete) and fate (deterministic or stochastic) and how space (topology) and the evolution of populations (procedures for birth and death) is represented. Other models are noticed for being less technical, especially in how heterogeneity (how individuals or entities differ from each other) is managed, how interaction is structured and how the types of individual behaviour are represented.

Crooks and Heppenstall (2012) highlighted three main advantages, stipulated by Bonabeau (2002), of agent-based modelling over the more traditional modelling techniques: a) the ability, as bottom-up approach, to capture emergent phenomena, b) the representation of real systems in a natural environment where it could be studied and c) flexibility in the development of models and consequently the ability to extend or adapt models over time. In addition to these advantages, Crooks et al. (2018) argued that agent-based models are dynamic and can simulate the emergence of phenomena over time, in contrast to earlier static models in urban planning studies.

4.2.1 Components of an Agent-Based Model

The general composition of an agent-based model reflects the presence of *agents* and the *environment* in which they interact. These fundamental components are briefly discussed below:

Agents

Agents are defined as the basic entities of agent-based modelling and can represent individual entities such as people, cars or buildings (Crooks and Heppenstall, 2012) and also or collections of entities such as organisations (Tesfatsion and Judd, 2006). Agents have *properties* (internal and external state) and *actions* (behaviours) executed by them (Wilensky and Rand, 2015). The internal state of an agent, such as emotional status, are not observable to other agents, while the external state may refer to race of language for example. Agent properties effectively describe the characteristics of agents, including who or what they are (represent), their appearance and location in geographic space (if relevant to the particular model). Agent characteristics not only distinguish agents from each other, but also provide more detailed descriptions for agents, such as vehicle type or the gender of an individual for example (Crooks et al., 2018). Agent actions or behaviours are the manners in which agents can change itself, other agents or the environment it functions in and are directly linked to the decision-making processes of these agents.

Further to the above-mentioned characteristics, there is general consensus that the features of agents include learning and adaptation, goal-orientation, intentionality, reactivity and proactivity (Wooldridge and Jennings, 1995; Gilbert and Troitzsch, 2005; Gilbert, 2008; Macal and North, 2010). However, the above-mentioned characteristics are not essential and for the modelling undertaken in this thesis, the following elements are most important:

- *Self-contained* – An agent can be identified as unique and consist of attributes allowing agents to be distinguished from other agents and also recognised by other agents.
- *Autonomous* – Agents act and make decisions independently from external factors or influence from a centralised control.
- *State* – Agents also have a state, which may vary over time and represents the variables associated with the current situation of the agent.
- *Heterogeneous* – Agents could be diverse across a population and may vary in terms of sophistication, attitude to interaction or even the amount of information it considers in making decisions.
- *Bounded Rationality* – Rational-choice models are generally based on the assumption that agents are rational entities. However, perfect rationality in human decision-making is absent due to limited availability of information and reasoning capacity. Nonetheless, decisions are taken to serve the relevant requirement despite limitations.

Environment

In an agent-based model the environment defines the area/space in which agents move or function and effectively comprises of the "conditions and habitats surrounding agents" as they are acting and also interacting within a model (Wilensky and Rand, 2015, p. 234). However, it should be noted that the model environment is not necessarily of a spatial nature and may either be neutral or have no effect on the agents (Gilbert, 2008). For example, simulation models of communication networks or institution relationships (information sharing) reflect a more abstract environment. Robertson (2003) studied the application of agent-based models to simulate banking networks, for example.

The environment of a spatial agent-based model may also support agents in their interaction with other agents or the environment. Hence, depending on the defined space for agent interaction, proximity can be defined by spatial distance, adjacency of grid cells or the connectivity found in social networks (Crooks and Heppenstall, 2012). Agents may be spatially explicit or implicit within the modelling environment. Spatially explicit agents have a location in geometrical space, while spatially implicit agents in contrast find their location to be irrelevant within the modelling environment (Crooks and Heppenstall, 2012).

The agent-based models in which the environment represents space geographically and potentially affect the agents moving around in it are particularly suitable for the simulation of phenomena in which distance plays a significant role, such as segregation models (Benenson and Portugali, 1997; Benenson et al., 2002; Crooks, 2008; Feitosa, 2010). In the segregation model this type of representation of space can provide geographical orientation which will allow agents to identify proximity and recognise other agents in their locality. It may also provide information on urban features, such as property prices and dwelling availability, which might be relevant to the decision-making processes of agents (Feitosa, 2010).

The integration of geographical information systems (GIS) into agent-based models allows for the representation of real world geographical space and phenomena (Heppenstall et al., 2011; Crooks and Castle, 2012; Crooks and Wise, 2013). This capability allows the model environment to rely on the geographical data provided by GIS after integration with the agent-based model and also the potential for analysing the model output in GIS again (Parker, 2005). The integration of GIS plays a significant role in the development of the agent-based model in this thesis and the methodology is presented in Chapter 5.

4.3 Agent-Based Modelling of Segregation

Given the discussed characteristics and potential of agents and their environments to represent real world systems in geographic space, agent-based modelling is a popular approach to study social phenomena, such as segregation. A variety of social phenomena were highlighted, which have been studied through the application of agent-based models (Macal and North, 2010), while other modelling approaches fall short of modelling their dynamics easily (Macy and Willer, 2002; Gilbert and Troitzsch, 2005).

Sakoda (1971) was one of the first researchers to formulate a social agent-based model, the Checkerboard Model, which incorporated the term ‘segregation’ in defining specific patterns. The model was a simulation of social interaction between the members of two groups, with their movement based on positive, neutral or negative attitudes toward one another. Thomas Schelling applied a similar approach in developing and proposing the Schelling segregation model as part of a set of models, known as the 'dynamic models of segregation', to explain racial segregation observed in American cities (Schelling, 1971, 1978). Although the Schelling model is quite abstract and deemed as only an instance of the Sakoda model (Hegselmann, 2017), Schelling was able to show that segregation patterns can emerge without being implied or consistent with the objectives of individual agents (Macal and North, 2010). Hence, it was one of first notable conceptual agent-based models in social science.

Subsequently, the Schelling model provided a significant foundation for agent-based modelling of segregation and influenced much work that followed, concerning the understanding of persistent segregation in the urban environment (Gilbert, 2008). It should be noted that the models of both Sakoda and Schelling were retrospectively labelled as agent-based models, as the field of agent-based modelling did not exist at the time of these studies, in the early 1970's. The Schelling segregation model forms the foundation on which the agent-based model in this thesis is based. The following sections respectively provide a brief discussion of the dynamic models of segregation by Schelling and examples of further studies that were based on the Schelling segregation model.

4.3.1 Dynamic Models of Segregation

Thomas Schelling's 'Models of Segregation' was first published in 1969 and comprised of a 'proximity model', a 'bounded-neighbourhood model' and a discussion of the subject of 'neighbourhood tipping', which is explored through the two mentioned models (Schelling, 1969). The proximity model was developed to show how individual preferences and perceptions of difference can result collectively in segregation. Initially, Schelling constructed a one-dimensional linear model to convey the general idea. As shown in Figure 4.1, this one-dimensional model reflected a population which was randomly spread along a straight line. The agents (individuals) consisted of two different groups, which were represented by "circles" and "crosses", and the neighbourhood (in brackets) include the four nearest neighbours to the left and four nearest to the right of the central agent (coloured in red and green). The circle in red represents an 'unhappy' agent and the circle in green an agent that is 'happy'.

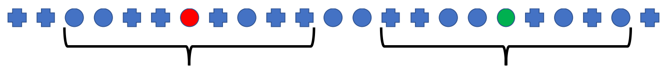


Figure 4.1: Schelling's Linear Proximity Model

Schelling then supposed that each agent in the model wants at least half (four of eight) of his neighbours to be the same kind as him in order for that agent to be happy (green). If less than half of its neighbours are of the same kind, the agent would be unhappy (red). The rule for the individuals that are located close to the ends of the line stated that the four neighbours towards the centre are considered and also whatever the number is on the other side. A rule was then determined for movement and entailed the movement of an individual to the nearest position where his "minimum demand" is met. Effectively it will be nearest point where half of his neighbours will be the same as him when he arrives. Thus, unhappiness (agent in red) in the ratio of neighbours results in the agent moving to various positions, until happiness is experienced (agent in green). It was evident in the model above that five specific elements were emphasized. These elements are the size of the neighbourhood, the percentage of "own kind" demanded, the ratio of one kind to the other in the total population, the rules governing movement and also the original configuration.

Following the proximity model, Schelling developed a two-dimensional model in the form of a grid or checkerboard (see Figure 4.2), which became widely known as the Schelling segregation model (Schelling, 1971, 1974, 1978). Where the eight neighbours of an agent in the proximity model were located on both sides of the agent, they were now situated in the eight grid cells around a particular agent's grid cell. This neighbourhood is also known as the Moore neighbourhood (Wilensky and Rand, 2015).

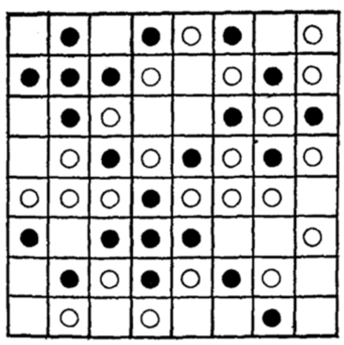


Figure 4.2: Initial Condition of Schelling's Two-Dimensional Model (Schelling, 1974)

When an individual moved in the linear model from between two neighbours to a new location, all other individuals would move to make room or fill the vacant location. In the two-dimensional model a rule was required to allow for the same type of movement – to govern who moves into which direction to make space for a new individual or to close up a vacant location. To solve this problem Schelling considered absolute space rather than a relative position. He divided the study area into a matrix of similar sized cells.

While some cells were left vacant, as shown in Figure 4.2, the rest of the cells were randomly occupied by individuals (agents) from two different groups. It was essential to leave an adequate number of vacant spaces in order for individuals to have significant choice of where to move. The neighbourhood in this environment was defined as the eight neighbouring cells of an individual. The movement rule was established and dictated that an individual who is discontent with his neighbourhood will move to the nearest vacant location which will surround him with a neighbourhood that meets his need. It was then specified what the neighbourhood demands are and also the movement rule of moving to the nearest location that is satisfactory.

A number of the parameters of the linear model was applied: an equal number of individuals for the two groups, distributed randomly among the squares/cells; the neighbourhood defined as the eight locations surrounding the individual's location (also known as the Moore neighbourhood) and the demand of at least 50% of the neighbours being of the same kind, with the dissatisfied moving to the nearest satisfactory vacant space. The pattern resulting from this process reflected a highly segregated state, as is evident in Figure 4.3.

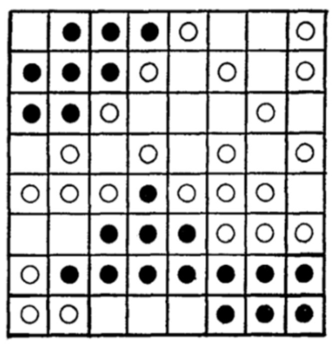


Figure 4.3: Segregated Pattern as Outcome of Schelling's Two-Dimensional Model (Schelling, 1974)

Schelling (1971) emphasized that even when a preference for similar neighbours is less than 50%, the outcome will still reflect a high degree of segregation. Considering the discussion of ‘preferential’ segregation (the preference of an agent for a specific percentage of its neighbours to be of the same kind), such a preference of less than 50% for similar neighbours may indicate the desire of individuals to be near their own kind, rather than reflect prejudice towards other types of neighbours.

Schelling’s segregation model has become one of the most acclaimed and cited models in economics and the emergence of segregation in this model was considered by Pancs and Vriend (2007, p. 2) as “intellectually intriguing”. Although motives and decisions at a micro (local) level result in behaviour at an aggregate level, this macro behaviour does not correspond to the underlying micro motives. This is evident in the fact that segregation occurs although not even one individual had a preference for it. Schelling’s model is also very informative, as it provides a relatively simple means to illustrate the concept of unintended consequences of interaction between different individuals. One of the main reasons for renewed interest in Schelling’s model is the fact that segregation in the urban environment became one of the largest socio-political and economic issues internationally.

The importance of the Schelling segregation model was also expressed by Clark and Fossett (2008), emphasizing the significance of understanding the social context of the model. The authors argue that, apart from the value of physical models explaining spatial distribution of segregation, the most important subject from a social perspective is the manner in which “choices play out in the social fabric” and lead to residential segregation patterns (2008, p. 4109). The authors concluded that further attention is required in the understanding of how segregation is shaped by a combination of socio-economic inequality and race/ethnicity residential choice. Hence, opportunity exists for the expansion of the body of research undertaken using the Schelling segregation model as foundation, to better understand the dynamics of segregation (especially regarding residential choice) in real urban geographies (Lloyd et al., 2015).

To date, various researchers have applied the Schelling model to real-world situations in order to provide likely approximated outcomes of segregated and complex distributions, which can be observed in cities. This is evident from the studies that tested this model with empirical data (Benenson et al., 2002; Bruch and Mare, 2006; Romans Pancs and Vriend, 2007; Zhang, 2004, 2011). The Schelling segregation model was also extended to model racial segregation in terms of neighbourhood preferences (Clark, 1991) and study residential segregation of ethnic groups in the urban context (Portugali et al., 1994). Cultural and income preferences of neighbourhoods were also incorporated to study segregation dynamics (Dean et al., 1999; Bruch, 2006) and researchers included dynamics like preferences for a certain neighbourhood status, quality of housing and varying levels of socio-economic inequality within different ethnic populations (Fossett and Senft, 2004; Abdou and Gilbert, 2009; Zhang, 2011; Patel et al., 2018).

Crooks (2008) also provided guidance on the development and potential expansion of agent-based models that incorporate GIS in segregation studies. The study of Benenson et al. (2002) provides a good example in the combination of individual census data and GIS data to represent urban infrastructure to study ethnic residential segregation in the neighbourhood of Yaffo in Tel Aviv, Israel. The authors studied the residential dynamics of Yaffo by constructing a real-world model of residential choice and migration to understand the factors influencing residential decision-making and also how residential dissonance could be quantified.

The discussion in this section not only provided a clear overview of the essential development and usefulness of agent-based modelling methodologies for studying the dynamics of segregation, but also presented case studies where the Schelling segregation model was applied as foundation to expand on and study real world segregation phenomena. Considering agent characteristics in the context of urban segregation modelling, it is evident that agent-based modelling presents a useful approach to the development of agents in such a modelling exercise. Heterogeneous individuals can thus assess their current state, make rational decisions on the relevant information they receive and act autonomously to alter their circumstances. However, the development of an agent-based model is a significant and important process and by no means a simple task. The following section provides a discussion on the modelling process and considers the design, construction, and evaluation of an agent-based model.

4.4 The Agent-Based Modelling Process

A number of fundamental stages are generally present in the modelling process, even though the methodological steps undertaken by different researchers may vary. This section discusses the following stages (Gilbert and Troitzsch, 2005; Heppenstall et al., 2011; Crooks et al., 2018): model design, model construction and model evaluation.

4.4.1 Model Design

The key starting point of a simulation study is the model design stage and the identification of a specific problem of interest and consequently specifying the objective of the study (Feitosa, 2010). This is established by defining the research target more specifically (Heppenstall et al., 2011). Agent-based models are usually based on assumptions of micro-level dynamics and such assumptions need to be communicated clearly and be supported and justified by existing theories (ibid). Defining the purpose of the model is another challenge and essential step, as it would guide the development of the model (Crooks et al., 2008). Once the research objectives have been established and the assumptions made around the target system, the theoretical and related conceptual formulation of the model is usually undertaken. Miller and Page (2007) suggested that specifying a theory is the reduction of the world to a set of elements and laws to understand a certain phenomenon better.

Since every model is effectively a simplification of the target system, the most challenging step in designing a model is the decision of what needs to be included and also what needs to be left out (Gilbert and Troitzsch, 2005). It is thus important to determine the level of detail that would be considered in the model and whether the type of model would be "abstract, middle range or facsimile" (Feitosa, 2010, p. 52). Consequently, there is a need at this stage to define how the real-world system will be represented as components in the model, in terms of the agents, their interaction and the environment (ibid). Thus, scientists build models for the purpose of reducing complexity of the studied world and to isolate the elements that causes the phenomenon to be explained (Salgado and Gilbert, 2013).

Subsequently, the conceptual model is generated to present a general overview of the considered agents, environment and interactions of the planned model and potential external factors that may influence the modelled phenomenon. Firstly, the researcher specifies the agents of the model, which would represent the 'actors' of the real-world system. The attributes and behavioural rules for each type of agent needs to be specified. The attributes are characteristics or features of an agent and the behavioural rules consist of a set of rules specifying how agents will act and potentially react to their direct environment (Salgado and Gilbert, 2013). The environment of the model also needs to be specified and how it could potentially influence or support the actions of the agents. Hence, would the environment be a geographical space potentially and if indeed so, would it consist of properties that will be considered by the agents?

The theoretical specification of the model components is undertaken and concerns the design and building of the model's architecture, including the details of the modules that the system will comprise of. It is important at this stage to define an approach for designing the architecture of the model's agents (Feitosa, 2010). Different approaches of agent architecture exist, depending on the envisaged tasks of the agent and their interaction with other agents and the environment (ibid). These approaches thus concern the design of an agent's perception of other agents and the environment, how they evaluate circumstances and how decision-making is undertaken in response. Once the design of the model has been specified, the following step concerns the building of the model.

4.4.2 Model Construction

The model construction or building stage of the agent-based modelling process concerns the translation of the conceptual model and related specification into a computer language. This stage could either involve the writing of a computer program from scratch or the application of an existing toolkit to assist in the development of the model. Gilbert (2008) suggests that although such a program can be written from scratch, it might be easier to apply one of many existing agent-based modelling platforms. However, Crooks and Heppenstall (2012) argue that programming languages like Java and C++ are frequently used to generate a model from scratch, as this approach provides total control over all aspects of the agent-based model, even though this approach could be very time-consuming.

Existing agent-based modelling toolkits do not require extensive coding experience and provide templates and conceptual frameworks allowing researchers to easily design and personalised model. A great advantage in the application of such a toolkit is the fact that there is no need for the user to spend time on cumbersome tasks like visualisation and graphical user interfaces (Heppenstall et al., 2011). Further consideration may also need to be given to the requirements of spatially explicit models for GIS data formats to be incorporated, in which case existing toolkits may be more accommodating and useful.

Examples of some of the most commonly used agent-based modelling platforms include Swarm (Minar et al., 1996), Cormas (Bousquet et al., 1998), Netlogo (Wilensky, 1999), MASON (Luke et al., 2005) and Repast (North et al., 2006). Although a number of researchers in agent-based modelling have provided reviews of and comparisons between these platforms, such as Abar et al. (2017), there exists general consensus that no platform is the most ideal and that it very much depend on the type of study undertaken (Railsback et al., 2006; Gilbert, 2008; Feitosa, 2010; Heppenstall et al., 2011; Crooks and Castle, 2012; Salgado and Gilbert, 2013). Hence, model construction requires careful consideration of the study to be undertaken to ensure that the most efficient platform is chosen. Once model construction has been completed, model evaluation is undertaken.

4.4.3 Model Evaluation

The model evaluation stage is one of the key challenges associated with agent-based models (Crooks et al., 2018), as the question is posed at this stage of how well the model simulates the studied phenomenon. The two model evaluation stages of verification and validation is discussed in this section. Balci (1994, pp. 121–123) stated: "Model validation deals with building the right model." "Model verification deals with building the model right."

Verification

Wilensky and Rand (2015, p. 311) defines model verification as the "process of determining whether an implemented model corresponds to the target conceptual model". Hence, the verification process is an exercise of checking if the simulation program executes what is stipulated in the theoretical specification (Feitosa, 2010). Model verification is important, due to the fact that errors in the writing of a program is a common occurrence, especially with more complicated programs (Heppenstall et al., 2011).

It should also be assumed that, regardless of how cautiously a simulation model is designed and built, it would still contain bugs (code doing something different than intended and expected) (Gilbert, 2008). The debugging process can be quite challenging to execute, especially with complex simulations, as it is difficult to be certain that all bugs were removed. The application of pseudo-random numbers in social science simulations are also expected to produce different outcomes, which also increases the difficulty of debugging a model (Gilbert and Troitzsch, 1999; Gilbert, 2008; Heppenstall et al., 2011).

Heppenstall et al. (2011) outlined model verification as a process consisting of two parts: face validation and sensitivity analysis. Face validation is applied to various aspects of the model at an early stage of development to ensure that the "processes and initial outcomes of the model are reasonable and plausible within the basic theoretical framework of the real system." (ibid:184) Firstly, visual validation is undertaken of agent attributes, agent behaviours and how accurate parameter changes are automatically updated in the interface (where relevant). Secondly, the model output is assessed to ensure that the results are within an acceptable range across all simulations. Thus, the model is run several times to generate the outputs regarding the characteristics of agents and the data visually analysed to ensure that it resides within a range corresponding to real world data. The final step in the face validation process concerns the checking of the level of consistency at which a model could generate similar outputs amongst different runs.

Sensitivity analysis is undertaken to study the influence of the input parameters on the behaviour and outcome of the model. This is an essential part of the verification process for selecting most significant and meaningful parameters before the model is applied. It may also result in the potential removal of parameters with an insignificant effect, ensuring that the model is more comprehensible and easier to operate. A common method is the modification of only one parameter at a time, while leaving the other parameter values unchanged (Happe, 2005). Heppenstall et al. (2011) agreed with this approach and proposed this simple verification method in the context of the Schelling segregation model, whereby extreme values are applied to each parameter in turn. This method effectively encapsulates what Gilbert and Troitzsch (2005, p. 24) refers to as the "principal behind sensitivity analysis" – varying the parameters and initial conditions of the model and observing differences experienced in the outcome.

Validation

While verification concerns whether the model is working as expected, model validation concerns the process of establishing whether an implemented model corresponds to the specific phenomenon in the real world it aims to simulate (Wilensky and Rand, 2015). Hence, the validity of a model can be established through the comparison of the model output to comparable data that was collected from the target system in reality (Crooks et al., 2008).

However, numerous challenges exist regarding the validation of social systems and these also attracts criticism of the application of multi-agent simulation models in the social sciences (Feitosa, 2010). The acquisition of suitable data for validating a model methodically remains a major challenge. Different criteria would also exist for model validation, as different models are developed for different purposes, including quantitative or qualitative predictions (Gilbert, 2008). The validation process also requires a clear understanding of what the model attempts to explain and what the rules are (Ormerod and Rosewell, 2009).

Gilbert and Troitzsch (2005) outlined a number of caveats for modellers to be mindful of. Firstly, it is likely that both the model and target processes are based on random factors (stochastic) and precise correspondence should not be expected. Secondly, the outcome of many simulations depends on (and may be sensitive to) specific initial conditions, which could affect the simulation. Thirdly, there may be aspects of the target system that the model cannot reproduce, even when the simulation results match those of the target. Fourthly, the possibility exists of data about the target system being incorrect, regardless of the fact that the model might be correct. Finally, it can also be challenging to relate the outcomes and conclusions made from a highly abstract model to any data or information from the target system.

Two areas were highlighted by Gilbert (2008) for consideration in validating models: firstly, how theory fits the model about that theory and secondly, how the model fits to the real-world phenomenon it is simulating. The first approach is best undertaken by considering theory to derive various proposals about the dynamics of the relationship between variables and then checking whether the expected distributions do occur when the model is run with various parameter settings. Gilbert (2008) stated that the choice of parameter combinations can be problematic and propose the application of prior knowledge of the target system to restrict parameter ranges. Secondly, the consideration of how the model fits the real-world phenomenon (empirical data) is necessary for models that are anticipated to match real-world scenarios. Such a comparison can analyse how reality agrees with the model outputs in both a qualitative or quantitative manner, depending on the type and purpose of the particular model (Feitosa, 2010).

Regarding validation and the Schelling model, Heppenstall (2011) pointed out that the main objective of the Schelling model is to provide an explanation for an existing persistent phenomenon rather than to replicate patterns of existing segregation and that the model was successful in this regard.

4.5 Agent-Based Modelling of Segregation in Cape Town

Agent-based modelling was chosen as favourable methodology for this study, to explore the role race and income play in the persistence of segregation in Cape Town. Applying agent-based simulation will allow for a bottom-up approach whereby the decisions of households and the influence of these decisions on other households could be considered at a micro-level and the resulting emergent segregation patterns explored at an aggregate macro-level (Zuccotti et al., 2021). Crooks et al. (2008) found that an increase in preference of agents to reside with specific group can result in the emergence of significant segregation that does not progress in a linear manner. In sociology, the contribution of agent-based modelling to segregation studies is recognised in its ability to represent processes in which agent (movement) behaviour may unintentionally change social structures and social structures also change agent behaviour (Chattoe-Brown, 2013).

An adaptation of the Schelling segregation model (Schelling, 1971) in this thesis, by incorporating household income dynamics, will allow for the exploration of an additional level of socio-economic complexity. With reference to the Schelling model (Schelling, 1971), Kurgan et al. (2019) pointed out that 'white flight' (where White people migrate from an area that is becoming more racially diverse) in American cities was never simply a result of unhappy individuals, but rather an occurrence that was encouraged by both federal housing policies and the underlying racism of the real estate sector and enhanced economic mobility of White households. Consequently, the authors argue that mathematical models cannot capture these complex processes easily (Kurgan et al., 2019).

Agent-based modelling provides a suitable methodology to study these complex systems, where numerous entities interact in a non-linear manner and may result in unexpected and even contradictory outcomes. Helbing and Balietti (2012, p. 36) argue that "even though linear models may be sensitive to parameter variations or perturbations, they cannot explain self-organization or emergent phenomena in socio-economic systems". Hence, methodologies for considering non-linear interaction are essential to understand processes in social and economic systems (Helbing and Balietti, 2010).

The development of a spatially explicit model for the study area in this thesis was enabled by the possibility of combining agent-based modelling interfaces with real world georeferenced data (in GIS format) to develop models based on empirical data. Consequently, the decision-making of agents is also influenced by spatial factors, such as neighbourhood size, non-residential urban land and physical barriers (Crooks, 2008). Camargo (2020) emphasises that the suitability of linear approaches is limited when considering model outputs that are fundamentally multi-dimensional and dependent on various factors.

4.6 Summary

This chapter discussed the fact that urban systems reflect a certain degree of inherent complexity and that urban research has evolved over the past five decades to enhance consideration of the occurrence of complexity in the city. Agent-based modelling was explored as a favourable methodology for simulating and exploring the complex dynamics of urban segregation from the bottom up. This discussion was supplemented by a consideration of basic agent-based modelling concepts and an outline of the methodological steps to conceptualise, generate and evaluate an agent-based model.

Applied to social processes, agent-based modelling uses concepts and tools from social science and computer science to present a methodological approach that could ultimately permit two important developments: (1) the exploration and extension of existing theories that may prove difficult to evaluate using alternative methodologies and (2) a deeper understanding of complex dynamics, such as persistent segregation, in multi-agent systems. The Schelling segregation model was highlighted as significant for the modelling of segregation and forms the foundation of the agent-based model developed in this thesis.

The following chapter introduces the study area of Cape Town and the methodologies applied in this thesis for the measurement and modelling of racial and socio-economic segregation in Cape Town. Furthermore, the data applied in the undertaking of these methodologies is discussed.

PART 2

The Measurement & Modelling of Segregation in Cape Town

Chapter 5
Methodology

Given the legacy of racial segregation and subsequent economic disparity in the South African city, the subjects of race and income were deemed as the most important demographic dimensions to consider in this thesis. Given the difficulty of quantifying dimensions such as wealth in the absence of essential information on asset ownership and debt (Chatterjee, 2019) in the South African context, income only serves as a proxy for socio-economic status. The subject of income has been used frequently to represent socio-economic levels in segregation and inequality studies (Dawkins, 2007; Feitosa et al., 2007; Reardon and Bischoff, 2011; Franca, 2016; Musterd et al., 2017). Although general collinearity exists between race and income in the South African context, theory discussed in Sections 2.3 and 2.5 suggest that this is not the case for upper-income communities.

The classification of a population's occupational status favours international standardisation of this dimension as a socio-economic index (Ganzeboom et al., 1992) and is also considered to be a preferable proxy for socio-economic status (Sydes and Wickes, 2021). However, the fine granularity of census data on occupation in South Africa would require reclassification into larger categories to support comparative analysis.

In this chapter, the objective is not only to discuss the study area and data that is applied in this thesis, but also to undertake a critical approach to the consideration of the methodologies that are applied for the measurement of segregation in Cape Town and the modelling thereof for further exploration. Section 5.1 presents the chosen study area of Cape Town and provides related geographic context and justification for the selection of this city as case study. Section 5.2 presents the spatial segregation indices that are applied to analyse the spatial patterns and relationship between racial groups and income groups in Cape Town. A discussion is provided in Section 5.3 of the agent-based modelling process that was developed for the exploration of racial and socio-economic segregation in Cape Town and includes justification for the modelling of racial preference. Finally, the geographic and numerical census data that was applied to the segregation measurement and modelling methodologies are discussed in Section 5.4.

5.1 Study Area of Cape Town

Cape Town was selected as study area for this research project, as it was the first settlement in South Africa to experience racial segregation and also remained the most segregated and physically fragmented city in South Africa to this day, as discussed in Section 2.4.3. Compared to the other cities in the country (with a predominantly Black African and/or White population), Cape Town also reflects a larger racial diversity, with a predominantly Coloured population, followed by a comparatively large Black African and White population.

Parry and van Eeden (2015) compared the level of racial segregation in Cape Town to that of Johannesburg, the largest city in South Africa. It was found that although segregation remains high and integration occurs at a slow pace in both cities, Cape Town remains more segregated than Johannesburg. The White population in Cape Town was also found to be more segregated from other groups than in Johannesburg. Segregation levels were derived from the application of the Information Theory Index (H), discussed in Chapter 3, with Cape Town exhibiting a H value of 0.66 compared to 0.59 for Johannesburg (Parry and van Eeden, 2015). These results are high compared to some of the most segregated cities in the United States. In 2000, Detroit was the most racially segregated city in the United States with a H value of 0.48. Chicago is also one of the most segregated cities In the US and reflected a H value of 0.42 (United States Census Bureau, n.d.).

Located at the south-western corner of South Africa (see Figure 5.1), the geographic extent of the official City of Cape Town metropolitan municipality extends far beyond the actual CBD of the city itself and covers a geographic area of 2 445 square kilometres (see boundary in blue in Figure 5.1). Hence, reference to the 'City of Cape Town' or 'Cape Town' as study area in this thesis entails the metropolitan region, rather than the much smaller CBD. According to the census of 2011 the total population of the City of Cape Town is 3 740 026 (42.4% Coloured, 38.6% Black African, 15.7% White, 1.4% Indian/Asian and 1.9% 'Other'/Unspecified) (City of Cape Town, 2012).

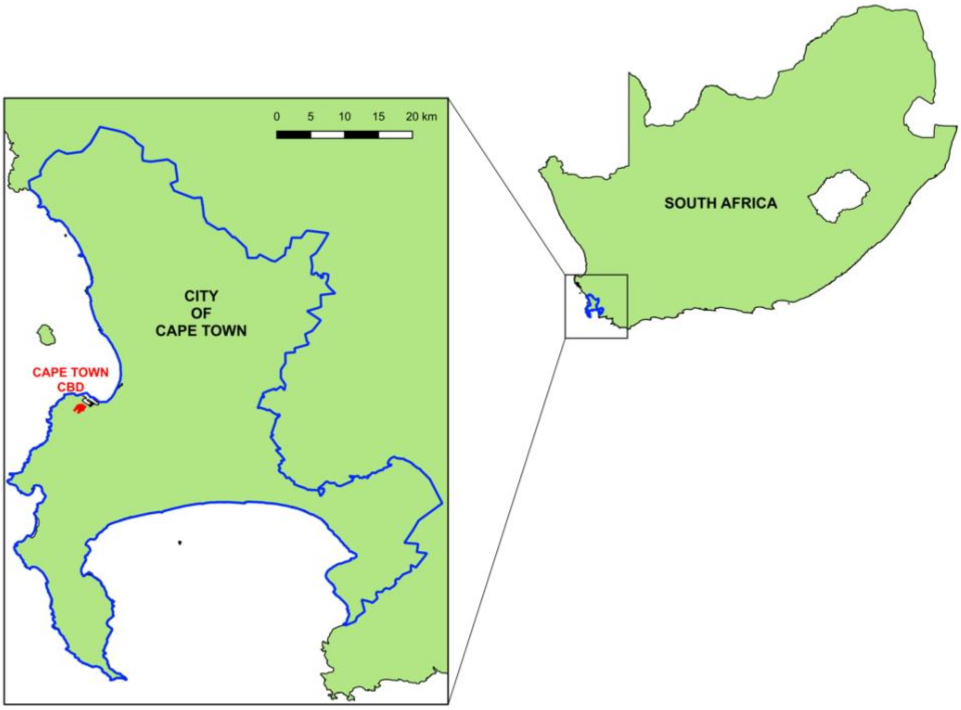


Figure 5.1: Cape Town Overview Map (©esri, Statistics South Africa)

Figure 5.2 shows the distribution of residential property sizes and density in Cape Town (City of Cape Town, 2014). The neighbourhoods in green (area A) show the largest residential properties in the upper-income areas of the city. The suburbs in orange (area B) present comparatively large properties of the middle-income neighbourhoods of the city, concentrated mostly in the Northern Suburbs (north-east of the CBD) and the Southern Suburbs (south of the CBD) of Cape Town. The suburbs in red (area C) reflect the highest density and lower income areas, which are situated furthest away from the Cape Town CBD and include informal settlements.

These highest density neighbourhoods are also where non-White citizens predominantly resided during apartheid and what is most notable is the general lack of vegetation in these areas, compared to the middle- and upper-income neighbourhoods. This occurrence also reflects the fact that the most undesirable land was chosen during the apartheid era to forcefully move the non-White population to.

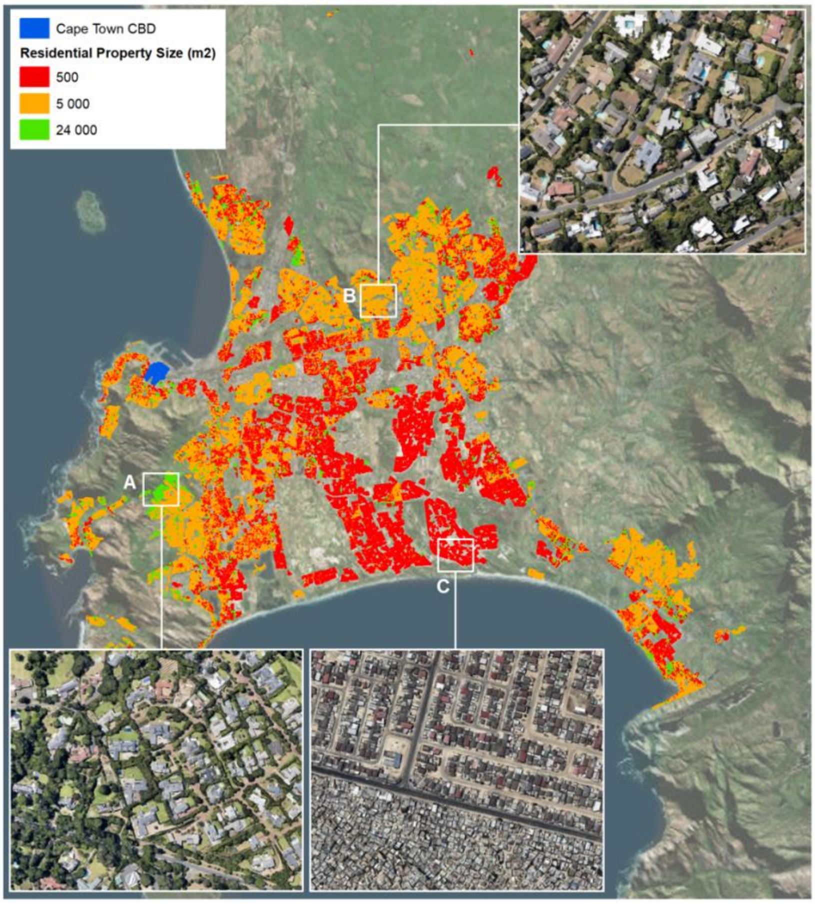
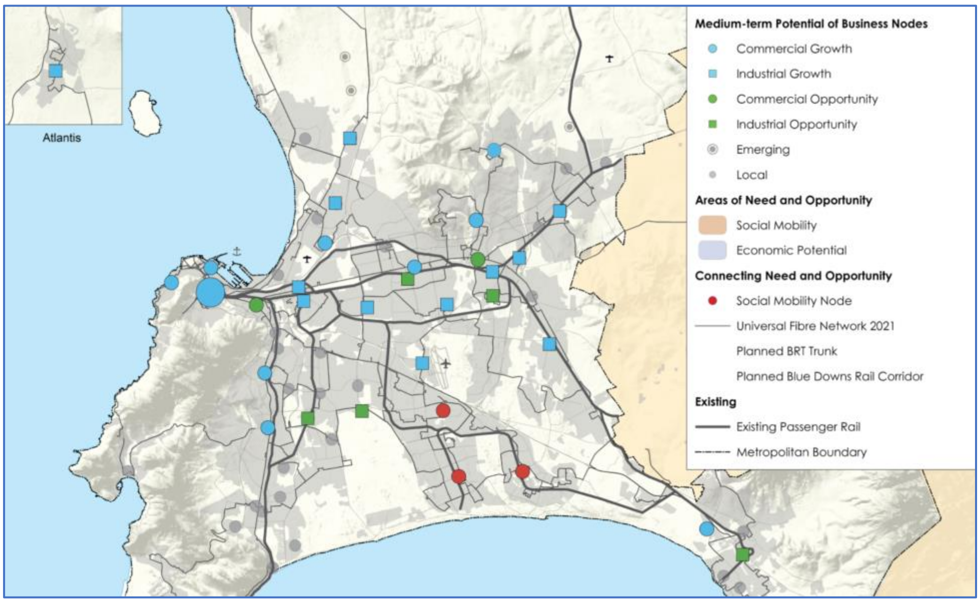


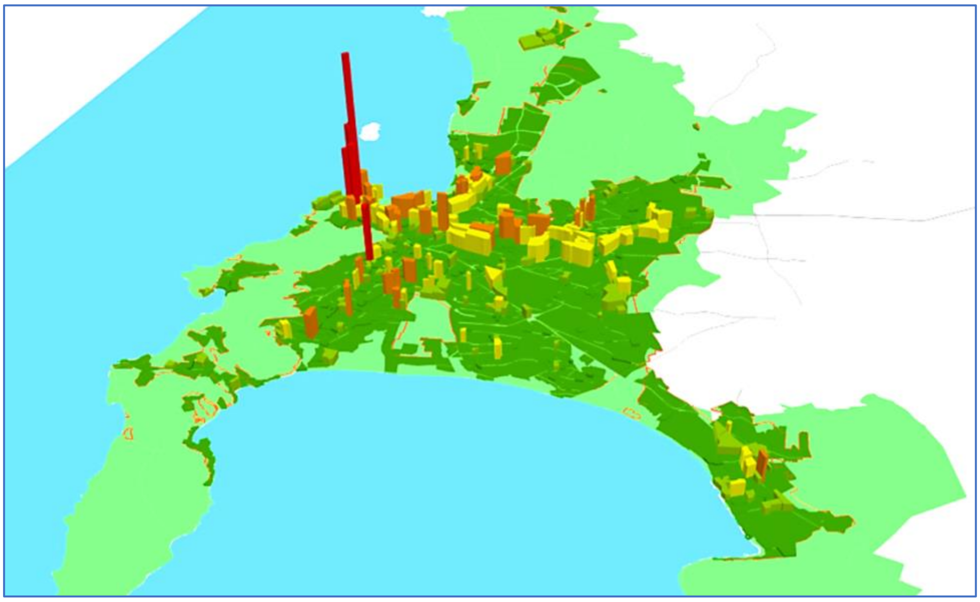
Figure 5.2: Residential Property Density in Cape Town (©City of Cape Town, Google Maps, Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID)

Moyo and Zuidgeest (2018) studied the marginalization of low-income areas, regarding economic activities in Cape Town, to assess whether accessibility has improved in terms of employment opportunities. It was found that middle- and upper-income residential areas are closer located closer to commercial land uses, compared to low-income residential areas.

The authors suggested that the “continuation of this growth trajectory perpetuates pre-1994 planning characteristics” and that their results “suggest a bias in the location of commercial land uses in prominent neighbourhoods indicating that middle- and high-income cohorts have better accessibility to employment destinations” (ibid:2018,536). Figure 5.3a presents nodes (in blue) for potential commercial and industrial growth, which are located predominantly in the middle- and upper-income White areas of the city. Figure 5.3b indicates the areas of highest employment density in the city, which supports the findings of Moyo and Zuidgeest (2018).



a.



b.

Figure 5.3: a) Economic Development in Cape Town & b) Employment Density (2013) (City of Cape Town, 2017a)

The phenomena of natural barriers and gated communities perpetuating spatial segregation in Cape Town has been studied frequently (e.g. Lemanski, 2006a; Lemanski and Oldfield, 2009; Ramoroka, 2014). Figure 5.4 shows the Steenberg Golf Estate south of the CBD of Cape Town, one of the most exclusive gated communities in the country.

Figure 5.4: Barriers Perpetuating Spatial Segregation: Steenberg Golf Estate (Miller, 2018)

This example is by no means exhaustive on the subject of socio-economic and spatial disparity in Cape Town but provides a clear overview of specific dynamics in the contemporary urban form of Cape Town that promotes continuous disparity.

5.2 Segregation Measurements for Cape Town

The work of Reardon and O'Sullivan (2004) was explored by Feitosa et al. (2007) and provided a basis for the authors to develop further spatial indices of segregation, as discussed in Chapter 3. These spatial indices by Feitosa et al. (2007, 2021) and Barros and Feitosa (2018) are applied in this thesis to measure segregation in Cape Town for three subjects: race, income and income-by-race. The objective is not only to understand the level of racial and income segregation, but also the extent to which different racial and income groups are exposed to each other or isolated from each other and effectively the role race and income plays in perpetuating segregation in the study area. For each of these subjects, the following methodology is applied:

Firstly, the segregation dimensions of evenness/clustering are measured to respectively explore the spatial distribution and clustering of the racial, income and income-by-race groups throughout the study area. For the measurement of evenness/clustering, the global spatial versions of the Generalised Dissimilarity Index $(\breve{D})$ and the Information Theory Index

($\breve{H}$) were measured (discussed in Chapter 3). Both the global Dissimilarity Index ($\breve{D}$) and Information Theory Index ($\breve{H}$) were measured aspatially (within each census tract) and spatially (at a Gaussian bandwidth from the centre of each census tract) from 1000m to 5000m (at 1000m intervals). The minimum of 1000m was chosen as an interpreted walkable distance in the study area. For further exploration of the results obtained for the global indices the global measures are followed by the local spatial versions of the dissimilarity ($\breve{d}_j$) and information theory index ($\breve{h}_j$), which were both measured at a bandwidth of 1000m and presented in maps.

Secondly, the segregation dimensions of exposure/isolation are measured to respectively explore the degree of isolation and exposure of the racial, income and income-by-race groups throughout the study area. For the measurement of exposure/isolation, the global spatial versions of the Exposure Index $\breve{P}^*_{(m,n)}$ and the Isolation Index $\breve{Q}_m$ were initially measured, again at a bandwidth of 1000m. The local spatial version of the exposure index $\breve{p}^*_{j(m,n)}$ and isolation index $\breve{q}^*_{j(m)}$ are finally measured and also presented in map format for further analysis. These indices reflect the same equations as the global exposure and isolation indices, but with the focus on a locality *j* and thus indicating how much each locality contributes to the study area's global segregation measure.

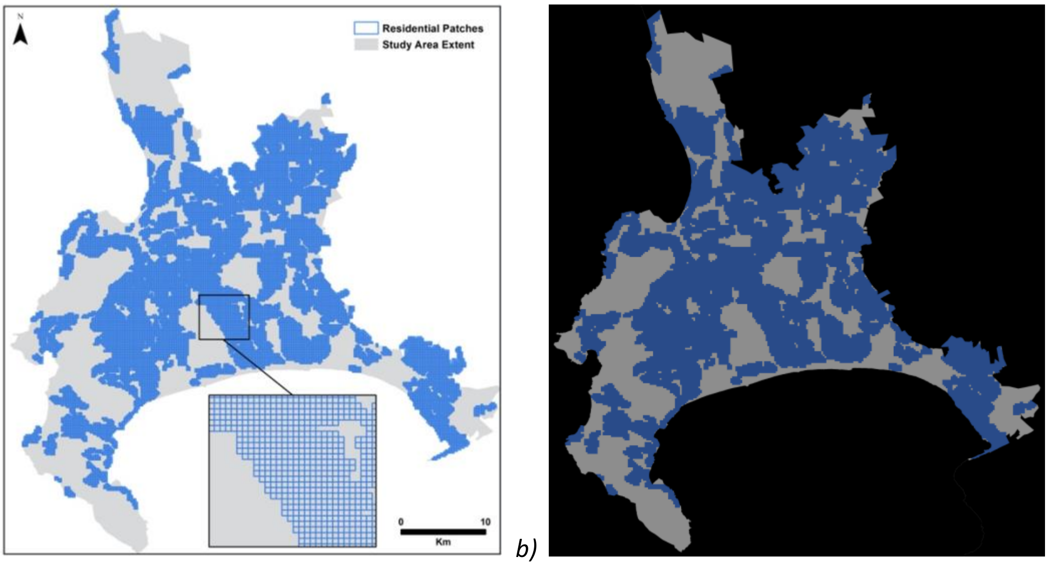
5.3 Agent-Based Modelling of Cape Town

This section provides a discussion of the agent-based modelling toolkit that is applied in this thesis and the components it consists of. The NetLogo agent-based modelling toolkit was chosen for this research project, as it is suitable for the simulation of evolving complex phenomena, allowing the modeller to explore emergent patterns (Feitosa, 2010). NetLogo is a modelling environment that is programmable to simulate complex social and natural phenomena and was authored by Uri Wilensky in 1999 (Wilensky, 1999) at Northwestern University, Evanston, Illinois. Netlogo originated from a combination of StarLisp (Lasser and Omohundro, 1986) and Logo (Papert, 1980) and also reflects the Logo principle of "ease of use" and a "low threshold" for new users (Tisue and Wilensky, 2004, p. 8). It is written predominantly in Scala, a general-purpose programming language, with some parts written in the Java programming language and allowing for it to run on most computing platforms.

As a dialect of Logo, NetLogo's language is extended to support three types of agents (discussed in Chapter 4): turtles (mobile agents moving around), patches (stationary grid of cells over which turtles move) and links (agent connecting turtles to generate networks and aggregates). The application of NetLogoWeb allows for models that are developed in NetLogo to run entirely on the Web and the R extension allows for statistical model analysis (Thiele and Grimm, 2010; Crooks et al., 2018). NetLogo also consists of various extensions, written by both the Centre for Connected Learning and Computer-based Modelling at Northwestern University and the wider global NetLogo community (see GitHub Netlogo Extensions).

The agents in the simulation model for Cape Town represent the households in the study area. The number of households presented in the model is obtained directly from the 2011 census data for Cape Town. However, the study area is comprised of more than one million households and due to the high computational requirements of large models, it was decided to extract a 5% sample from the total number of households for the simulation model. It should be noted that although the Indian/Asian population group is studied in the measurement of segregation in Cape Town, it is excluded from the simulation study due to its small size. Similarly, the 'No Income' (unspecified) category of the census income classification was excluded from both the measurement and modelling processes. This is discussed in further detail in Section 5.4.2.

The environment of the model is composed of a regular grid of 200 by 200 metre square cells. This patch size was chosen in consideration of computational limitations, but also to be compatible with the sizes of the sub-place census tracts that are relevant to the model and the ratio of household numbers to these census tracts. Figure 5.5a presents the data for the extent of the study area and residential land in vector format in GIS and Figure 5.5b presents the same data in a raster grid format in the model environment within Netlogo.



a) *b)*

Figure 5.5: Implementation of Study Area: a) Study area in ArcGIS© and b) Study area in Netlogo©

Although spatial scales are applied in terms of the study area extent and that of census tracts, the size of individual patches in the model environment may not correspond to the scale of a single residential plot. Further discussion on model implementation is provided in Section 7.3. A final aspect incorporated in the model environment is the GIS layer of the 2011 census Sub-Place tract boundaries (see Figure 5.6). Although not visible in the model environment, the properties (identity codes) of the census tracts are assigned to the relevant patches and will ensure that the agents are introduced to the model environment in the correct census areas.

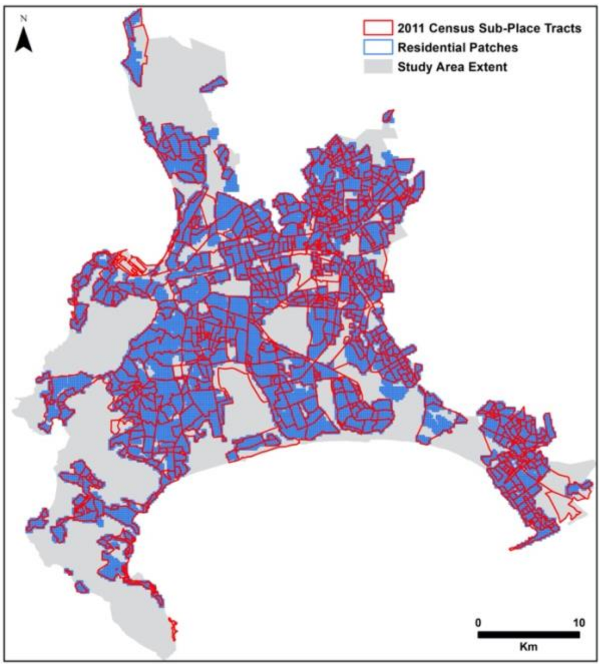


Figure 5.6: 2011 Census Sub-Place Layer in GIS

Considering these datasets that are relevant to represent the spatial extent of the study area, each patch within the study area (metropolitan boundary) will have the following input properties: zoning (either residential or non-residential), corresponding colour (blue for residential or grey for non-residential) and census tract ID (either present or void for the patches irrelevant to the study). The significance of these properties is further discussed in Section 7.3 on implementation.

At the implementation stage of the model various data types are introduced to assign properties to the relevant agents and the environment they will act in. To enable the input of data into the model, three essential NetLogo extensions have been applied: the GIS (Geographic Information Systems), CSV and Vid extensions.

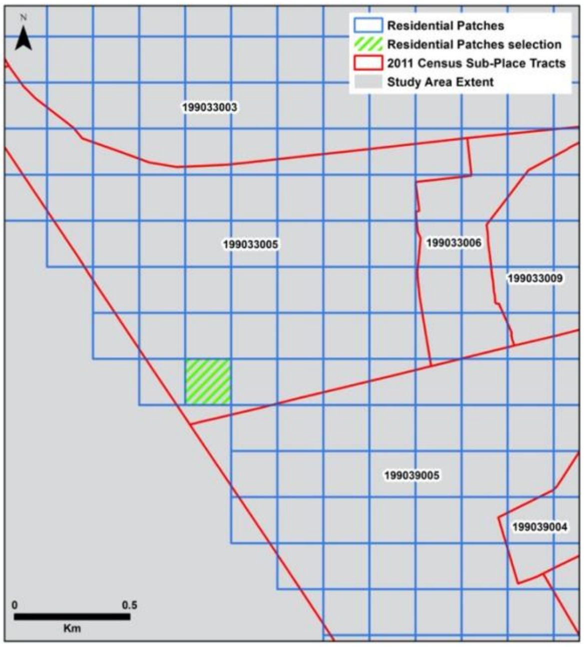
The GIS extension provides for the ability to load GIS data in both vector (points, lines and polygons) and raster (grid) data files into a model (Crooks et al., 2018). Vector data is supported in the form of ESRI shapefiles (.shp) and raster data in ESRI ASCII Grid files. The model makes use of both these data types. Vector data is applied to the model environment to specify the extent of the study area, the location of the residential patches and the extent of the 2011 census sub-place areas (see Figure 5.6).

The CSV extension provides for the ability to read data into a model from a CSV file. This extension was applied to the model to assist with the generation of the household agents. To align with the segregation measurement process, the model consists of three modules to simulate household dynamics by race, income and income-by-race. These modules are discussed in detail in Section 7.1. The 2011 sub-place census data for both the racial population groups and income groups were read into the respective modules and the number and types of agents were generated accordingly. Hence, agents were generated from the CSV files of the 2011 census data (5% sample of 50 894) for the head of the household, which effectively provides the number of households by race and income for each sub-place census tract in the study area.

A similar procedure was followed for the third Racial Income module, where agents were generated from 'income-by-race' census data (the race of the head of household for each relevant income group). All agents were randomly placed in their relevant census areas in the environment of the model and given the small number of residential patches, each residential patch contains more than one household agent. The Vid extension for NetLogo provides a video recorder to record the duration of a simulation run in a series of frames.

Figure 5.7 shows a location in the study area where a cell was inspected in GIS first (see Figure 5.7a), indicating that it resides within the residential area and a specific census sub-place. The same patch is visualised, after land use data implementation, in Netlogo (see Figure 5.7b) and the properties of residential zoning and census tract ID is noticeable.

a)



b)

Figure 5.7: Residential Patches (200x200 metres) in a) GIS and b) Netlogo

The following section discusses the specific data types and relevant datasets that were applied to model to undertake a further exploration of the dynamics of racial and socio-economic segregation in the study area.

5.3.1 Modelling Racial Preference

One of the predominant features of the model that was developed in this thesis is the subject of racial preference, capturing the phenomenon of homophily. The word "homophily" was coined by Lazarsfeld and Merton (1954) in an essay exploring the friendship in a mixed-race housing project in Pittsburgh, Pennsylvania. Homophily refers to the inclination for friendships or relationships to occur "between similar people at a higher rate than among dissimilar people" (McPherson et al., 2001, p. 416). As a foundation for the aphorism of 'birds of a feather flock together', Neal and Neal (2014) pointed out that the tendency toward homophily is frequently observed along the dimensions of race, ethnicity, age, education, class and beliefs in human populations. The functional role homophily plays have been studied in a variety of domains (Fu et al., 2012), including social segregation (Schelling, 1971), cultural polarization (Axelrod, 1997), patterns of friendship formation (Currarini et al., 2009), health behavior (Centola, 2011) and dynamic social networks (Rand et al., 2011).

The model developed by Thomas Schelling (1971) to simulate the dynamics of residential segregation is highlighted as one of the first influential and spatial applications of the concept of homophily. The assumption of homophily and its racial history was developed into the rules of the model (Kurgan et al., 2019) and was evident in the clustering of agents of the same kind and behaviour. Exploring the conditions under which settlement processes result in segregation, Petrescu-Prahova (2009) expanded on the Schelling segregation model by incorporating household characteristics, such as relationships among neighbourhoods, and distinguishing between the effects of in-group preference (homophily) and out-group avoidance (xenophobia). The study finds that homophily and xenophobia affects residential segregation most when acting together (Petrescu-Prahova, 2009).

The study of Bruch (2014) examined how choices regarding social affiliation based on one attribute can either intensify or decrease segregation on another correlated attribute. The role of racial and economic factors in producing patterns of racial residential segregation was investigated. Agent-based modelling was applied to explore how the joint distribution of race and income form patterns of racial residential segregation patterns (Bruch, 2014). The objective is to understand why, when and how income inequality between and within racial groups affect racial segregation. The study was undertaken by means of identifying three population parameters that determine how racial segregation is affected by income inequality between racial groups – between-group inequality, within-group inequality and relative group size. Bruch (2014) found that when enough within-race income inequality occurs, an increase in income inequality between racial groups increases the exposure of lower income Blacks to Black neighbourhoods, but decreases the exposure of higher income Blacks to Black neighbours.

The general segregation patterns resulting from the residential movement of individuals, based on their diverse preferences and constraints, remains a challenge in ethnic neighbourhood segregation studies and is explored by Zuccotti et al. (2021). The authors applied agent-based modelling to extend the Schelling segregation model (Schelling, 1971) and focussed on the role of ethnic and socio-economic homophily preferences and housing constraints as contributing factors to residential choice. Different weights for preferences of similar ethnic and socio-economic neighbourhood composition were modelled and combinations of these variables were adjusted to establish how segregation in reality could be replicated in the Bradford local authority in the UK (Zuccotti et al., 2021).

Similar to Schelling's model, it was found that even slight preferences to reside close to neighbours of the same ethnicity result in high segregation levels. However, the additional incorporation of socio-economic factors into the model served as counterbalance to these results of intense segregation. Consequently, segregation patterns similar to real data occur when the preference for socio-economic similarity is higher than ethnic similarity preferences and even more so with the consideration of housing constraints in agent relocation movement (Zuccotti et al., 2021).

5.4 Data

5.4.1 Geographic Data

Further to the geographic context of Cape Town, presented in Section 5.1, the geographic extent of the study area and related spatial data for this thesis was chosen to encapsulate only the urban footprint (built environment) of Metropolitan Cape Town (see Figure 5.8). This study area is also located within the official 'urban edge' of Metropolitan Cape Town (see Figure 5.8, inset map), which was instated by the City of Cape Town council to limit urban sprawl and fragmented development. The data for the urban edge was obtained from the Information and Knowledge Management Department at the City of Cape Town council (City of Cape Town, 2021). Census data for 2011 was obtained from Statistics South Africa and at sub-place level for the study area.

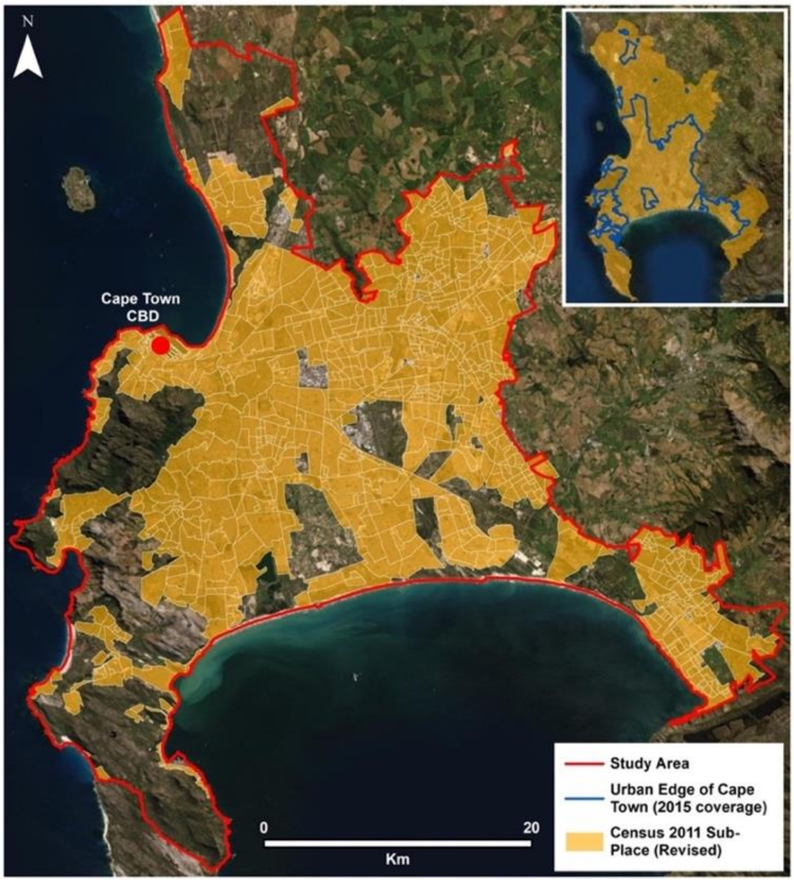


Figure 5.8: Geographic Extent and Relevant Data of Study Area (Sources: ESRI, Digital Globe, City of Cape Town and Statistics South Africa)

The sub-place enumeration census tracts were deemed efficient for the research study, given the large extent of the study area and the fact that sub-places represent named suburban neighbourhoods in the city. The average size of these sub-places units is 1.1 square kilometre (1180 households), with significant variation in sizes. Given the fragmented urban form and large open spaces of natural, agricultural and industrial land in Cape Town, the boundaries of the census tracts were also revised in relevant locations (see Figure 5.8) to align more to the built environment of the study area and exclude undeveloped space.

The intention of adjusting the census tract boundaries was also to decrease the effect of the modifiable areal unit problem (MAUP), which was highlighted by Reardon and O'Sullivan (2004) and cited in Chapter 3. Nonetheless, the limitation of aggregated census data and spatial scaling issues are acknowledged. The fact that the segregation measures in this study rely on data aggregated by areal units means that the accuracy of results will always be bound by scale and zonal dynamics.

5.4.2 Numerical Census Data Applied

The numerical census data for the sub-place layer of the 2011 census was obtained from Statistics South Africa and features household counts by census tract for the different racial, income and income-by-race groups in the study area. These counts reflect the race of the household heads and the annual income of households. The decision to use data at household rather than individual level is two-fold: 1) the household level provides consistency in counts between the racial and income groups in the study area, as both the race and the income of the household is obtained from the head of the household 2) the simulation model discussed in Chapter 7 to Chapter 9 studies the residential dynamics of racial and income groups and for this study the assumption is made that relocation occurs by household and not by individual. This section provides a brief overview of the numerical census data that was applied to measure segregation by race, income and income-by-race in the study area.

Race

For the measurement of racial segregation in the study area, the four census population groups of Black African, Coloured, Indian/Asian and White were applied. The composition of households by race in the study area reflects a 42.3% majority of Black African households and the Indian/Asian households the smallest total at only 1.4%, as shown in Figure 5.9. The fifth census group of "Other" was omitted from this study, as it is composed of individuals for which race was not specified.

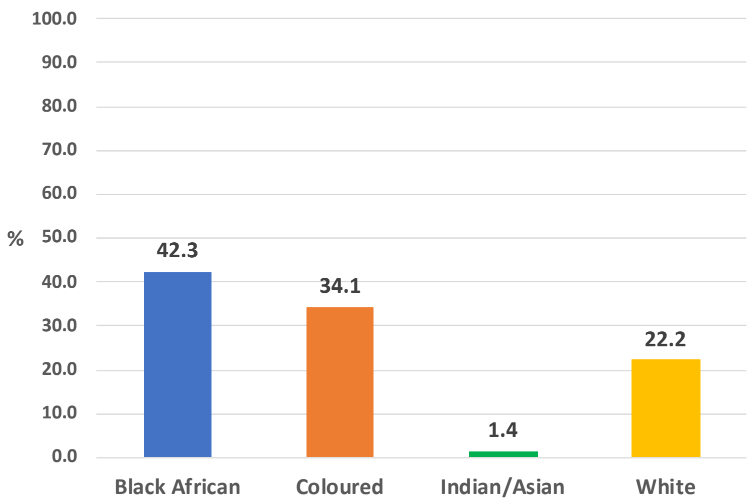


Figure 5.9: Households by Racial Group for the Study Area

Figure 5.10 shows the spatial distribution of the households for the four population groups in the previously discussed study area in Cape Town. The Black African population group (see Figure 5.10A) is predominantly located to the south of the study area. The Coloured population group (see Figure 5.10B) is located predominantly adjacent to the Black African neighbourhoods and distributed to the south, central and western areas of the study area. The Indian/Asian population group (see Figure 5.10C) is mostly distributed in very low numbers to the west of the study area, with the largest concentration in two adjacent census tracts. The distribution of the White population group (see Figure 5.10D) reflects a contrasting pattern to all three of the other population groups, with the predominant number of White households located to the north, west and southeast of the study area.

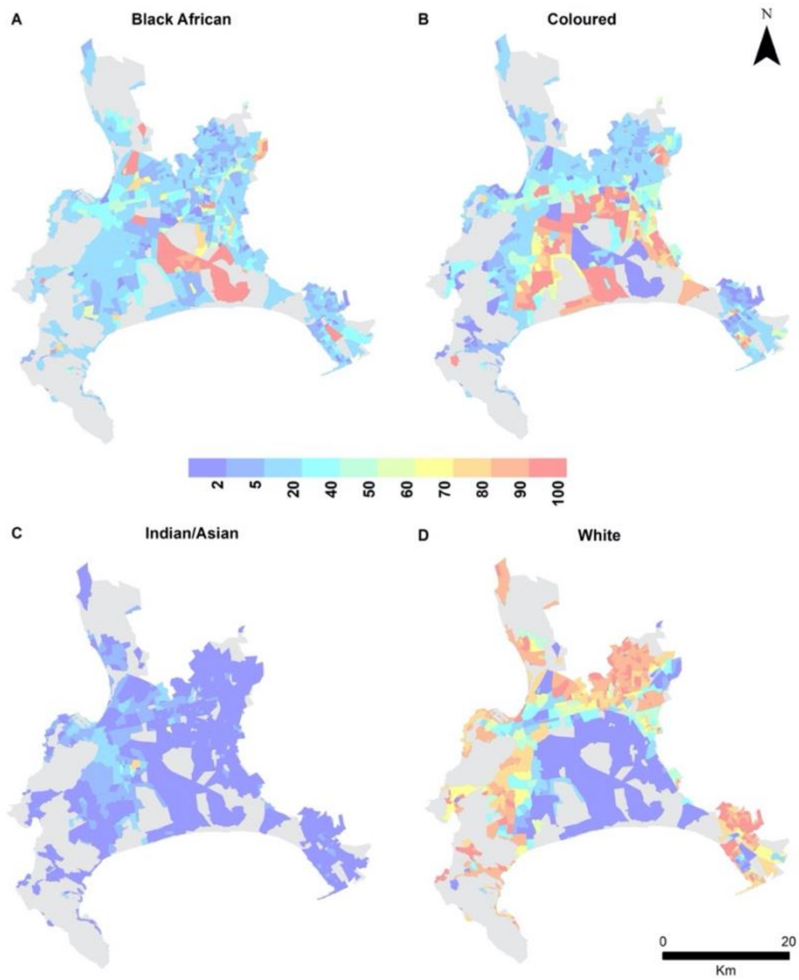


Figure 5.10: Spatial Distribution of Population Groups Showing the Percentage of Households by Race and per Census Tract

Income

As discussed in Chapter 2, segregation in Cape Town is not only by race, but also by income. Hence, the aim of the segregation measurement exercise in this chapter is to understand the role income plays, in comparison with race, in perpetuating segregation in Cape Town. Annual income data by household was obtained at sub-place aggregation for the 2011 census. The 12 income categories presented in the 2011 census enumeration process were reclassified into three categories of low-, middle- and upper-income (see Table 5.1). Taking annual inflation in consideration, this reclassification follows the classification of the 2016 socio-economic study for Cape Town by the Western Cape provincial government (Western Cape Government, 2016).

Table 5.1: Low-, Middle- and Upper-Income Categories from Socio-Economic Study for Cape Town (Western Cape Government, 2016)

LOW INCOME	**R1 – R38 200**
MIDDLE INCOME	**R38 201 – R307 200**
UPPER INCOME	**R307 201 and above**

However, the category of 'No Income' was excluded from this study due to the fact that this classification in the 2011 South African census does not only comprise of counts of households with no actual income, but also counts for the households which refused to disclose their income (Statistics South Africa, 2015, p. 14). Consequently, a degree of uncertainty is presented in the fact that the households with no actual income cannot be distinguished from the households which declined to disclose their income in the enumeration results. The income composition of Cape Town (see Figure 5.11) reflects a majority of middle-income households (45.5%), with the upper-income population the smallest at only 16%.

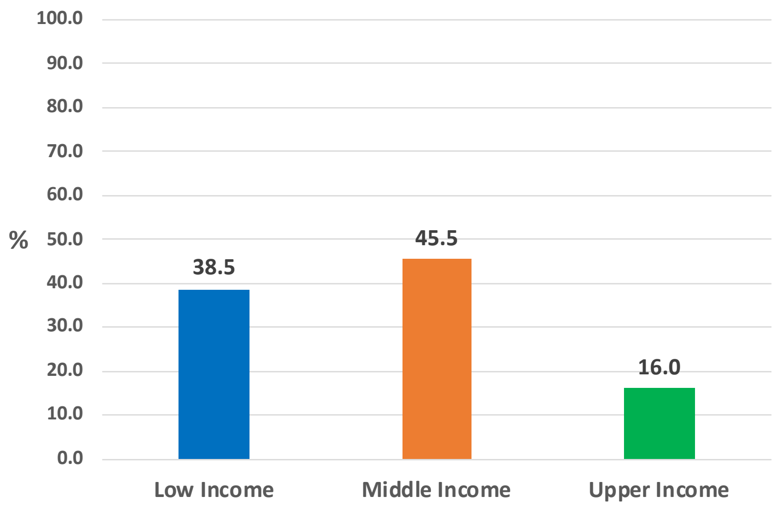


Figure 5.11: Annual Household Income Groups for the Study Area (based on the Categorisation as per Table 5.1)

Figure.5.12 presents the spatial distribution of the three income categories in the study area. It is evident that the low-income group (see Figure.5.12A) is mostly concentrated to the south of the study area. The middle-income group (see Figure.5.12B) is widely distributed throughout the study area, but also indicating higher concentrations in the southern, eastern and north-western parts of the study area. In contrast to the low-income group distribution, the upper-income group (see Figure.5.12C) is situated more to the northern, western and south-eastern parts of the study area. Thus, a clear contrast between the distribution of low- and upper-income households is evident, with the middle-income distribution encompassing both.

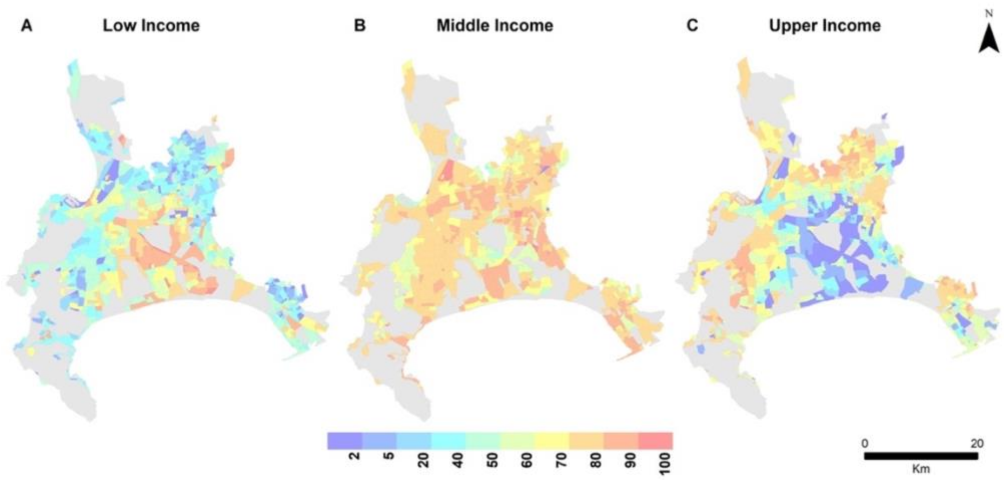


Figure.5.12: Spatial Distribution of Income Groups Showing the Percentage of Households by Income Group per Census Tract

Income-by-Race

For the measurement of segregation of the combination of race and income, the four population groups and three reclassified income categories were combined to generate twelve 'income-by-race' categories (see Figure 5.13) for the study area. The Black African low-income group is shown to be the largest at 24.9%, followed by Coloured middle-income at 19.0%. The smallest categories are Indian/Asian low-income and Indian/Asian upper-income groups at 0.2% and 0.5% respectively.

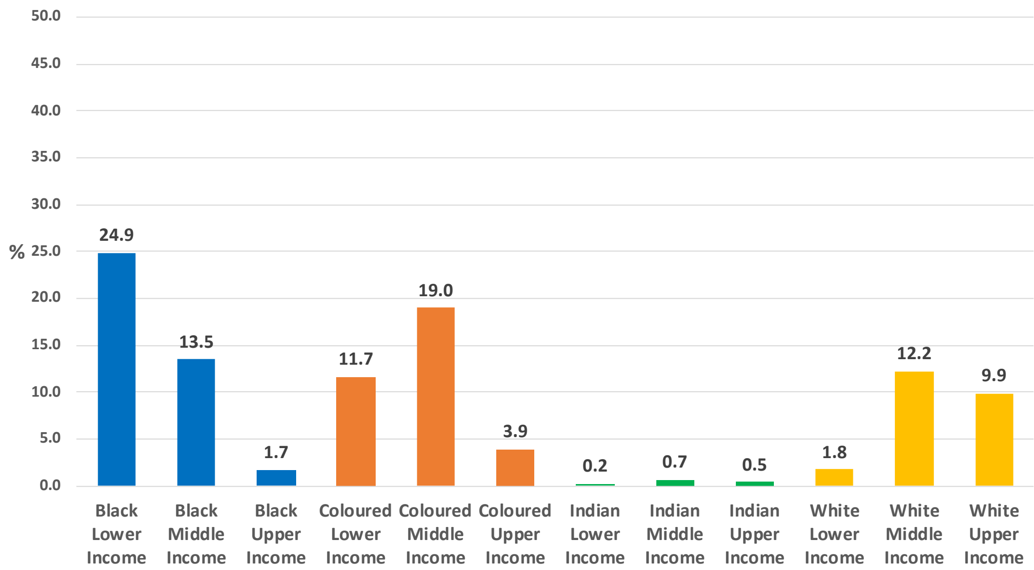


Figure 5.13: Income-by-Race Category for the Study Area

It is important to acknowledge that income is a continuous variable and although the generalised categories of low-, middle- and upper-income were formulated and applied to measure socio-economic segregation, no clear definition exists for what would constitute as low-, middle- and upper-income. Thus, segregation measures applied in this study are more adequate for race, as a categorical variable. The division of a continuous variable, such as income, into a restrictive number of income groups presents a limitation. Hence, the variable of income is applied as proxy for socio-economic status in this thesis.

Moreover, the segregation measurements undertaken in this thesis are limited to the 2011 census data for the study area, due to the unavailability of usable numerical and spatial data for the 2001 census year. Consequently, the opportunity did not exist at present for a comparative analysis to be undertaken for the 2001 and 2011 census data on race and income, which would have presented the potential of studying changes in segregation levels and spatial distribution of racial and income groups over time. Nonetheless, the intention for such a future study is addressed in Chapter 10 as future work.

5.5 Summary

This chapter presented the methodology and data applied in this thesis to firstly measure racial and socio-economic segregation in the study area of Cape Town and secondly to model the dynamics of racial and socio-economic segregation for further exploration. A geodemographic overview of the study area is presented with further context to the level of segregation in Cape Town, serving as justification for choosing this South African city as study area. A discussion is provided on the segregation measurements applied in this thesis to study the level and patterns of segregation between racial, income and income-by-race groups and the role race and income play in the persistence segregation in Cape Town. The agent-based modelling process that is applied for the exploration of racial and socio-economic segregation is discussed and justification is provided for the modelling of homophily. Finally, the spatial and numerical census data applied to the study is presented and justification provided for the selection of these specific datasets.

The following chapter presents the measurements undertaken of racial and socio-economic segregation in the study area. Segregation measurements are applied to the three subjects of race, income and income-by-race and accompanied by an analysis and discussion of the findings of these measurements.

Chapter 6

Measuring Racial and Socio-Economic Segregation in Cape Town

In this chapter, the spatial segregation metrics of Feitosa et al. (2007, 2021) and Barros and Feitosa (2018), discussed in Chapter 3, are applied to measure racial and income segregation in Cape Town. The objective of this chapter is to investigate the role income plays, compared to race, in the persistence of segregation in Cape Town, building on the work by Christopher (2001a), Rospabe and Selod (2006) and Parry and van Eeden (2015) on the measurement of racial segregation. For that, three sets of experiments will be presented. Section 6.1 presents a brief spatial overview of the Group Areas of the apartheid era, followed by the segregation measurements of racial groups. To contextualise segregation in Cape Town the measurements of racial segregation were also undertaken for an approximation of the apartheid group areas. The measurement of segregation among income groups is presented in Section 6.2. Finally, Section 6.3 presents the segregation measurements of groups combining the race and income categories.

Below, the analysis of segregation indices for each grouping will be presented in the following order: firstly, analysis using the dissimilarity and theory of information indices, which portray the evenness/clustering dimension; secondly, isolation and exposure indices will be used to explore the dimension of same name. Global exposure indices will be used to investigate the degree of potential contact between different groups. For each index, global values will be presented first as multiscalar segregation profiles followed by analysis of spatial patterns looking using local indices. In this thesis the term 'profile' is applied in reference to the curve depicting the level of segregation across a range of spatial scales (Reardon et al., 2008).

6.1 Spatial Segregation Measurements of Racial Groups

For a meaningful analysis of the spatial patterns, it is important to highlight results in specific areas of Cape Town which historically have been areas of either high segregation or integration during apartheid. Figure 6.1 shows the spatial distribution of 'group areas' during apartheid, to which all racial groups were restricted by law. The Black African population was confined to the central and south-eastern parts of the study area, with Coloured areas to the north and south of these Black African areas and the Indian/Asian area concentrated in the centre of the study area. The group areas of these three racial groups were the areas to which all non-White residents of Cape Town were moved to during the apartheid era. The White population was situated to the north, west and south-east of the rest of the population.

Figure *6.1* is accompanied by a summary (Table *6.1*) of the importance of the racial groups to the analysis – as discussed in Chapter 2. The neighbourhoods that are referred to in this study are presented in this table and indicates in which type of former apartheid group area each of these neighbourhoods are situated. In addition, the grey areas (racially integrated throughout the apartheid era) that were discussed in Chapter 2 are also listed.

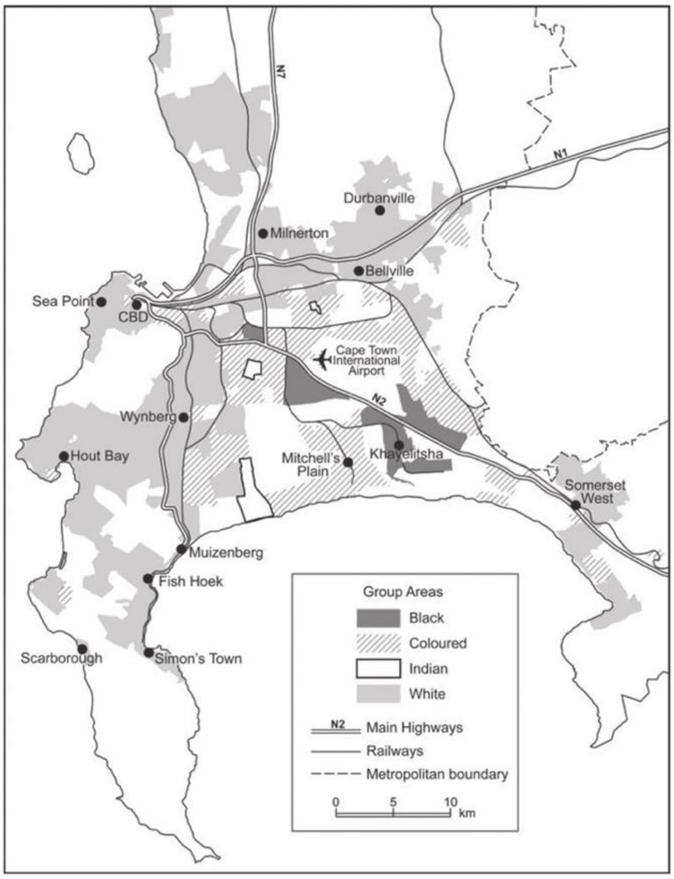


Figure 6.1: Group Areas during Apartheid (Crankshaw, 2012) (for reference; identical to Figure 2.5)

*Table 6.1: Group Area Classification During Apartheid (*Post-apartheid neighbourhoods in former group areas)*

Group/Grey Areas During Apartheid	**Suburbs/Neighbourhoods**
Black African Group Areas (BGA) *(Areas that were established at the periphery of the city to which Black African communities were moved during apartheid)*	Browns Farm
	Gugulethu
	Ikwezi Park
	Khayelitsha
	Langa
	Mfuleni*
	Nyanga
Coloured Group Areas (CGA) *(Areas adjacent to the Black African group areas to which the Coloured population was removed during apartheid)*	Hanover Park
	Manenberg
	Mitchells Plain
	Windermere
White Group Areas (WGA) *(Areas declared as group areas for the White population and from where all non-White residents were forcefully removed during apartheid)*	Claremont
	District Six
	Mowbray
	Sea Point
	Table View
	Simon's Town
	Wynberg
Integrated During Apartheid – 'Grey Areas' (IDA) *(Areas that remained racially integrated during apartheid)*	Observatory
	Salt River
	Woodstock

6.1.1 Dissimilarity and Information Theory Indices

Measurements were firstly undertaken for the racial groups in the study area and Figure 6.2 presents the segregation profiles for the global spatial segregation measurements of both the generalised (multi-group) dissimilarity index ($\breve{D}$) and the information theory Index ($\breve{H}$). In this context, the segregation profiles are graphs of the global values measured for different scales (bandwidths). The graph in Figure 6.2 also includes the aspatial (bandwidth = 0) global values. The global values for the indices decrease as the bandwidth increase, which is expected as a larger number of households are included in the calculation. The purpose of the segregation analysis is to look at the slope of the curves, which reveal insights into the multiscalar nature of segregation.

As expected, the values for the aspatial measurements are higher than those using larger bandwidths as it considers the population composition within an areal unit and not the interaction between groups over census tract boundaries.

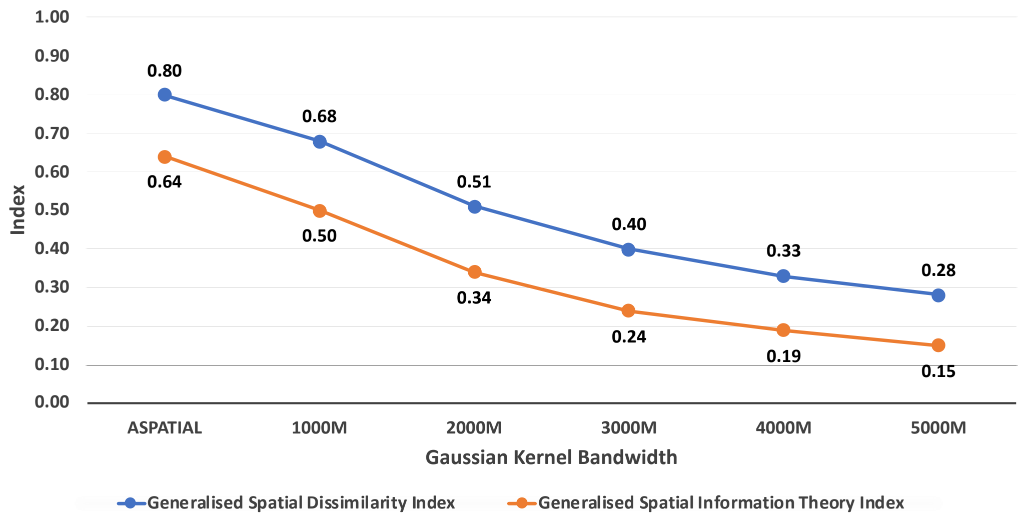


Figure 6.2: Evenness/Clustering Segregation Indices Applied to Race (Census 2011: Generalised Spatial Dissimilarity Index ($\breve{D}$) and the Information Theory Index ($\breve{H}$))

The map presented in Figure 6.3 shows the contribution each locality makes to the overall composition of the index globally (the whole study area), allowing for spatial patterns to be investigated. The red shaded areas in the map indicate areas with highest dissimilarity – the localities where the composition of the population differs most from the overall population composition of the study area and thus reflect a large majority of one racial group.

It is evident that the areas of highest dissimilarity are predominantly found as clusters towards the south of the study area where localities reflect very high percentages of either Black African households (such as the suburb of Khayelitsha, Browns Farm and Gugulethu) or Coloured households (such as the suburbs of Bonteheuwel and Hanover Park), with very low percentages of other population groups. The small red area to the north of the study area is the low-cost public housing development of Dunoon, which consists of Black African households predominantly. The orange areas to the west (Sea Point and Claremont) and red area to the north (Table View) of the study area indicate areas with a very high percentage of White households, with very low percentages of other racial groups.

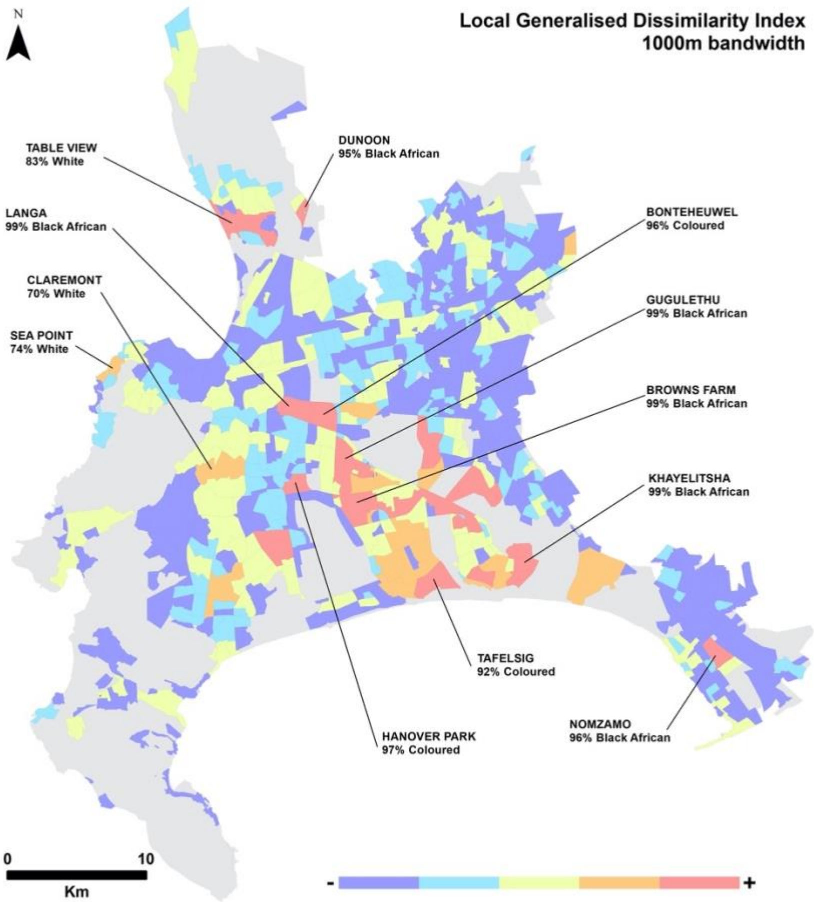


Figure 6.3: Local indices of Generalized Dissimilarity for Racial Groups
(Census 2011: Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

Figure 6.4 presents the output from Figure 6.3 with an overlay of the apartheid group areas for each of the four racial groups in the study area, which enables visualisation of the same local dissimilarity measurements but in the context of different group areas. These group area boundaries were derived from the group areas presented in Figure 6.1.

It is noticeable that the Black African group (see Figure 6.4A) is still mostly segregated in the region of the previous Black African group areas to the south of the study area. Although a similar occurrence is evident for the Coloured population to the south (see Figure 6.4B), much lower levels of racial dissimilarity are evident in the former Coloured group areas to the east and west of the study area. Similarly, the White suburbs in the former White group areas (see Figure 6.4D) reflect a lower degree of dissimilarity, with the exception of the discussed suburbs of Sea Point, Claremont and Tableview. Although the group areas for the Indian/Asian group are presented for reference, no discussion is provided due to their size and minimal change in these areas.

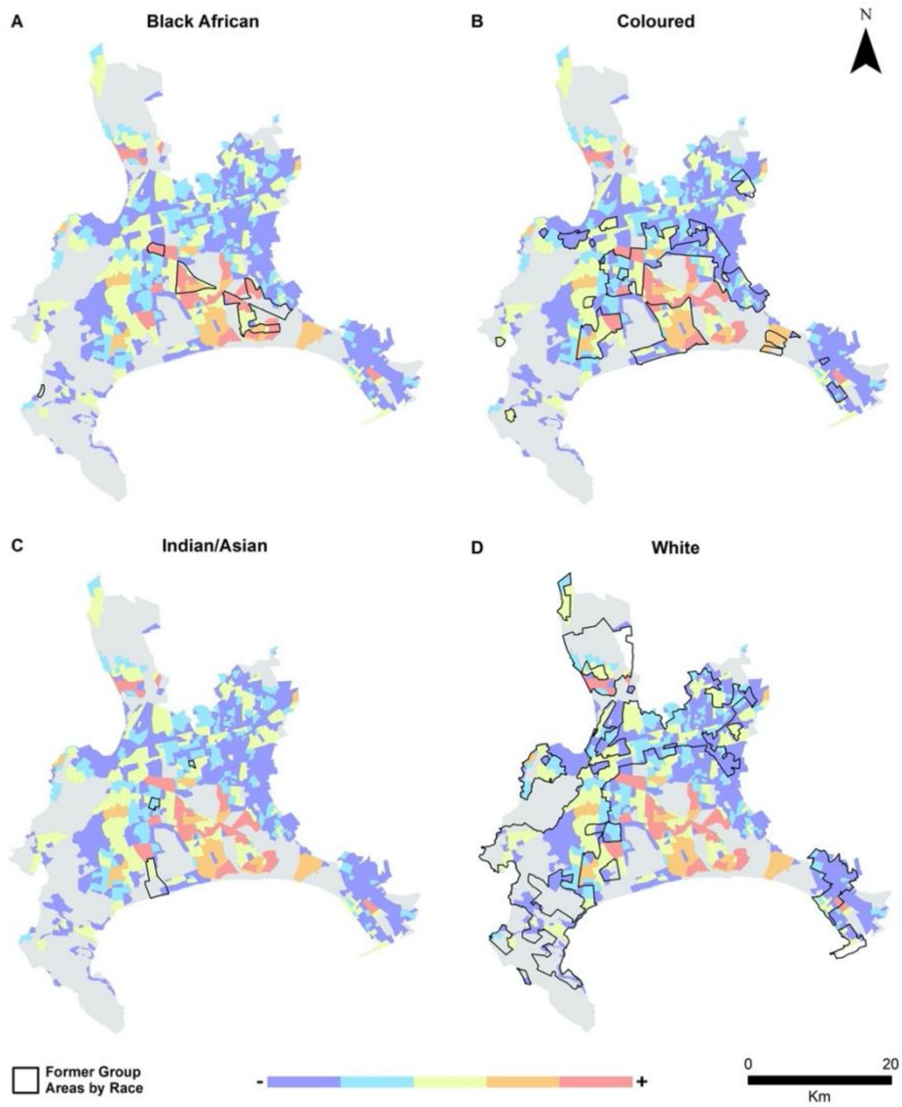


Figure 6.4: Local indices of Generalized Dissimilarity for Racial Groups by Group Area
(Census 2011: Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

The initial establishment of racial segregation in Cape Town, discussed in Section 2.4.1, remains evident in the clustering of predominantly Black African and Coloured neighbourhoods presented here. To contextualise this issue the 2011 census data for the four racial groups were applied respectively to the group areas, presented in Figure Figure 6.1, and the census boundaries adjusted as approximation of these group areas. For each group area a 100% ethnicity count was assigned to each census tract for the racial group of that particular area and the local dissimilarity index measured. Hence, local dissimilarity measurements were undertaken for an approximation of the apartheid scenario, whereby racial groups were forced to dwell in their designated group areas. Figure 6.5 shows the output of these measurements by the group areas of each race.

Compared to the measurements undertaken with the 2011 census data (see Figure 6.3), the approximation for the Black African households (see Figure 6.5A) shows a similar distribution with most households segregated to the south of the study area. Even though the intensity is expectedly higher, the distribution of higher dissimilarity areas for the Coloured group (see Figure 6.5B) is similar to that of the 2011 census data. The distribution of White households in the White group areas (see Figure 6.5D) reflects higher degrees of dissimilarity in the same suburbs highlighted in the 2011 census data.

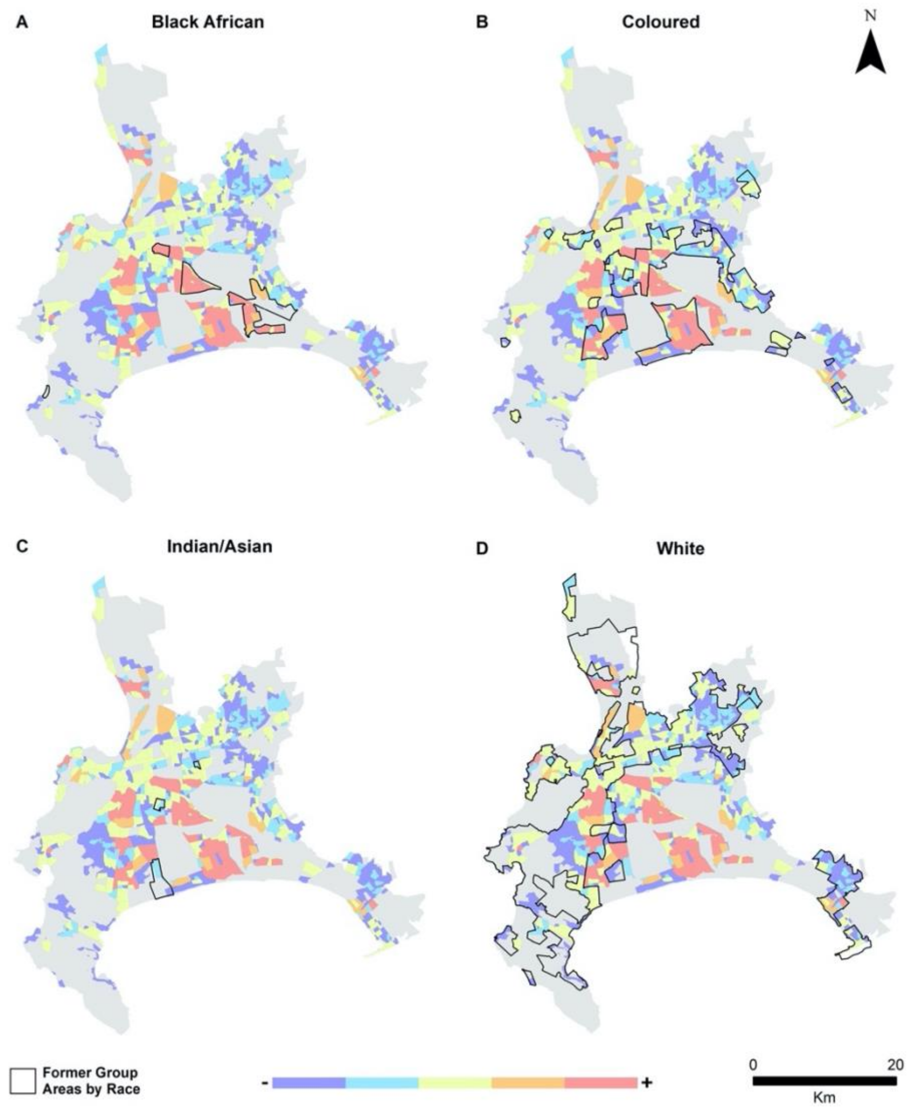


Figure 6.5: Local indices of Generalized Dissimilarity for Racial Groups by Apartheid Group Area (Apartheid Approximation: Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

Unlike the dissimilarity index, which always reflects positive values, the local information theory index may reflect both positive values (where a locality is less even than the study area as a whole) and negative values (where the locality is more even than the whole study area). The map in Figure 6.6 presents the results obtained for the local information theory index. The areas in orange and red indicate positive values where localities have a lower entropy (less racial evenness) than that of the whole of Cape Town. These suburbs are visible towards the south of the study area (Browns Farm, Mfuleni and Ikwezi Park) and correspond with the highest dissimilarity areas shown in Figure 6.3. These predominantly Black African neighbourhoods are in the same location as the former Black African group areas during the apartheid era (see Table 6.1). It is thus evident from the local information theory index results that these patterns of racial segregation remain mostly unchanged.

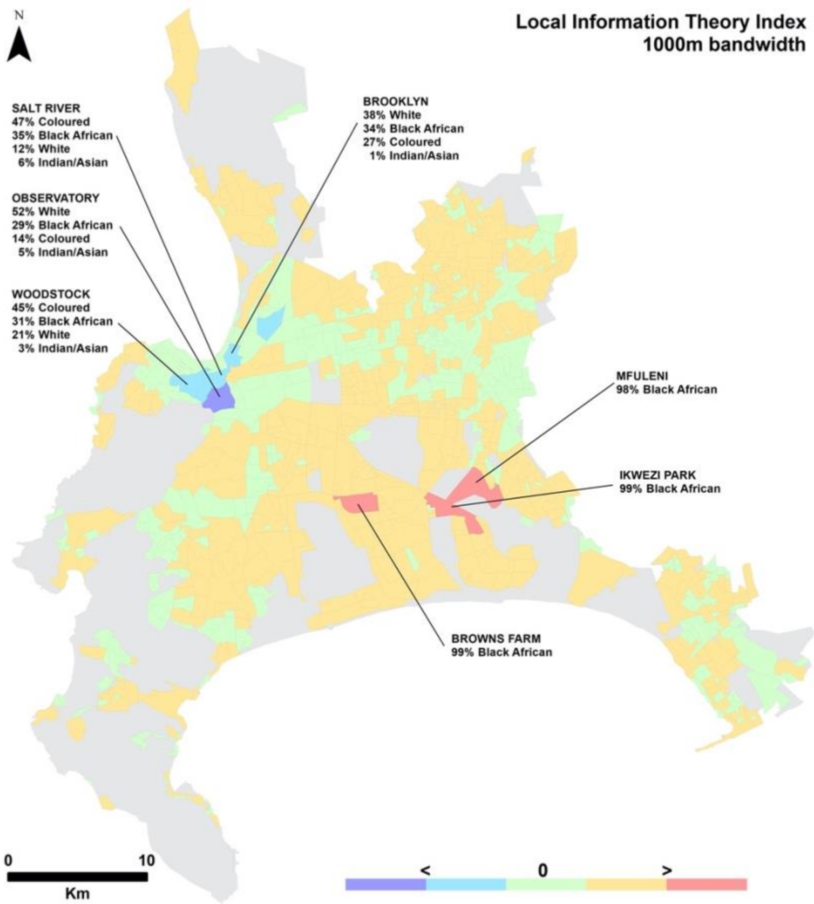


Figure 6.6: Local Spatial Information Theory Index for Racial Groups
(Census 2011: Computed for the four racial groups at 1000m bandwidth)

The localities in light and darker blue reflect negative values, indicating localities with a higher entropy (racial evenness) than the study area as a whole. These localities are situated close to the CBD of Cape Town and reflect the suburbs of Observatory, Woodstock and Salt River, which were highlighted as 'grey areas' in Chapter 2 (residential areas of illegal racial integration during apartheid – see Table 6.1). It is evident that these neighbourhoods have remained racially even. In contrast, the Black African and Coloured group areas of the apartheid era (see Table 6.1) are highlighted as the least even to the southern periphery of the study area.

Figure 6.7 shows the findings of Figure 6.6 by the group areas for each racial group. It is noticeable that the suburbs of higher racial unevenness in the 2011 census data are still situated among the former Black African (see Figure 6.7A) and Coloured group areas (see Figure 6.7B) of the apartheid era. Generally, the former White group areas (see Figure 6.7D) show a lower degree of racial unevenness in 2011, with the discussed grey areas of racial integration situated in both the former White and Coloured group areas.

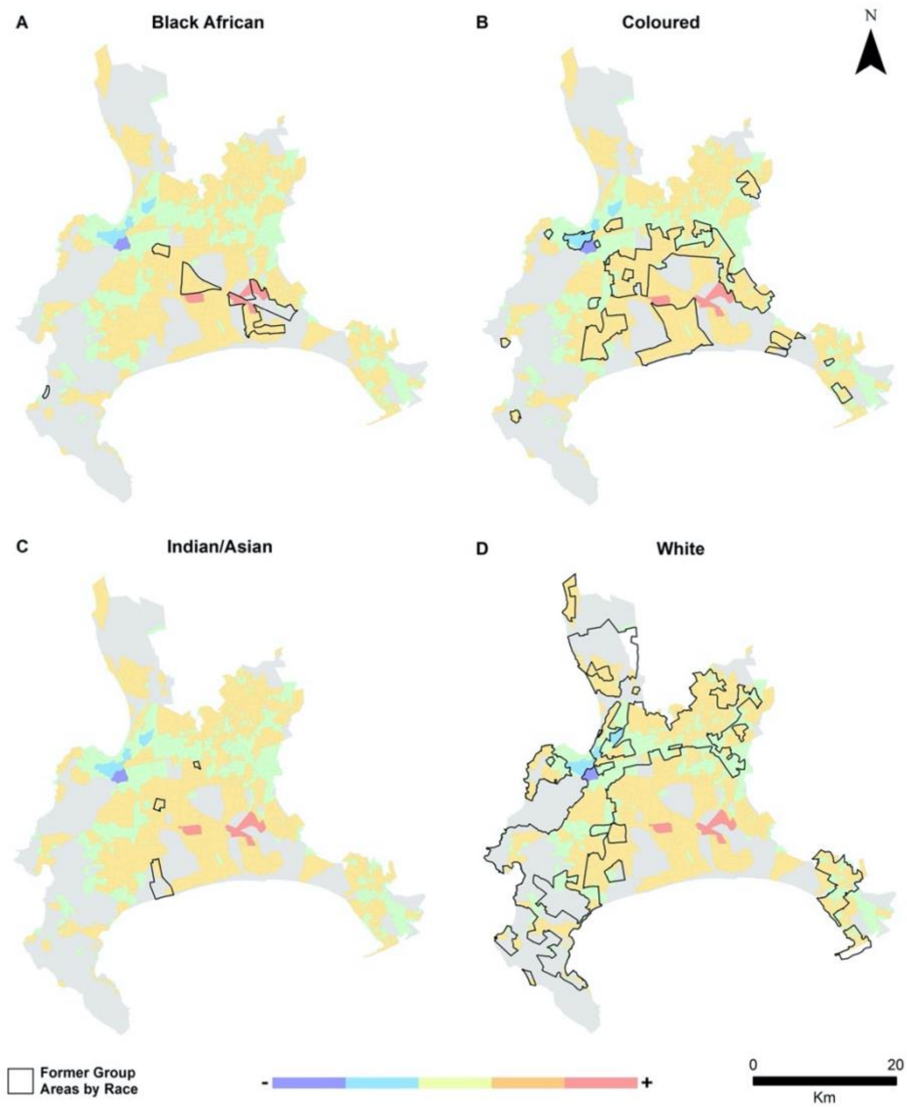


Figure 6.7: Local Spatial Information Theory Index for Racial Groups by Group Area (Census 2011: Computed for the four racial groups at 1000m bandwidth)

The exercise of approximating the degree of segregation during apartheid was extended to the measurement of the local spatial information theory index. Figure 6.8 shows the measurement output by each of the former apartheid group areas. The suburbs that are racially most uneven are found to be predominantly situated in the former Black African (see Figure 6.8A) and Coloured group areas (see Figure 6.8B). Again, this occurrence is very similar to the findings of the 2011 census measurements and highlights the persistence of racial segregation in the study area.

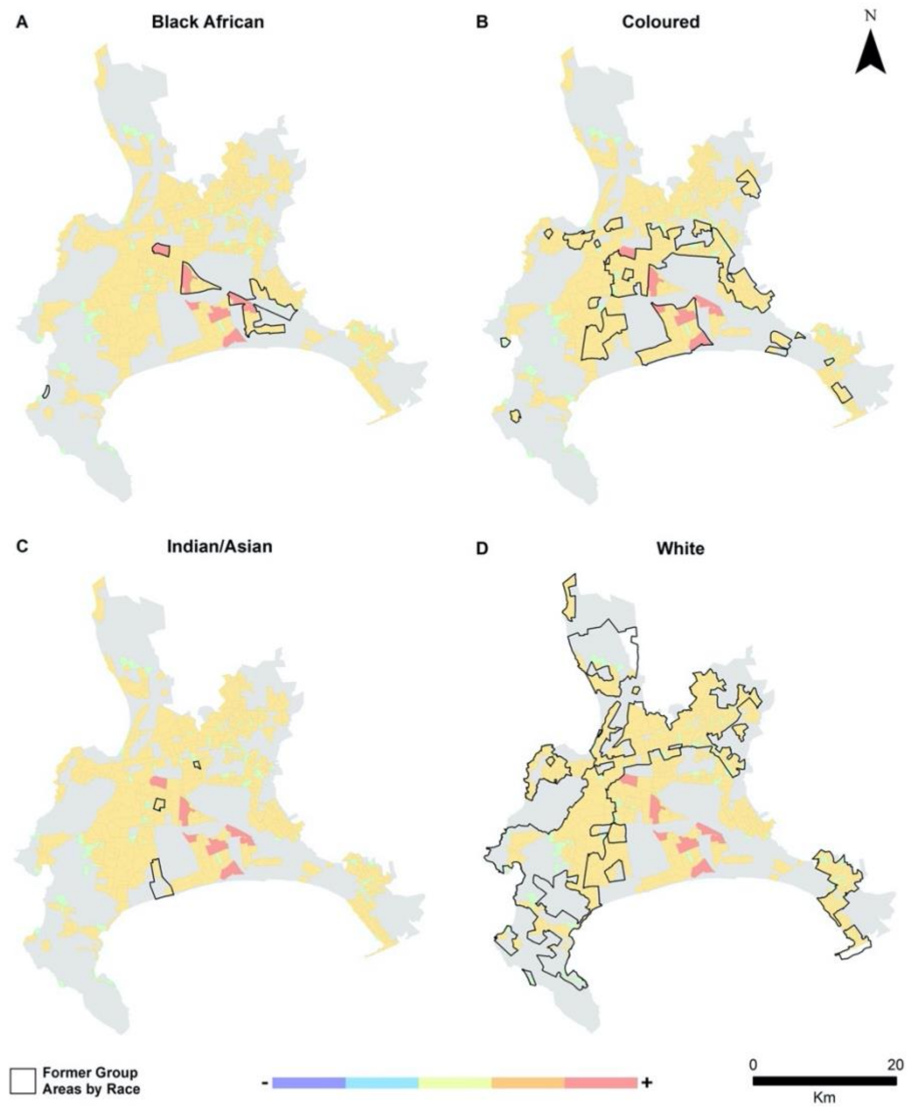


Figure 6.8: Local Spatial Information Theory Index for Racial Groups by by Apartheid Group Area (Apartheid Approximation: Computed for the four racial groups at 1000m bandwidth)

The approximation of segregation levels during the apartheid era not only offered contextualisation of segregation in the study area, but also allowed for a comparative analysis of these segregation measurements and the findings from the 2011 census data for

Cape Town. It is evident from these measurements of racial evenness/clustering that patterns of non-White segregation especially persisted since the apartheid era.

6.1.2 Isolation/Exposure Index

Figure 6.9 shows the normalised global isolation index values for racial groups as a segregation profile. Black African, Coloured and White groups exhibit very stable values across scales, suggesting that these groups are present throughout the urban area of Cape Town. The Indian/Asian group presents very high values when calculated using bandwidth equal to zero (aspatial) and 1000m. This is a reflection of the fact that the group has a small representation (1.4%) and is concentrated in specific areas of the city.

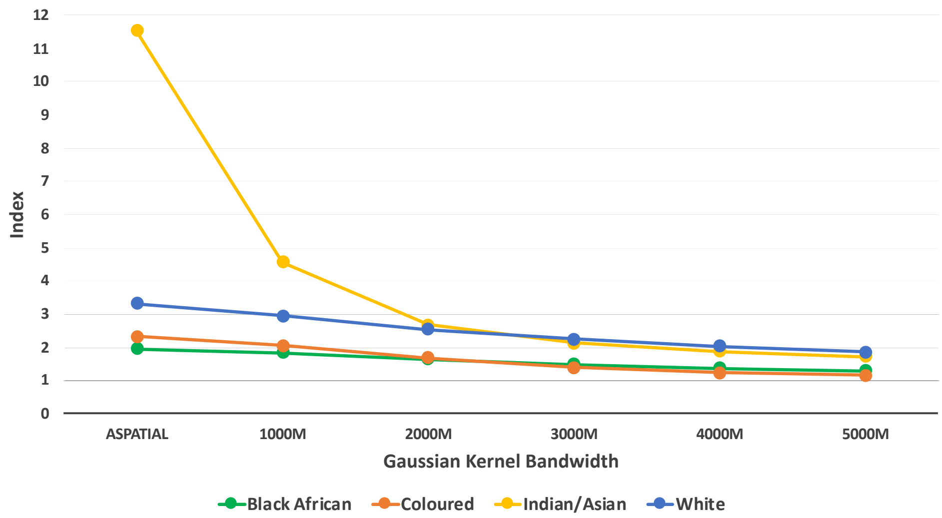


Figure 6.9: Normalised Global Aspatial and Spatial Isolation of Racial Groups

In order to further explore the exposure between the different groups, the normalised global results for a bandwidth of 1000m will be discussed in more detail below.

Figure 6.10 presents a summary of the normalised global isolation and exposure levels (bandwidth = 1000m) for the four racial groups in the study area. As discussed in Chapter 3, absolute isolation and exposure indices, ranging between 0 and 1, are significantly dependent on the city-wide proportions of the studied groups and that such a dependency proves to be problematic for comparative studies. Thus, in support of the interpretation of results in this study, normalised isolation and exposure indices are applied, by which the original figures for each group are divided by the city-wide proportion of that specific group. For example, each absolute value calculated for the Black African group, spatially or at a specific spatial bandwidth, is divided by the Black African proportion of all households in the study area.

The normalisation process changes the way in which the results are interpreted. A normalised value of 1 means that the global isolation of a group is equal to its proportion in the study area and, thus, corresponds to a non-segregated spatial arrangement. Values can be interpreted as the number of times (or fraction if less than 1) that isolation is higher or lower than expected in a non-segregated situation. As such, groups reflecting Exposure Index values lower than 1 are less exposed to each other than expected, while values higher than 1 indicates more exposure.

It is important to note that normalised values vary between 0 and ∞, meaning the range of values below 1 is much smaller (between 0 and 1) than above 1, which needs to be taken in consideration during the interpretation of results. To aid visualisation of such differences, the exposure and isolation have been log transformed so values between 0 and 1 are plotted proportionally to the ones above 1. Although the values show in the result table are the original normalised values, they have been colour-coded to mitigate the differences in ranges, so the darker the colour of the cell, the farthest the value is from the reference value (1) in the log scale (as plotted).

Figure 6.10(A) shows the results of exposure between each pair of groups, with isolation values in the diagonal line (exposure from one group to itself), also plotted (log transformed) in Figure 6.10(B). The normalised isolation value for the Indian/Asian group is the highest, 4.5 times of what would be expected in a non-segregated spatial arrangement. It is important to consider this is a group with a very small representation in the study area (1.4% of the total population) and results indicate they are concentrated in specific areas of the city. The other racial groups also present high isolation values: White (2.85), Coloured (2.05), and Black African (1.83).

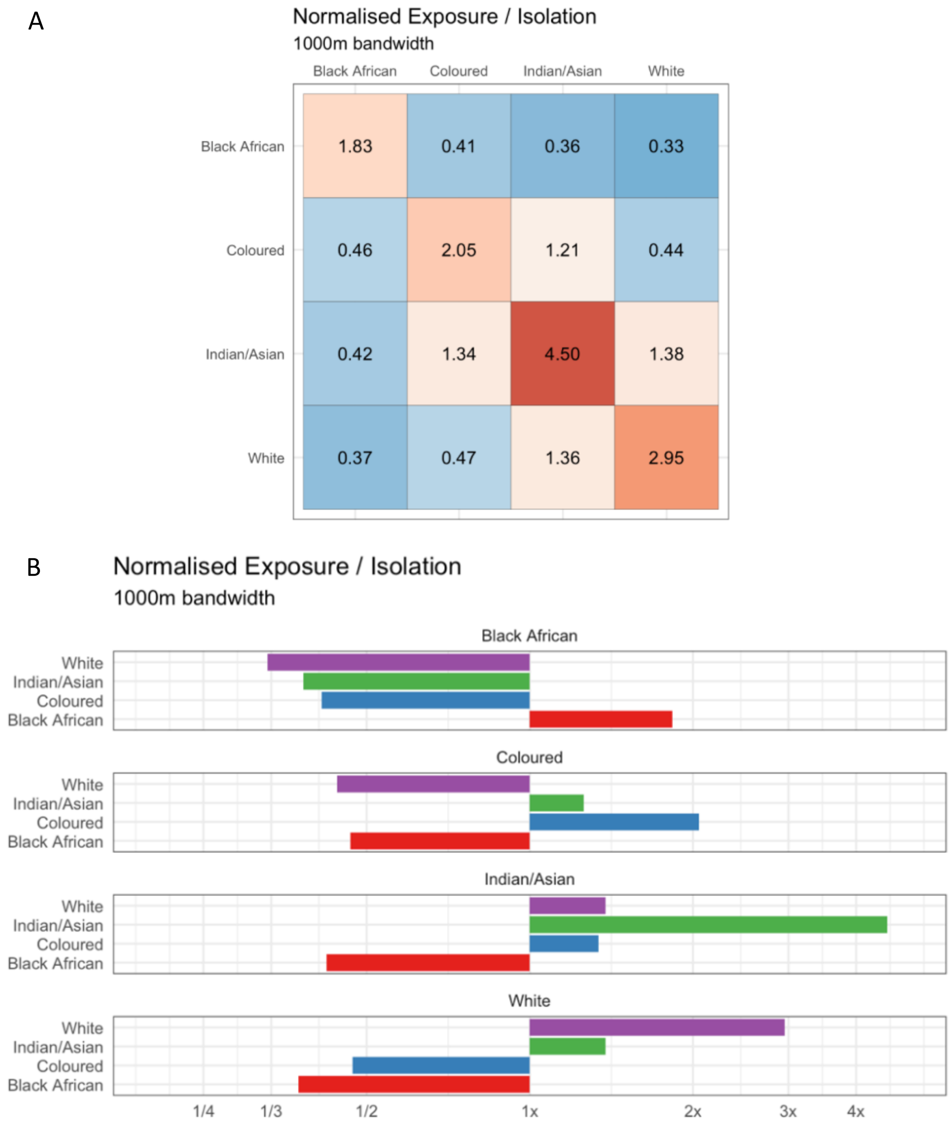


Figure 6.10: (A) Table and (B) Histogram of Normalised Global Spatial Isolation & Exposure Indices for Racial Groups at Measurements of 1000m Bandwidth

Normalised values of exposure indicate the degree of potential integration between the groups. It is interesting to note there is very little exposure between Black African and all other groups. The lowest exposure value for the Black African group is to the White group, demonstrating the persistence segregation between these two groups since the colonial era. Against the suggestion that the Coloured population is the most integrated in the contemporary Cape Town (see Chapter 2), results indicate a very low level of exposure of Coloured to White and Black African groups. The low exposure of the Coloured population to the White population supports the findings of Christopher (2001a), Rospabe and Selod (2006) and Parry and van Eeden (2015).

Comparatively, the Coloured and White groups are more exposed to the Indian/Asian group, with the Coloured group most exposed to the Indian/Asian population and confirming a higher level of integration between these two racial groups. This phenomenon was identified by Rospabe and Selod (2006) in the 1996 census data and by Parry and van Eeden (2015) in the census data between 1991 and 2011 and confirms persistence over time. The global spatial isolation and exposure measurements for the four racial groups at a 1000m bandwidth suggests that the post-apartheid city still reflects persistent racial segregation similar to the patterns of the apartheid city.

Figure 6.11 shows the results of the local spatial isolation index maps for the four population groups. The former apartheid group areas are overlayed to provide additional context to historical segregation in the study area. The Black African group (see Figure 6.11A) is most isolated in a cluster towards the south of the study area and correspond largely to the layout of the former Black African group areas. These patterns are also similar to those of Figure 6.3 and Figure 6.6, which respectively showed the areas of highest dissimilarity and areas that have a much lower entropy (Browns Farm, Gugulethu, Ikwezi Park & Mfuleni) than the study area as a whole, reflecting the findings of Geyer and Mohammed (2016), concerning hypersegregation (discussed in Chapter 2).

The Coloured group (see Figure 6.11B) is most isolated to the south and central part of the study area, with areas to the south showing similar patterns to high levels of dissimilarity (see Figure 6.3) and evident segregation from the adjacent Black African regions. It is noticeable how the distribution of higher isolation aligns with the location of the former Coloured group areas of Cape Town. However, it is found that the Coloured neighbourhoods have also extended into formerly White group areas to the north and west of the former Coloured group areas by 2011. Both the Indian/Asian group to the west (see Figure 6.11C) and the White population group (see Figure 6.11D) to the north and west of the study area reflect lower levels of isolation, but clear spatial segregation from the Coloured and Black African groups. These distribution patterns are also similar to the distribution of lower dissimilarity levels found in Figure 6.3, with the distribution of more isolated White households similar to the location of the former White group areas. This occurrence supports the findings of Crankshaw (2012) in Section 2.4.2. The findings for the local spatial isolation measurement for the four racial groups reflect similar patterns to the general distribution of the four racial groups.

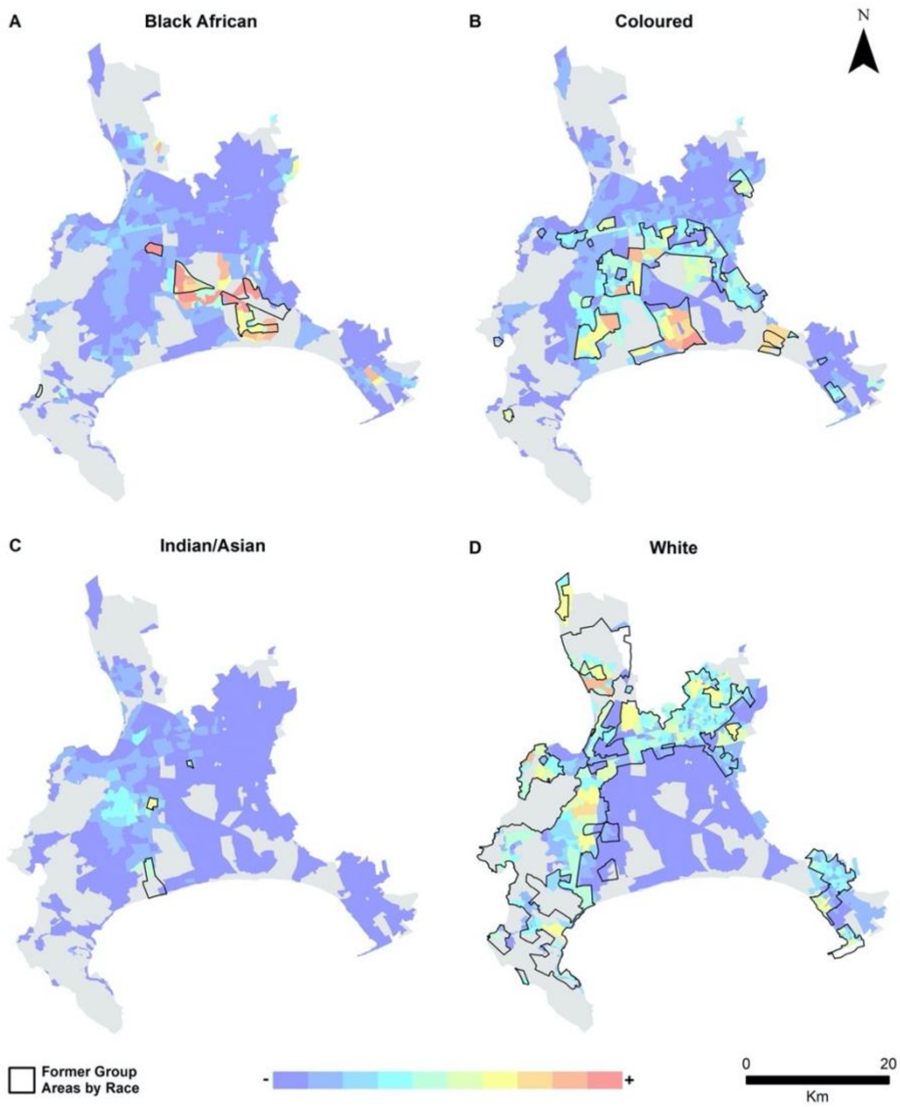


Figure 6.11: Local Spatial Isolation of Racial Groups by Group Area
(Census 2011: 1000m bandwidth – manual classification, 10 classes between 0 and 1)

The measurement of local spatial isolation levels for the respective group area approximations is presented in Figure 6.12. Similar to the findings from the 2011 census data, the distribution of most isolated Black African (see Figure 6.12A), Coloured (see Figure 6.12B) and White households (see Figure 6.12D) correspond to the distribution of the respective former group areas of these racial groups.

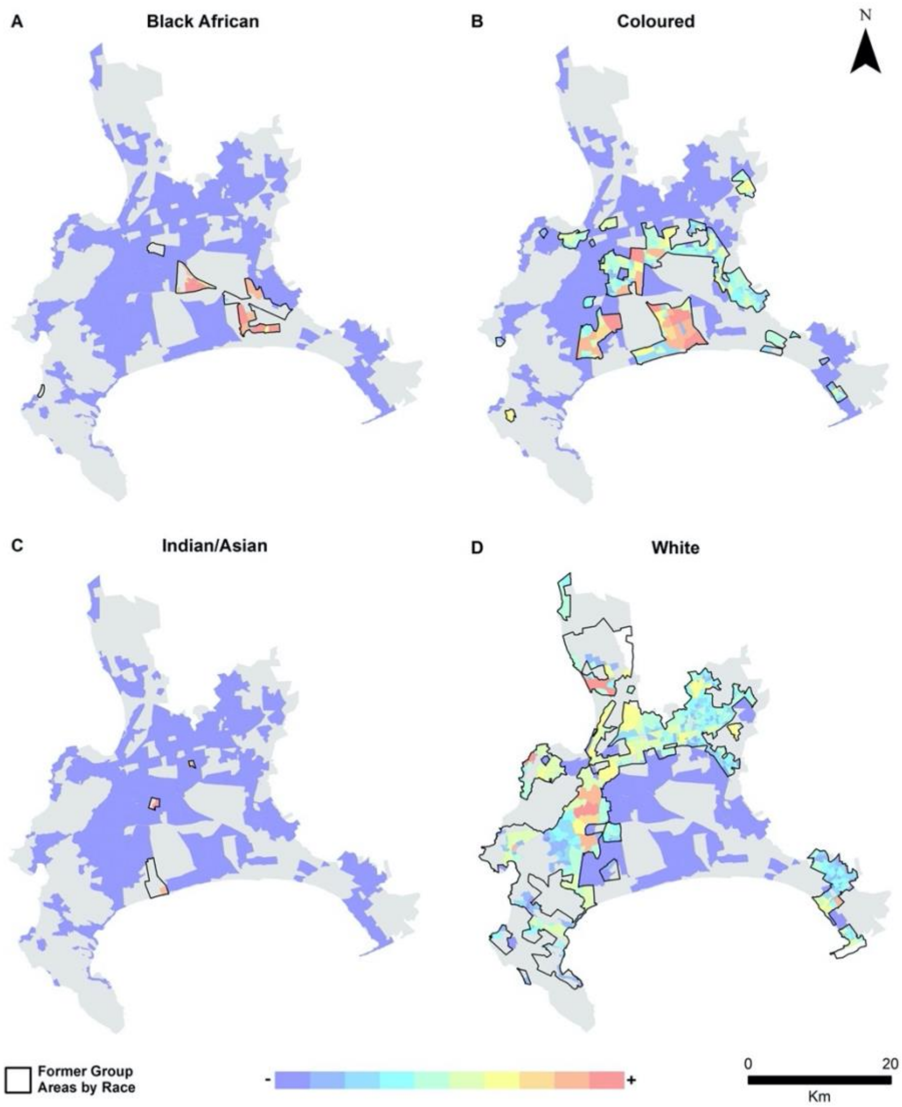


Figure 6.12: Local Spatial Isolation of Racial Groups by Group Area
(Apartheid Approximation: 1000m bandwidth – manual classification, 10 classes between 0 and 1)

Figure 6.11 shows that the Black African and White population groups are spatially most segregated from each other. To better understand exposure between these two groups the local spatial exposure between the Black African and White racial groups were mapped (see Figure 6.13) and the respective group areas of these two groups overlayed. The locations reflecting the most exposure of Black African households to the households of the White population (see Figure 6.13A) highlight three Black African townships (underdeveloped or informal areas) of Joe Slovo Park to the north-west, Imizamo Yethu to the south-west and Nomzamo to the south-east. Imizamo Yethu was also referred to in Section 2.4.2 as a small informal settlement in close vicinity to a very affluent and predominantly White neighbourhood.

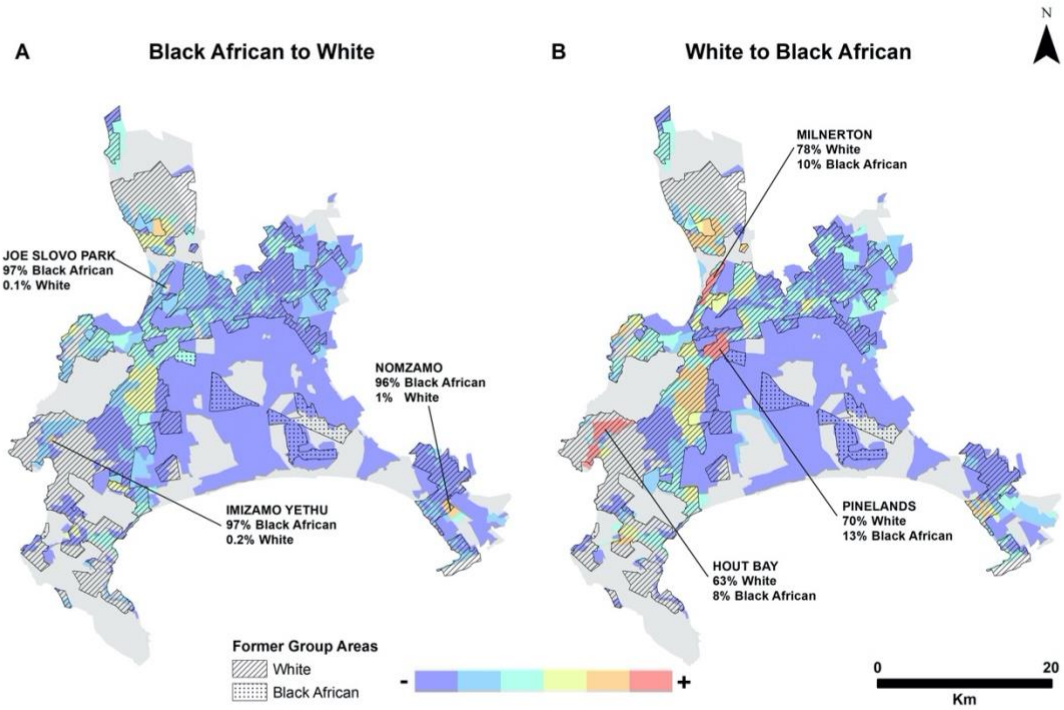


Figure 6.13: Local Spatial Exposure of (A) Black African to White Households and (B) White to Black African Households

The White group is most exposed to the Black African group (see Figure 6.13B) in the modern suburbs of Milnerton (adjacent to Joe Slovo Park), Pinelands to the north-west of the study area and Hout Bay (adjacent to Imizamo Yethu) to the south-west. It is noticeable that the higher levels of exposure in both instances only occur in former White group areas. It is thus evident that racial integration between these two racial groups only occurred only in the predominantly White suburbs of Cape Town.

6.2 Spatial Segregation Measurements of Income Groups

6.2.1 Dissimilarity and Information Theory Indices

Following measurements for the racial groups, segregation by annual household income (low, middle and upper) in the study area was measured. In comparison to the results obtained using racial groups (see Figure 6.2), the results for both global spatial dissimilarity and information theory indices (see Figure 6.14) reflects much lower values across all bandwidths for income and a more gradual decrease across bandwidths. Similar trends are also clear between the two indices, with the information theory index reflecting lower values.

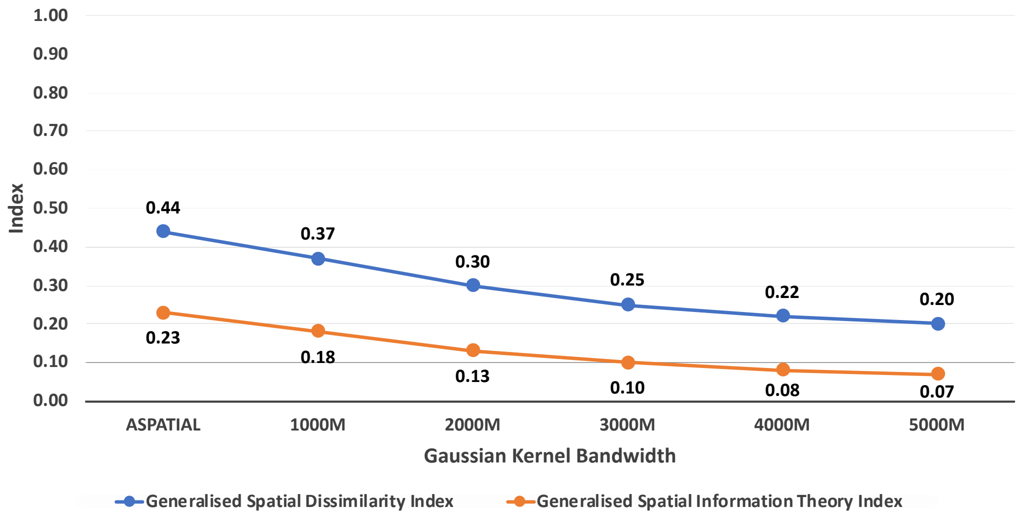


Figure 6.14: Evenness/Clustering Segregation Indices for the Annual Household Income variable (Generalised Spatial Dissimilarity Index (D) and the Information Theory Index (H))

Figure 6.15 presents the local spatial dissimilarity index map. It is evident that the areas of highest dissimilarity (in red) are found towards the centre of the study area (the suburbs of Delft, Mfuleni, Ikwezi Park and Browns Farm), where localities reflect high percentages of low-income households in predominantly Black African and Coloured suburbs (presented in Figure 5.10). These areas also corroborate with the Black African and Coloured areas that reflected high levels of racial dissimilarity and low levels of racial evenness.

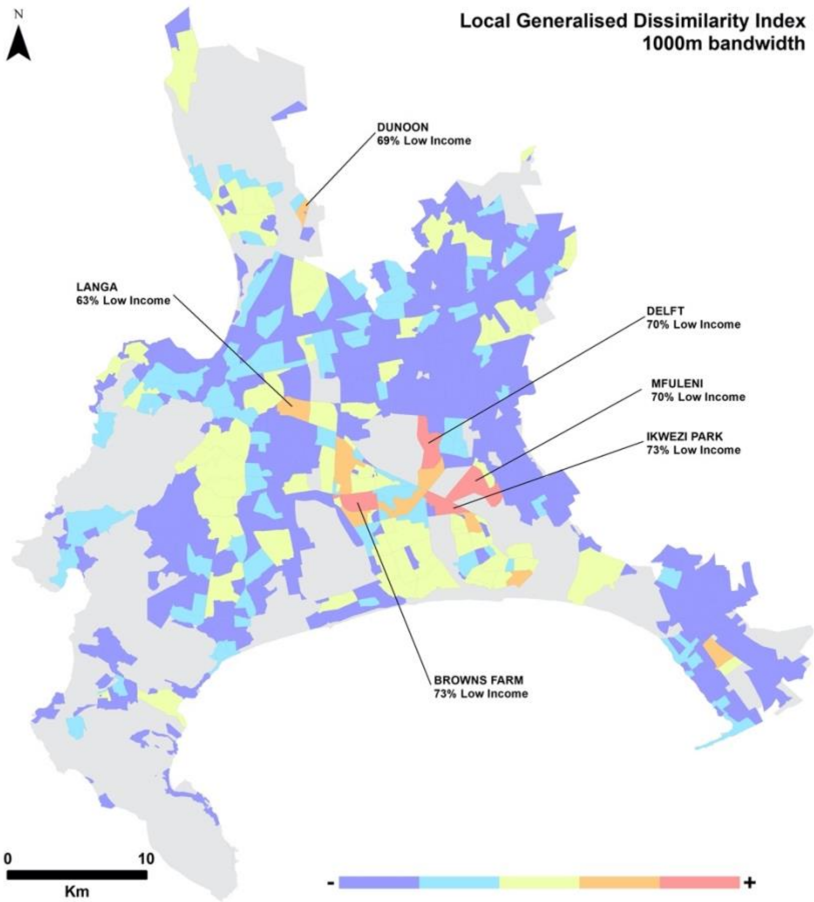


Figure 6.15: Local indices of Generalized Dissimilarity for Income Groups
(Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

The measurements presented in Figure 6.15 are shown with an overlay of each of the four racial group areas in Figure 6.16. Hence, all four maps present the same dissimilarity index measurements for income, but with the different former group areas included. Although it is found that some of the most isolated low-income suburbs expanded beyond the former group areas, it is evident that these neighbourhoods are situated between the former Black African (see Figure 6.16A) and Coloured (see Figure 6.16B) group areas. Nonetheless, a majority of the most isolated low-income suburbs are located within the former Black African group areas. In contrast, the former Coloured and White group areas (see Figure 6.16D) indicate considerably less dissimilarity in the composition of income groups in 2011.

Figure 6.16: Local indices of Generalized Dissimilarity for Income Groups by Group Area (Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

Figure 6.17 presents the results of the local spatial information theory index calculated for the households of the three income groups. The localities in light and dark blue indicate areas that reflect a higher evenness than the study area as a whole. In contrast, the areas in orange and red indicate values where localities have a lower evenness than the whole study area. It is noticeable that the areas of highest income evenness are predominantly middle- and upper-income areas, while the least even suburbs are predominantly composed of low-income households. The areas presented in green have a composition of income groups that is more akin to the composition of the study area as a whole and these areas effectively contribute to a decrease in segregation.

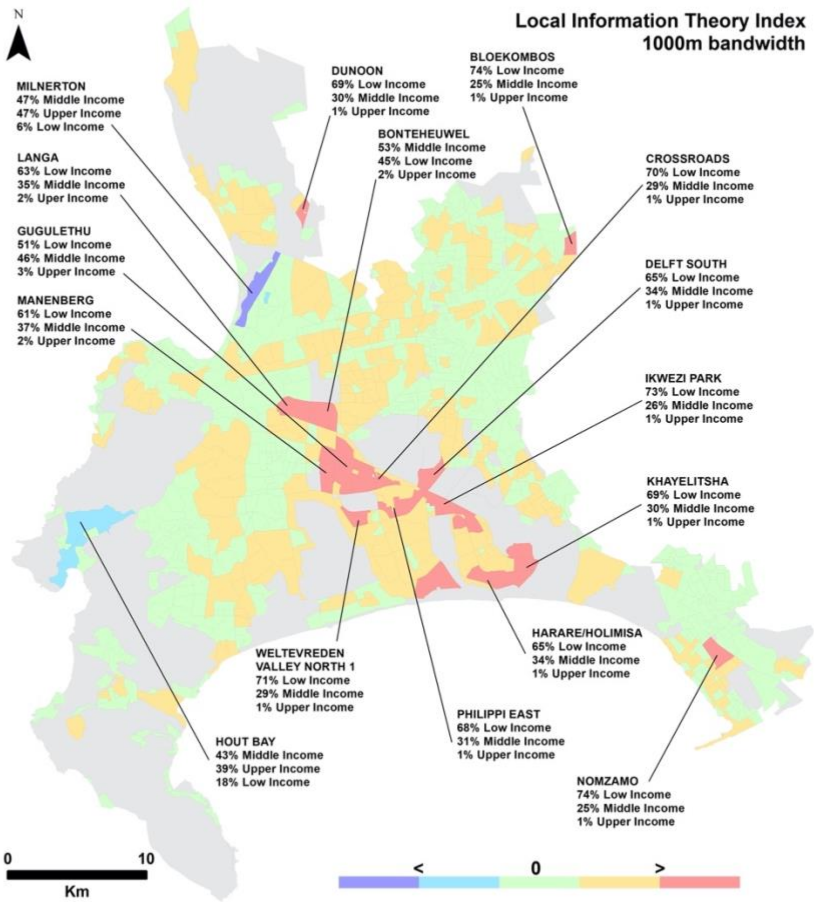


Figure 6.17: Local Spatial Information Theory Index for Income Groups (Computed for the four income groups at 1000m bandwidth)

The areas more even (equal in distribution) than the study area, in terms of income groups, are found to the west of the study area in the suburb of Hout Bay to the east. These localities reflect an even income spectrum from middle- to upper-income in Hout Bay and low- to middle-income in Imizamo Yethu. The localities reflecting less evenness than that of the study area are found to the south of the study area in the predominantly Black African neighbourhoods of Crossroads, Gugulethu, Ikwezi Park, Langa and Khayelitsha or the Coloured suburbs of Bonteheuwel, Delft South, Manenberg and Tafelsig (Mitchells Plain) where large percentages of low-income households are situated, with very little upper-income households.

Figure 6.18 presents the measurements shown in Figure 6.17, but again with the different racial group areas overlayed for context. The majority of low-income suburbs to the south of the study area, that are most uneven compared to the study area as a whole, are still situated where the former Black African (see Figure 6.18A) and Coloured (see Figure 6.18B) group areas were located.

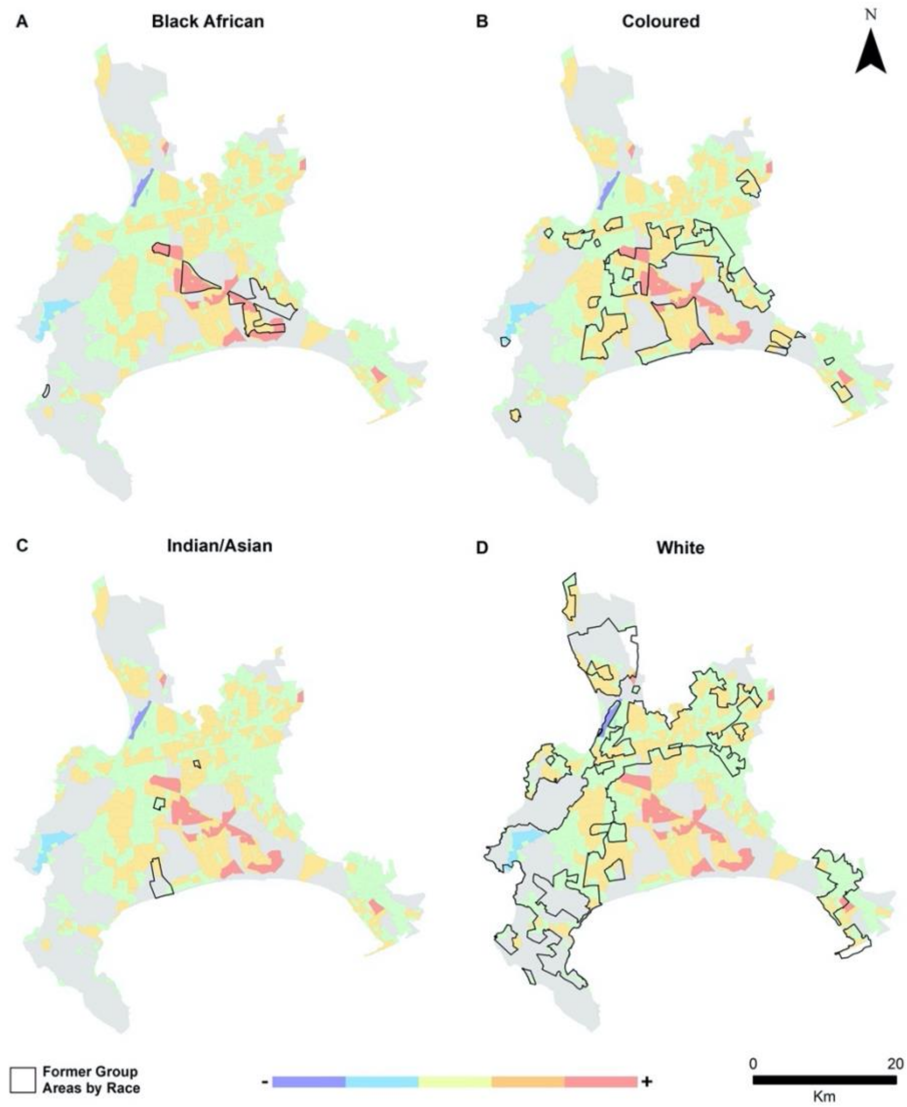


Figure 6.18: Local Spatial Information Theory Index for Income Groups by Group Area (Computed for the four income groups at 1000m bandwidth)

In addition to the findings of the dissimilarity index measurement of income groups this occurrence emphasises the persistence of segregation in Cape Town, as discussed in Section 2.4. This is especially evident in Figure 6.18D where the highest levels of evenness are found in the middle- to upper-income suburbs of the former White group areas.

6.2.2 Isolation/Exposure Index

Figure 6.19 presents the normalised global isolation calculated using different bandwidths as before. The upper-income group is clearly the most isolated group across scales, followed by the low-income group. It is also interesting to note the difference in the curves for the different groups. The middle-income curve is very flat in comparison to the other two groups. It ranges around the 1.00 value, indicating a similar level of presence throughout the urban area. The curve for the low-income group is slightly more accentuated, while the upper-income group's curve is much more accentuated, suggesting segregation at a local scale for the upper-income group. Although the low-income curve is higher than that of the middle-income group, demonstrating a higher level of isolation across all scales in comparison to middle-income, the curve for the upper income group is most accentuated, with higher differences between 1000 and 5000m bandwidths, suggesting that this group is more concentrated in small areas than the lower- and middle-income groups.

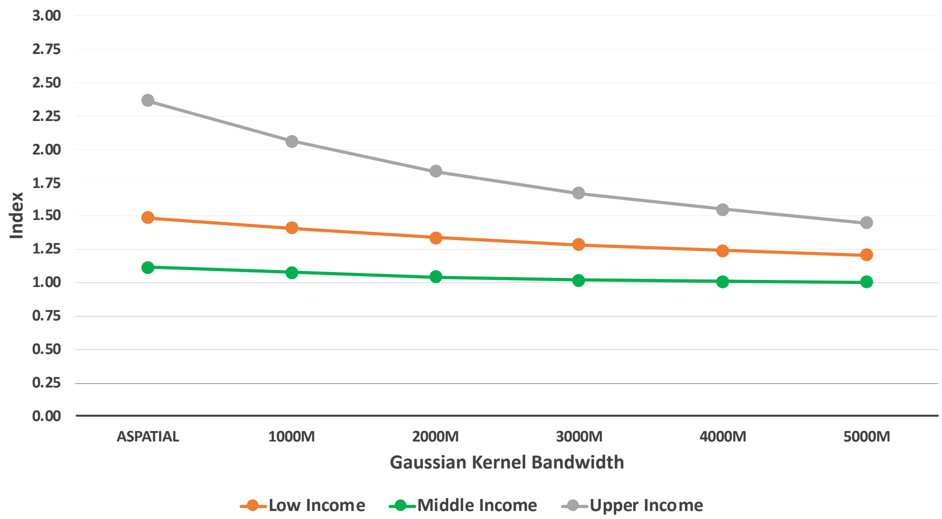


Figure 6.19: Normalised Global Aspatial and Spatial Isolation Indices for Income Groups

Figure 6.20A and B present the normalised global isolation/exposure results for the three income groups, which shows that the upper-income group is most isolated, followed by the low-income group. The middle-income group is least isolated with a value very close to 1, which refers to a non-segregated arrangement. Exposure values of this group to the other two income groups are close to 1 suggesting this group is more integrated to the other, with slightly higher levels of exposure to the upper-income group. It is inferred that this is due to the large number and wide geographic distribution of the middle-income households across the study area. The most striking result, however, is the low values of exposure between upper- and low-income groups. These results, together with the isolation of both the upper-income and low-income groups, support the argument in Section 2.4.2 that post-apartheid Cape Town remains significantly polarised socio-economically, which is in line with other studies (Christopher, 2000; Turok and Watson, 2001).

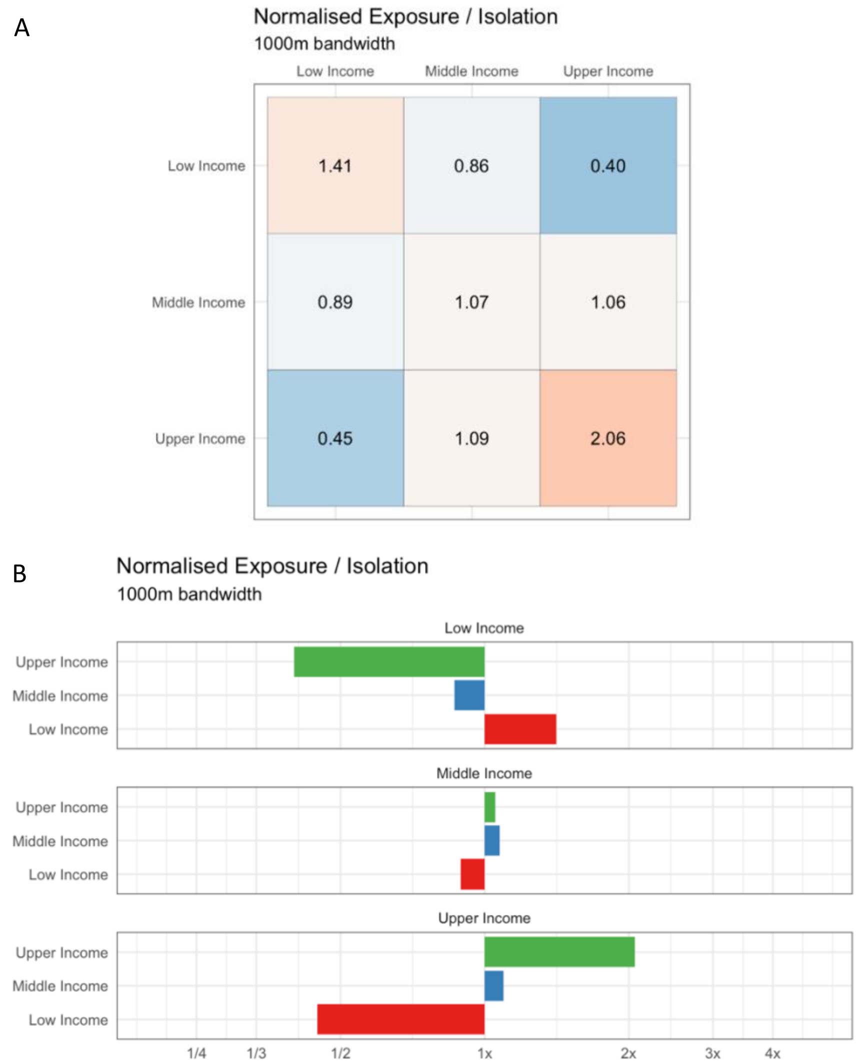


Figure 6.20: (A) Table and (B) Histogram of Normalised Global Spatial Isolation & Exposure Indices for Income Groups at Measurements of 1000m Bandwidth

Figure 6.21 presents maps for the local spatial isolation measurement of all three income groups. To contextualise the patterns of isolation, the former Black African, Coloured and White group area boundaries were respectively added to the low-, middle- and upper-income maps. The highest isolation for the low-income group (see Figure 6.21A) is found in the south of the study area, with the distribution of these suburbs conforming mostly to the former Black African group areas. Although the most isolated middle-income areas (see Figure 6.21B) are also clustered in the former Coloured group areas to the south, such areas are also evident to the west of the study area.

The local spatial isolation map for upper-income (see Figure 6.21C) reflects a contrasting distribution of isolation levels to the middle- and especially low-income distribution. The suburbs reflecting the highest level of upper-income isolation are located predominantly to the west and the northwest of the study area, conforming to the former White group areas of the apartheid era. It was presumed that the high level of upper-income isolation occurs due to the adjacent suburbs reflecting a similar composition of upper-income households.

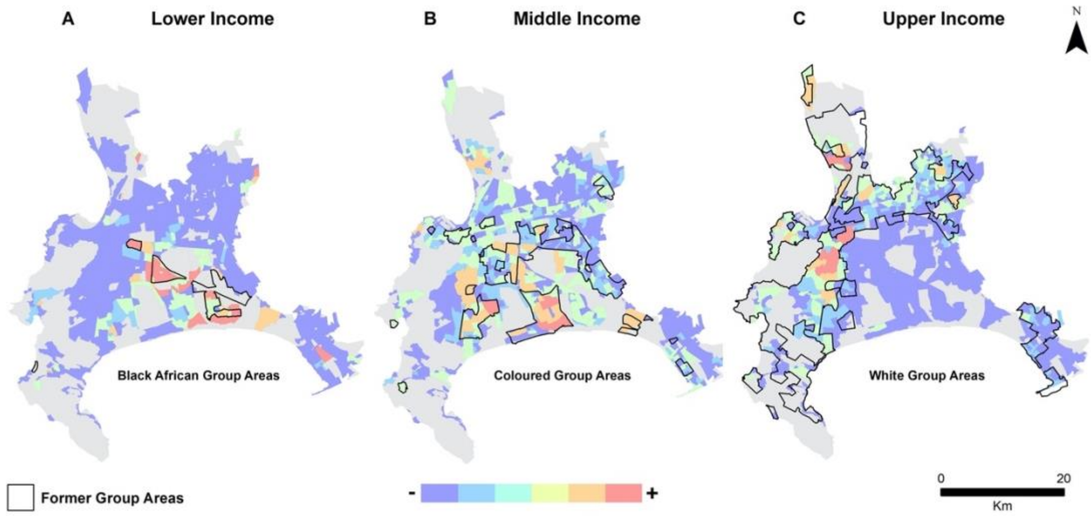


Figure 6.21: Local Spatial Isolation of Income Groups (1000m bandwidth)

The highest levels of integration between the middle- and upper-income group, revealed in Figure 6.20, was studied at a local scale and consequently mapped (see Figure 6.22). In addition, the former Coloured and White group areas were added for context. The highest level of exposure of upper- to middle-income (see Figure 6.22A) is evident in the suburbs of Table View, Sea Point and Parklands to the north-west of the study area and Plumstead, Pinelands, Rondebosch and Kenilworth to the west. It is notable that these suburbs reflect a very low percentage of low-income households.

The lower exposure of the middle- to upper-income group (see Figure 6.22B) is evident in the suburbs of Table View, Sea Point and Claremont to the west and north-west of the study area. In general, it is noticeable that most of the exposure between these two income groups occurs predominantly in the former White group areas, with much less occurrence in the former non-White suburbs of Cape Town.

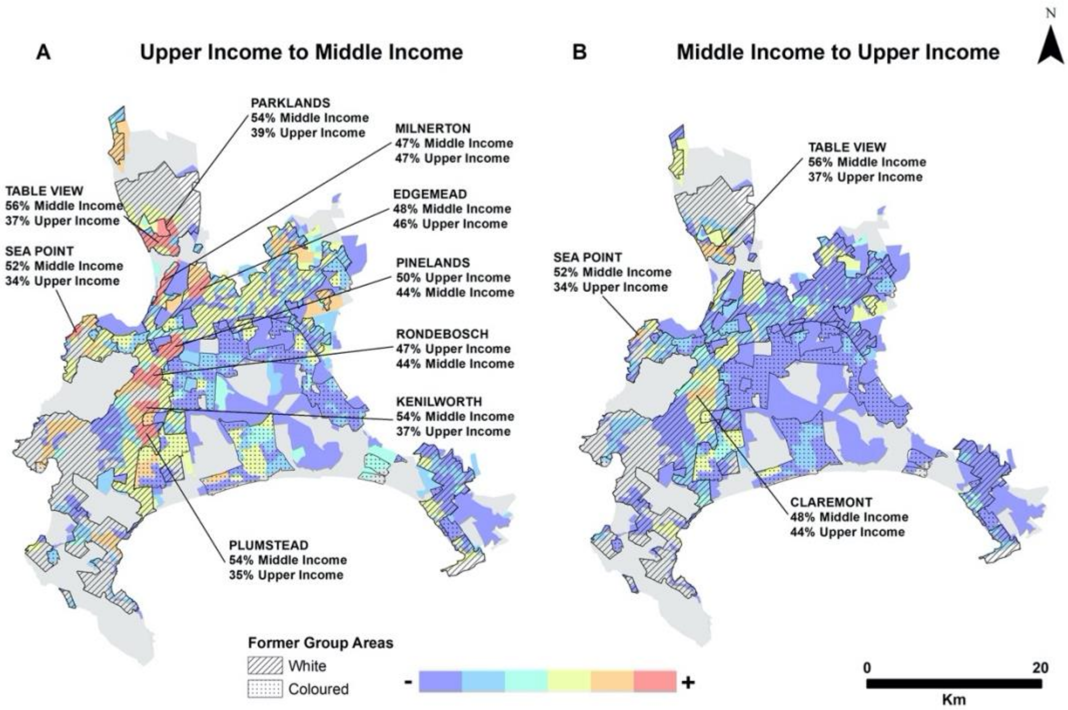


Figure 6.22: Local Spatial Exposure of Middle- and Upper-Income Groups (1000m bandwidth)

In this section it was evident that the segregation indices values for income were all lower than for race, suggesting that race is still the predominantly factor in residential segregation in Cape Town. Results show that although there is clear segregation between the upper- and low-income groups, the middle-income group seems to be more integrated to other groups. The next section explores the combined race and income classes to further explore these aspects.

6.3 Spatial Segregation Measurements of Income-By-Race Groups

6.3.1 Dissimilarity and Information Theory Indices

This section explores the results of segregation indices when analysed using combined income and race groups. As explained in Chapter 5, twelve 'income-by-race' categories were used for this analysis. Figure 6.23 presents the segregation profiles of the aspatial and spatial measurements of the generalised spatial dissimilarity and information theory indices.

The dissimilarity index profile reflects a similar trend to that of the racial measurement with a comparatively high aspatial value and spatial values decreasing more significantly to the 5000m radius, suggesting that segregation at local scales is relevant for Cape Town. Where the dissimilarity values for the income-by-race groups are slightly lower than that of the racial values, it is significantly higher than the dissimilarity values for the analysis using income groups alone. The same trends can be observed for the global information theory index values.

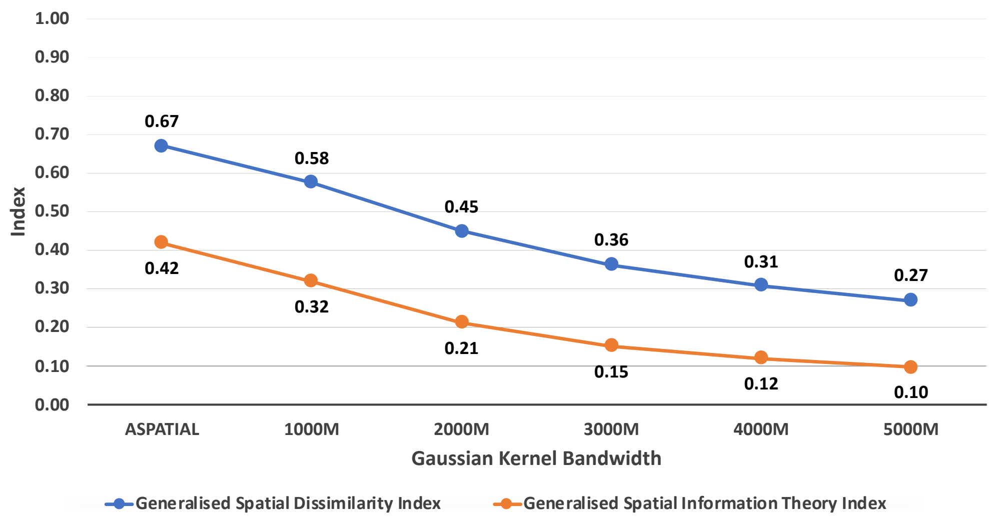


Figure 6.23: Evenness/Clustering Segregation Indices for the Income-by-Race Categories (Generalised Spatial Dissimilarity Index (D) and the Information Theory Index (H))

Figure 6.24 presents the local generalized dissimilarity index for the income-by-race categories. It is evident that the localities of highest dissimilarity are again found towards the centre and south of the study area and show a similar distribution to the local dissimilarity patterns of the racial groups (see Figure 6.3). The predominantly White middle- to upper-income areas of Claremont, Sea Point and Table View to the west and north-west of the study area also reflect a relatively high level of segregation (orange).

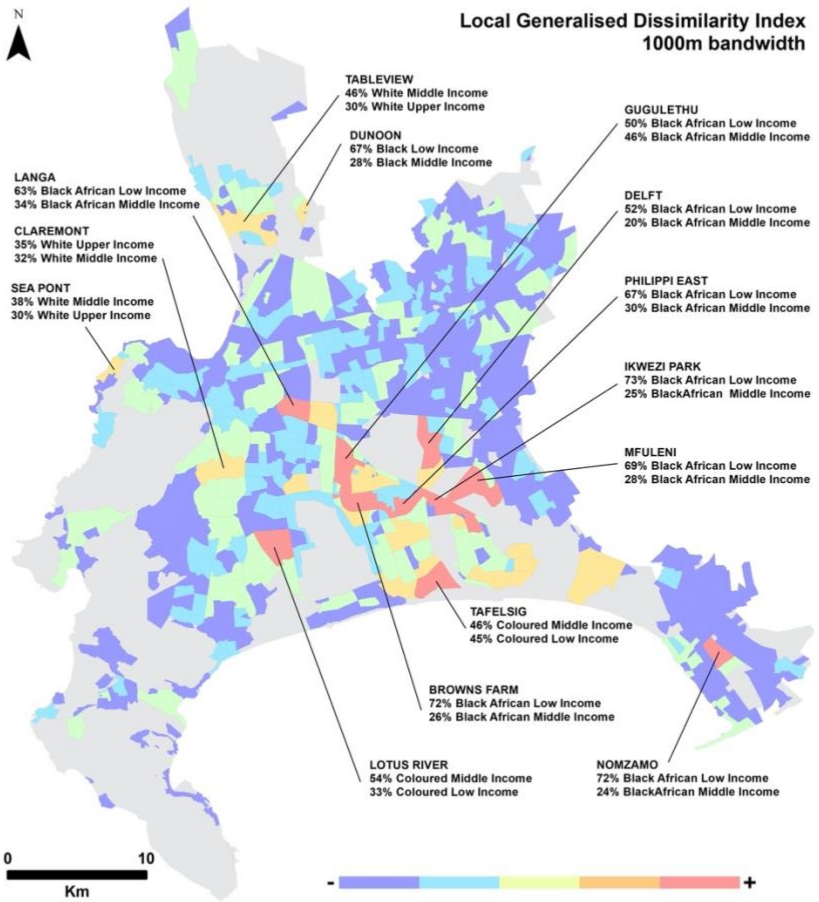


Figure 6.24: Local indices of Generalized Dissimilarity for Income-by-Race Groups (Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

This distribution of dissimilarity for the income groups by race are presented in Figure 6.25 with the boundaries of the racial group areas overlayed. The suburbs of highest income-by-race dissimilarity, compared to the study area as a whole, are predominantly Black African low-income suburbs in the former Black African group areas to the south of the study area (see Figure 6.25A). Although to a lesser degree, a similar occurrence is noticeable in the former Coloured group areas (see Figure 6.25B) to the south. Similar to the distribution of dissimilarity levels for the racial groups (see Figure 6.4), the former White group areas reflect significantly lower levels of income-by-race dissimilarity (see Figure 6.25D).

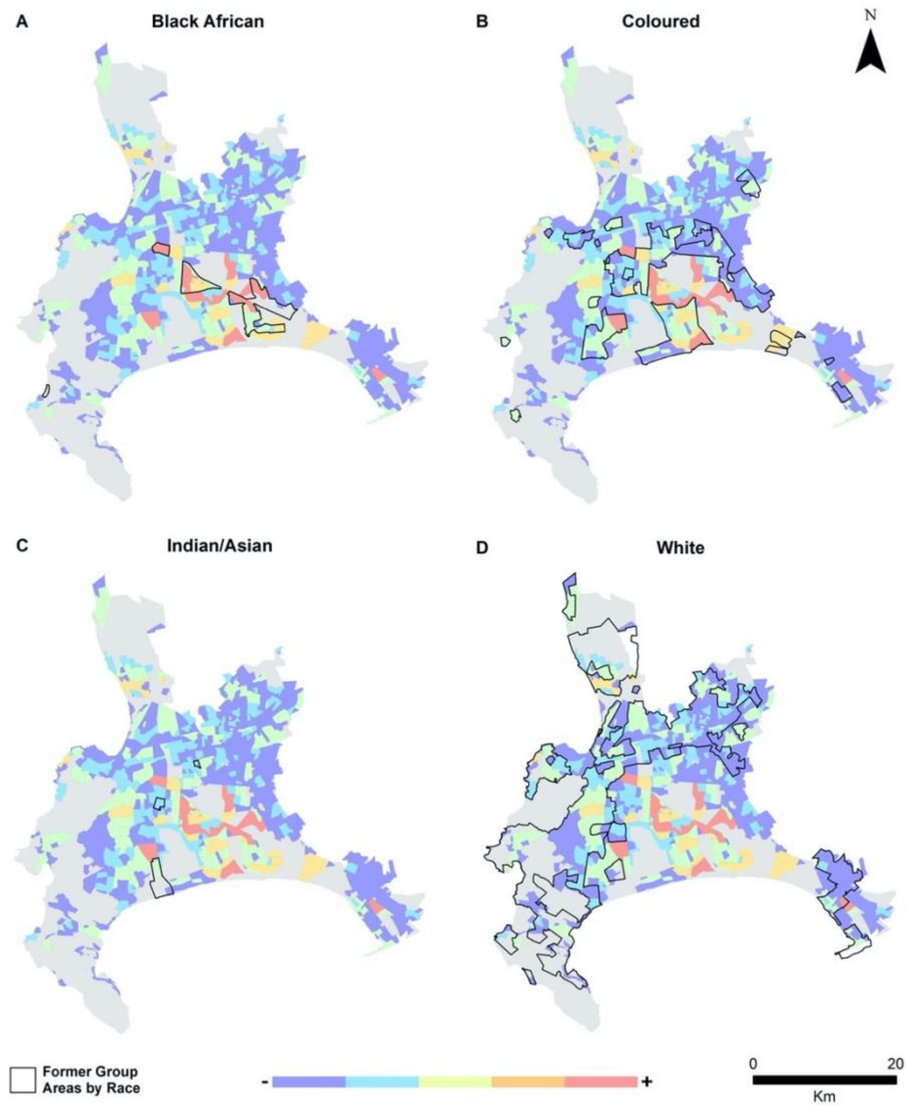


Figure 6.25: Local indices of Generalized Dissimilarity for Income-by-Race Groups
(Computed for the four racial groups at 1000m bandwidth – 5 classes between 0 and 1)

Figure 6.26 presents the local information theory index calculated for the income-by-race categories. The localities, reflecting a higher level of evenness (blue) than the study area as a whole, are located closer to the CBD of Cape Town and include the racially even suburbs of Salt River, Woodstock and Observatory. The more evenness Southern Suburbs of Rondebosch East, Landsdowne, Romp Vallei and Wynberg reflect a composition of White and Coloured middle- and upper-income households. The suburbs with the lowest measures of evenness (red) are located to the centre and south of the study area and include neighbourhoods that are predominantly Black African low- and middle-income areas.

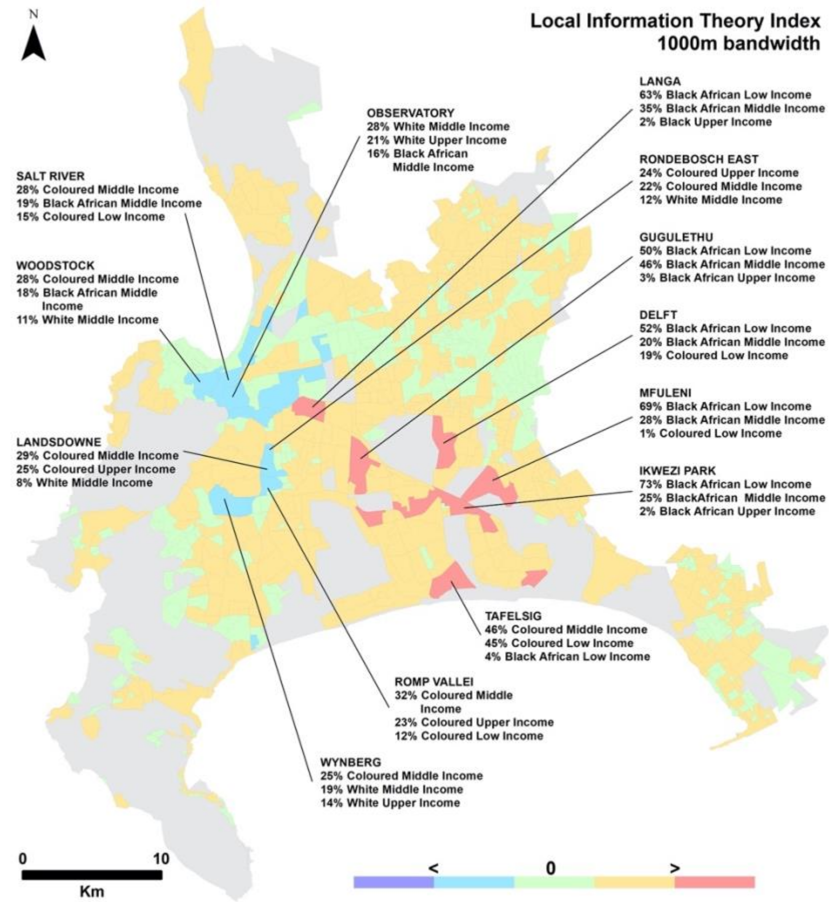


Figure 6.26: Local Spatial Information Theory Index for Income-by-Race Groups (Computed for the four racial groups at 1000m bandwidth)

It was also noticed that the distribution of the localities of higher evenness, in terms of income-by-race, are similar to the localities of higher racial evenness (see Figure 6.6) and the distribution of areas of lowest income-by-race evenness are more similar to the localities of low-income evenness (see Figure 6.17).

Figure 6.27 presents the local spatial information theory index from Figure 6.26 with an overlay of each of the former group area boundaries of the four racial groups in Cape Town. Similar to the local information theory index measurements undertaken separately for race and income, the localities of highest unevenness are located to the south of the study area. These suburbs of predominantly Black African low- to middle-income households are still mostly located in the former Black African group areas (see Figure 6.27A), reflecting the persistence of segregation since the apartheid era. This is also evident in the Coloured low- to middle-income suburb of Tafelsig that is located in a former Coloured group area of Cape Town (see Figure 6.27B).

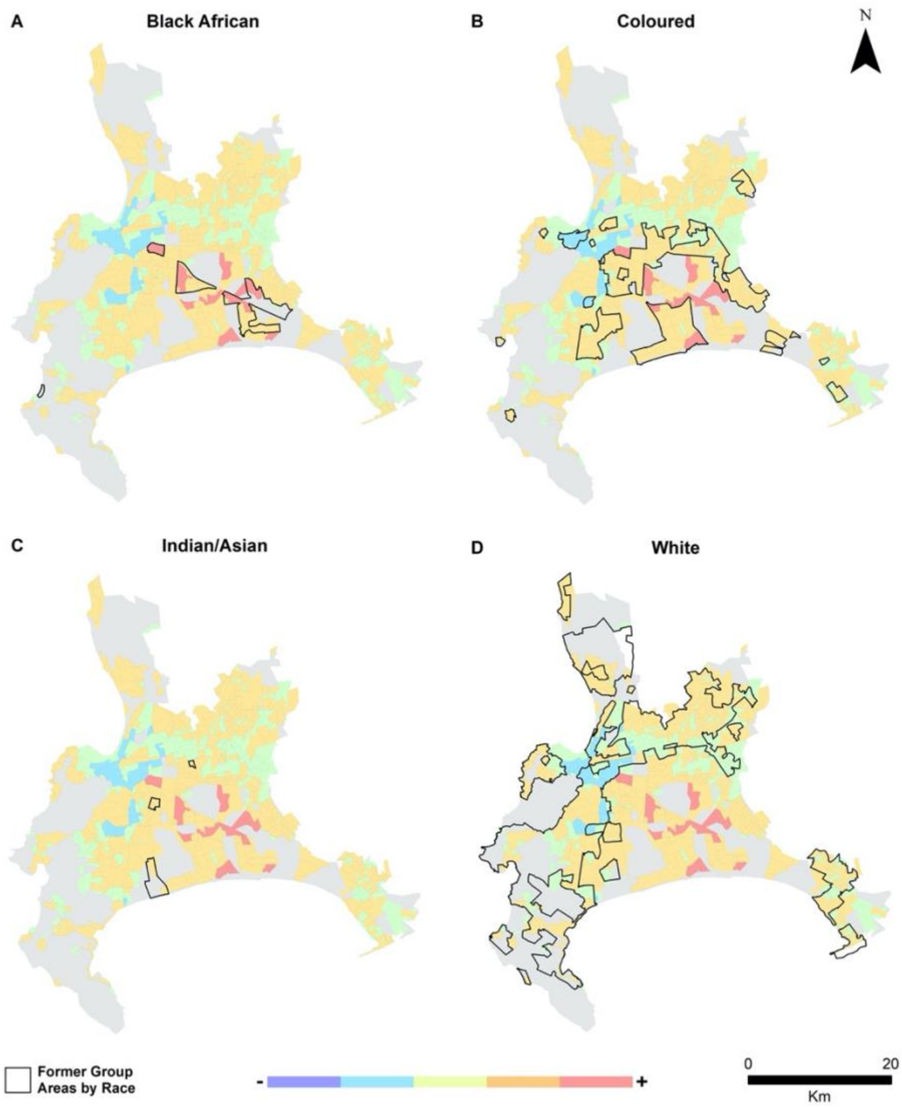


Figure 6.27: Local Spatial Information Theory Index for Income-by-Race Groups (Computed for the four racial groups at 1000m bandwidth)

When considering the most even localities, in terms of income by race, it is evident that these suburbs are predominantly located in the former White group areas (see (see Figure 6.27D). This phenomenon indicates that integration occurs by income in the suburbs that were predominantly White previously.

6.3.2 Isolation/Exposure Index

The segregation profiles for normalised isolation of income-by-race categories are presented in Figure 6.28. The profiles indicate that the income subcategories for each racial group follow the same patterns found for the overall racial groups, as discussed in Section 6.1.2.

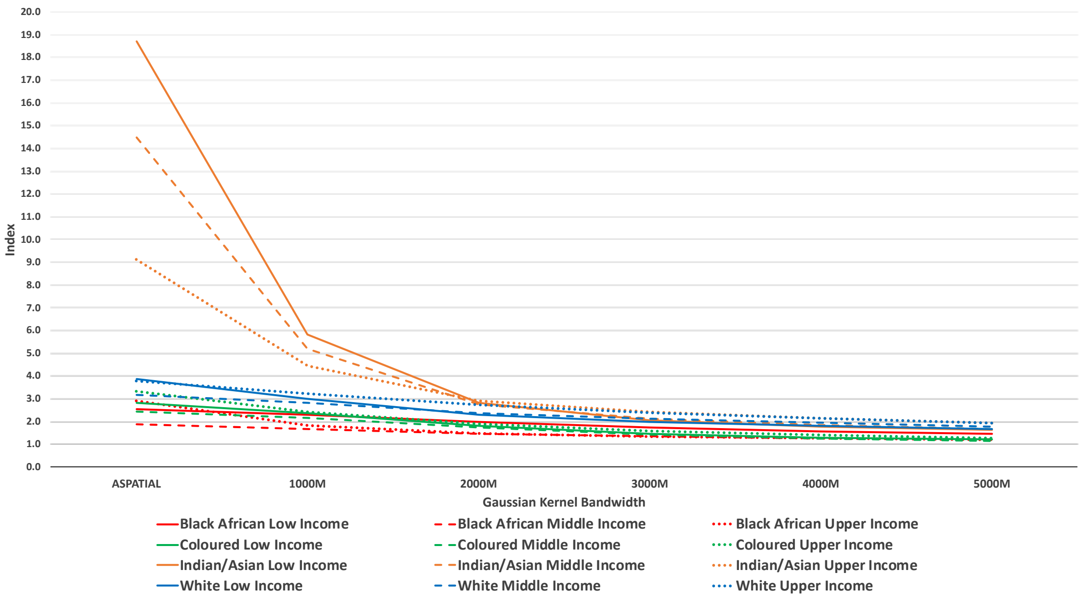


Figure 6.28: Normalised Global Spatial and Aspatial Isolation Indices for Income Groups by Race

Table 6.2 presents the normalised global isolation and exposure measurements for the households of the income-by-race categories. The same results are shown in Table 6.3, presenting the values in a different order (ordered by income rather than racial groups). In both tables the intensity of the colour indicates the intensity of the values, with red colours indicating values above 1 and blue colours indicating values lower than 1.

When visually comparing the two tables, it is interesting to note in Table 6.2, which has been ordered by racial group, that there's a pattern of warm colours attributed to values of isolation and exposure to subcategories within the same racial group. The only exception is the Black African upper-income group, which presents normalised exposure lower than 1 to the Black African low-income group and very close to 1 to the Black African middle-income groups. When ordering the same results by income, the emerging colour pattern is very different, as shown in Table 6.3. This demonstrates the role of race in the exposure/isolation patterns of Cape Town.

Table 6.2 shows isolation above 1.8 to all subcategories. As with the analysis using racial groups alone, the Indian/Asian income groups show the highest values of isolation and exposure amongst themselves. Those results must be interpreted carefully, as the Indian/Asian group has a very low overall proportion in the study area (1.4%), which is further reduced when subdivided into income groups. In order to avoid misinterpreting results due to the low representation of those groups, the remainder of this section will not consider the results for individuals of the subcategories of the Indian/Asian group.

The second highest isolation is observed for the subcategories of the White group, followed by Coloured subcategories (between 2.15 and 2.44). Normalised isolation values for Black African subcategories are lower than of the other groups, ranging from 1.66 to 2.31, with the highest value (2.31) of isolation for the Black African low-income group.

The analysis of the exposure between income-by-race groups reveals interesting insights. Exposure of White groups to other group categories is clearly mediated by income, with values above 1 to Black African upper-income group (1.53 to 1.59), Coloured upper-income group (1 to 1.31) and Indian/Asian middle- and upper-income groups (1.14 to 1.80). When looking at exposure values of White income groups to themselves, it is clear they are more exposed to themselves than to any of other racial groups (all exposure values above 2.25). However, the White low- and middle-income groups are also exposed to the upper-income groups of all other races. Similar exposure patterns were revealed for the White upper-income group, apart from a lower exposure to the Coloured upper-income group.

Coloured income groups show exposure values above 1 to all Indian/Asian groups. Exposure between Coloured and White groups are clearly mediated by income: exposure values above 1 are only present for Coloured upper-income and Black African upper-income, and Coloured upper-income and White (all three income categories). This is in line with the exposure between the Coloured upper-income and White upper-income groups, which is very close to 1 (0.95/1) and slightly higher for White middle-income (1.15/1.15) and White low-income (1.28/1.31). The Coloured upper-income group is more exposed to all Indian/Asian income groups than to other Coloured income groups, while the Coloured low- and middle-income groups are most exposed to each other.

When analysing Black African low-income exposure to other race groups, it is clear they present very low exposure to all other racial groups, independent of income. In fact, it only presents exposure close or above 1 to Black middle (1.82) and itself (2.31). It is interesting to note that its exposure to Black Upper income is 0.76, that while higher than its exposure to other groups (ranging between 0.17 and 0.50) is significantly below 1.

Perhaps more striking is the fact that the Black African upper-income group is significantly more exposed to the Indian/Asian upper-income group and all White income groups than to the other Black African income groups. This finding contrasts with the low level of exposure between the overall Black African and White groups presented in Figure 6.10 and demonstrates the relevance of income to fully understand the segregation between groups in Cape Town.

Table 6.2: Normalised Global Spatial Isolation & Exposure Indices for Income Groups by Race at Measurements of 1000m Bandwidth

Normalised Exposure / Isolation

1000m bandwidth

	bLI	bMI	bUI	cLI	cMI	cUI	iLI	iMI	iUI	wLI	wMI	wUI
bLI	2.31	1.82	0.76	0.46	0.31	0.21	0.50	0.29	0.20	0.22	0.17	0.16
bMI	1.82	1.66	1.06	0.56	0.50	0.49	0.50	0.57	0.60	0.56	0.51	0.46
bUI	0.79	1.07	1.88	0.53	0.69	1.15	1.00	1.29	1.60	1.56	1.57	1.55
cLI	0.52	0.59	0.53	2.36	2.03	1.18	1.50	1.14	0.60	0.33	0.27	0.22
cMI	0.37	0.54	0.71	2.06	2.15	1.62	1.50	1.29	0.80	0.56	0.44	0.32
cUI	0.25	0.53	1.18	1.26	1.68	2.44	2.00	2.00	1.80	1.28	1.15	0.95
iLI	0.46	0.64	0.88	1.67	1.63	1.69	6.00	5.14	3.20	0.78	0.63	0.60
iMI	0.26	0.56	1.24	1.24	1.40	1.95	5.50	5.29	4.00	1.33	1.22	1.12
iUI	0.21	0.58	1.65	0.77	0.97	1.90	3.50	4.14	4.20	1.78	1.78	1.88
wLI	0.25	0.61	1.53	0.38	0.60	1.31	1.00	1.43	1.60	3.00	2.65	2.25
wMI	0.22	0.54	1.59	0.29	0.47	1.15	0.50	1.29	1.60	2.67	2.82	2.70
wUI	0.21	0.50	1.59	0.24	0.36	1.00	0.50	1.14	1.80	2.33	2.78	3.22

bLI - Black African Low Income, bMI - Black African Middle Income, bUI - Black African Upper Income
cLI - Coloured Low Income, cMI - Coloured Middle Income, cUI - Coloured Upper Income
iLI - Indian/Asian Low Income, iMI - Indian/Asian Middle Income, iUI - Indian/Asian Upper Income

The role of income and particularly the upper-income groups is further evident in Table 6.3 which shows there is higher exposure (cells coloured in warm tones – values from 0.95 to 4.20) between racial groups of upper-income in comparison to other income subcategories within racial groups in other income categories. An interesting finding is that the expectation that middle-income groups would present higher exposure to other groups, as inferred in Section 6.2.2, has not been confirmed by the results.

Table 6.3: Normalised Global Spatial Isolation & Exposure Indices for Income Groups by Race at Measurements of 1000m Bandwidth

Normalised Exposure / Isolation

1000m bandwidth

	bLI	cLI	iLI	wLI	bMI	cMI	iMI	wMI	bUI	cUI	iUI	wUI
bLI	2.31	0.46	0.50	0.22	1.82	0.31	0.29	0.17	0.76	0.21	0.20	0.16
cLI	0.52	2.36	1.50	0.33	0.59	2.03	1.14	0.27	0.53	1.18	0.60	0.22
iLI	0.46	1.67	6.00	0.78	0.64	1.63	5.14	0.63	0.88	1.69	3.20	0.60
wLI	0.25	0.38	1.00	3.00	0.61	0.60	1.43	2.65	1.53	1.31	1.60	2.25
bMI	1.82	0.56	0.50	0.56	1.66	0.50	0.57	0.51	1.06	0.49	0.60	0.46
cMI	0.37	2.06	1.50	0.56	0.54	2.15	1.29	0.44	0.71	1.62	0.80	0.32
iMI	0.26	1.24	5.50	1.33	0.56	1.40	5.29	1.22	1.24	1.95	4.00	1.12
wMI	0.22	0.29	0.50	2.67	0.54	0.47	1.29	2.82	1.59	1.15	1.60	2.70
bUI	0.79	0.53	1.00	1.56	1.07	0.69	1.29	1.57	1.88	1.15	1.60	1.55
cUI	0.25	1.26	2.00	1.28	0.53	1.68	2.00	1.15	1.18	2.44	1.80	0.95
iUI	0.21	0.77	3.50	1.78	0.58	0.97	4.14	1.78	1.65	1.90	4.20	1.88
wUI	0.21	0.24	0.50	2.33	0.50	0.36	1.14	2.78	1.59	1.00	1.80	3.22

bLI - Black African Low Income, bMI - Black African Middle Income, bUI - Black African Upper Income
cLI - Coloured Low Income, cMI - Coloured Middle Income, cUI - Coloured Upper Income
iLI - Indian/Asian Low Income, iMI - Indian/Asian Middle Income, iUI - Indian/Asian Upper Income

Figure 6.29 presents the histogram for each of the values obtained in Table 6.2 above and highlights the main findings discussed for the income groups by racial group.

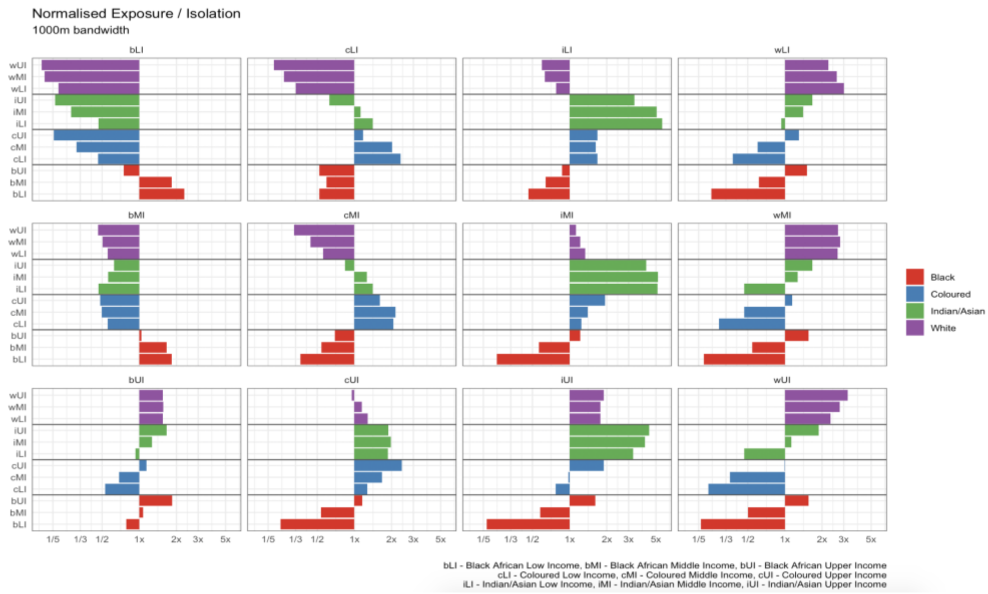


Figure 6.29: Histogram of Normalised Global Spatial Isolation & Exposure Indices for Income Groups by Race at Measurements of 1000m Bandwidth

Figure 6.30 presents the local spatial isolation measurements for the Black African income groups. It is noticeable in Figure 6.30A that the Black African low-income localities that are most isolated in the study area are located predominantly in the former Black African group areas. Although a similar occurrence is evident for the Black African middle-income group (see Figure 6.30B), a degree of integration occurs within the predominantly White suburbs to the west of the study area occurs. In contrast, the Black African upper-income group is predominantly integrated with other groups in the predominantly White suburbs (see Figure 6.30C).

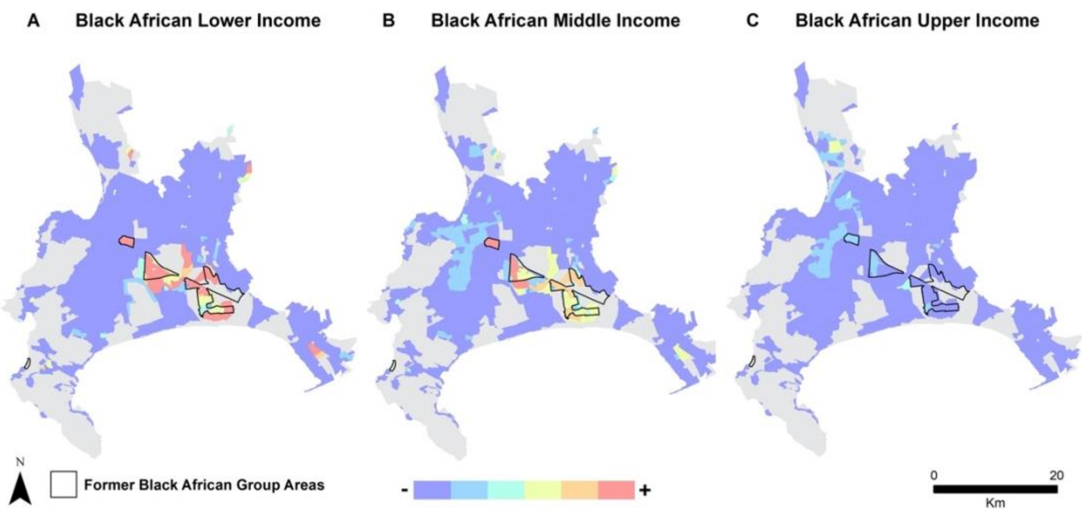


Figure 6.30: Local Spatial Isolation of Black African Income Groups (1000m bandwidth)

The local spatial isolation measurements for the Coloured income groups are presented in Figure 6.31. Both the Coloured low-income group (see Figure 6.31A) and middle-income group (see Figure 6.31B) are most isolated in the former Coloured group areas. However, it is evident that integration of the middle-income group occurs within suburbs beyond these group area boundaries to the west and north-west of the study area. The level of isolation of the Coloured upper-income group is much lower and also occurs predominantly within the White suburbs adjacent to the former Coloured group areas (see Figure 6.31C).

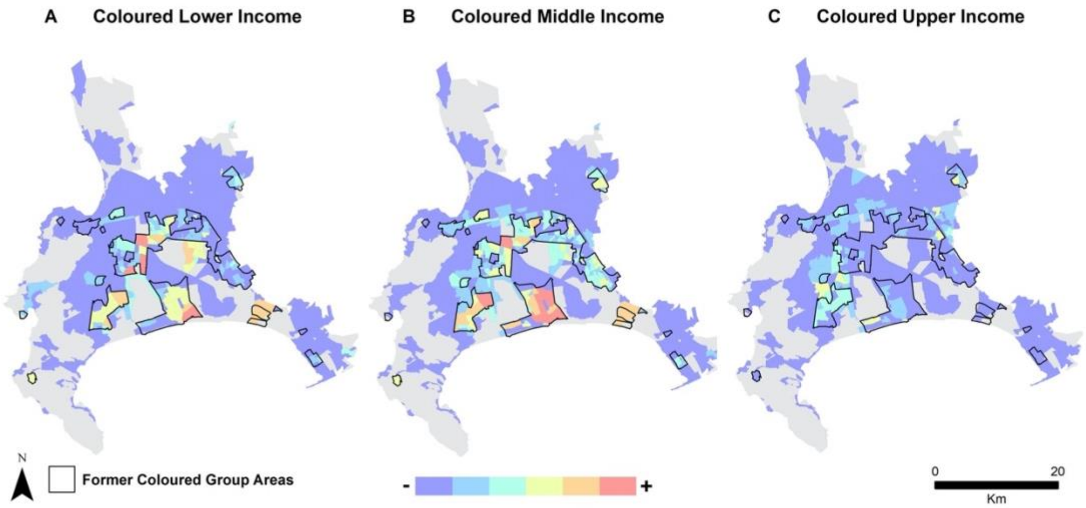


Figure 6.31: Local Spatial Isolation of Coloured Income Groups (1000m bandwidth)

It is quite evident in Figure 6.32 that all White income groups are most isolated within the former White group areas of apartheid, with virtually no interaction with other racial groups beyond these boundaries.

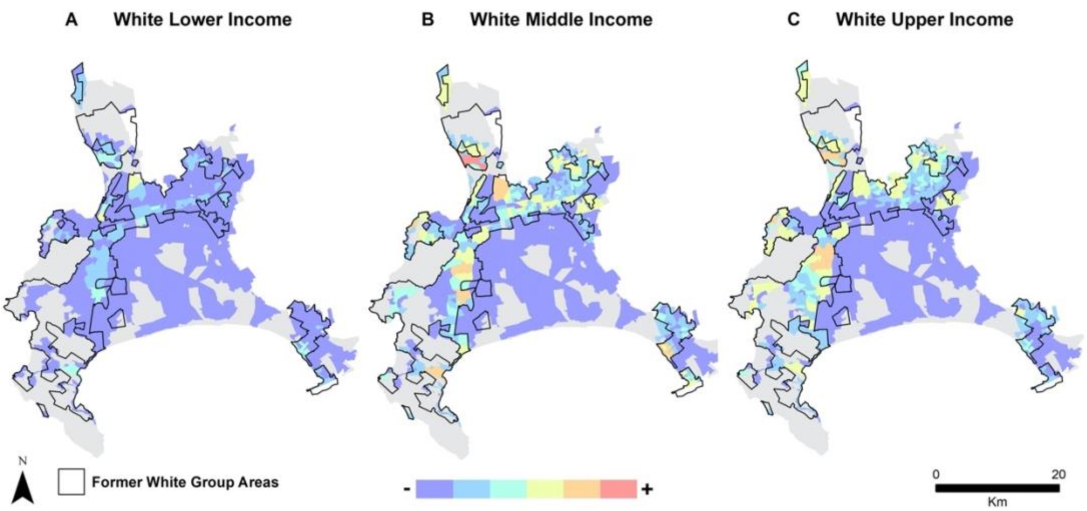


Figure 6.32: Local Spatial Isolation of White Income Groups (1000m bandwidth)

Figure 6.33 presents local exposure between the White and Black African upper-income groups, with an overlay of the former White group area boundaries. Figure 6.33A shows the suburbs of Table View and Parklands to the north of the study area where the White upper-income group is most exposed to Black African upper-income. Figure 6.33B shows a similar distribution where Black African upper-income is most exposed to White upper-income to the north and Pinelands, Claremont and Kenilworth to the west of the study area. However, a higher level of Black African upper-income exposure to White upper-income reflects a minority of Black African households that moved into predominantly White suburbs, where they are super-exposed to these White communities.

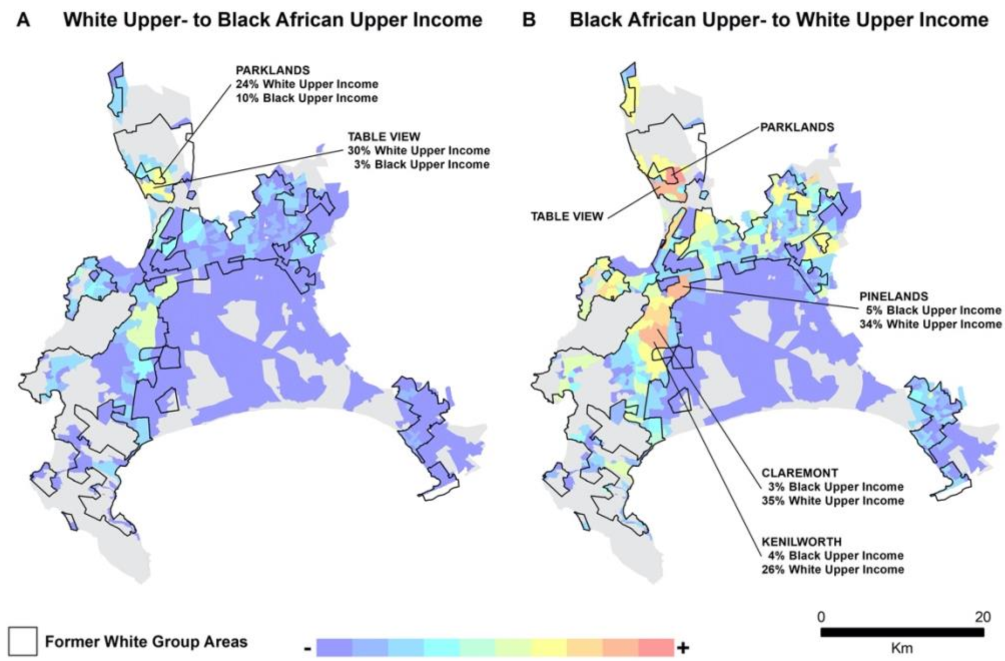


Figure 6.33: Local Spatial Exposure between Black African Upper-Income and White Upper-Income

6.4 Discussion

The combined results of the segregation indices for the different grouping systems have clearly demonstrated that residential segregation in Cape Town remains strongly racial in nature. When comparing the results obtained for racial and income groups, all indices present higher values for racial groups. The similarity of the findings for income-by-race to race indicates the significance of racial segregation in Cape Town. The analyses using the combined income-by-race grouping has, nevertheless, revealed that high income can also act as a racial integration factor. While this does not apply across all income groups nor has an even effect across all races, income is clearly important to understand the nature of residential segregation in Cape Town. This is particularly noted on upper-income groups which generally tend to be more integrated racially than other groups. In contrast, it is also clear that Black African and Coloured middle- and low-income groups are particularly segregated from others, while White income groups are more integrated with each other rather than with other groups.

The spatial distribution patterns obtained from the local segregation measurements of race and income revealed that the most segregated localities, racially and socio-economically, are located to the central and southern regions of the study area where the group areas for all non-White racial groups were established during apartheid. These regions are predominantly composed of Black African and Coloured low- to middle-income households and in contrast to the segregated White middle- to upper-income localities to the west and north-west of the study area. This occurrence reflects a persistent pattern of segregation between the White and non-White communities of Cape Town since the apartheid era.

These findings are supported by the information theory index measures for race and income in the study area. The localities that are racially most even are situated near the CBD of Cape Town. Historical background to these suburbs suggests that these levels of evenness conform to theoretical findings. The suburbs of Woodstock, Salt River and Observatory provide the best examples, with a history of being racially even and integrated 'grey areas' during the apartheid era. However, the localities that are more even, in terms of income, are not situated in the same region and consist predominantly of a White middle-to upper-income population. An interesting observation of localities of highest evenness being racially even highlights the fact that localities of lowest evenness may have income level as impetus and reflects the findings of Geyer and Mohammed (2016) - where upward socio-economic mobility of certain households result in the remaining lower income community becoming racially more similar.

The occurrence of high exposure between the low- and middle-income groups within each racial group corroborates these findings. The contrasting findings of higher racial integration among upper-income groups is particularly evident with the Black African upper-income group, being more exposed to the upper-income groups of all other races than to the Black African low- or middle-income groups. These occurrences correspond to the findings of Seekings (2000), as discussed in Section 2.3.2, suggesting that race and socio-economic class in the South African city do not share the same meaning or spatial patterns anymore and that inequality between races decline due to socio-economic upward mobility, but that lower income groups become racially more segregated as a result.

Contradicting the studies that suggest that the Coloured group is most integrated (discussed in Chapter 2), the Coloured group shows low exposure to both the Black African and White groups and highlights the fact that segregation in the post-apartheid city is a reflection of the apartheid city. These findings are supported by the measures of income-by-race, showing that Coloured income groups are mostly exposed to each other and that the exposure between the Coloured and White income groups are only mediated by income, as the Coloured upper-income group shows high exposure to all White income groups.

Further insight was gained from the exposure measurements of the income-by-race groups. The exposure of the White income groups to all other racial income groups is evidently mediated by income, as all White income groups show a high level of exposure only to the upper-income groups of the other races. The exposure of the White upper-income group to Black-African upper-income being higher than exposure to other upper-income groups is an interesting occurrence, as it contradicts the findings of the racial measures. Furthermore, the remarkable occurrence of the Black African upper-income group being more exposed to all White income groups than to other Black African income groups highlights the relevance of income in understanding segregation in Cape Town.

6.5 Summary

This chapter builds on the previous work and findings of Christopher (2001a), Rospabe and Selod (2006) and Parry and van Eeden (2015). The application of generalised spatial segregation indices not only provides for the ability of multi-group segregation measurements, but also for spatial segregation patterns and spatial relationships between groups to be studied. Secondly, the measurement of socio-economic segregation allowed for income groups to be studied and a comparative analysis, in terms of spatial distribution, to be undertaken with the racial measurements. Finally, the measurement of combined racial and income groups enabled the unfolding of more subtle patterns of spatial segregation among income groups by race. While the measurement of segregation revealed contrasting local patterns of spatial segregation, the addition of the former racial group area boundaries from the apartheid era not only provided context to segregation in Cape Town, but also highlighted the persistence of segregation in the study area.

Most importantly, the combined study of income groups by race unveiled the roles income and race play in the persistence of segregation in Cape Town. It is thus concluded that although Cape Town is more segregated by race, income plays the most significant role in the persistence of segregation in Cape Town. Wider research places much emphasis on the evolution of segregation from racial to that of socio-economic class in the context of Cape Town, as seen in Chapter 2. However, the findings in this chapter indicates that race is still a significant factor perpetuating segregation in the study area, but also that the subject of income is the dominant factor in the persistence of segregation in Cape Town.

The spatial segregation measurements undertaken in this chapter will benefit from further analysis. A spatial autocorrelation exercise would be an efficient way of exploring wider urban dynamics in relation to the findings from these measurements. The relationship between the low-income (most segregated) areas and the level of accessibility to employment opportunities and amenities will enrich understanding of these neighbourhoods. Similarly, the relationship between income and crime levels could be studied in a spatial manner.

The following chapter introduces District94, a spatial agent-based model and adaptation of the Schelling segregation model, for an exploration of the dynamics of race and income and the role of these two subjects in the persistence of segregation in Cape Town.

Chapter 7

District94: A Multi-Agent Simulation Model for Urban Segregation

This chapter introduces District94, a model for the exploration of segregation in the South African city of Cape Town. The District94 model is built on the theory of racial and socio-economic segregation in Cape Town, discussed in Chapter 2, and the findings of the spatial segregation measurements for Cape Town in Chapter 6. The agent-based modelling methodology is built on the Schelling segregation model, discussed in Chapter 4. The design and implementation of the model is discussed in the following sections.

This chapter is structured in three parts. Section 7.1 presents the working hypothesis and rationale and objectives of the three modules the model is composed of. Section 7.2 discusses the architecture of the model, in terms of the agents and environment applied and the program interface. Section 7.3 discusses model implementation, focussing on the data applied, model parameters, simulation procedure and finally the model output.

7.1 Model Rationale and Objectives

It is hypothesised in this thesis that, although racial segregation resulted in income disparity in the post-apartheid era, both the subjects of race and income continues to play a role in the persistence of segregation in Cape Town. Literature on the theme of segregation in Cape Town reflects the evolution of racial to socio-economic segregation (see Chapter 2), while the spatial measurements of segregation in Cape Town, undertaken in Chapter 6, demonstrated that although Cape Town is still predominantly segregated by race, income plays the most significant role in the persistence of segregation. Thus, it might be expected that the role of race in persistent segregation might not diminish, as the role of income becomes more prominent.

The main objective of the District94 model is to test the working hypothesis and thus the role of income and race on the patterns of segregation and its persistence in Cape Town through the application of an agent-based modelling methodology to test and explore different scenarios. Consequently, it is developed to focus on the same three subjects studied in Chapter 6: race, income and income by race. The District94 model adapts the Schelling model in three different manners to represent these subjects in the form of three modules: The *Racial Preference module*, *Income Constraint module* and *Racial Income module*.

The introduction of the Racial Preference module to the District94 model enables the exploration of the phenomenon of racial homophily in the context of Cape Town. As discussed in Section 5.3.1, segregation is one of the domains in which homophily is studied and the preferences of individuals remain a challenge in ethnic neighbourhood segregation studies (Zuccotti et al., 2021). The findings from Section 6.1 on the spatial measurement of racial segregation in Cape Town showed that race still plays a significant role in segregation. Studying the role of race in persistent segregation in Cape Town, through the inclusion of the Racial Preference Module, this thesis builds on the foundational work of Schelling (1971) highlighted in previous chapters of this study. Although the homophilic preferences of individuals or households cannot be directly addressed through integrated development policy formulation it would have implications for such policies, prompting the local authority to consider the development of mixed housing and education facilities to promote integration.

The discussion in Chapter 2 highlighted that the legacy of apartheid did not only orchestrate perpetuated racial segregation, but also persisting income disparity. The findings from Section 6.2 on the spatial measurement of income segregation in the study area showed that significant segregation persists, especially between the low- and upper-income groups, even though the middle-income group is more integrated. However, the findings from Section 6.3 on the spatial measurement of the segregation of income groups by race revealed that finer dynamics exist when the subjects of income and race are combined. It was evident that the subject of income is the dominant factor in the persistence of segregation in Cape Town. The implications of this occurrence could prompt the local authority to direct policy formulation to poverty alleviation and subsequently the planning of low-cost public housing.

The title of the District94 simulation model is based on a combination of District Six (the neighbourhood in Cape Town from which thousands of non-White inhabitants were forcefully removed during apartheid) and 1994 (the year South Africa became a democracy after apartheid). The District94 model is inspired by- and an adaptation of the Schelling segregation model, discussed in Chapter 4. The proposed model adapts the types and number of agent groups applied and also the manner in which the environment plays a role in the model. As the architecture and implementation of the District94 model is presented in this chapter, the way in which aspect of the Schelling segregation model were used and adapted for the District94 model will be detailed.

7.1.1 Module One: Racial Preference

Module 1 assumes that the main rule of segregation is related to race. It assumes that all racial groups desire to reside with their own kind and consequently have locational preferences which are determined by the percentage of similar neighbours they desire, in terms of race. Given the existence and frequent study of the phenomenon of homophily (see Section 5.3.1) and more importantly the effect it has on individual choice, the general assumption of this module is deemed reasonable. Hence, all households have the same objective of finding a location that satisfies their preference for a specific racial composition of their neighbourhood. The model thus focusses on the phenomenon of 'racial preference' and explores the distribution of population groups in accordance with preference for their own race or other racial groups as neighbours (hereinafter referred to as the Racial Preference module).

The underlying logic of this module is based on the dynamics of a household's degree of preference for racially similar neighbours, reflecting the core homophilic dynamic of the Schelling model (Kurgan et al., 2019). As discussed in Chapter 4, Thomas Schelling's findings proposed that even the smallest degree of preference of inhabitants for neighbours of their own culture will collectively result in segregated patterns.

The main objective of the Racial Preference Module is to explore the dynamics of racial preference (homophily) and how it affects spatial segregation in the study area. The module simulates both the processes of preferred self-segregation and the contrasting integration of racial groups in Cape Town. These processes were respectively discussed in Chapter 2 as the development of secluded gated communities and the racially integrated and diverse suburbs, such as Woodstock and Observatory. The population is represented by three of the four main racial groups in Cape Town: Black African, Coloured and White. The Indian/Asian group is excluded from the modelling procedure, due to the low representation of this group in Cape Town, as discussed in Chapter 6.

The behaviour of the three racial groups is differentiated by this degree of preference each racial group reflects for its own kind and also the restriction on their residential mobility (the radial distance from a current location in which alternative dwellings can be identified and considered). For example, a greater distance might potentially offer a household more alternative locations to consider and move to. The rules are discussed in further detail in Section 7.3.3.

7.1.2 Module Two: Income Constraint & Preference

Module 2 assumes that the main rule of segregation is related to income. It is based on the assumption that all income groups have either a degree of constraint or desire to reside with their own kind, in terms of income. The spatial distribution of the three income groups this study considers (low-, middle- and upper-income) was presented in Chapter 6 and the variation in distribution between these groups are quite significant. Hence, the second module consists of the income constraint of the low- and middle-income groups and preferences of the upper-income group. The module explores the effect of both preference and constraint levels of income groups on the distribution of the study area's population (hereinafter referred to as the Income Constraint module).

All households in the Income Constraint module have the same objective, which is to reside in a neighbourhood that is economically affordable/satisfactory to their specific requirements. However, the low- and middle-income households experience a degree of constraint in terms of the locations they are able to reside in, while the upper-income group has no constraint, but rather a degree of preference (homophily) for neighbouring households of a similar income (Petrescu-Prahova, 2009). The rationale for this decision is that, while low-income households are constrained from residing with any other income groups, middle-income households are constrained from residing in upper-income neighbourhoods.

Rather than actively seeking similar neighbours to reside with, the low-income households are expelled from their residential locations with the influx of higher income households due to the occurrence of gentrification. These low-income households are then forced to seek affordable neighbourhoods to relocate to. This phenomenon is highlighted in Section 2.4.3, with the occurrence of gentrification in Cape Town (Visser and Kotze, 2008) and related displacement of poorer residents (Turok, 2012, p. 42). Hence, the lack of economic power results in low-income households residing together, rather than homophilic choice. Low-income households seeking neighbourhoods where a similar income group resides serves as proxy for the affordability of the area (Petrescu-Prahova, 2009).

The main objective of the Income Constraint module is to explore the dynamics related to the degree at which households are potentially either constrained or unconstrained by income from considering alternative dwelling locations. Hence, this module simulates both the processes of income constraint on the possibility for low- and middle-income households to relocate to a more preferential location and the preference of the upper-income group to reside with their own income group. The population is thus represented by the households of the three mentioned income groups in the study area of low-, middle- and upper-income.

In contrast to the general notion of choice in the Racial Preference module, the Income Constraint module also reflects a degree of restriction on households. The behaviour of each of the three income groups (low, middle and upper) is differentiated by this degree of constraint or level of preference and the logic of the module is limited to these dynamics. Similar to the Racial Preference module, residential mobility also plays a role in the behaviour of households and the rules are discussed in further detail in Section 7.3.3.

7.1.3 Module Three: Racial Income Preference & Constraint

Module 3 comprises of the combination of racial preference and income constraint/preference, applied in Modules 1 and 2 respectively, and explores the combined effect of these two dynamics on residential choice and mobility (hereinafter referred to as the Racial Income (Loury, 1977) module). The discussion in Chapter 2 on post-apartheid planning and neo-liberal dynamics of urban growth in the city of Cape Town highlighted the persistence of socio-economic segregation in the city and outlined how racial residential preference and forced segregation evolved into perpetuated income disparity.

The objective of the Racial Income module is to provide a means for the exploration of the complex dynamics generated from the combination of both racial preference and income constraint in residential location decision-making. The Racial Income module thus represents a combination of the presented Racial Preference and Income Constraint modules. Consequently, the combination of the three population groups and three income groups presents the following nine 'racial-income' types of households: *Black African low-income, Black African middle-income, Black African upper-income, Coloured low-income, Coloured middle-income, Coloured upper-income, White low-income, White middle-income and White upper-income.* Hence, the main aim of the Racial Income module is to explore the decision-making dynamics of households in the study area when both racial preference and income constraint/preference is explored in conjunction.

The logic of the module concerns two subjects: firstly, the degree to which households are constrained or unrestricted to their respective neighbourhoods due to their income levels and secondly, the preference these households have for a certain racial composition of their neighbourhood. All households in the Racial Income module share the same objective of residing in a neighbourhood that is satisfactory in terms of both their income level and preference for similar type neighbours (racially).

Hence, the behaviour of the different 'racial-income' groups of households is governed by both the degree to which they are constrained or unrestricted by their income to their current neighbourhoods and their preference for racially similar neighbours. The rules for this module are discussed in further detail in Section 7.3.3.

7.2 Model Architecture

7.2.1 Agents & Environment

The Schelling segregation model considers two different groups of agents to explore how individual preference for a certain type of neighbour can lead to segregation between these two groups. The District94 model modifies this dynamic by not only considering more agent groups, but also different types of agents (both race and income types).

The agents in the Racial Preference module represent the households of the three largest population groups in Cape Town: *Black African*, *Coloured* and *White*. The agents in the Income Constraint module represent the households of the three different income groups in Cape Town: *low-income*, *middle-income* and *upper-income*. Consequently, the agents in the Racial Income module represent the households of Cape Town with their race and income types (groups) combined and reflect 9 different income classes: *Black low-income*, *Black* *middle-income*, *Black upper-income*, *Coloured low-income*, *Coloured middle-income*, *Coloured upper-income*, *White low-income*, *White middle-income* and *White upper-income*.

The environment applied in the Schelling segregation model, discussed in Chapter 4, consisted of a two-dimensional grid in which the two types of agents resided and relocated. The environment of the District94 model adapts the Schelling segregation model to represent the urban/built environment of Metropolitan Cape Town in a spatially explicit manner, with only the existing residential land selected to represent the study area in which the household dynamics are simulated and to which households are also restricted.

7.2.2 Program Interface

The main window of Netlogo presents the graphical user interface (GUI) of the simulation model. This window has three tabs at the top labelled "Interface", "Info" and "Code" with a toolbar underneath (see Figure 7.1). A dropdown list allows for the addition of control items to the model and a slider in the centre to control the speed of a simulation run. The "view updates" tick box allows for the updating of agents in the model to be visible.

Figure 7.1: NetLogo Toolbar and Controls

The "Model Settings" tab (see Figure 7.2) provides model settings for the adjustment of the model environment, including the size of the 'world' (environment), the size of patches and agent label fonts.

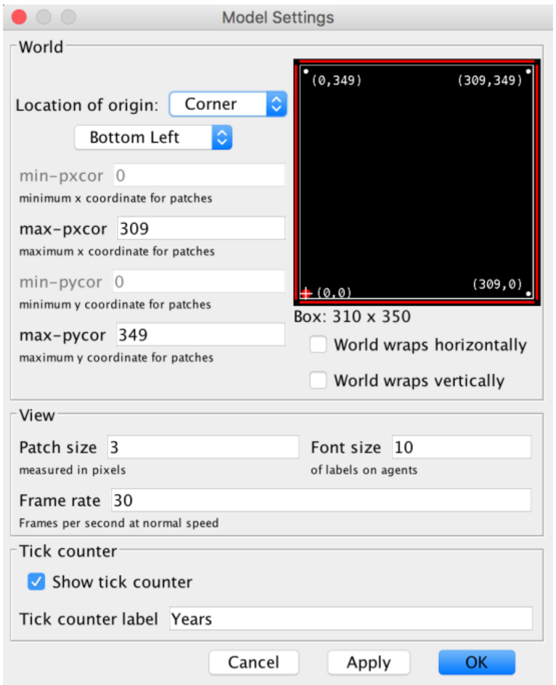


Figure 7.2: Model Settings

The Interface tab (see Figure 7.3) presents the display window or world **(1)** of the simulation model, a two-dimensional grid in which the simulation takes place. The topology of the world in NetLogo can represent four different forms: torus, box, vertical cylinder or horizontal cylinder. Although the default form of the world is that of a torus, a box is applied to the District94 model. The world does not wrap in both directions, like the torus where the top and bottom edges of the world are connected.

The interface tools (see Figure 7.3) that are model specific and can be generated to best suite a simulation model. These items include the following, which are relevant to this study: switches **(2)** providing a visual representation for global variables that are true/false, sliders **(3)** that are global variables allowing for a quick change of agent variables and are accessed by agents, buttons **(4)** executing commands either in a once off manner or continuously, notes **(5)** for the ability to add information in text format to the model interface, plots **(6)** showing the data that is generated by the model and monitors **(7)** displaying the values of reporters in the model.

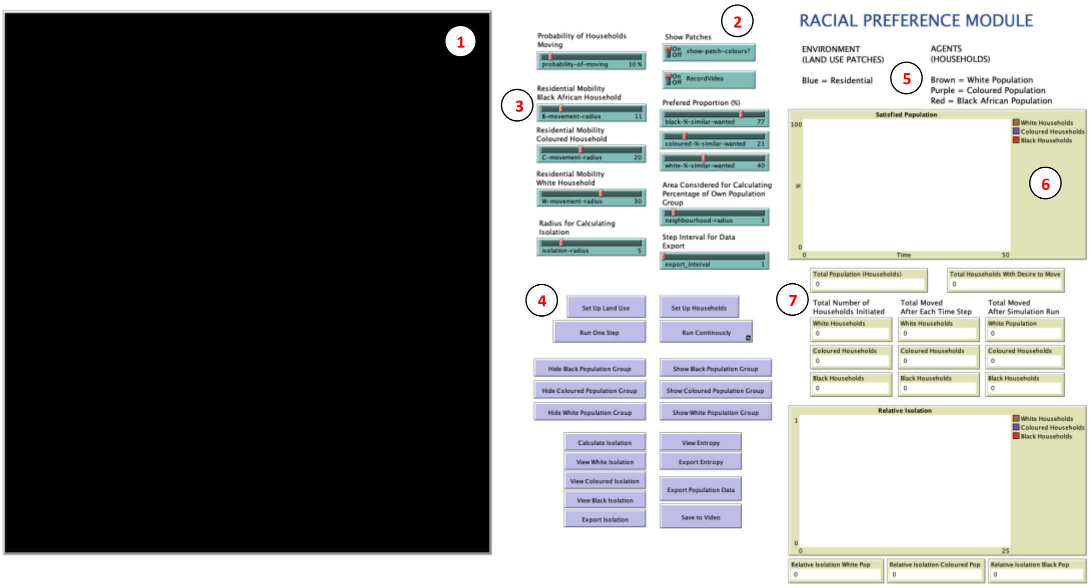


Figure 7.3: NetLogo Interface

The physical composition of the District94 model can best be represented by referring to the interface of the modules in Netlogo. Residential land use in the study area was identified and represented by blue cells (patches) in the model environment. A total of 16 263 residential patches are present in the model. The patches are only a representation of residential land and each patch does not necessarily represent a residential property.

Figure 7.4 presents the interface of each of the three modules: a) Racial Preference, b) Income Constraint and c) Racial Income Preference and Constraint.

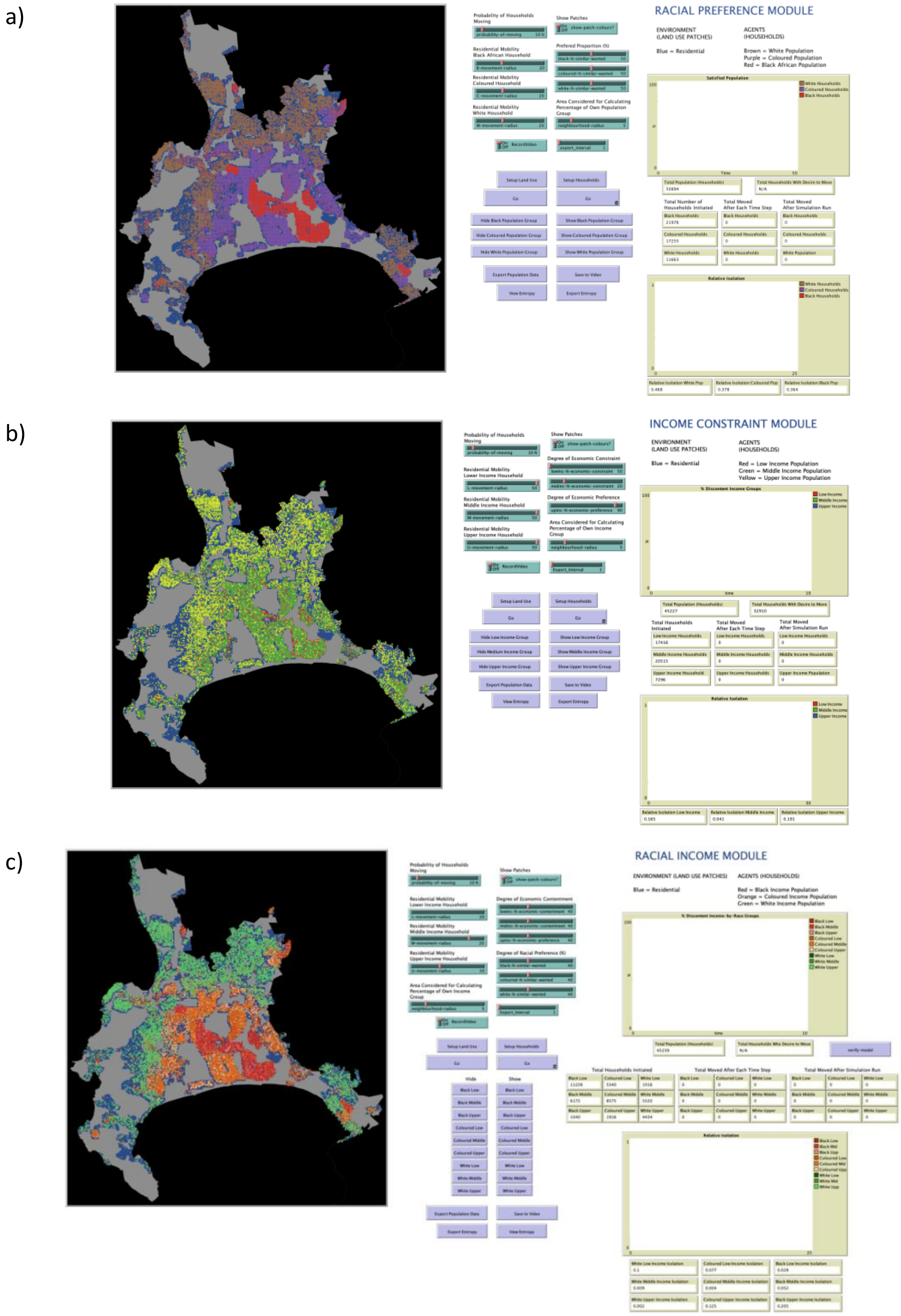


Figure 7.4: Interface of a) Racial Preference b) Income Constraint and c) Racial Income Modules in NetLogo

Although the three modules of the District94 model vary, each module builds on the previous one. Hence, there are a set of 'universal controls' (Table 7.1) that were implemented in the interface of all modules. Switches were added to allow for patch colours to be turned off and also for a video to be recorded of a simulation run. Sliders were implemented for adjusting values of the parameters of neighbourhood radius and residential mobility discussed in Section 7.3.2. In addition, a probability of moving slider was generated to stipulate the percentage of the total population of the study area that would consider moving. For exporting outputs, a slider was implemented to choose the time step intervals at which output data would be exported.

Buttons were implemented in the interface to set up land use patches and agents in the model environment at initiation and also to run the simulation for either a single time step or continuously. Different groups of agents can also be turned on or off separately in the model environment to enable visualisation of distribution at various stages of a simulation run. Further buttons were also generated to calculate, view and export isolation and entropy levels among the relevant groups in a particular simulation. A video of the simulation can finally be exported in MP4 file format to visualise changing patterns in the simulation over time.

Table 7.1: Universal Model Interface Controls

Control Item	Function	Description
Switch	*show-patch-colours?*	Show or hide study area and residential patch colours
	RecordVideo	Choose whether the simulation run should be recorded to MP4 file format
Sliders	*probability-of-moving*	Percentage of total population considering moving
	neighbourhood-radius	Radius at which households calculate the composition of their neighbourhood
	*movement-radius**	Radius at which each household searches for an alternative dwelling location
	export-interval	Exporting outputs at step intervals during a simulation run
Buttons	*setup-patches*	Setup Land Use - study area and residential patches
	setup-agents	Setup Households - the different types of household agents
	go	Initiate simulation run for one step
	go (forever)	Initiate simulation run for a continuous number of steps
	*hide-turtle**	Hide agents of a specific group
	*show-turtle**	Show agents of a specific group
	calculate-isolation	Calculating the level of isolation for each group
	view-isolation	View the isolation in the environment for each group
	export-isolation	Export isolation values to ASCII (raster) format

Control Item	Function	Description
	view-entropy	View Entropy - Household entropy at each patch (calculated for a neighbourhood radius)
	export-entropy	Export entropy values to ASCII (raster) format
	export-population	Export population data for each group to ASCII (raster) format
	VideoSave	Save a video of a simulation run as output (MP4) file
Monitors	*count**	Total number of households implemented & total number of agents per group
	*count turtles with [want-to-move]**	Total number of households desiring to move
	*population-moved**	Number of households of a specific group that moved at each step
	*population-moved-acc**	Total number of households of a specific population group that moved during simulation
Plots	*Satisfied Population*	Line diagrams presenting satisfaction measures of agent types throughout simulation
	Relative Isolation	Line diagrams presenting isolation measures of agent types throughout simulation

* Function assigned to each group type to allow for separate control

Monitors were added to allow for the total population count of the agents (and separately by group) to be viewed and also the total number of agents which desire to move. Additional monitors reflect the number of agents, by group, that moved at each time step and the total that moved by the end of a simulation. Finally, two plots were implemented to show the satisfaction dynamics/levels of agent groups throughout the simulation run and also the level of isolation level of each group.

Apart from the universal controls, applied to all three modules of the District94 model, controls were also implemented that were unique to one or two of the three modules (see Table 7.2). These controls reflect the logic discussed for the three modules in Section 7.1 and subsequently a slider was implemented for the Racial Preference and Racial Income modules to control the level of preference for similar neighbours (hereinafter referred to as the *preferred racial proportion or PrP*). As economic constraint is unique to the Income Constraint module, a slider was implemented in this module to control the level of economic constraint that restricts a low- and middle-income household from relocating to an alternative location (henceforth referred to as *income constrain proportion or IcP*). The preference for neighbours of similar income is unique to the Income Constraint and Racial Income modules and thus a slider was implemented to control the degree of preference of upper-income households for similar income neighbours (henceforth referred to as *preferred income proportion or PiP*).

Table 7.2: Unique Module Interface Controls

Control Item	Racial Preference Module	Income Constraint Module	Racial Income Module	Function Properties	Description
Sliders				*%-similar-wanted*	Percentage neighbours of similar kind desired (or restricted to) by each household of each population group
				%-income-constraint	
				%-income-preference	

In the following section the implementation phase of the District94 model is discussed and provides further information on the input data, parameters and simulation procedures of each of the three modules.

7.3 Model Implementation

At the implementation stage of the model the input data, discussed in Chapter 5, and parameters are implemented in turn to govern the choices and behaviour of the agents. The simulation then follows specific procedures at execution and provide specific types of output data. These subjects of input data, parameters and procedures and output data are discussed in this section:

7.3.1 Data Input

Following the implementation of the agents to the model environments of the three modules, their distribution can be viewed for each racial and income group in turn. Figure 7.5 shows the distribution of the three racial groups in the Racial Preference module. These patterns reflect the varying distribution of racial groups in the study area, as shown in Figure 5.10.

a) Black African b) Coloured c) White

Figure 7.5: Agents Initiated for Module 1 (Racial Preference)

Figure 7.6 shows the distribution of the initiated agents by income group. As initially shown in Figure.5.12, a distinct difference in spatial distribution between the low-income (see Figure 7.6a) and upper-income groups (see Figure 7.6c) are evident, with the middle-income group (see Figure 7.6b) reflecting a wider and more even distribution across the study area.

a) Low-Income b) Middle-Income c) Upper-Income

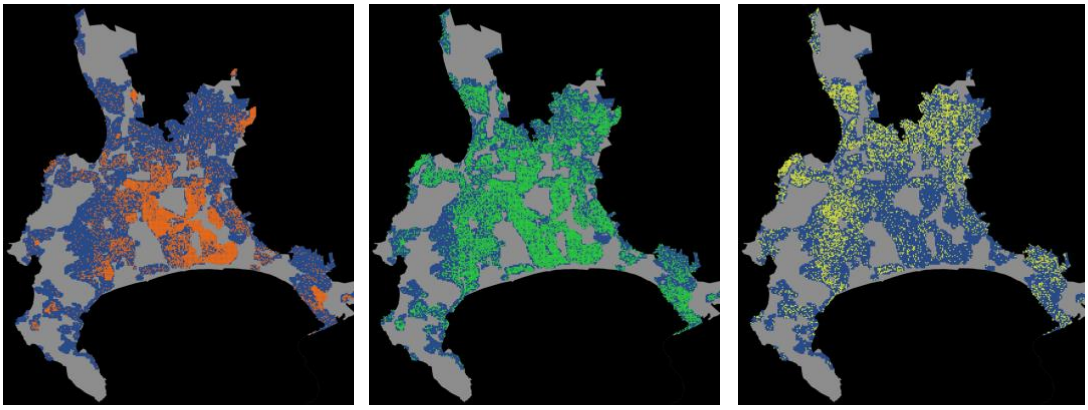


Figure 7.6: Agents Initiated for Module 2 (Income Constraint/Preference)

Finally, the nine categories of income-by-race agents were initiated for the third (Racial Income) module and the distribution of these groups visualised separately (see Figure 7.7). An interesting observation is the distinct difference in spatial distribution of the middle-income groups of each race, which is not noticeable in the Income Constraint module alone.

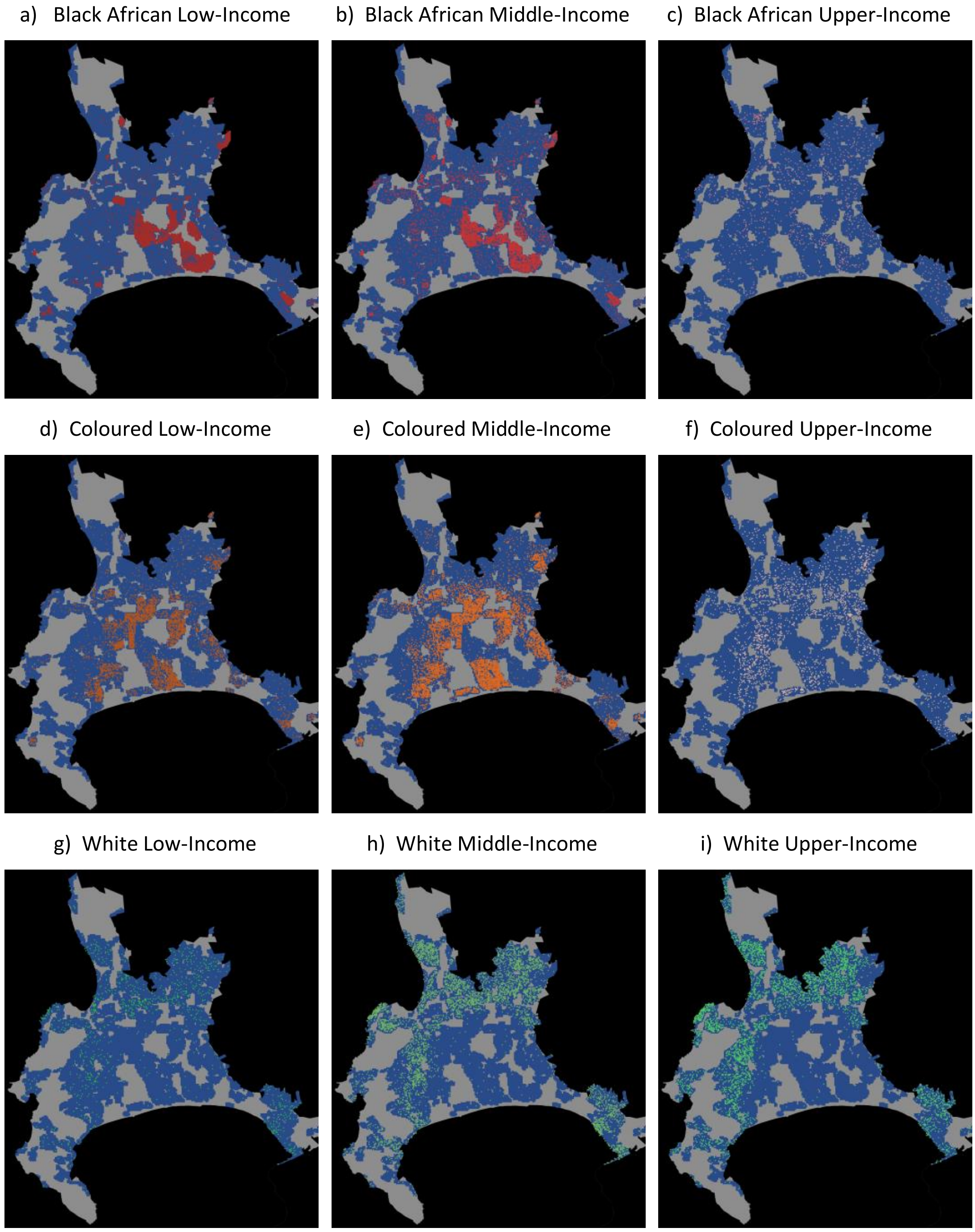


Figure 7.7: Agents Initiated for Module 3 (Racial Preference and Income Constraint/Preference)

The following section presents the parameters that were applied to each of the three modules of the District94 model.

7.3.2 Parameters

The behaviour of the Racial Preference module is governed by three main parameters: *preferred racial proportion* (preference for neighbours of similar race), *neighbourhood radius* and *residential mobility* (see Figure 7.8). *Preferred racial proportion (PrP)* establishes the degree to which households prefer their neighbours to be of the same racial group as them (percentage of similar neighbours desired by a specific racial group).

The *neighbourhood radius* specifies the size of an agent's surrounding neighbourhood in which that agent would determine the composition of racial groups. Thus, the percentage of similar agents will be calculated within the extent of the neighbourhood radius. *Residential mobility* is the distance an agent would travel to find an alternative dwelling location. The parameter specifies an adjustable radius around an agent's current location in which that agent would search for an alternative dwelling. One neighbourhood radius parameter was implemented for all three population groups. However, the PrP and residential mobility was implemented in such a way that both can vary between population groups, which reflects these dynamics in reality better. For example, a lower-income household that is more segregated might not have the financial means or mobility of an upper-income household to consider alternative dwellings far away from its current location.

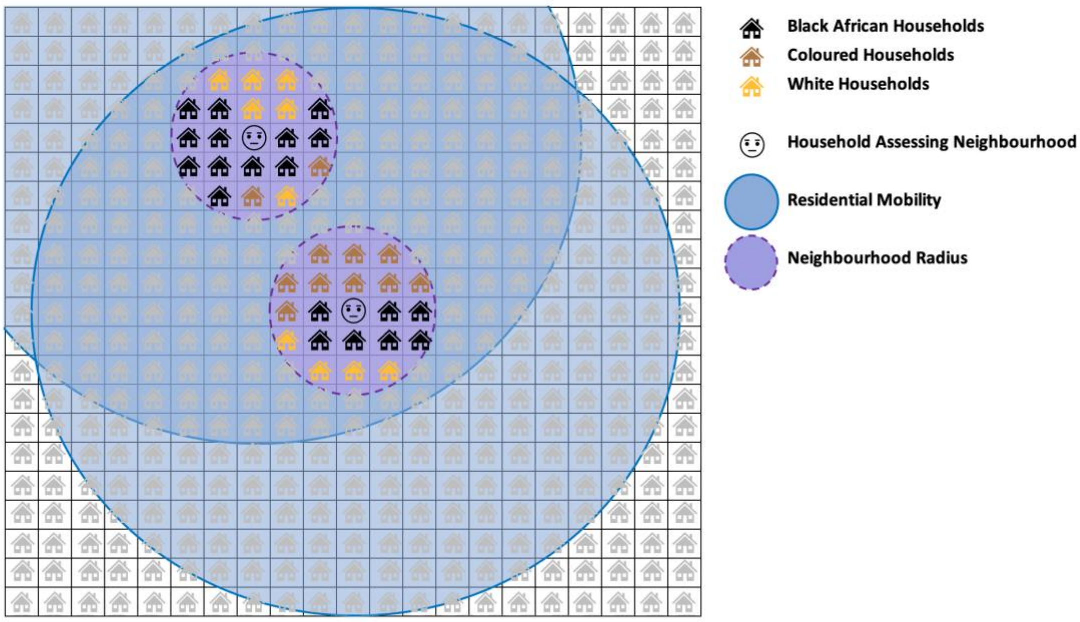


Figure 7.8: Households with Residential Mobility and Neighbourhood Radius Extents

Four main parameters govern the behaviour of the Income Constraint module: *income constraint proportion (IcP), preferred income proportion (PiP), neighbourhood radius and residential mobility*. *Income constraint* determines the degree to which a household from a specific (low or middle) income group is restricted to a neighbourhood where the majority of the population is similar, in terms of income. The *preferred income proportion* parameter applies to the upper-income households that are unconstrained in terms of income and it specifies the percentage of similar neighbours such an income group would prefer in its neighbourhood.

As with the Racial Preference module, the *neighbourhood radius* specifies the size of an agent's surrounding neighbourhood in which it considers the composition of income groups. Thus, the percentage of similar income group agents a household prefers or is constrained to will be calculated within the extent of this neighbourhood radius. *Residential mobility* is applied in the same manner as in the Racial Preference module. The constraint to- and preference for similar income group neighbours and residential mobility was implemented in such a way that they can vary between income groups.

The parameters implemented for the Racial Income module reflects a combination of the parameters of the Racial Preference module and those of the Income Constraint module. Consequently, the behaviour of the Racial Income module is directed by the following five parameters: *IcP, PiP, PrP*, *neighbourhood radius and residential mobility*. The role these parameters play in the simulation procedure of the module is similar to the first two modules, although the sequence in which they are applied is different.

7.3.3 Simulation Procedures

In this section the procedural steps are discussed for a typical simulation process of the three modules of the District94 model.

Racial Preference Module: Procedural Steps

$\Rightarrow$ Step 1 – Agent Satisfaction Assessment

At the setup stage of the model the satisfaction of the households of each population group is calculated. Whether they are content or discontent at their current location is determined by the racial composition of their neighbourhood and whether it meets their individual levels of preference or not. For example, a Black African household which desires at least 50% of its neighbours to also be Black African (see Figure 7.9) will be content at its current location if the neighbourhood composition reflects a Black African population equal or bigger than 50%. In contrast, the same household will be discontent at its current location when the above-mentioned requirement is not met.

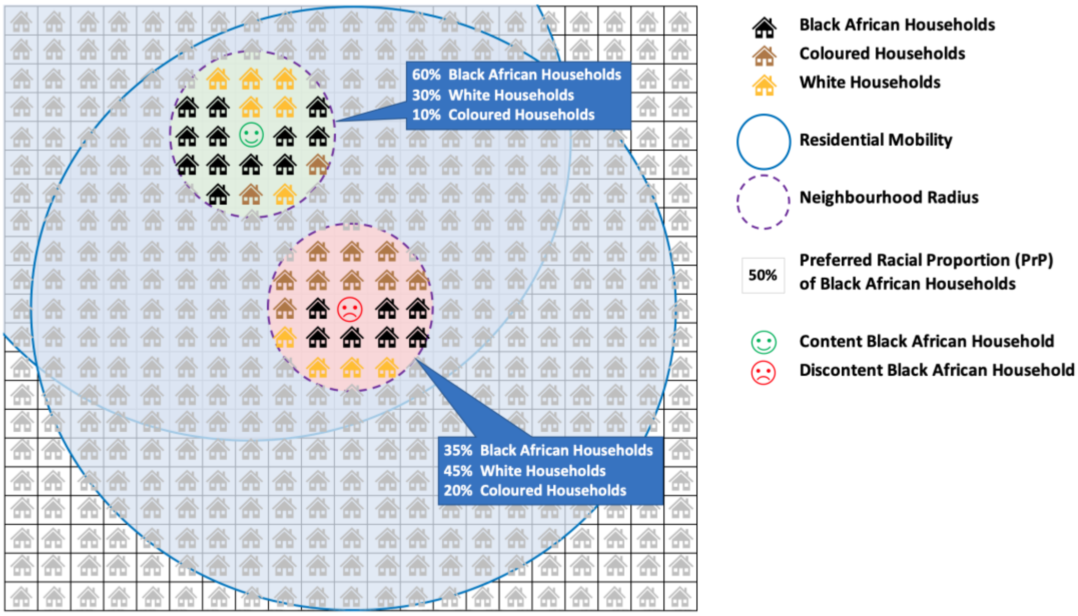


Figure 7.9: Black African Households Assessing Neighbourhoods against a 50% PrP

⇒ Step 2 – Relocation Probability Testing

The module allows for the stipulation of a percentage probability of households which will consider moving. This logic reflects the unlikely occurrence in reality that a whole population of a city would consider moving to a new location at the same time. Thus, a probability percentage of all households in the study area can be specified for consideration of moving. For example, if a 10% probability is assigned to the model at the setup stage, only 10% of all households will consider relocating. The remaining households will remain at their current location, regardless of their satisfaction status. This step will also allow for the testing of different population sizes considering relocation and the effect this would have on the dynamics of the model as a whole.

The simulation procedure and related rules of the Racial Preference module are represented by the flowcharts in Figure 7.10 and Figure 7.11 respectively and the decision-making processes/rules of the module's households (three racial groups) are discussed in accordance.

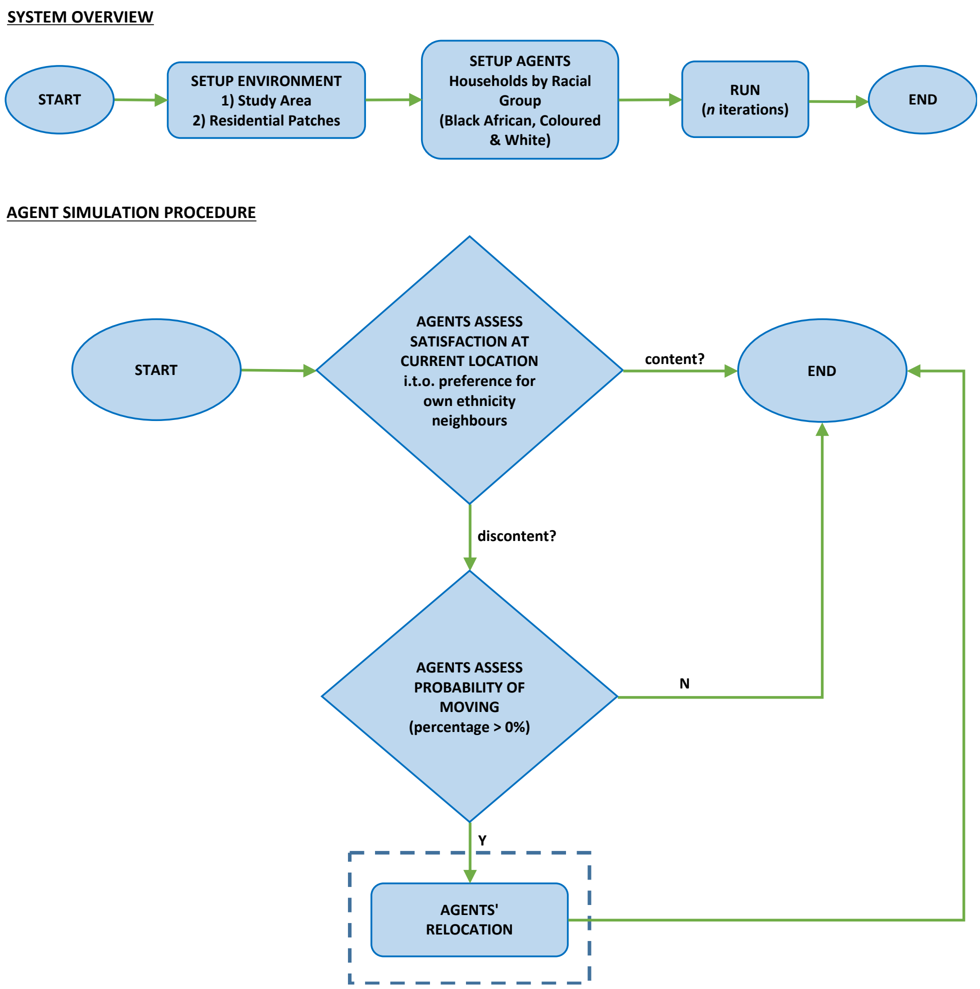


Figure 7.10: Flow Diagram for Racial Preference Module Simulation Procedure

⇒ Step 3 – Agent Relocation

The agents forming part of the probability percentage, which considers moving, will then follow specific relocation rules (see Figure 7.11) in relation to their race and preference of neighbourhood composition. If an agent (household of any race) finds that the composition of neighbours in his neighbourhood suits his specific preference, he is satisfied and remains at that location. However, should an agent find that the racial composition of his neighbourhood does not conform to his requirement/preference, it will search for an alternative location to move to within a specific radius from its current location. This residential mobility radius was incorporated to enable the specification of a different radius size for each population group and draws upon the information outlined on residential mobility in the Comprehensive Integrated Transport Plan for Cape Town (City of Cape Town and Transport for Cape Town, 2013).

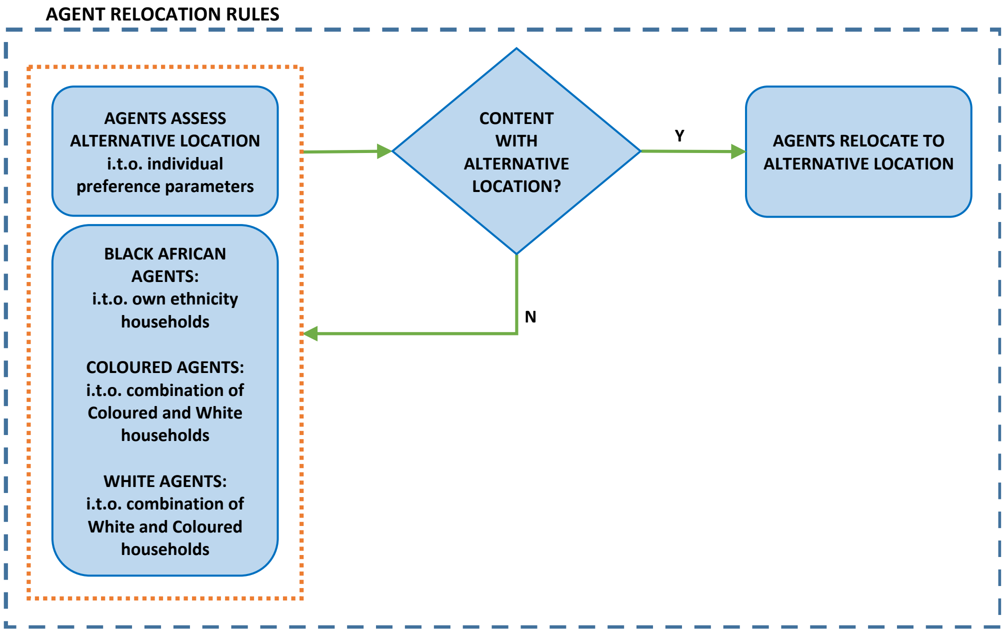


Figure 7.11: Relocation Rules for Racial Preference Module Agents

Consequently, the following rules were instated for the different household types: If a Black African household is discontent with the racial composition of its neighbourhood, it searches for an alternative location, within a specific radius from its current location, to move to. If such an alternative location with a satisfactory racial composition is found, the Black African household will move there. If no alternative location is found, the household will remain in his current location and reassess his circumstances at the next step of the simulation.

If a Coloured household is discontent with the racial composition of its neighbourhood, it searches for an alternative location, also within a specific radius from its current location, to move to. If the Coloured household succeeds in finding a satisfactory alternative location, in terms of racial composition of that neighbourhood, it will move there. If such a location is not found, the Coloured household will consider an alternative location to relocate to, where a combination of Coloured and also White households will reflect a satisfactory neighbourhood composition (racially). If such an alternative location is also not found, the Coloured household remains in its initial location and reassess his circumstances at the next step of the simulation.

White households will also search for an alternative location to move to, should it find at the setup stage that the racial composition of its neighbourhood is not racially satisfactory. If an alternative location is found that is satisfactory, the White household will move there. If such a location is not found, it will seek a location at which the neighbourhood is a combination of White and also Coloured households. If such a location is found it will relocate there and if not, it will remain at its current location.

⇒ Step 4 – Agents and Patches Updated

After every event in which households followed their relocation rules respectively, both the patches and the agents in the module are updated. The household properties are updated in terms of their satisfaction of the new location and the residential patches are updated in terms of the number and composition of the different racial household types it is occupied by.

Income Constraint Module: Procedural Steps

The following simulation steps and behaviour rules of the Income Constraint module are represented by the flowcharts in Figure 7.12 and Figure 7.13 respectively and the decision-making processes of the module's agents (households of the three income groups) are discussed in accordance.

⇒ Step 1 – Agent Constraint/Preference Assessment

Firstly, the level of income constraint or preference of the households of each income group is assessed at the setup stage of the module. The income group the households belong to determines whether they are restricted to their current location or unconstrained to have a preference of location to dwell. While the low- and middle-income households experience a degree of constraint, the upper-income households have no constraint, but rather a preference level for neighbours of similar income. For example, a low-income household with a neighbourhood that has a higher number of other low-income households than his income constraint threshold is constrained to that specific neighbourhood and will remain there. However, should a low-income household experience a neighbourhood where the low-income population is below its constraint threshold it seeks an alternative neighbourhood where the number of low-income neighbours satisfies the constraint threshold. This example is discussed in further detail in the third (agent relocation) step.

⇒ Step 2 – Relocation Probability Testing

As was found with the Racial Preference module, the Income Constraint module allows for the specification of a percentage probability of households who will consider moving. Hence, only a percentage of the total number of households in the study area will consider relocating.

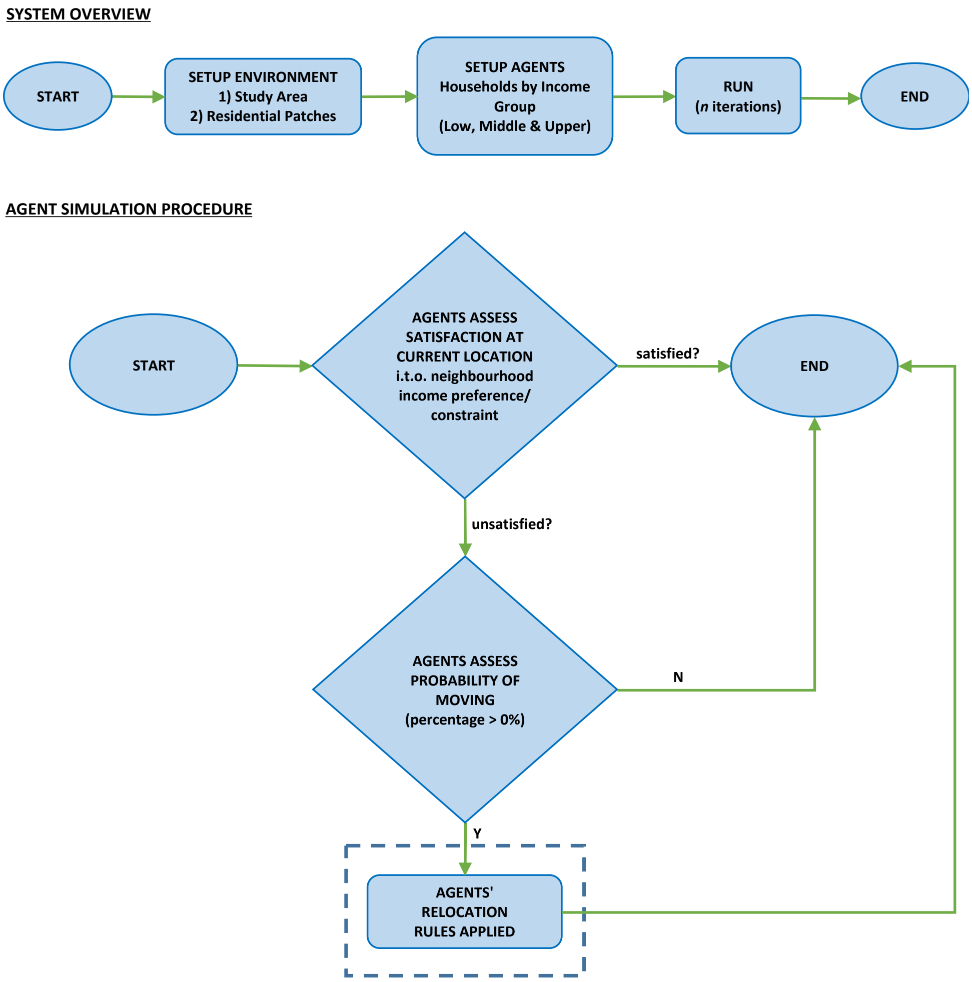


Figure 7.12: Flow Diagram for Income Constraint Module

⇒ Step 3 – Agent Relocation

The agents forming part of the percentage of the population that considers moving, will then follow specific relocation rules in relation to the income groups they belong to. If a household finds that the degree of constraint or preference to his current neighbourhood is at a certain intensity (level), he will remain at that location. However, should any household feel that its current location is not satisfactory it will search for an alternative location to move to. The relocation of the different income groups is governed by the following rules in Figure 6.16:

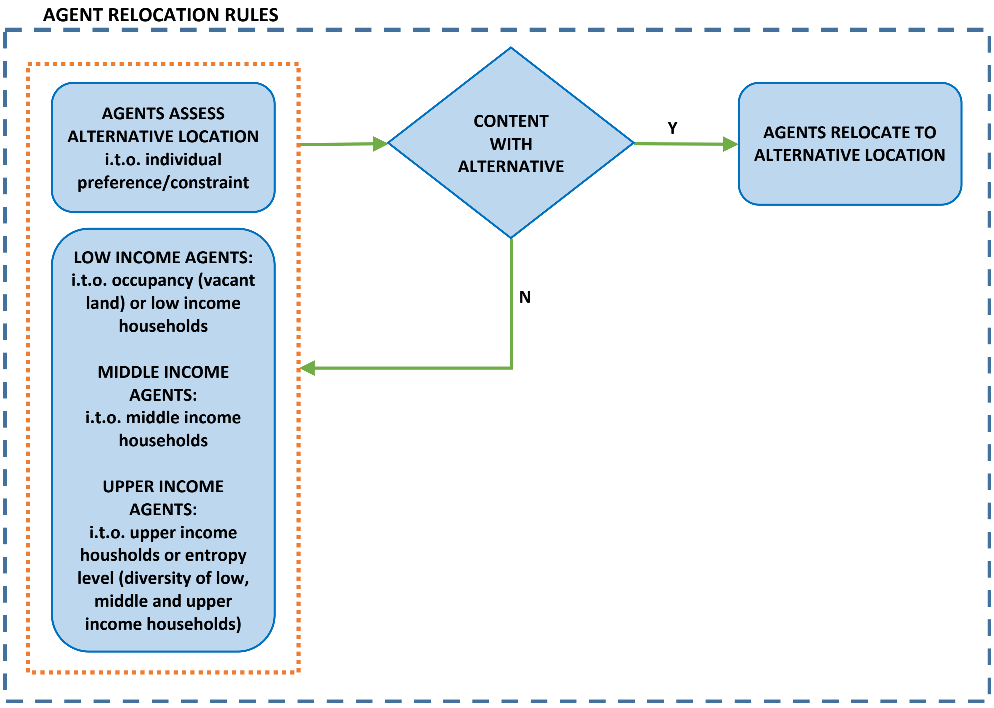


Figure 7.13: Relocation Rules for Income Constraint Module Agents

If low-income households experience a high level of constraint it effectively means that those households are constrained to a neighbourhood with a majority of similar neighbours. However, if such a neighbourhood composition is not found, the only other alternative for a low-income household would be to search for a location that is vacant. For example, a low-income household with a 60% constraint level will be restricted to a neighbourhood reflecting a composition of 60% or higher low-income households. An influx of middle- or upper-income households will effectively lower this percentage and prompt the low-income household to seek an alternative dwelling that is more satisfactory. If no alternative options are found, the low-income household remains at its current location.

If a middle-income household reflects a constraint level lower than a specified threshold, it will indicate that its current neighbourhood is composed of a minority of his own income group. If the majority of neighbours are low-income, it would persuade the middle-income household to search for an alternative dwelling location where the neighbourhood is predominantly middle-income. If such an alternative location is not found, the middle-income household remains at its current location.

If the neighbourhood of an upper-income household does not conform to its preference for a certain composition of similar neighbours, the upper-income household searches for an alternative location. If such an alternative location is found the household will move there. If such a location is not found the household will remain at its current location.

⇒ Step 4 – Agents and Patches Updated

As with the Racial Preference module, both the patches and the agents in the module are updated after every step, in which households followed their relocation rules and moved accordingly. The household properties are updated in terms of either their constraint or satisfaction of the new location and the residential patches are updated in terms of the number and composition of the different income group types it is occupied by.

Racial Income Module: Procedural Steps

In contrast to the Racial Preference and Income Constraint modules, where the subjects of racial preference and income constraint/preference were explored separately, the Racial Income module combines these preferences and restrictions to explore the complex interrelated dynamics between them. The behaviour of the households is differentiated: firstly, by the degree of constraint to a neighbourhood of similar income or preference for a neighbourhood of a certain income composition and secondly, by the degree of preference for neighbours of similar race. The simulation procedure followed for the Racial Income module is represented by the flowcharts in Figure 7.14 and Figure 7.15 and the decision-making processes/rules of the households are discussed in accordance.

⇒ Step 1 – Agent Constraint Assessment

The first step undertaken after the setup of the study area and residential patches is the assessment of a household's income constraint. Every household in the study area is assessed in terms of its income constraint at its current location. The low- and middle-income households that are found to be constrained will remain at that location, regardless of the fact that they might be discontent in terms of preference to a specific racial neighbourhood composition. These constrained households are effectively restricted to dwell in areas of predominantly the same income households as they are. The upper-income household that are found to be content with their current location will also remain. Although these upper-income households are not constrained to any location, they reflect a level of preference for a specific income composition of a neighbourhood. Thus, if their current location conforms to their degree of preference, they remain at that location.

⇒ Step 2 – Relocation Probability Testing

The same process of probability testing found in modules 1 and 2 is followed, with only a percentage of the total population considering moving. Hence, the low- and middle-income households that are not completely constrained and the upper-income households that have a high preference for similar neighbours will consider relocating to a location that is more satisfactory, should they be included in the relocation probability percentage.

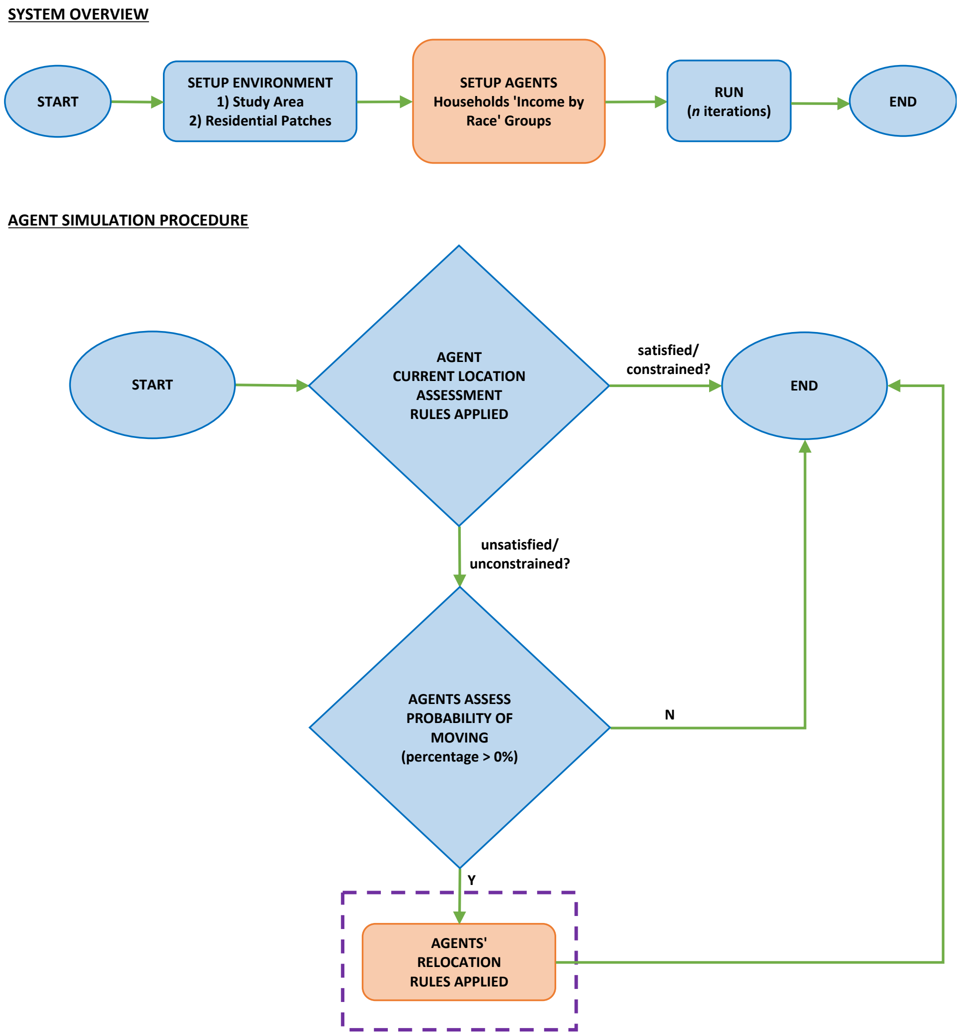


Figure 7.14: Flow Diagram for Racial Income Module

⇒ Step 3 – Agent Relocation

The agents which would consider relocating will follow a set of rules, composed of a combination of the first two modules' rules, in relation to the type of income group and racial group they belong to. As mentioned before, the income status of a household will be the overriding factor influencing the decision-making and related behaviour of that household. For example, if the White low-income household is largely (financially) constrained to his current neighbourhood, the preference for a more satisfactory racial combination of neighbours will be of no relevance. The low- and middle-income households that are not constrained to their respective income groups and are inclined to find an alternative residential location. The upper-income households will also consider alternative locations to move to in order to satisfy its level of preference for neighbours of a similar income group.

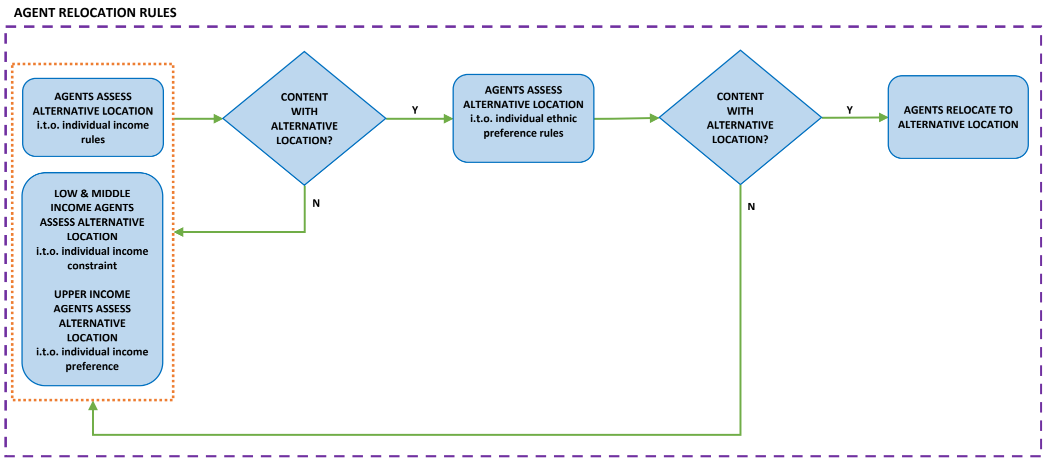


Figure 7.15: Relocation Rules for Racial Income Module Agents

Once these low- and middle-income households find an alternative location that is satisfactory in terms of its neighbourhood composition of income groups, they will assess the same location in terms of their racial preference. If the neighbourhood of this location also satisfies their racial preference in terms of racial composition, the households move there. Should the alternative location not be satisfactory in terms of the low- and middle-income household's preference, these households will seek another location at the following step and start their assessment again with an income evaluation first. Although the upper-income household has no income constraint it only focusses on its preference level for similar neighbours.

7.3.4 Model Output

The output data and related values obtained from each simulation run of the three modules are presented in three different formats: CSV (numerical format), ASCII (raster image format) and MP4 (video format).

The numerical data output is presented in two different CSV files showing the parameter settings for the particular simulation and the statistics and values generated at each time step during the simulation. This includes the total of households that want to relocate, the total of households (by group) that want to relocate and the total of households that were able to relocate. The level of isolation for each different group of households is also included for each step of the simulation exercise.

The agent (household) distribution after each simulation time step is exported to ASCII raster format for further analysis in GIS. These files include the distribution of each group of households, the distribution of households in terms of isolation and also the distribution of each group of households in terms of entropy. The Vid extension for NetLogo provides for the output of a video recording for the duration of a simulation run. It allows for the recording of a series of frames of a simulation run, which are merged together to present a MP4 video file for further visual exploration of a simulation run. Thus, moving forward and backward through frames allows for repeated inspection of agent movement, without the need to re-initiate and run the model a second time.

7.4 Summary

This chapter presented the conceptual and architectural formulation of the District94 model and serves as foundation for the following chapter. Firstly, the working hypothesis was presented and subsequently the related rationale and objectives for each of the three modules were discussed. This is complimented by a discussion of the implications of both racial and income segregation for the formulation of integrated development policies by the City of Cape Town council. Segregation in the study area will ultimately persist if urban integration policies fail to consider the alleviation of poverty, but also the racial homophilic preferences of households and their willingness to integrate. This was followed by a presentation of the architecture (components) of each of the modules of the model and an introduction of the model agents and environment. Finally, the model implementation section focussed on the relevant data input to the model, the model parameters and simulation procedures of each module and the output from the model.

The following chapter will explore the evaluation processes for the three modules including the sensitivity analysis of various components. This will comprise of a systematic approach of evaluating different aspects of each of the three modules.

Chapter 8

District94: Model Evaluation and Sensitivity Analysis

Following the conceptual formulation and implementation of the District94 model, discussed in Chapter 7, this chapter concerns the evaluation processes of the three modules the District94 model is composed of. Sensitivity analysis is undertaken as an essential process, prior to simulation experiments, to ensure that confidence is enhanced in the construction of the model and the way it intends to simulate target dynamics.

Sensitivity analysis is undertaken to ensure that the model is correctly constructed as conceptually formulated and to assess the influence of different parameters and their values on particular behaviours or outputs of the model. This process is introduced as a set of various tests, which are systematically undertaken to understand how the variation of parameters will affect racial and socio-economic segregation levels in the study area, both spatially and quantitatively. Consequently, all parameters are set at a fixed level and then tested one at a time to understand the influence of that parameter change on the outcome of the simulation. The sensitivity analysis for all three modules focusses on three specific parameters of each module and how value changes in these parameters affect segregation levels in the relevant modules: 1) preferred racial proportion (PrP), income constraint proportion (IcP) and preferred income proportion (PiP), 2) neighbourhood radius and 3) residential mobility.

Given the fact that the underlying logic of the District94 model is based on that of the Schelling segregation model, even a small degree of homophilic preference will perpetuate segregation. Nonetheless, the City of Cape Town council can promote integration through the establishment of racially mixed neighbourhoods and the alleviation of poverty, given that post-apartheid segregation is also intrinsically connected to economic well-being.

This chapter is comprised of six sections. Firstly, the initial process of code testing is briefly discussed in Section 8.1. Section 8.2 concerns the establishment of a suitable simulation run length - the number of steps the simulation should run to effectively simulate the target dynamics. This is followed by the testing of the sensitivity of the model, in Section 8.3, to the systematic change of parameter settings for racial preference and income constraint/preference levels. In Section 8.4 the effect of initial conditions on the model is tested through the simulation of a scenario of complete racial and income integration and a scenario of complete segregation. The effect of the neighbourhood radius parameter is then tested Section 8.5 and finally the sensitivity of the model to the effects of residential mobility change is tested in Section 8.6.

8.1 Preliminary Model Verification

Given the fact that the agent-based model in this thesis consists of three modules, it was essential for a preliminary verification process to be undertaken after the development of each of the modules. This ensures that it is possible to determine whether these modules correspond to the theoretical and conceptual specifications of the model and also that each module functions properly, before the next one was developed and implemented. As discussed in Section 4.4.3, the occurrence of errors in the writing of a program is a common phenomenon. Hence, a number of steps were undertaken to ensure that the model behaves in an expected manner.

Firstly, the model code was evaluated for potential semantic errors that are common when variable names are mistyped or the incorrect assignment of parameter values occurs (Crooks et al., 2018). Apart from the careful rereading of all code, a word search was undertaken on comments that were added to the code at the development stage to highlight variables. This allowed for a quick comparison of all variable names to ensure conformity. Additional comments that were incorporated to briefly describe each procedure also enable verification of the order in which the code is structured.

Following code testing, visual interface validation was undertaken on various aspects of each module to ensure that data is initiated correctly and as specified by the code. The model environment is inspected to ensure that census tract and land use attribution from the imported GIS data is reflected. Monitors that were introduced to the interface to report agent totals were checked against the imported population data to ensure that the correct number of agents are initiated at the setup stage of a simulation. Parameter functionality was then evaluated at a high level by means of specific monitors. For example, a monitor was established in each module to report the number of agents that desire to move to an alternative location at each time step of a simulation. By specifying a high parameter value for the preference of agents for similar neighbours in the first (racial preference) module, a higher number of agents with a desire to relocate was reported.

Finally, a simplification of the model environment was established to verify each module. Such an exercise enables a modeller to subject agents to simplified environmental conditions that would in turn assist the clear identification of agent behaviours that are not expected (Crooks et al., 2018). For each module the model environment was reconfigured into a simple grid of four square census tracts and a sample of the total agent population was produced. This allowed for a clear evaluation of the assignment of agents to the correct census tracts and residential land use patches. It also enabled the testing of different parameter settings and the evaluation of agent behaviour in relation to these settings.

8.2 Simulation Run Length Specification

Since a standard length for an agent-based model's simulation run is non-existent, it was decided to test simulation runs at various run lengths (number of time steps) and establish the most suitable version. Suitability was measured by both the stage in a simulation run at which agent movement reaches stability (movement either ends or is minimal) and the notion of an abstract period of urban residential change in the real world . Although time is abstract in this model, every five time steps could be considered as one year. Therefore, the duration of a whole simulation run would reflect a period of ten years (50 time steps). Consequently, the Racial Preference and Income Constraint modules were tested at a maximum of 50 time steps and different parameter settings. However, a default neighbourhood radius (*nr*) of 5 was maintained. For both the Racial Preference and Income Constraint modules the respective parameters of racial preference and income constraint/preference were set at 0.2 for the first simulation for each module and 0.8 for the second simulation. It was found for the simulations of both modules that the trend in agent movement for all three races and income groups have either stabilised or show very little further movement at the 50th time step.

With the completion of specifying a satisfactory run length for simulations undertaken for each module, the sensitivity analysis procedure is commenced for all three modules in the following sections.

8.3 Racial Preference and Income Constraints Parameters

The first sensitivity analysis procedure concerned the testing of the parameters of preferred racial proportion (PrP) of the Racial Preference module. Parameter sensitivity analysis was also undertaken in terms of the output from the simulation runs. The concept of parameter sweeping was applied whereby variables were adjusted systematically. The purpose of this exercise was to test the effect that a change in racial preference or income constraint of households will have on the outcome of the simulation, while other parameters are kept to a standard baseline or default setting.

Firstly, the level of discontent agents for each racial and income group was considered by inspecting the trends in line graph format for each of the simulation runs to understand how the changes in parameter settings affect the level of discontent agents and effectively the level of segregation between the racial groups and income groups respectively. Secondly, the spatial distribution of agents for the various groups were inspected. The distribution of each group was first captured separately in the model environment at the setup stage of the model (time step 0), where these distributions reflect their initial condition. Each of the four simulation runs were then undertaken and at the end of each simulation the distribution pattern of each racial group was captured again in the model environment at the final time step (50) and exported for comparison against the initial distribution of each group at the set-up stage.

Table 8.1 presents the three simulation runs that were undertaken to test a variation in parameter settings in the race module. Simulation run 1 entailed the fixed PrP setting of 0.2 for all three racial groups. Indicated in red for runs 2 to 4, the PrP for each racial type were systematically set to 0.8 (preference for 80% of neighbours to be of the same racial type), while the PrP for the other racial types were kept at a default of 0.2 PrP.

Table 8.1: Settings for Race Module Parameter Testing

Simulation Run	Black African Household PrP	Coloured Household PrP	White Household PrP	Neighbourhood Radius	Residential Mobility (radius)		
					Black African	Coloured	White
1	0.2	0.2	0.2	5	20	20	20
2	**0.8**	0.2	0.2	5	20	20	20
3	0.2	**0.8**	0.2	5	20	20	20
4	0.2	0.2	**0.8**	5	20	20	20

Figure 8.1 presents line graphs of the numerical outputs obtained from the three simulation runs outlined in Table 6.1 and shows the trends of the number of discontent agents of each racial group over 50 time-steps. The graph for Simulation Run 1 shows the output for the three racial groups at a fixed PrP value of 0.2 and consequently an initial low level of discontent with relatively similar trends for all three groups between time step 1 and 50.

The graph for Simulation Run 2 shows a very high level of discontent among Black African agents, which in turn reflects the high PrP value of 0.8 that was set only for that racial group. In contrast, the Coloured and White agents indicate a much lower number of discontent households, reflecting the low PrP setting for these population groups in Simulation Run 2. Simulation Runs 3 and 4 present similar trends, but respectively with Coloured and White households being most discontent and the other groups the least, conforming to the parameter settings for each of the third and fourth run.

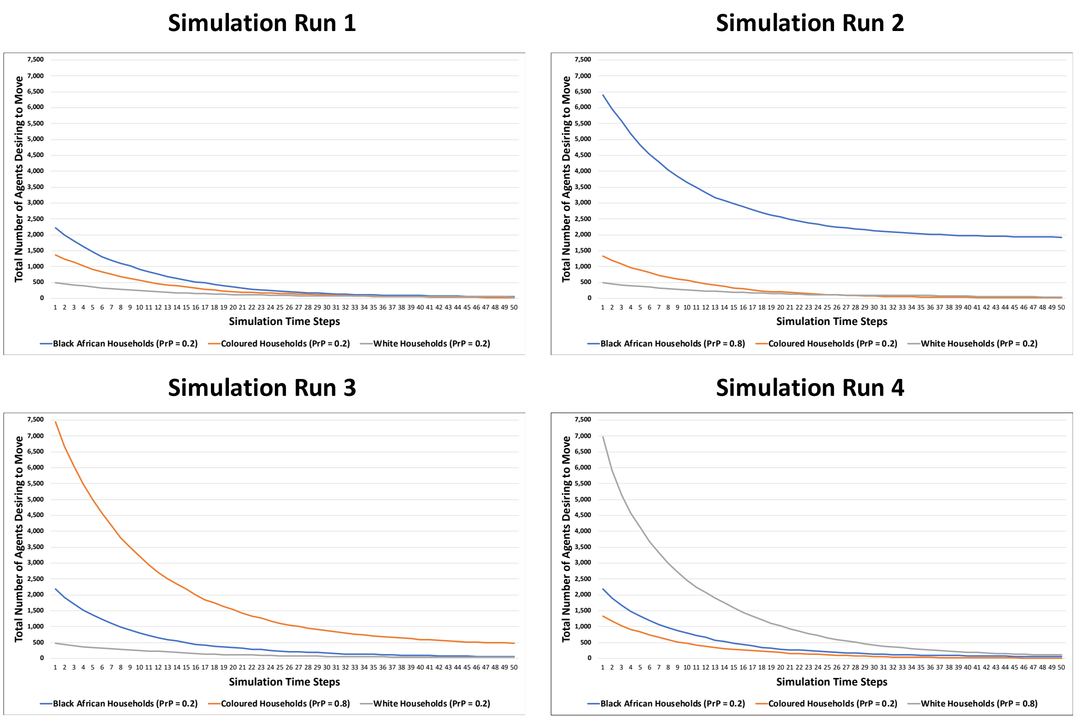


Figure 8.1: Racial Preference Module Sensitivity Analysis. Simulation Output as Number of Discontent Agents by Race

Following the consideration of the numerical outputs of the four simulation runs, the spatial distribution of agents with a 0.8 PrP were inspected for Simulation Run 2 to 4 at both the initial setup stage (time-step 0) and at the end of the simulation run (time-step 50). The objective was to understand the effect of the PrP parameter settings on the levels of segregation and related racial distribution.

Figure 8.2 shows the distribution of agents for the three racial groups at Simulation Runs 2-4 at time-steps 0 and 50. The simulation for each racial group was run individually, with each parameter change undertaken separately. For example, the Black African PrP value was changed first for the first simulation, while the PrP value for both the Coloured and White groups remained unchanged. The following simulation then reflects a parameter change only for the Coloured group, while the PrP value for the Black African and White groups remain at a default setting.

The first row (see Figure 8.2A to Figure 8.2C) reflects the initial conditions (time step 0) of each of the racial groups. The second row (see Figure 8.2D to Figure 8.2F) shows the final time steps for each racial group's simulation when the default parameters remained unchanged each time. The third row (see Figure 8.2G to Figure 8.2I) reflects the distribution of each racial group at the final time step when the PrP value for each group is increased to 0.8 individually.

No substantial change is detected in the second row, with the default PrP values of each racial group remaining unchanged. This indicates that even when the PrP value of one group is at 0.8, the level of segregation between the three racial groups is so high that the other groups remain mostly unaffected in terms of distribution. However, significant changes are evident in the third row, with the increase of each racial group's PrP value to 0.8 at each individual simulation run.

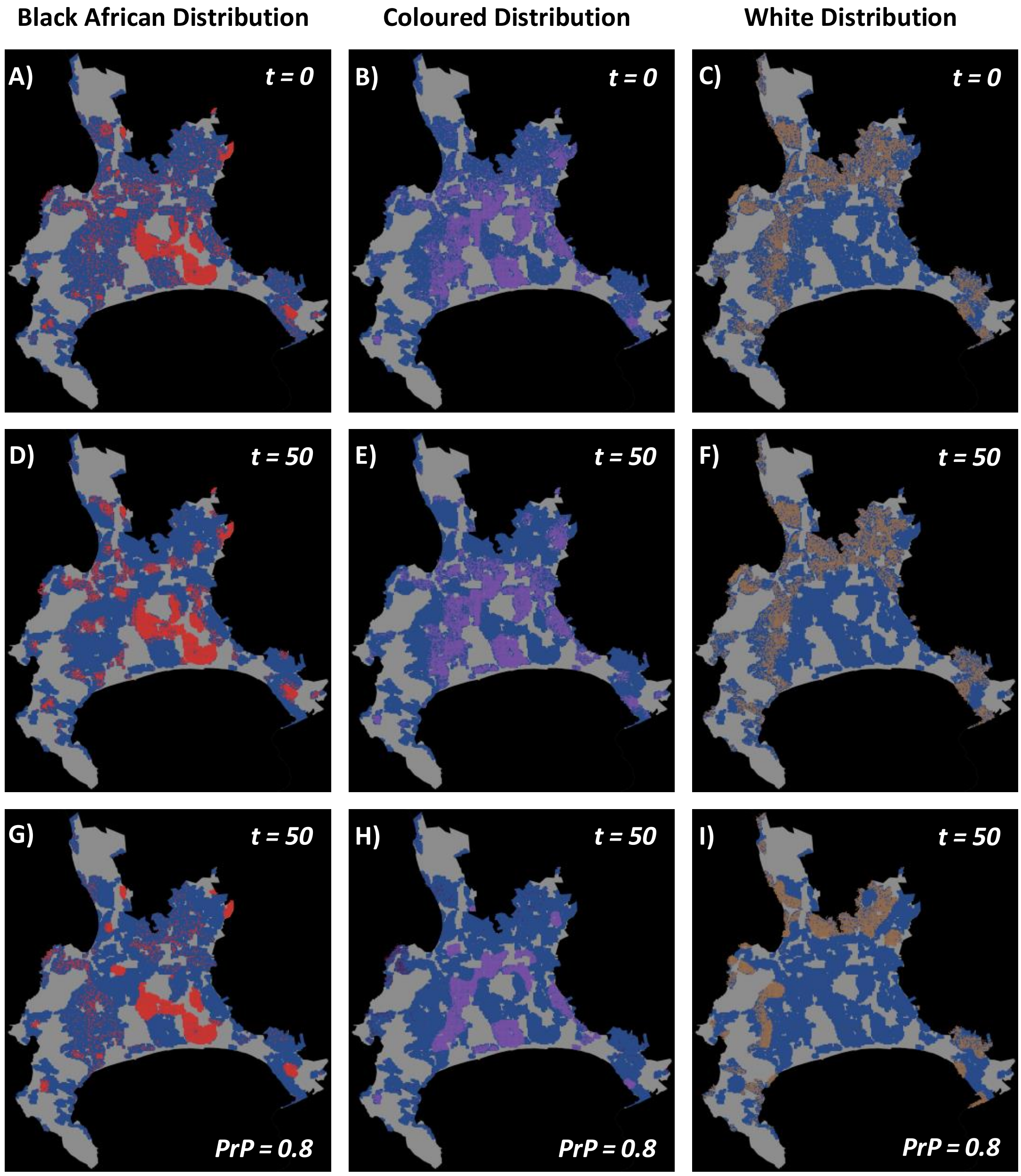


Figure 8.2: Simulation Runs 2-4: Spatial Distribution of Racial Groups at Time-steps 0 and 50

Segregation measures were undertaken for the racial distribution patterns in Figure 8.2 to enhance visualisation. Figure 8.3 shows the isolation measures for each racial group at time step 0 and time step 50, where PrP level was set to 0.8 for each racial group individually. With the Black African PrP value at 0.8, it is noticeable that the distribution of Black African agents at time step 50 (see Figure 8.3D) is more clustered in the regions of the study area where this group's concentration was highest initially. Enhanced clustering also occurs to the west of the study area where the Black African population is in the minority at time step 0 (see Figure 8.3A).

It is also noticeable in Figure 8.2 that the Coloured and White agents that were present in predominantly Black African regions at time step 0 are absent at time step 50, due to the high preference level of the Black African group for racially similar neighbours. This is particularly evident towards the south of the study area where the Black African population group predominantly resides. It is thus evident from these changes in distribution for all three racial groups that the high preference level of the Black African group for similar neighbours does not only affect the distribution and segregation level of that group, but also has an effect on the distribution and effectively level of segregation of the Coloured and White groups.

The setting of the PrP value at 0.8 for the Coloured population group shows a clear variation in distribution of the agents of this group between time step 0 and time step 50 (see Figure 8.2H). This is particularly evident in Figure 8.3E where the predominantly Coloured regions in the study area are found to be more clustered than before, especially to the west of the study area. The regions where small concentrations of Coloured households reside to the north-east and south-east of the study area intensified in terms of isolation levels, but stayed fairly unchanged in distribution as Coloured agents remained in their current location, due to the lack of alternative locations in these predominantly White neighbourhoods.

The change in distribution of the Coloured population group also influenced the outcome of the Black African and White population distribution patterns at the end of the simulation. This is particularly evident for the Black African group, where the wider distribution to the north and west of the study area (at time step 0) resulted in numerous clusters of households at the final time step (see Figure 8.2D). The distribution of the White population was affected less, apart from the regions where the Coloured population predominantly resides.

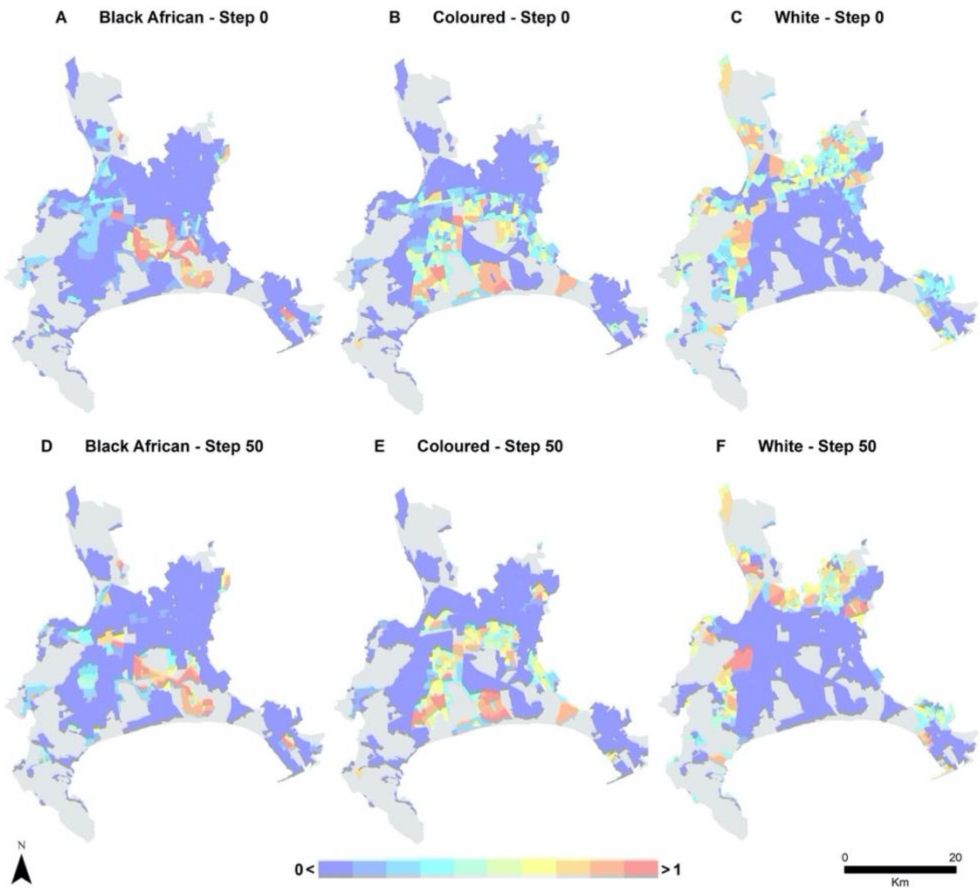


Figure 8.3: Local Spatial Isolation of Racial Groups at Time Steps 0 and 50 with PrP Value Set to 0.8 for Each Group Individually (1000m bandwidth – manual classification, 10 classes between 0 and 1)

It is evident that the PrP setting of 0.8 for the White population group resulted in further clustering of the already segregated distribution of the group at the start of the simulation (see Figure 8.3F). Both the Black African and Coloured population groups were generally little affected by the evolving White distribution, apart from the regions where households of these non-White groups resided in predominantly White neighbourhoods. In these particular areas the Black African group was found to be more clustered at the end of the simulation (see Figure 8.2H).

The same parameter sweeping exercise was undertaken for the Income Constraint module to execute sensitivity analysis on the outputs for the various parameter settings. Table 8.2 presents the four simulation runs that were undertaken, reflecting the same parameter settings that were applied to the racial preference model. However, these settings concern the income constraint (IcP) and preference (PiP) of agents.

Simulation Run 1 consisted of a 20% constraint/preference setting for all income groups. Simulation Run 2 presents a constraint level setting of 80% (to similar low-income neighbours) for the low-income agents. Simulation Run 3 entails an 80% constraint (to similar middle-income neighbours) setting for middle-income agents and Simulation Run 4 an 80% preference (for similar neighbours) setting for upper-income. At each simulation run where a specific group has an 80% setting, the other two groups reflect a default setting of 20% constraint/preference. Additionally, a default residential mobility setting of 20 is applied to all four simulation runs.

Table 8.2: Settings for Income Module Parameter Testing

Simulation Run	Low-Income Household IcP	Middle-Income Household IcP	Upper-Income Household PiP	Neighbourhood Radius	Residential Mobility (radius)		
					Low-Income Agents	Middle-Income Agents	Upper-Income Agents
1	0.2	0.2	0.2	5	20	20	20
2	**0.8**	0.2	0.2	5	20	20	20
3	0.2	**0.8**	0.2	5	20	20	20
4	0.2	0.2	**0.8**	5	20	20	20

Figure 8.4 presents the graphical (numerical) output obtained from the four simulation runs for the Income Constraint module outlined in Table 8.2 and show the trends of the number of discontent agents over a period of 50 time steps. The graph for Simulation Run 1 shows a high level of discontent middle-income agents throughout the simulation, regardless of the fact that all group have a low default constraint (IcP)/preference (PiP) level of 0.2. This occurrence may be attributed to the wide distribution of the middle-income group throughout the study area, largely overlapping both the low- and upper-income areas.

The graph for Simulation Run 2 shows a high level of discontent low-income agents at the initial stage (time step 0) of the simulation. Although this occurrence is expected due to the high constraint level setting of 0.8 for the low-income group, the middle-income group remains the most discontent throughout the simulation. Simulation Run 3 shows similar trends to the first simulation, regardless of the middle-income constraint level now being set to a high level of 0.8. The graph for Simulation Run 4 shows a higher level of discontent upper-income agents as expected, even though this trend line is relatively lower than that of low-income in Simulation Run 2. This may be attributed to the fact that the upper-income group is very segregated already and that even a high preference level of similar neighbours results in only a relatively small number of discontent upper-income households.

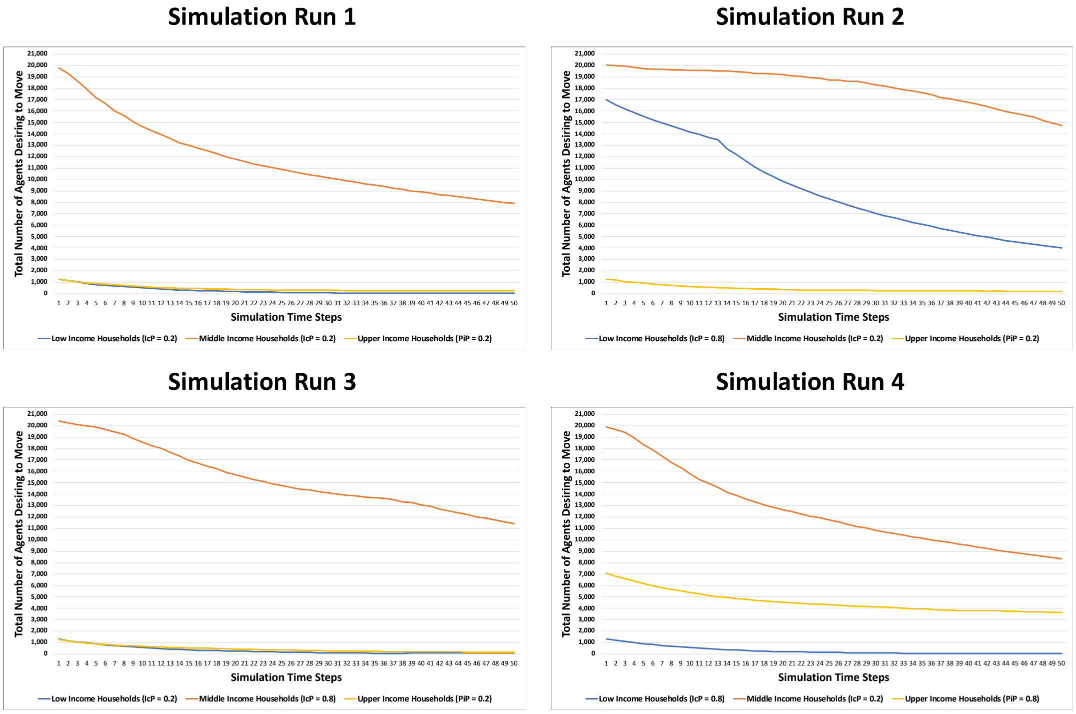


Figure 8.4: Income Constraint & Preference Model Sensitivity Analysis. Simulation Output as Number of Discontent Agents by Race

As with the racial groups, the spatial distribution of income groups with an 80% constraint or preference levels was inspected for Simulation Runs 2 to 4 at both time-step 0 and time-step 50. These spatial distribution outputs from the various simulation runs were considered separately by income group to enable comparison of the different outcomes.

Figure 8.5 presents the distribution of agents for the three income groups at Simulation Run 2 at time-steps 0 and 50. With the high value of constraint (IcP) that was set for the low-income group, it is noticeable that the distribution of low-income agents is more clustered to the south and peripheral areas of the study area. The clusters to the west and south-east of the study area indicate that clustering did not only occur in areas where low-income agents were mostly concentrated, but also in areas away from the other income groups. The low-income agents to the centre of the study area have not been able to relocate at time step 50 and may be ascribed to the predominant presence of middle-income agents.

The distribution of the middle-income agents to the centre of the study area shows the large number of discontent agents noticed in Figure 8.5 (Simulation Run2) that were also unable to successfully relocate at time step 50. The distribution for the upper-income agents remained predominantly unchanged, apart from the areas of higher numbers or clusters of low-income agents are present.

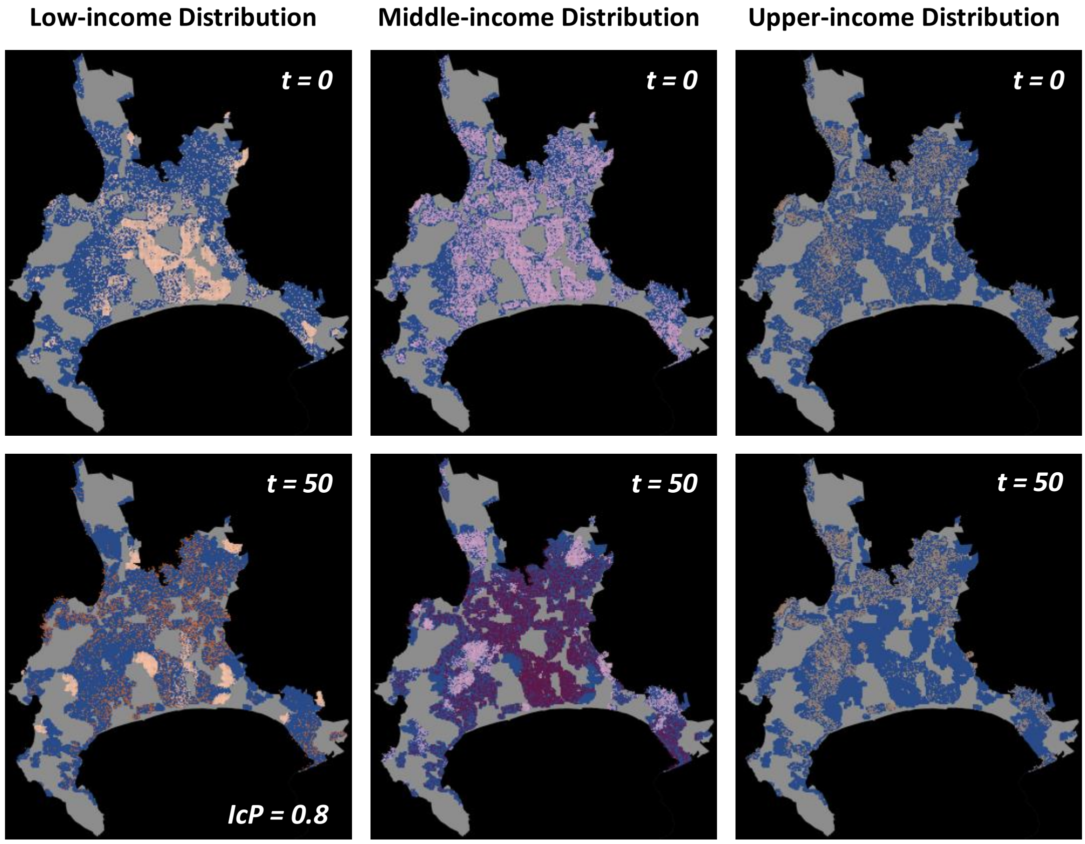


Figure 8.5: Simulation Run 2: Spatial Distribution of Income Groups at Time-steps 0 and 50

Figure 8.6 presents the income group distribution of agents of Simulation Run 3 for the three income groups at time-steps 0 and 50. With a high constraint level of 0.8 set for the middle-income group, it is noticeable that although distribution patterns remained predominantly unchanged to the west of the study area, evident clusters of middle-income agents are present in the north, east and south.

A comparison to the low- and upper-income distribution at time step 0 reveals that these middle-income clusters are located mostly where low levels of the other income group resided at model initiation. Both the low- and upper-income groups were most affected by the middle-income group where low density (highly dispersed) distributions are evident for these two groups. The regions of higher low- and upper-income density remain predominantly unchanged.

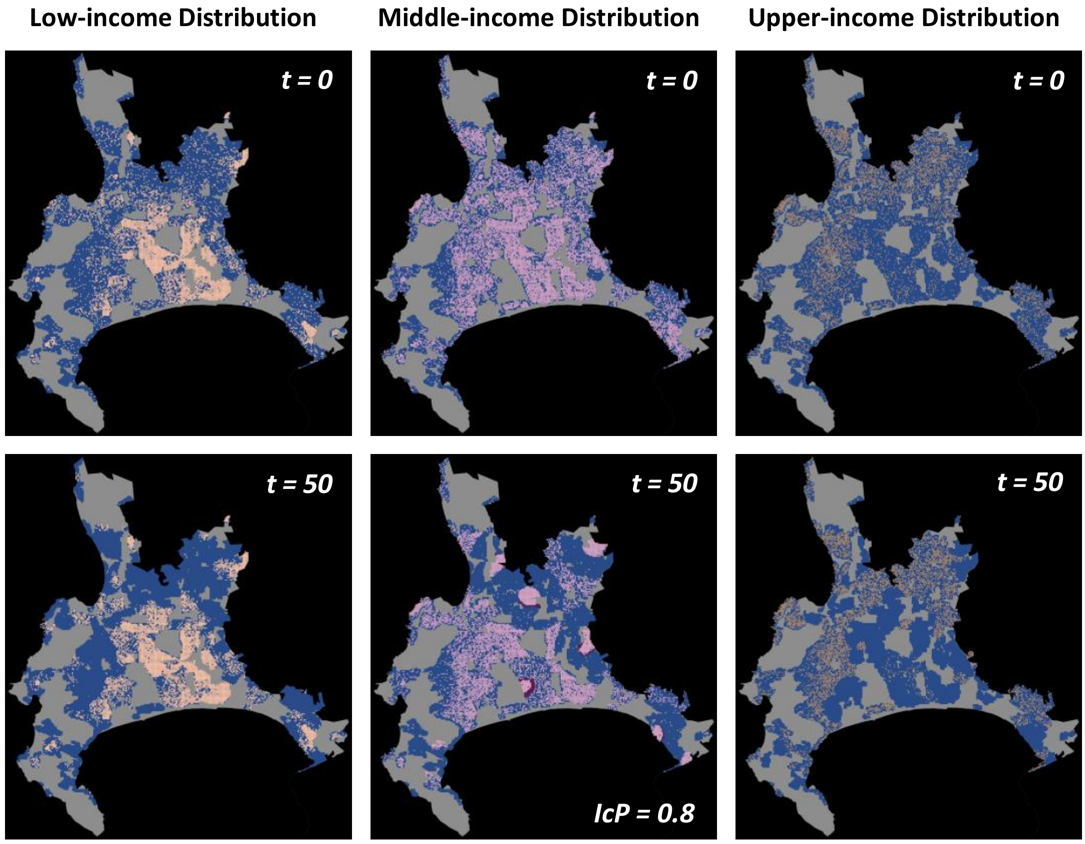


Figure 8.6: Simulation Run 3: Spatial Distribution of Income Groups at Time-steps 0 and 50

Figure 8.7 presents the distribution for Simulation Run 4, with the preferred income proportion (PiP) for the upper-income group set to 0.8 and the other groups at a 0.2 default level of income constraint (IcP). In the distribution of the upper-income agents it is evident that clustering occurred predominantly to the north and west of the study area and away from the adjacent middle-income group. In contrast, the more even and less concentrated distribution of upper-income agents to the central, eastern and southern parts of the study area remained mostly unchanged. This may be attributed to the large number of middle-income agents in this region, restricting the relocation of the upper-income agents to alternative locations where a 0.8 neighbour preference can be satisfied.

The distribution of the middle-income group at time step 50 shows a less dispersed distribution to the periphery of the study area, especially in the vicinity of the upper-income clusters. A noticeable occurrence is the group of middle-income agents to the centre and south of the study area being unable to find an alternative location at time step 50. This pattern corresponds to the concentration of the low-income group at time step 50 in those regions. Apart from this large clustering of low-income agents to the centre and south of the study area, smaller clusters of low-income agents are evident to the northern, western and south-eastern periphery of the study area.

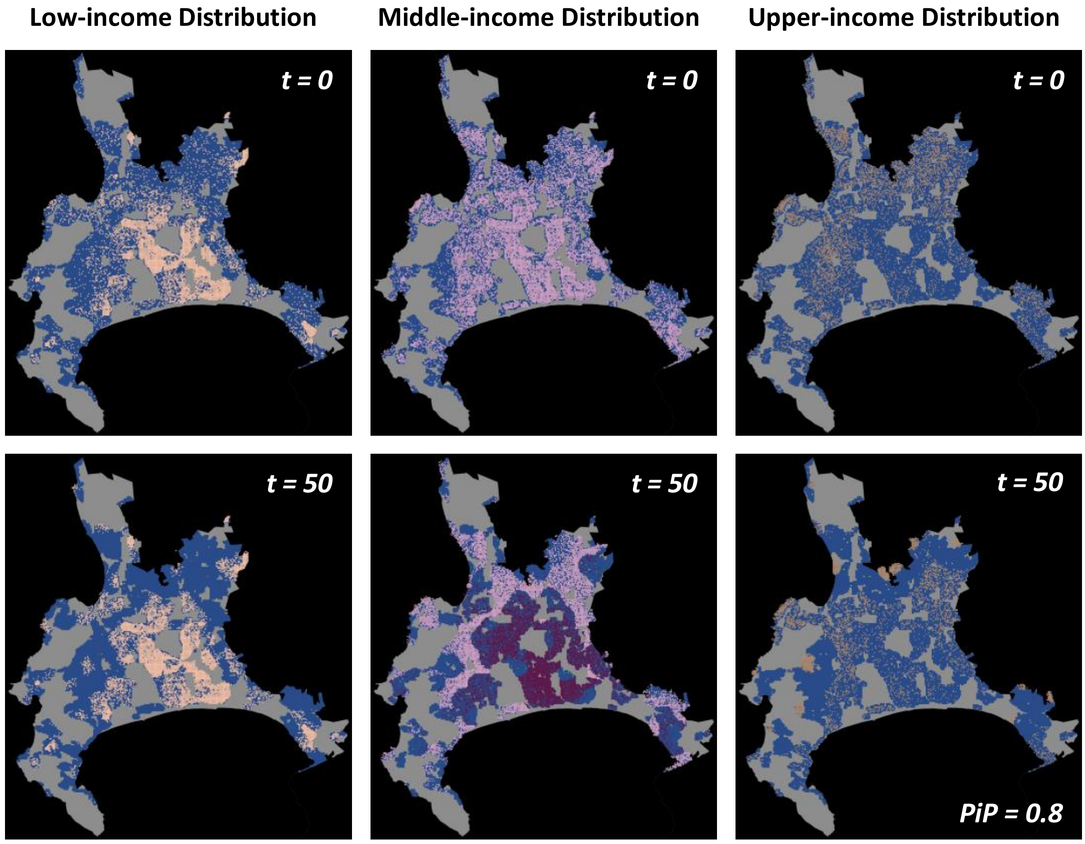


Figure 8.7: Simulation Run 4: Spatial Distribution of Income Groups at Time-steps 0 and 50

The most noticeable phenomenon detected in studying the simulation outputs, in terms of spatial distribution patterns, of the racial and income groups is the fact that the change of a specific group's parameter values not only affects the dynamics of that group throughout the simulation run, but also the dynamics and response of the other groups that are set to a much lower default parameter value at the time. It is thus evident that the agent groups respond to both the parameter manipulation exercises and the rules governing the relationship between groups.

Sensitivity analysis for each module of the District94 model is also extended to test the initial conditions of segregation levels of the different racial and income groups. The following section discusses the introduction of varying initial conditions to each of the modules to test how the model is affected by these changes.

8.4 Initial Conditions

The previous section concerned the systematic changing of racial preference and income constraint parameter values and applied real data for each module of the District94 model. In this section the parameters are fixed for all racial and income groups at a value of 50% preference and constraint, but the initial conditions for each module vary. Firstly, an initial state of complete integration is tested, whereby each census tract in the study area consists of an equal number of agents from each of the groups relevant to the module. For example, the Racial Preference module will reflect an equal number of Black African, Coloured and White household agents in each census tract in the study area. Secondly, an initial state of complete segregation was tested, whereby the majority group in a census tract was completely assigned to that particular census tract. For example, a census tract with a majority of Black African agents will now consist only of Black African agents and no other group members.

Figure 8.8 shows the profiles for the three racial groups, following sensitivity analysis of both integrated and segregated initial conditions. Figure 8.8a shows that the number of discontent agents (desiring to relocate) was equally high at step 0, due to the high level of integration and equal level of preference for similar neighbours (PrP of 50%). However, a dramatic decrease in discontent agents is noticeable between time steps 0 and 50. In contrast, Figure 8.8b shows a much lower level of discontent among all three groups and a more gradual decrease in agents desiring to relocate. This is due to the high level of segregation experienced at time step 0 already.

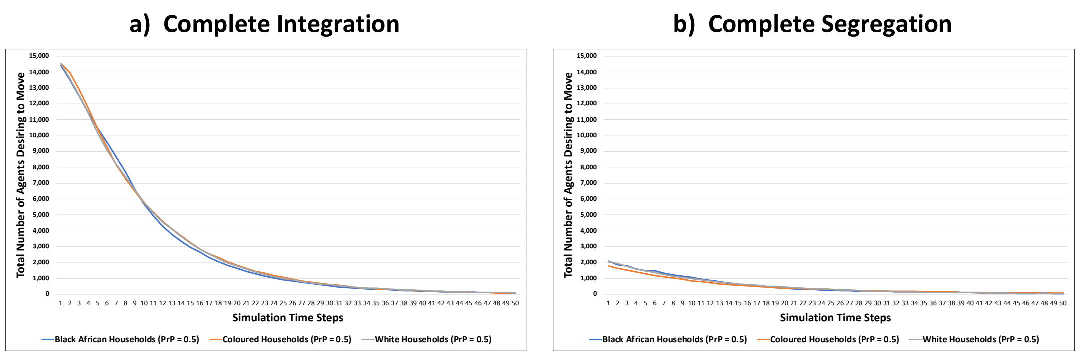


Figure 8.8: Racial Preference Module: Sensitivity Analysis of Initial Conditions

Figure 8.9 presents the distribution of racial groups at time step 0 (t=0) and time step 50 (t=50), with the initial conditions set to complete integration. In addition to the 50% PrP level, a PrP level of 30% was firstly tested for all three racial groups to allow for comparison between the outcomes of the two levels of preference for similar neighbours. It is noticeable how the equal distribution of different racial groups reflects an increase in clustering with an increase in preference for similar neighbours from time step 0 to time step 50. The equal initial conditions between the three groups and their equal levels of PrP is evident in the similarity of pattern emergence across the three groups.

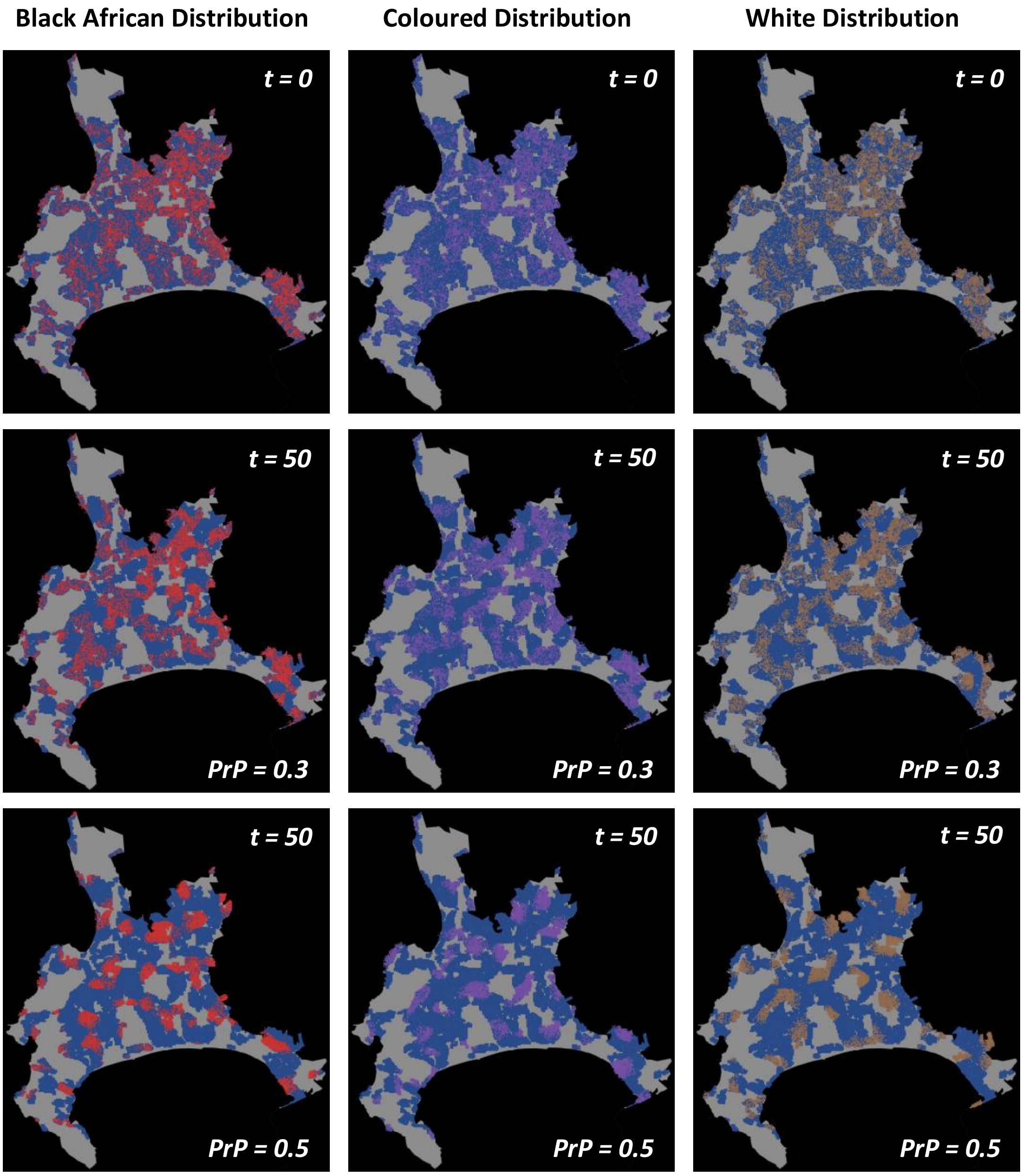


Figure 8.9: Racial Preference Module: Integrated Initial Conditions of Racial Groups at Time-steps 0 and 50

Figure 8.10 presents the distribution of racial groups at time step 0 and 50, with the initial conditions now set to complete segregation. Again the 30% PrP level was applied, in addition to the 50% PrP level, for all three racial groups to allow for comparison between the outcomes of the two levels. At time step 0 the initial conditions of distinct segregation patterns are noticeable for the three population groups. However, this high level of segregation results in minor distributional change and gradual clustering for all groups between time step 0 and 50, regardless of the varying PrP levels.

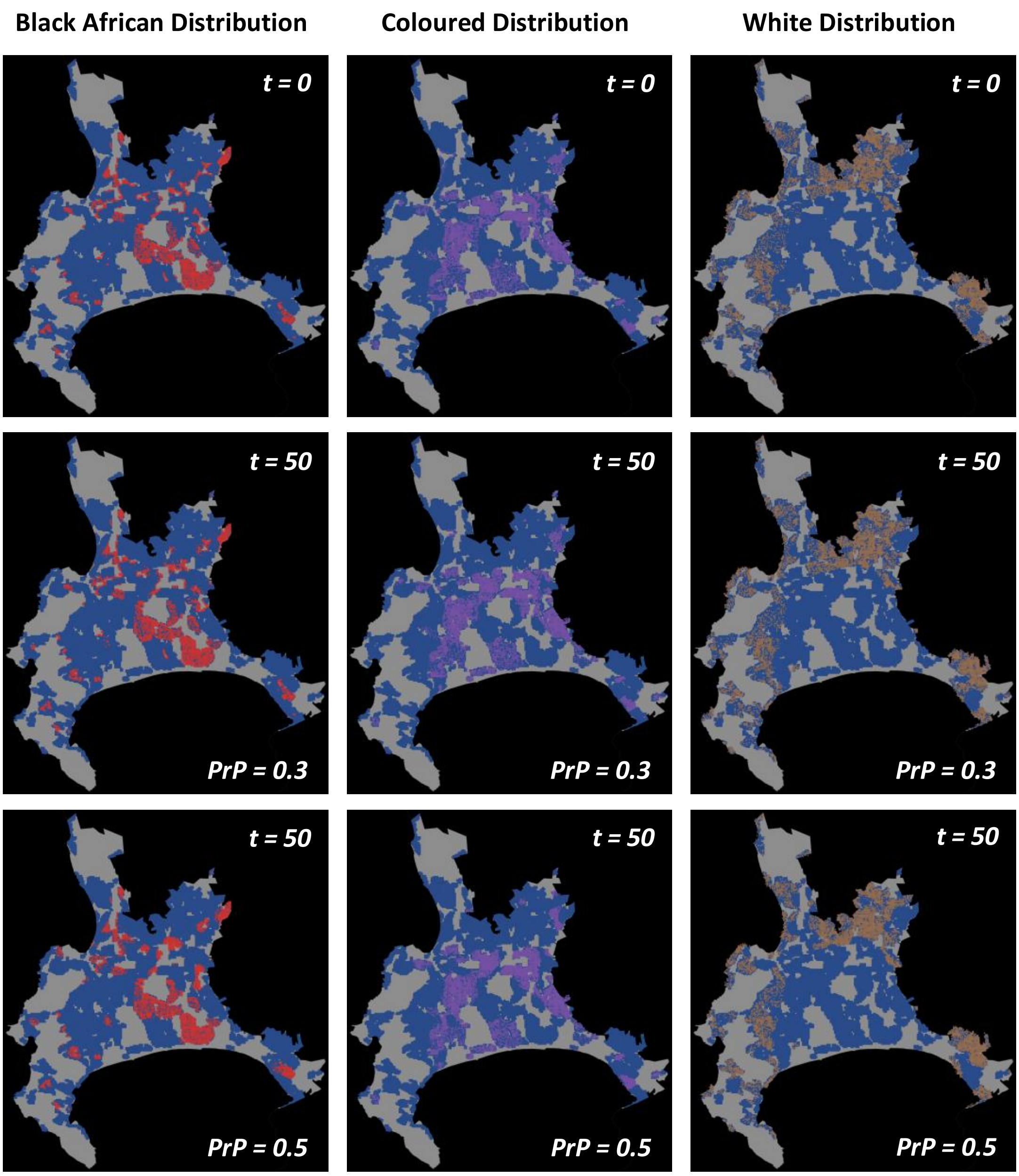


Figure 8.10: Racial Preference Module: Segregated Initial Conditions of Racial Groups at Time-steps 0 and 50

The same exercise of testing the sensitivity of the Racial Preference module to initial agent conditions was undertaken for the Income Constraint module. Firstly, the behaviour of the number of discontent agents of each population group was studied with the same two initial agent conditions set as for the racial groups: one of complete integration and one of complete segregation. A default income constraint level (IcP) for the low-and middle-income groups and income preference level (PiP) for the upper-income group was set at 50%. Secondly, the geographic distribution of all three income groups in the model environment was studied at time step 0 and time step 50. Apart from the same IcP and PiP level of 50%, an additional test was undertaken at 30%, as per the racial groups.

Figure 8.11 shows the profiles for the three income groups, following sensitivity analysis of both integrated (see Figure 8.11a) and segregated (see Figure 8.11b) initial conditions. Figure 8.11a shows that the number of discontent agents (desiring to relocate) was high at step 0, again due to a high level of integration and equally high level of constraint or preference for similar neighbours (IcP & PiP of 50%). In contrast, Figure 8.11b shows a much lower level of discontent among the low- and middle-income groups and a more gradual decrease in agents desiring to relocate. Although the middle-income group was noticeably more discontent at step 0, this number decreased to step 50.

a) Complete Integration **b) Complete Segregation**

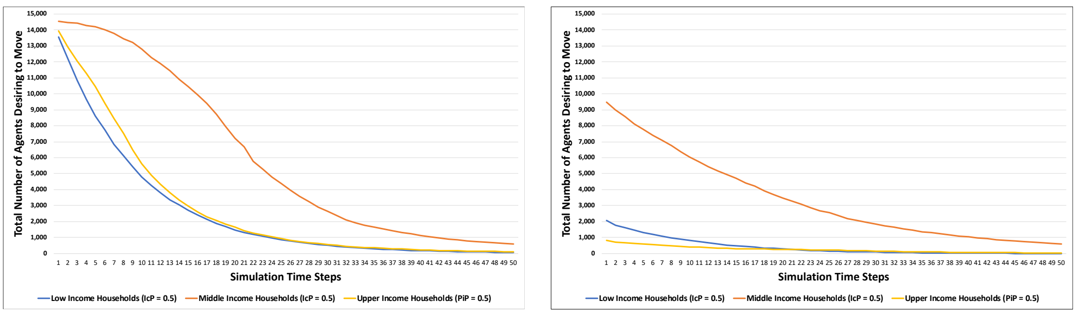


Figure 8.11: Income Constraint Module: Sensitivity Analysis of Initial Conditions

Figure 8.12 shows the distribution of the three income groups at time step 0 (t=0) and time step 50 (t=50), with the initial conditions set to complete integration (equal spatial distribution). As mentioned before, both constraint and preference levels of 30% (IcP & PiP=0.3) and 50% (IcP & PiP=0.5) were tested for each relevant income group.

With constraint and preference levels set at only 30% initially, the emergence of clustering is already evident for all three income groups at time step 50. It is noticeable that these patterns of clustering are formed predominantly in the areas where higher densities of these groups occurred at the setup stage of the simulation. As expected, further clustering occurred for all three income groups at an IcP and PiP level of 50%, indicating a higher level of constraint of low- and middle-income agents to similar neighbours and a higher level of preference to similar income neighbours of the upper-income group.

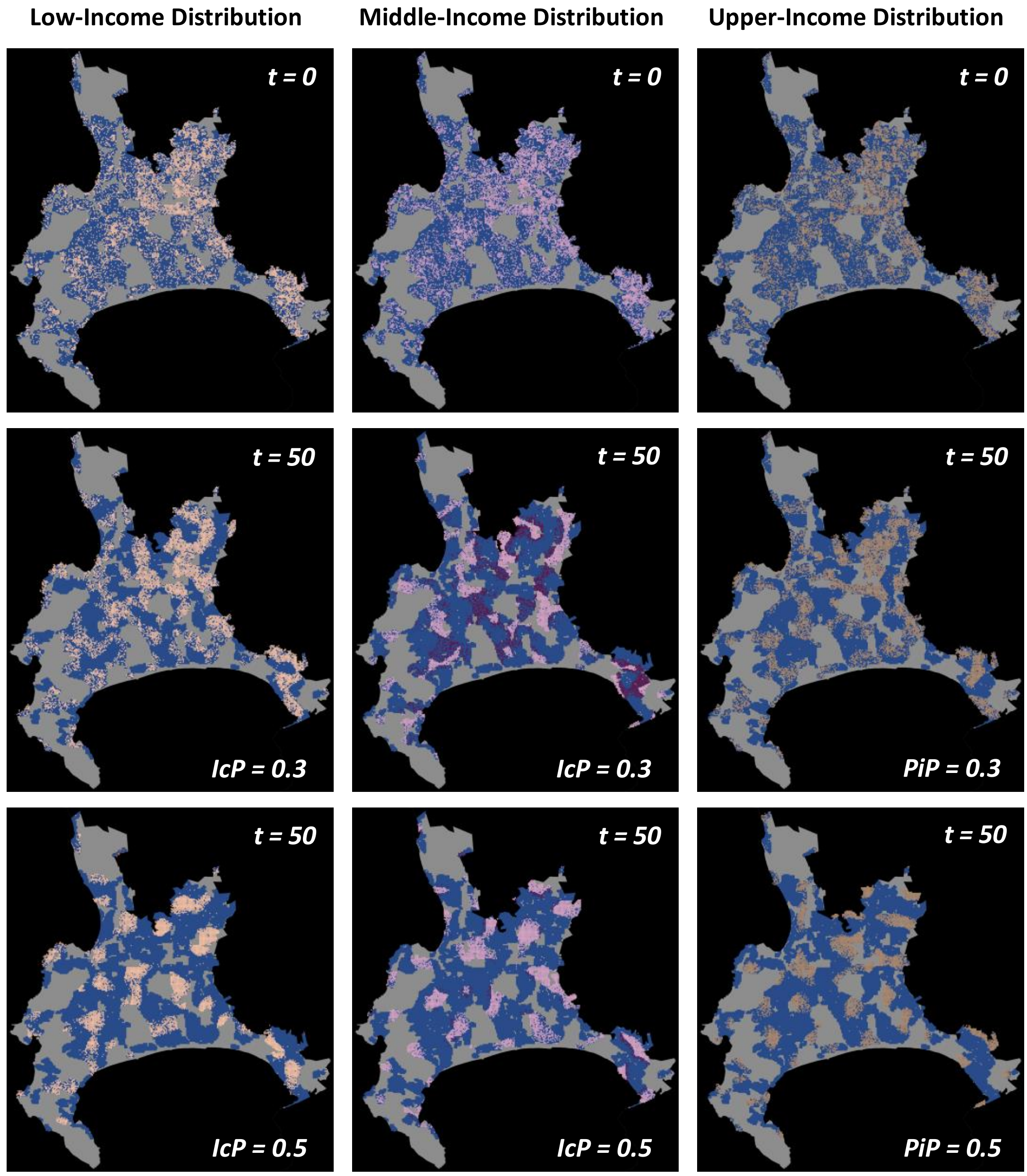


Figure 8.12: Income Constraint Module: Integrated Initial Conditions of Income Groups at Time-steps 0 and 50

Figure 8.13 shows the distribution of the three income groups at time step 0 and 50, with the initial conditions now set to complete segregation. At an IcP and PiP level of both 30% and

50%, very little change is detected for the low- and upper-income groups, as these two income groups are already quite segregated initially. In contrast, clustering is more evident in the middle-income group with an increase in constraint and preference levels.

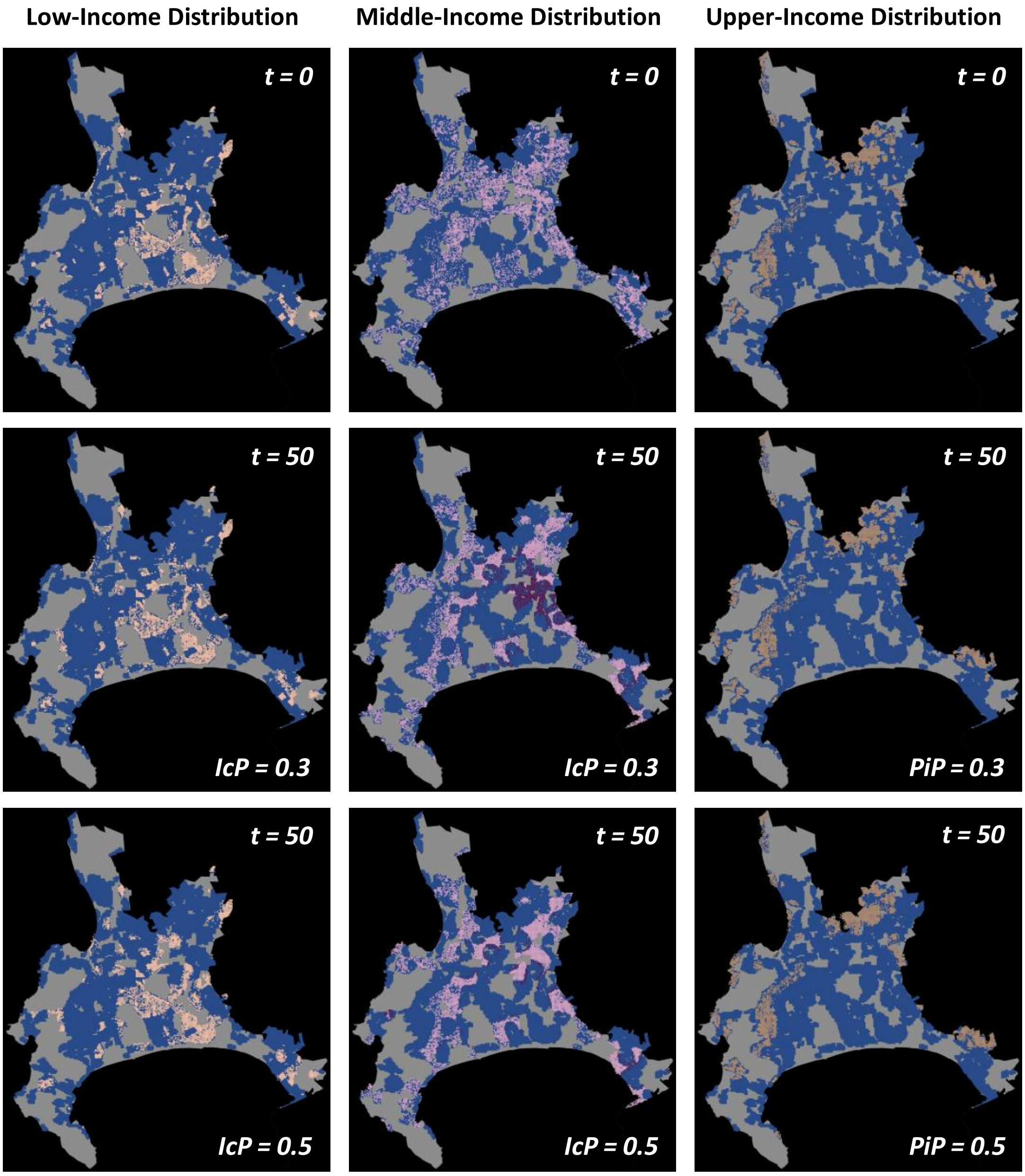


Figure 8.13: Income Constraint Module: Segregated Initial Conditions of Income Groups at Time-steps 0 and 50

This sensitivity analysis of initial conditions was completed with the same procedure undertaken for the Racial Income module, with the outputs presented in Appendices A and B.

8.5 Neighbourhood Radius

The neighbourhoods in each module are represented by using a buffer at a specified radius around each agent and consequently does not make use of the more traditional von Neumann or Moore (cellular) neighbourhoods (see Chapter 4). The size of the neighbourhood would effectively have an influence on the behaviour of the agents (Crooks, 2010), as it affects the racial or income group composition of that neighbourhood. To test this influence, a range of neighbourhood radius (NR) sizes ranging from 200m to 2000m were tested for each of the three modules at 10 simulation runs. For all modules a default preference/constraint level of 50% was set. Table 8.3 presents summary statistics for each of the three modules, showing the total number of agents desiring to relocate at each time step and the average of this number for each simulation run.

Table 8.3: Summary Statistics for Module Neighbourhood Size Sensitivity Testing

NR	Number of Steps										Average	SD
	1	2	3	4	5	6	7	8	9	10		
Racial Preference Module												
200m	7636	6731	5854	5213	4669	4179	3748	3364	3040	2730	**4716.4**	**1630.9**
400m	8192	7270	6519	5796	5158	4646	4171	3777	3398	3066	**5199.3**	**1716.8**
600m	8755	7710	6868	6194	5573	5080	4604	4171	3826	3478	**5625.9**	**1742.1**
800m	9110	8215	7384	6686	6143	5580	5122	4715	4319	3940	**6121.4**	**1716.1**
1000m	9563	8677	7885	7192	6530	5998	5537	5090	4683	4345	**6550.0**	**1751.4**
1200m	9860	8968	8194	7539	6939	6362	5869	5372	4923	4564	**6859.0**	**1768.8**
1400m	10094	9228	8439	7713	7080	6556	6060	5623	5235	4863	**7089.1**	**1754.4**
1600m	10500	9509	8703	8070	7453	6917	6410	5974	5582	5221	**7433.9**	**1747.9**
1800m	10986	10052	9231	8452	7752	7140	6603	6117	5701	5321	**7735.5**	**1912.2**
2000m	11493	10576	9680	8851	8178	7580	7023	6568	6149	5753	**8185.1**	**1935.9**
Income Constraint Module												
200m	23854	22207	20663	19240	17832	16557	15390	14235	13070	12148	**17519.6**	**3943.2**
400m	27155	25538	24136	22636	21289	19939	18527	17240	16018	14879	**20735.7**	**4137.1**
600m	28845	27449	26105	24872	23540	22342	20891	19761	18530	17329	**22966.4**	**3871.5**
800m	29714	28317	27245	26212	25033	23830	22734	21548	20419	19207	**24425.9**	**3486.5**
1000m	30300	29129	28091	27139	26198	25227	24162	22918	21904	20872	**25594.0**	**3142.7**
1200m	30765	29478	28426	27409	26544	25603	24813	23876	22843	21869	**26162.6**	**2902.4**
1400m	31132	29862	28896	27862	26991	26176	25350	24571	23699	22956	**26749.5**	**2698.3**
1600m	31497	30299	29372	28446	27571	26878	26196	25384	24716	23926	**27428.5**	**2477.7**
1800m	31775	30582	29577	28624	27694	26786	26062	25257	24541	23807	**27470.5**	**2653.8**
2000m	32047	30877	29924	29183	28384	27641	26909	26111	25263	24519	**28085.8**	**2456.9**
Racial Income Module												
200m	13559	12219	10951	9933	8929	8104	7299	6561	5947	5331	**8883.3**	**2751.2**
400m	15718	14103	12701	11468	10421	9464	8539	7744	7027	6405	**10359.0**	**3111.7**
600m	16870	15262	13744	12561	11487	10526	9694	8855	8162	7534	**11469.5**	**3113.0**
800m	17388	15871	14578	13470	12458	11481	10672	9896	9189	8505	**12350.8**	**2951.0**
1000m	18098	16519	15156	14000	12940	11981	11184	10487	9800	9253	**12941.8**	**2961.3**
1200m	18576	17056	15703	14540	13586	12670	11863	11151	10454	9840	**13543.9**	**2903.9**
1400m	18967	17423	16145	14907	13925	13018	12267	11539	10830	10240	**13926.1**	**2905.4**
1600m	19305	17744	16468	15340	14362	13478	12693	11883	11164	10584	**14302.1**	**2895.2**
1800m	19788	18102	16799	15689	14767	13929	13106	12454	11807	11214	**14765.5**	**2818.8**
2000m	20235	18825	17659	16635	15649	14734	13993	13270	12590	12000	**15559.0**	**2748.0**

It is evident for all three modules that the average number of agents desiring to move increases with an increase in neighbourhood size. The only difference is found in the standard deviation, with a slight increase in the Racial Preference module, a slight decrease in the Income Constraint module and very slight decrease in the Racial Income module. This indicates that neighbourhood size affects the behaviour of agents, as a larger neighbourhood size presents a larger composition of agents from which each agent needs to determine if its 0.5 PiP is satisfied. Thus, the larger the neighbourhood the more difficult it is to satisfy the agent's preference level.

8.6 Residential Mobility

As stated in Chapter 7, residential mobility in the context of this study refers to the geographic extent in which an agent that considers relocating would search for an alternative location. As with the neighbourhood radius, residential mobility is also represented as a specified radius buffer around each agent. Chapter 7 also presents the fact that the three modules were constructed in a manner which allows for each different agent type to have a unique residential mobility. To test the role residential mobility plays in the behaviour of agents, the three modules were again run for 10 simulation runs and 50 time steps each, with the residential mobility radius systematically changed.

In this exercise the neighbourhood radius was set at a default 1000m and all other parameters remained the same as in Section 8.4, apart from residential mobility. For each of the racial groups the residential mobility radius was systematically increased by 1000m and ranged from 1 000m to 10 000m, while the other two groups remained at a default of 1000m for all 10 simulations. Thus, the effect of residential mobility was tested for each group in the three modules and to understand how the levels of discontent agents per group is affected.

Figure 8.14 shows the testing of residential mobility on the total number of discontent agents for each of the different racial groups of the Racial Preference module. It is evident that the group considered for testing shows a more rapid decrease in discontent agents for each simulation run with an increase in the residential mobility radius, especially the Black African group (see Figure 8.14a).

In contrast, the groups with a default residential mobility show a stable decrease in discontent agents, which very similar profiles across all 10 simulation runs for each group. However, it is noticeable that the change in residential mobility for the White group (see Figure 8.14i) has little effect on the movement dynamics of the agents. Consequently, it is evident that residential mobility plays a role to a certain extent in the behaviour of agents and it is inferred that the larger the residential mobility radius is, the larger the area is in which an alternative location is searched for and the quicker discontent agents find a more suitable location to relocate to.

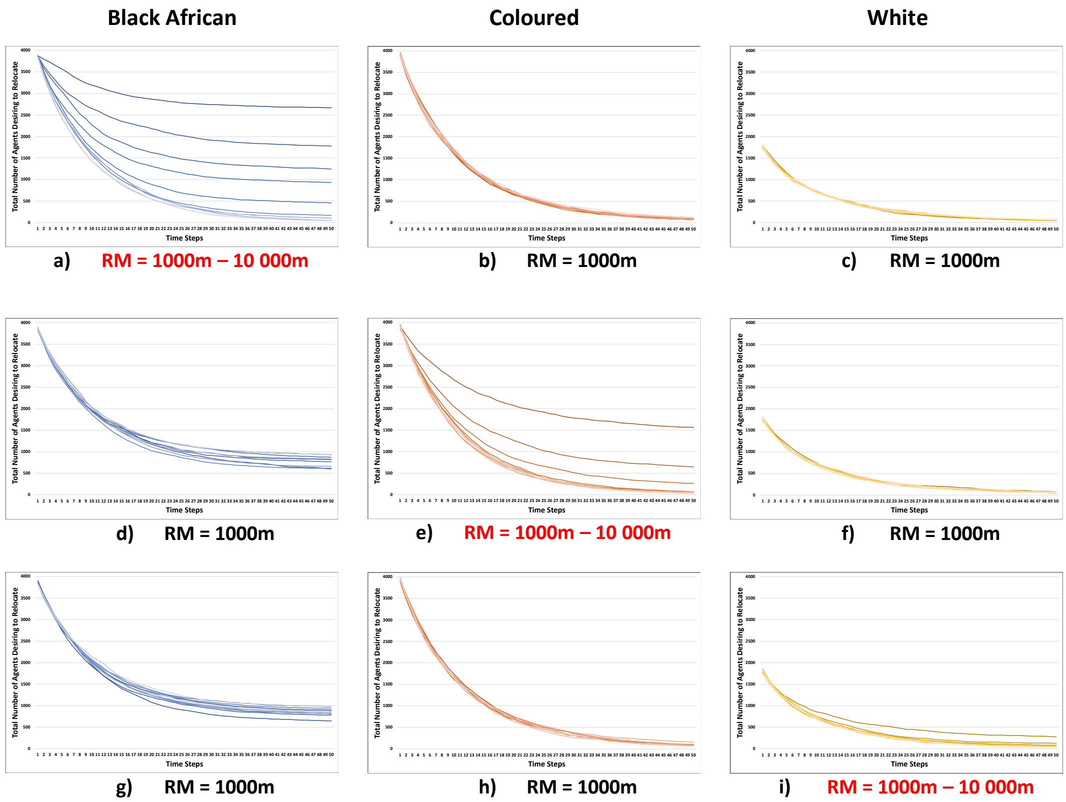


Figure 8.14: Residential Mobility Testing for Racial Preference Module

Figure 8.15 shows the testing of residential mobility for each of the different income groups of the Income Constraint module. Although it is evident that the low-income group's profiles decline gradually with an increase in residential mobility (see Figure 8.15a), the effect is more noticeable on the middle-income group (see Figure 8.15b) even though this group is at a default residential mobility setting across all 10 simulation runs. In contrast, the upper-income group (see Figure 8.15c) shows a stable decrease of discontent agents with the profiles across all 10 simulation runs being very similar.

However, with an increase in residential mobility for the middle-income group (see Figure 8.15e) a predominantly similar outcome is noted than found in Figure 8.15b when the residential mobility for the middle-income group was at a default setting. With the increase in residential mobility for the upper-income group (see Figure 8.15i) a gradual decrease is notable in the number of discontent agents as mobility increases. An interesting observation is that the low- and upper-income groups have no effect on each other, while changes in the low-income residential mobility (see Figure 8.15a) affect the behaviour of the middle-income group (see Figure 8.15b).

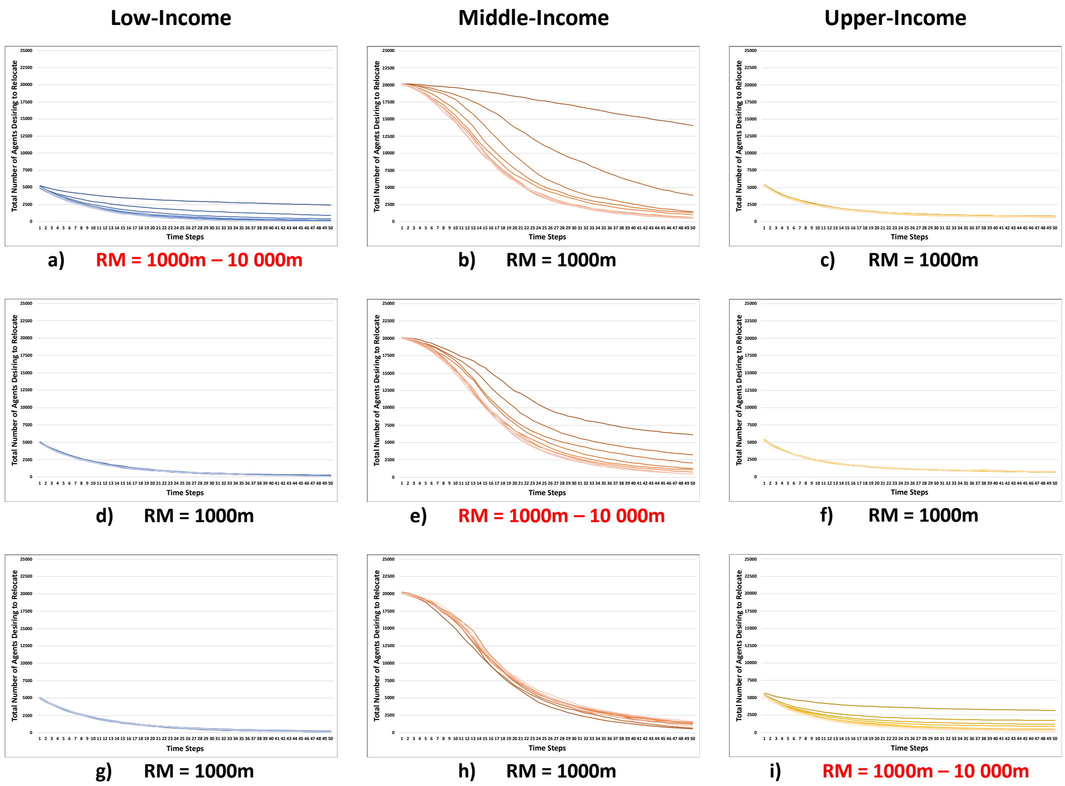


Figure 8.15: Residential Mobility Testing for Income Constraint Module

It is evident from the analysis above that no deterministic behaviour is present concerning the behaviour of parameters and the effect they have on agent behaviour. Appendix C, D and E respectively presents the residential mobility testing for the low-, middle- and upper-income groups for the Racial Income module.

8.7 Summary

This chapter presented the evaluation of the three simulation modules of the District94 model, ensuring that these implemented modules correspond to the conceptual model discussed in Chapter 7. Sensitivity analysis was applied to assess the impact the parameters of each module have on agent dynamics and also how sensitive the model is to the initial conditions of agents, in terms of geographic distribution.

A significant discovery made in this chapter was the fact that the outcome of simulation exercises is defined not only by the influence of specific parameters within the modules, but also by path dependence within each module. Hence, it was found that although parameter changes impacted general trends in simulation outcomes, the modules were very sensitive to initial conditions regarding the geographic (distributional) context of agent groups.

One of the most noticeable characteristics of the behaviour of different modules is the varied effects of specific parameters on the dynamics of specific modules. For example, the size of the neighbourhood mostly affects the income groups and residential mobility affect the dynamics of the racial groups most. A specific parameter might also have different effects on different agent types within the same module. Tests have shown that although the Black African group in the Racial Preference module might be substantially affected by a change in residential mobility, the White group shows very little effects from changes in its residential mobility. However, it is important to recognise that data on household decision-making and related behaviour is not available and consequently the processes of model verification and validation are more complicated.

The model evaluation and sensitivity analysis procedures in this chapter provides a better understanding of the behaviour of the three different modules that make up the District94 model, especially concerning the effect of various parameter settings on the outcome. Sensitivity analysis allowed for the enhancement of confidence in the model and an understanding of model behaviour as a result of parameter values.

The following chapter comprises of the empirical application of the District94 model to explore the dynamics of persistent racial and socio-economic segregation in the study area through the initiation of realistic parameter settings.

Chapter 9

Empirical Application of the District94 Model

Since the transition to a democracy in 1994, the aspiration of all three levels of government in South Africa (national, provincial and local) is for a racially and economically integrated and inclusive society. At the local government level, the City of Cape Town council established numerous policies, frameworks, and strategies to address racial and economic disparity and related spatial segregation that persists in the city and to promote integrated development. The most relevant of these policies and frameworks are the Five-Year Integrated Development Plan (IDP) (City of Cape Town, 2017b) and the Cape Town Municipal Spatial Development Framework (MSDF) (City of Cape Town, 2018), which translates the vision and objectives for socio-economic integration of the IDP into spatial development and integrated urban form. Figure 9.1 shows the 8 MSDF districts and the technical report and accompanying spatial development plan for the Southern District. Each district has a similar report and plan.

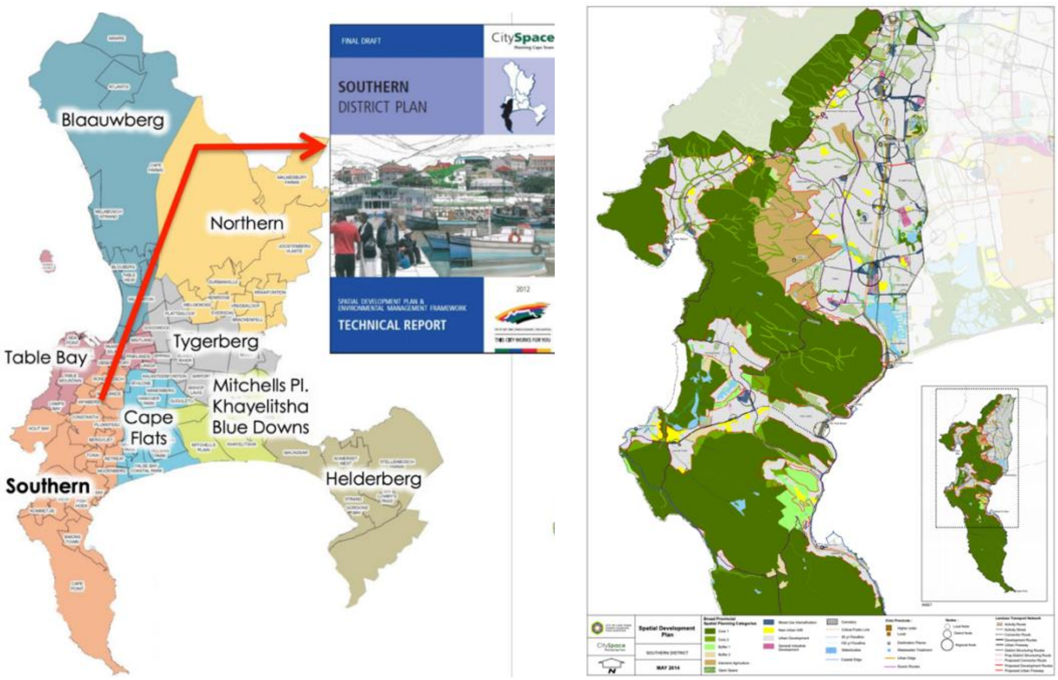


Figure 9.1: City of Cape Town Municipal Spatial Development Framework Districts, Technical Report and Spatial Development Plan (City of Cape Town, 2019)

This chapter presents simulation exercises undertaken to explore real-world scenarios, in terms of the dynamics of racial and socio-economic segregation in the city of Cape Town. It builds on the empirical context established in Chapter 2 on persistent racial and socio-economic segregation in the study area, the spatial segregation measurements undertaken in Chapter 6 and the conceptual formulation of the District94 model in Chapter 7. The objective of this chapter is to explore the role race and income play in the persistence of segregation in Cape Town. Subsequently, what-if scenarios that are based on the integrated development policies of Cape Town are explored. The hypothesis of this thesis, presented in Chapter 7, is that both race and income play a role in persistent segregation in Cape Town, even though racial segregation resulted in income disparity in the post-apartheid era. Throughout this chapter, this hypothesis will be tested with a series of simulation exercises and related questions. Each exercise will build on the previous one, exploring different aspects of the hypothesis.

The chapter consists of three simulation exercises. Each simulation exercise focusses on one of the three modules (Racial Preference, Income Constraint and Racial Income) discussed in Section 7.1. *Simulation exercise one* (Section 9.1) applies the Racial Preference module and explores the effects of the dynamics of preferential self-segregation in terms of race in Cape Town and thus the role that race and racial preference play in perpetuating segregation. *Simulation exercise two* (Section 9.2) applies the Income Constraint module and explores the dynamics of income constraint and preference in terms of residential choice and how these subjects promote the persistent nature of segregation in the Cape Town. *Simulation exercise three* (Section 9.3) applies the Racial Income module and explores the combined dynamics of racial preference and income constraint and the potential effects on segregation in Cape Town.

Each of these three simulation exercises consists of two experiments. A research question is presented for each experiment, whereby the hypothesis is tested. Experiment 1 of each simulation exercise explores the role race and income play in persistent segregation in the study area and thus explores a baseline scenario for the study area, in terms of racial and socio-economic segregation. Hence, the assumptions presented in this first experiment of each simulation exercise are respectively based on the findings of the segregation measurements undertaken for race, income and income-by-race in Chapter 6. For example, a high level of isolation of the White or upper-income group will form the basis of an assumption of a high preference parameter value for these groups in the relevant experiments.

Experiment 2 explores what-if scenarios, in terms of the dynamics of racial and socio-economic segregation in the study area, when model parameters are adapted to the objectives of the Cape Town MSDF. The outcome is then compared to the findings of the segregation measurements in Chapter 6 to understand whether segregation patterns have changed. For example, the (MSDF) promotion of integrated and mixed-income housing will result in the reduction of the residential mobility constraint of low- and/or middle-income households and thus a potential expansion of the residential mobility of these groups. So, if the relevant model parameters are adapted, how would the outcome compare with the findings of the segregation measurements? Finally, a comparative analysis and related discussion of the two experiments are undertaken for each of the three simulation exercises.

Agents represent households in Cape Town in all three modules and have differing locational preferences or constraints (dependent on the composition of their neighbourhoods) and differing residential mobility restrictions (the radius in which an agent searches for an alternative location to move to). However, default settings are applied to the following two parameters for all simulation exercises: the '*probability of moving'* is set to 5% and reflect the total number of households in the study area that considers relocating at the start of a simulation; *'neighbourhood radius'* is set to 1km and represents the radius at which each household (considering relocating) assesses the composition of its neighbourhood at the particular time.

9.1 Simulation Exercise I: Racial Preference

As outlined in Chapter 7, the Racial Preference module was constructed on the foundation of the level of preference different racial groups have for a specific racial composition of the neighbourhood they prefer to reside in. Thus, the percentage of neighbouring households they prefer to be of the same race as themselves. This module is based on the findings of the racial segregation measurements undertaken in Chapter 6 (Section 6.1). Furthermore, the racial residential dynamics in Cape Town, discussed in Chapter 2, and the preferences for ethnic neighbourhood composition that guides residential choice behaviour of different ethnic communities (Ibraimovic et al., 2017) was considered.

9.1.1 Experiment 1: Baseline Racial Preference Simulation

Research Question: Given the level of homophilic preference of each racial group, derived from the segregation measurements, will residential segregation persist and potentially increase in the study area?

As mentioned before, the first experiment undertaken for Racial Preference module explores the role of race in persistent segregation in Cape Town and presents the parameter settings for the simulation at a baseline scenario. For this simulation experiment it was assumed that the findings of the racial isolation and exposure measurements resulted from the level of preference of the different racial groups for similar neighbours. Hence, the *preferred racial proportion* (PrP) level for similar type neighbours of the three racial groups in the study were set accordingly: 80% for White households (found to be most isolated), 60% for Black African households (reflecting the second highest level of isolation) and 50% for the Coloured population (least isolated among the three groups, but only slightly lower than the Black African population).

Although the decision to apply these preference levels was predominantly based on the findings of the segregation measurements in Chapter 6, literature also suggests the phenomenon of varying residential choice by race. Emerson et al. (2001) explored the neighbourhood preferences of Whites in the United States and found that although White people are not concerned about neighbourhoods with an Asian and Hispanic composition, predominantly African American neighbourhoods are a great concern to them due to the perception of high crime rates and a low quality of education. The authors found the preferences of Whites to be a powerful factor in the shaping of racial residential segregation. The neighbourhood preferences of African Americans in the United States were examined by Krysan and Farley (2002) and it was found that these individuals prefer a more equally mixed neighbourhood of Black and White inhabitants, with the predominant reason being the fear of White hostility.

In the context of Cape Town, Ibraimovic et al. (2017) explored whether the preferences of racially different households for racial neighbourhood composition suggest a voluntary desire for residential mixing. It was found that racial neighbourhood composition played a significant role in influencing residential choice behaviour, with each racial group reflecting a strong preference for racially similar neighbours and varying sensitivities to the presence of other racial groups. It was discovered that these racial preferences followed a certain order of desired racial groups. White respondents were mostly indifferent between the proportion of Coloured and Black neighbours, while the Coloured respondents preferred White to Black African neighbours and Black African respondents reflected a slight preference for Coloured neighbours.

The residential mobility radius was set as follows: 2km for Black-African households, 10km for Coloured households and 20km for White households. These differing levels were formulated around the theoretical discussion provided in Chapter 2 on residential dynamics of racial groups and also the Comprehensive Integrated Transport Plan for Cape Town (City of Cape Town and Transport for Cape Town, 2013), outlining residential mobility. Therefore, the low degree of residential mobility of the Black African community reflects a predominant reliance on public transport, limiting the distance at which residential relocation could be undertaken and consequently affecting the residential choice of this community. In addition, the occurrence of public housing developments in these predominantly Black African suburbs results in residential relocation being mostly limited to the same neighbourhoods. The higher level of residential mobility for the Coloured population is derived from the fact that a higher degree of private vehicle transport is found in the predominantly Coloured suburbs. The fact that only a small portion of the White population in Cape Town rely on public transport, resulted in a maximum level of residential mobility for this group.

Figure 9.2 shows the graph for each of the three racial groups, in terms of discontentment with their current location and consequent desire to move to an alternative location. The White population reflects the highest number of discontent households at the initiation stage of the model simulation and can be ascribed to the high PrP level (preferring at least 80% of neighbours also to be White). However, a rapid decline in discontent White households is noticeable between time step 0 and 50 and may be due to the high level of segregation already occurring in White suburbs. In contrast, the Black African and Coloured households have a lower level of discontentment at time step 0, reflecting the lower PrP levels of these two groups, with a more gradual decrease over time. This gradual decrease may be attributed to a higher level of exposure of these groups to other racial groups and consequently slower progress in finding the preferred alternative location to move to.

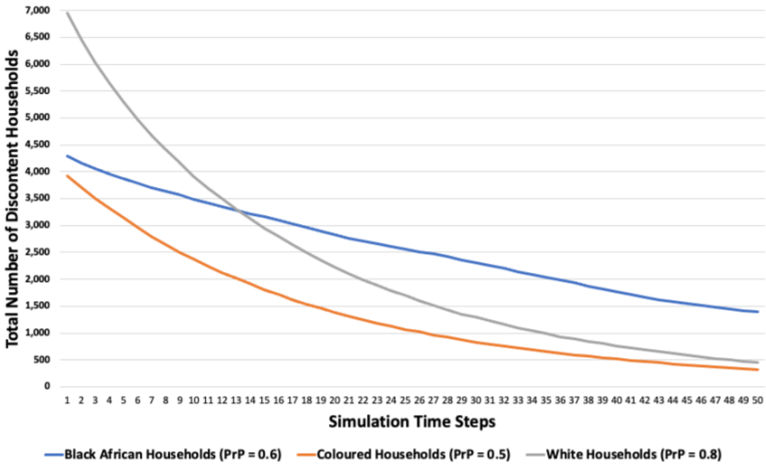


Figure 9.2: Number of Households of Each Racial Group Desiring to Relocate (Average of 10 Simulation Runs)

Figure 9.3 provides a comparison of the distribution of Black African households at the initial setup stage (see Figure 9.3a) of the model and at the last time step (see Figure 9.3b) of the simulation run. The green areas represent a lower number of households for each racial group, while the yellow, orange and red areas indicate locations of higher household concentration. The households that were initially more widely dispersed, especially to the north-west and south-west of the study area, were found to be more clustered at time step 50.

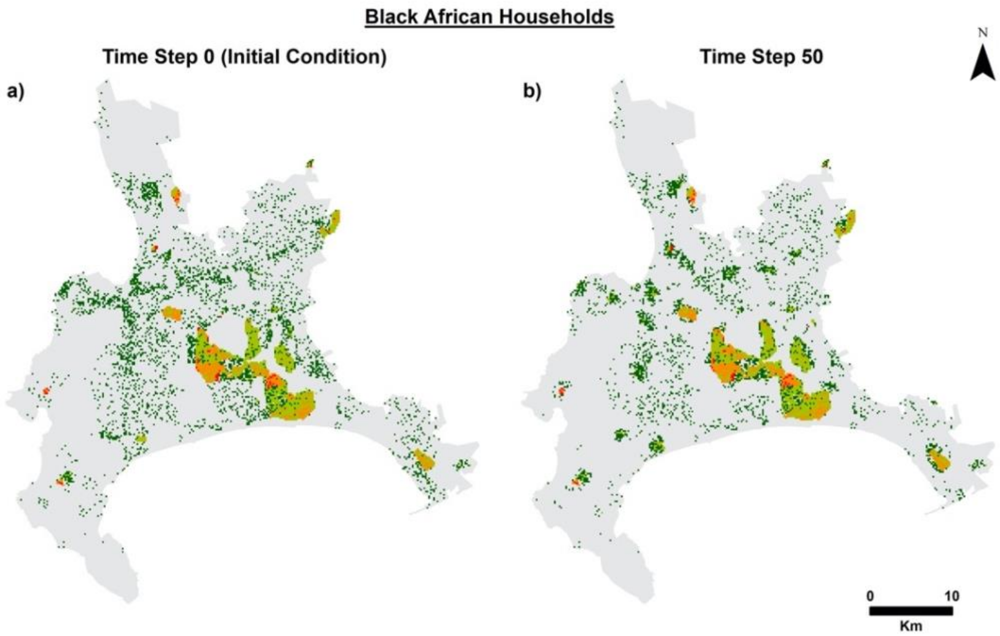


Figure 9.3: Maps Showing the Distribution of Black African Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Small pockets of more significant clustering are evident (see Figure 9.3b), especially in Delft and Silversands to the east and Capricorn to the south-west of the study area, which are all predominantly Coloured settlements and the predominantly Black African settlement of Nomzamo to the south-east. Consequently, these suburbs show a noticeable decrease in Coloured households. Areas of high concentration Black African households (at the initial setup stage of the simulation) remain mostly unchanged.

Figure 9.4 presents the spatial distribution of Coloured households at time steps 0 and 50 of the simulation. It is evident that clustering intensified where initial clusters of Coloured households were situated at time step 0. This occurrence resulted in more dispersed patterns of households decreasing to time step 50. Again, little change occurred to the main clusters that were present at the setup stage of the model. Clustering of Coloured households also occurred predominantly to the centre of the study area, the Coloured neighbourhoods of Scottsdene, Northpine and Eikendal to the north-east and the Coloured suburbs of Rusthof and Gustrow to the south-east. The Coloured households that are more dispersed in predominantly White neighbourhoods to the north and west of the study area decreased noticeably.

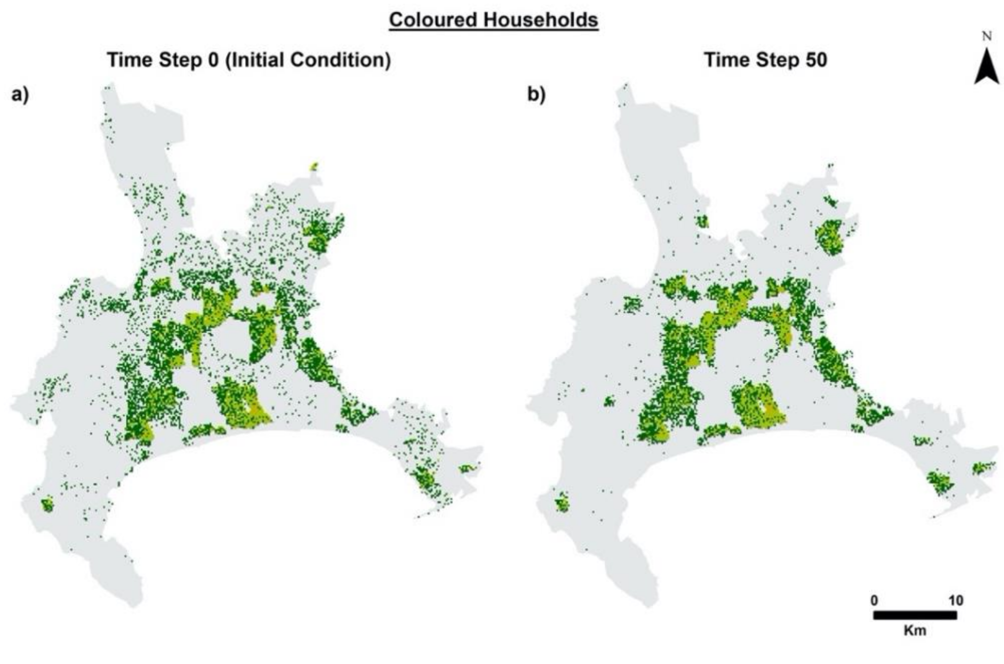


Figure 9.4: Maps Showing the Distribution of Coloured Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

The spatial distribution of White households is shown in Figure 9.5. It is evident that the regions of higher density to the north, west and south-east of the study area reflect increased clustering at time step 50, especially the predominantly White neighbourhoods of Protea Hoogte to the north-east and Newlands, Bishops Court and Bel Ombre to the west. In contrast, the widely dispersed households to the centre and south of the study area in Fig. 8.5a are mostly concentrated in the areas of high density (see Figure 9.5b).

A noticeable change occurred to the north-west of the study area where a high concentration of White households decreased in the suburbs of Green Point, Sea Point and Fresnaye between time steps 0 and 50 of the simulation. The White households also reflect more distinct patterns of population decrease along the fringes of the centre of the study area where the White and Coloured suburbs meet, especially in the region of Newlands, Bishops Court and Bel Ombre to the west [2] in the west.

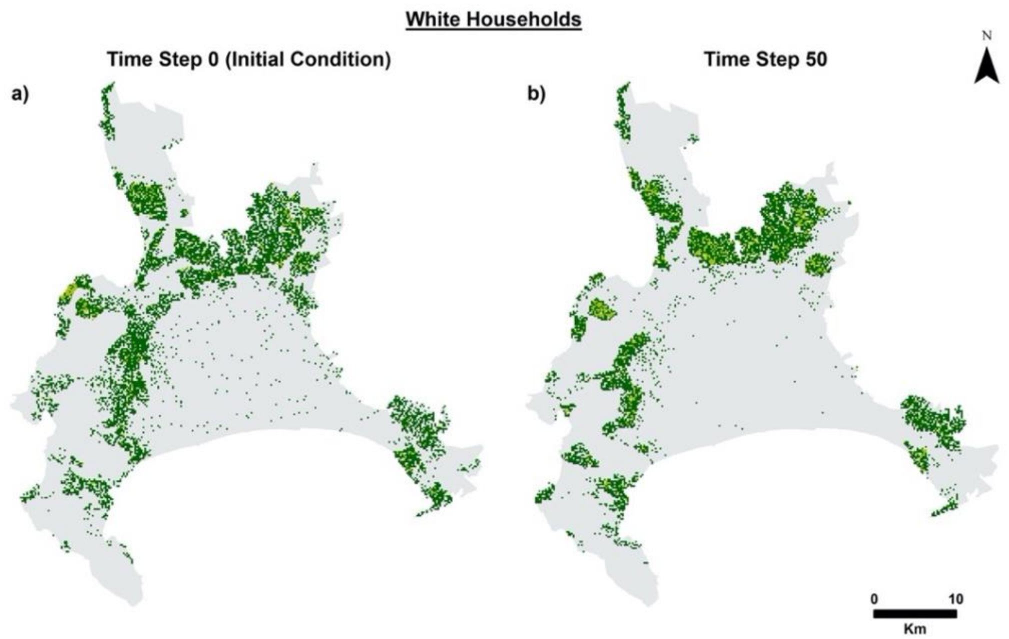


Figure 9.5: Maps Showing the Distribution of White Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Finally, the levels of isolation of each racial group, as per the discussed assumption, were studied to determine the impact the specific parameter settings Experiment 1 had on the different racial groups. Figure 9.6 shows that all three racial groups had a gradual and similar increase in isolation levels from the initiation of the simulation to the final time step, reflecting a general increase in segregation levels among racial groups. The relatively high level of isolation of all groups may be ascribed to the initial condition of the model reflecting quite a segregated setting.

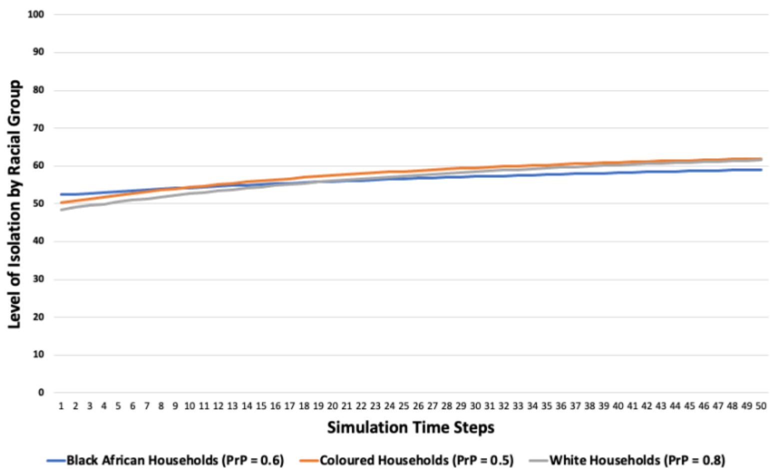


Figure 9.6: Levels of Global Isolation for Each Racial Group (Average of 10 Simulation Runs)

Considering the research question posed for this experiment, it is found that segregation persisted indeed in an already highly segregated study area. Segregation also increased, especially in the predominantly White suburbs.

Following on from Experiment 1, which presented an assumed baseline scenario of segregation dynamics in terms of racial preference, Experiment 2 explores racial segregation levels when real racial integration policies are applied to the study area.

9.1.2 Experiment 2: Testing Policy for Racial Residential Integration

Research Question: Will a reduced level of racial homophily for all groups result in the increase of racial integration in the study area?

The second experiment undertaken with the Racial Preference module tests the objectives of the MSDF District Plans for Cape Town, concerning the promotion of a racially inclusive and integrated urban environment. It is important at this stage to distinguish between preference (homophily, guiding voluntary residential choices) and discrimination (involuntary constraint on residential choices) when considering integrated housing policy (Clark and Fossett, 2008), even though it can be argued that these two subjects may be interrelated.

Although no housing policy can address the preferences of individual households for a different neighbourhood racial composition per se, the City of Cape Town council plays a direct role in promoting urban desegregation and eradicating constraint on residential choice. This is particularly evident in the suburb of Delft South, where racial integration was promoted through the development of a new desegregated residential area for both Black African and Coloured households (Oldfield, 2004). Although the White population remains less open to change, Black African and Coloured households became more integrated (Christopher, 2001b).

Subsequently, the racial preference level (PrP) for each racial group is adjusted for this simulation experiment. With the council focussing on residential desegregation especially in Coloured and Black African neighbourhoods, the previous PrP levels of 50% and 60% of these two groups (respectively) are reduced to 30% for both. With the upliftment of marginalised communities in the more affluent suburbs through urban regeneration (MSDF Northern District Plan), the PrP level of the White population group is decreased from 80% to 60%. In addition, the residential mobility of the Black African households is increased from 2 kilometres to 5 kilometres. Apart from these changes, all other parameters remained the same as the settings for the first experiment.

Figure 9.7 presents the profiles for the number of households of each racial group which desire to relocate in accordance with their preference level. It is immediately evident that the decrease in PrP levels for all three groups resulted in a significantly lower number of discontent households at the initiation of the simulation (time step 0), compared to the findings of the first experiment (see Figure 9.2). Apart from the Coloured population group having fewer discontent households than the other two groups throughout the simulation, similar trends and gradual decrease in discontent households are noticeable for all three groups. The number of discontent households at time step 50 is also significantly lower for the Black African group.

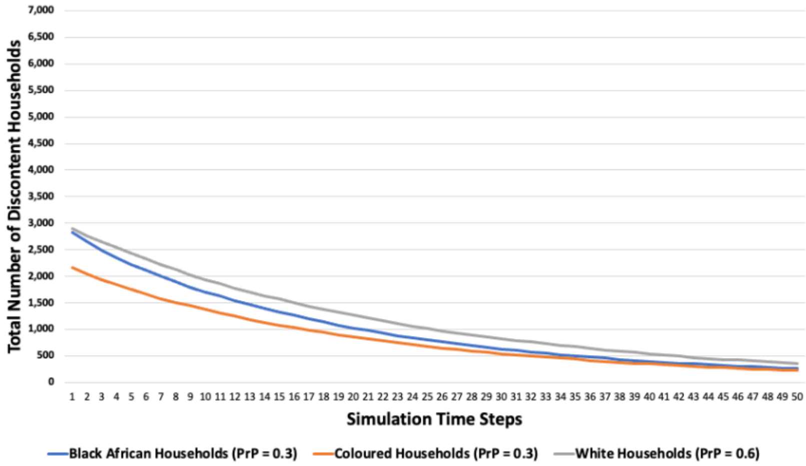


Figure 9.7: Number of Households of Each Racial Group Desiring to Relocate (Average of 10 Simulation Runs)

Figure 9.8 shows the spatial distribution of Black African households at the setup stage and last time step of the second simulation experiment. Compared to the distribution of households at time step 50 in the previous experiment (see Figure 9.3b), the predominant clusters of Black African households to the north, centre and south-east of the study area reflect only slight change.

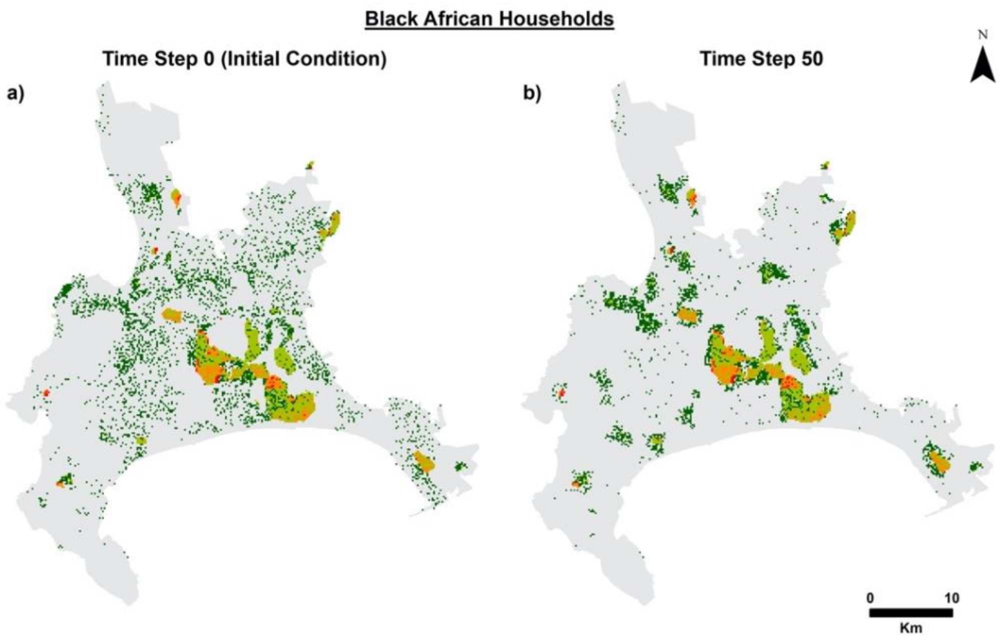


Figure 9.8: Maps Showing the Distribution of Black African Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

However, new clusters emerged to the north-west in the suburbs of Woodstock, Observatory and Zonnebloem (highlighted in Chapter 2 as racially diverse neighbourhoods) and to the north-east in the predominantly White suburbs of Chrismar, Thalmen and Oakdale and Black African suburbs of Eversdal Extension 21. It is thus noticeable that the more dispersed households to the north and west (at time step 0) formed more significant clusters at time step 50 than in the first experiment, regardless of the fact that the PrP level was reduced from 60% to 30%.

Figure 9.9 shows the spatial distribution of the Coloured households in the second experiment, which is similar to the pattern obtained from experiment one (see Figure 9.4b), with the initially dispersed households (time step 0) clustering again to the north and west of the study area, regardless of the decrease in PrP level from 50% to 30%. However, an increase in clustering is noticeable in the racially diverse suburbs of Maitland and Brooklyn. The large cluster of Coloured households to the west of the study area also expanded into the predominantly White suburb of Wynberg.

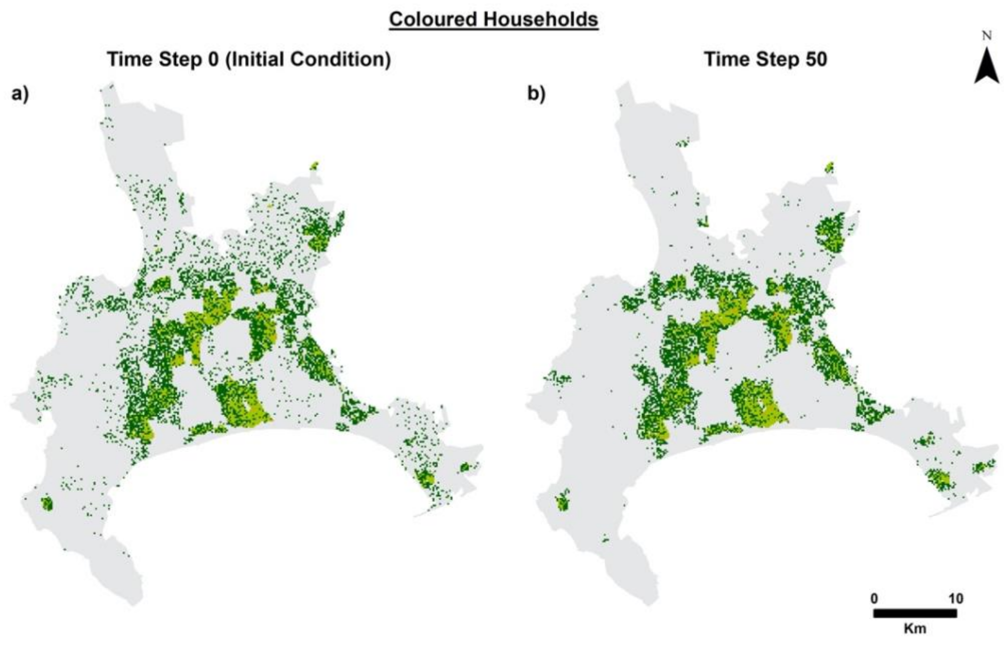


Figure 9.9: Maps Showing the Distribution of Coloured Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

However, an increase in clustering is noticeable in the racially diverse suburbs of Maitland and Brooklyn. The large cluster of Coloured households to the west of the study area also expanded into the predominantly White suburb of Wynberg.

Figure 9.10 shows the distribution of White households in experiment 2. Although the distribution at time step 50 (see Figure 9.10b) remained predominantly similar to the outcome of experiment 1 (see Figure 9.10b), potentially due to the PrP level still being high at 60%, differences are evident to the north-west and west of the study area. However, unlike the outcome of the first experiment the clusters of White households in the predominantly White suburbs of Sea Point and Fresnaye and Pinelands remained in place and did not disperse. In contrast, the predominantly White suburbs to the west and south-west reflected a lower degree of clustering than in the first experiment.

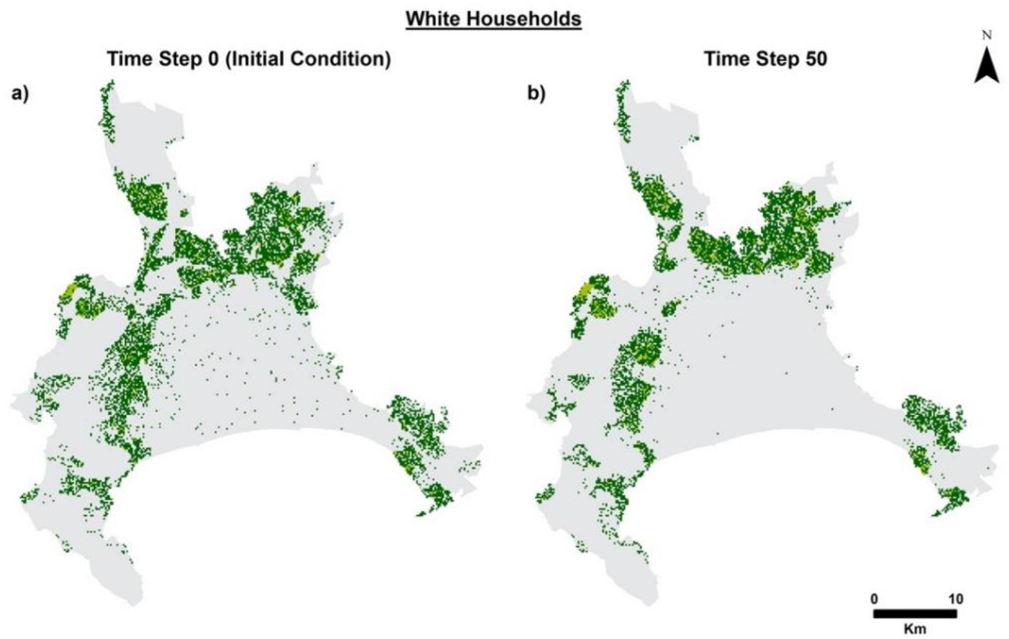


Figure 9.10: Maps Showing the Distribution of White Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.11 shows the degree of isolation of each agent type during the second simulation experiment. Although the profiles for all three groups reflect a gradual increase similar to the first simulation experiment, it is evident that all groups are slightly more isolated at the end of the simulation run. This is especially evident of the White households, reflecting a higher degree of isolation than the other groups.

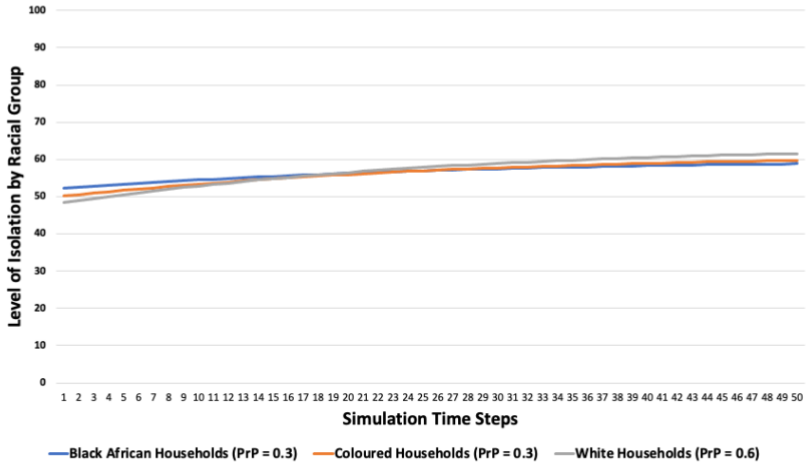


Figure 9.11: Levels of Global Isolation for Each Racial Group (Average of 10 Simulation Runs)

To undertake a comparison of the findings of the two experiments, cell statistics were applied to highlight the changes in spatial distribution between time steps 0 and 50 for each of the racial groups in each experiment. Figure 9.12 shows the areas where a decrease in Black African households occurred (in blue) and the areas where an increase of households occurred (amber & red) at time step 50 for both experiments. It is noticeable that the higher Black African PrP level of 60% in the first experiment (see Figure 9.12a) resulted in more prominent clustering of Black African households, especially to the north and west of the study area where predominantly White neighbourhoods are located.

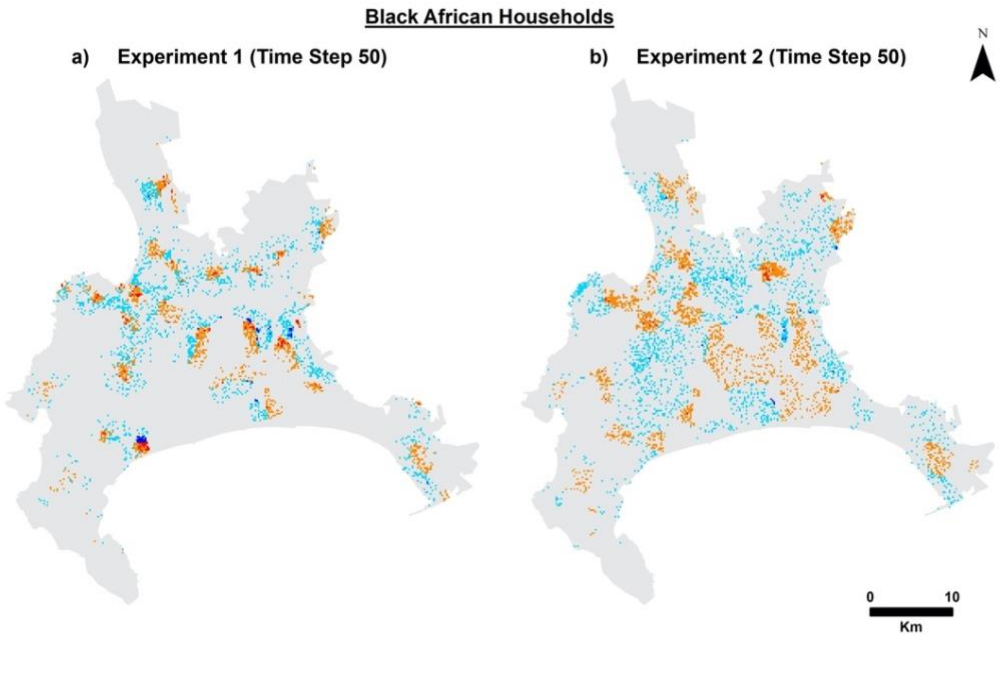


Figure 9.12: Maps Showing the Spatial Distribution Change of Black African Households at Time Step 50 for Experiment 1 & 2. Both maps were generated by using 4 similar breaks (Manual classification)

Clustering is also noticeable to the south of the study area where the predominantly Black African neighbourhoods are situated and especially to the east of the study area, where an increase in Coloured households occurred (see Figure 9.13a). Although the second experiment, with a Black African PrP level of 30%, also reflect a level of clustering (see Figure 9.12b), a more even distribution of households in general is evident. This is especially apparent in the northwest of the study area where the more racially diverse neighbourhoods of Woodstock and Observatory are located.

The changes in distribution of Coloured households between experiments 1 and 2 are quite distinct in Figure 9.13. The higher PrP value of 50% in the first experiment resulted in a more concentrated band of households around the centre of the study area (see Figure 9.13a), with a contrasting decrease along the outer edges where White neighbourhoods are situated and the inner region where Black African neighbourhoods are found. The final time step of the second experiment (see Figure 9.13b) reflects distinctively less clustering of Coloured households and even though a noticable decrease occurs in the centre of the study area, more integrated patterns with the White neighbourhoods to the west of the study area is detected.

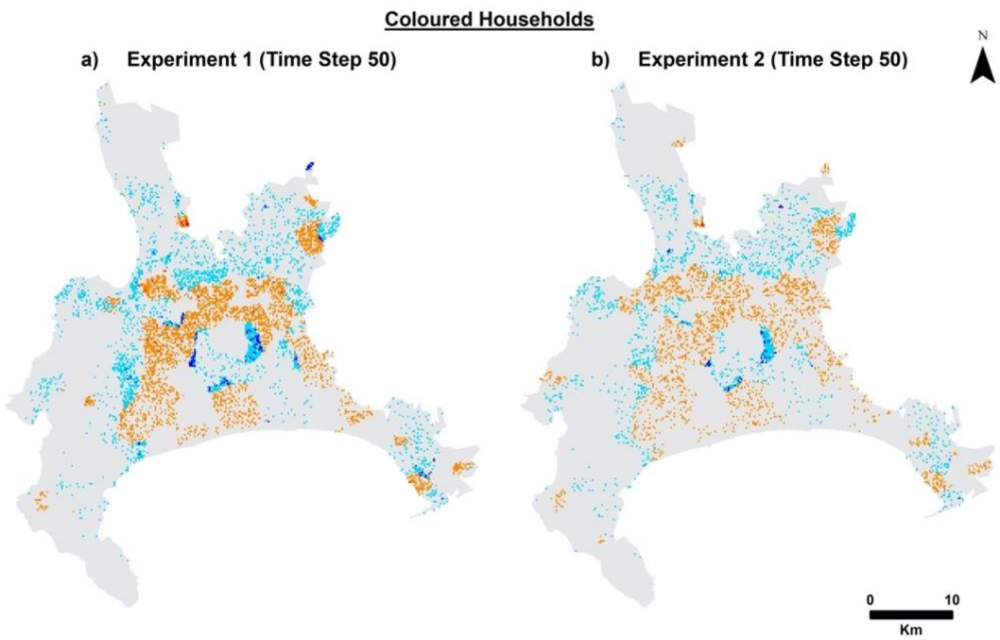


Figure 9.13: Maps Showing the Spatial Distribution Change of Coloured Households at Time Step 50 for Experiment 1 & 2. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.14 shows the difference in White household distribution between the final time steps of the first and second experiment. Even though the high PrP value of 80% resulted in extensive clustering to the north and west of the study area (see Figure 9.14a), a lower PrP value of 60% reflected a similar pattern in White household movement (see Figure 9.14b), especially where White households decrease significantly around the study area's central region. The movement of Coloured households into the White neighbourhoods to the west, identified in Figure 9.14b, resulted in the decrease of White households in this particular region.

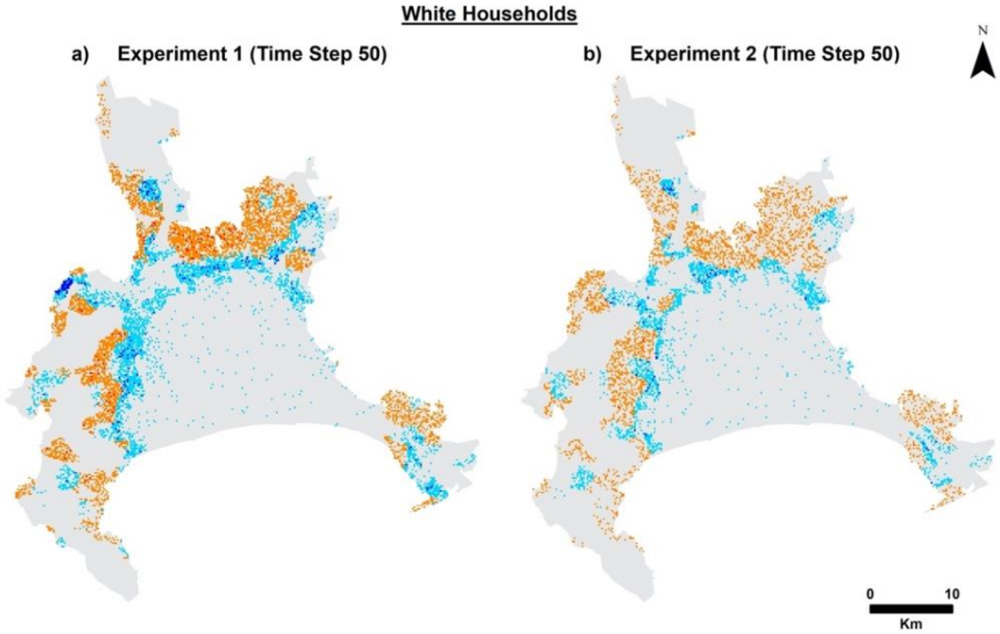


Figure 9.14: Maps Showing the Spatial Distribution Change of White Households at Time Step 50 for Experiment 1 & 2. Both maps were generated by using 4 similar breaks (Manual classification)

Further exploration of the racial segregation patterns of the two experiments are undertaken through the application of segregation measurements. Although it was found that the global dissimilarity value decreased only slightly from 0.83 in the first experiment to 0.80 in the second experiment, these values increased more significantly from the initial condition (0.70) at time step 0. This occurrence is a clear indication of the significance of racial preference in perpetuating segregation at a global (city-wide) scale.

Figure 9.15 shows the global isolation and exposure index values at time steps 0 and 50 for both experiments. It is important to note that the colour saturation scale is not an indication of the intensity of values, but rather an equivalence between positive and negative values.

A general comparison between time step 0 (see Figure 9.15A) and the output from the two experiments (see Figure 9.15B & C) shows that an increase in isolation occurred for all racial groups, especially for the Coloured and White groups. Comparing the output of the two experiments, it is evident in the second experiment (see Figure 9.15C) that although there is a decrease in isolation levels of the Coloured (2.34) and White households (3.67), the level of Black African isolation remained at 1.99.

Examination of the exposure levels between the three racial groups reveal interesting patterns. Although exposure between the Black African and the Coloured groups and between the Coloured and the White groups decreased between time step 0 and time step 50 of the first experiment as a result of the high PrP levels, exposure between these groups decrease again in the second experiment, with a decrease in PrP levels.

In contrast, exposure between the Black African and White groups not only decrease significantly in the first experiment, but also continue to decrease in the second experiment, regardless of a decrease in PrP levels. This is especially evident in the exposure of Black African to White households, decreasing from -2.87 at time step 0 to -4.83 at time step 50 of experiment 1 (see Figure 9.15B) and then to -5.40 in experiment 2 (see Figure 9.15C). This occurrence highlights the homophilic preferences of the Black African and White groups as most important in perpetuation racial residential segregation. A significant decrease in exposure between the Coloured and White groups is evident, even though exposure increases again between the two experiments.

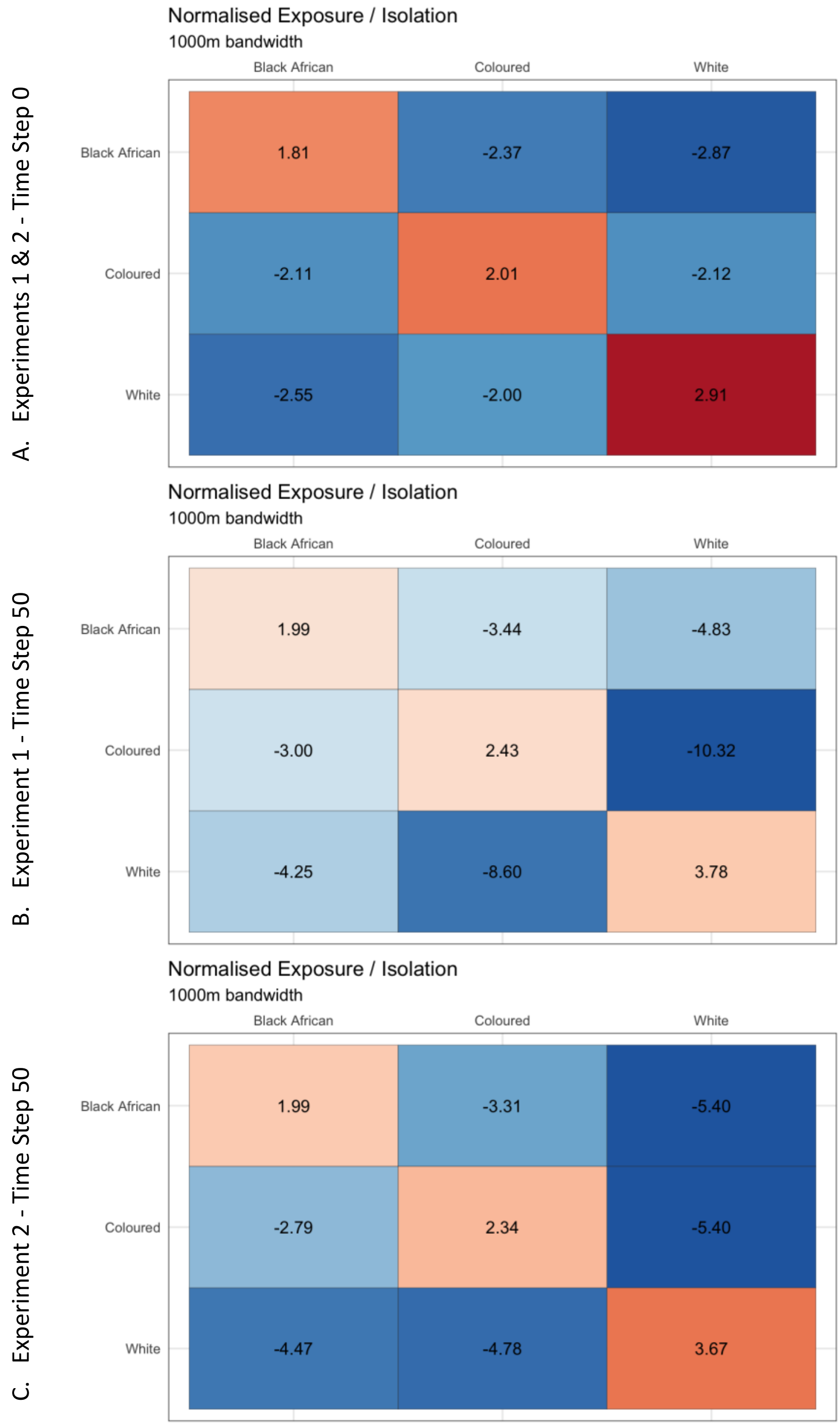


Figure 9.15: Table of Normalised Global Spatial Isolation & Exposure Indices for Experiments 1 & 2 at Time Steps 0 & 50 and Measurements of 1000m Bandwidth

These global isolation values are accompanied by maps, showing the distribution of local spatial isolation levels of the racial groups. Figure 9.16 presents the local spatial isolation patterns for the Black African households at time step 0 and the final time steps of both experiments. The region to the south of the study area where the largest portion of Black

African households reside, remained mostly unchanged between the first and last time step in each experiment and reflect a high level of isolation. However, the decrease in isolation that is noticeable to the west of the study area in the first experiment (see Figure 9.16b) expands even further to racially diverse suburbs in the north-west of the study area in the second experiment (See Figure 9.16c).

Figure 9.16: Maps Showing the Local Spatial Isolation of Black African Households at Time Steps 0 & 50 for Experiment 1 & 2. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.17 shows the local spatial isolation patterns for the Coloured households at time steps 0 and 50 for both experiments. It is noticeable that no significant change occurred in the distribution of most isolated Coloured localities between the two experiments. Although a lower PrP value for all racial groups resulted in the extension of Coloured neighbourhoods into White areas to the west of the study area (see Figure 9.17c), a higher level of isolation suggests that the White households retreated from these neighbourhoods with the increase of Coloured households.

Figure 9.17: Maps Showing the Local Spatial Isolation of Coloure Households at Time Steps 0 & 50 for Experiment 1 & 2. Both maps were generated by using 4 similar breaks (Manual classification)

The local spatial isolation measurements for the White households in Figure 9.18 reveal no significant changes in distribution between time steps 0 and 50 for both experiments. However, it is noticeable that the increased clustering of more isolated localities at time step 50 of the first experiment (see Figure 9.18b) remains quite similar at the end of the second experiment (see Figure 9.18c), especially to the north of the study area. However, clustering of more isolated White households increased to the west of the study area in the second experiment (see Figure 9.18c).

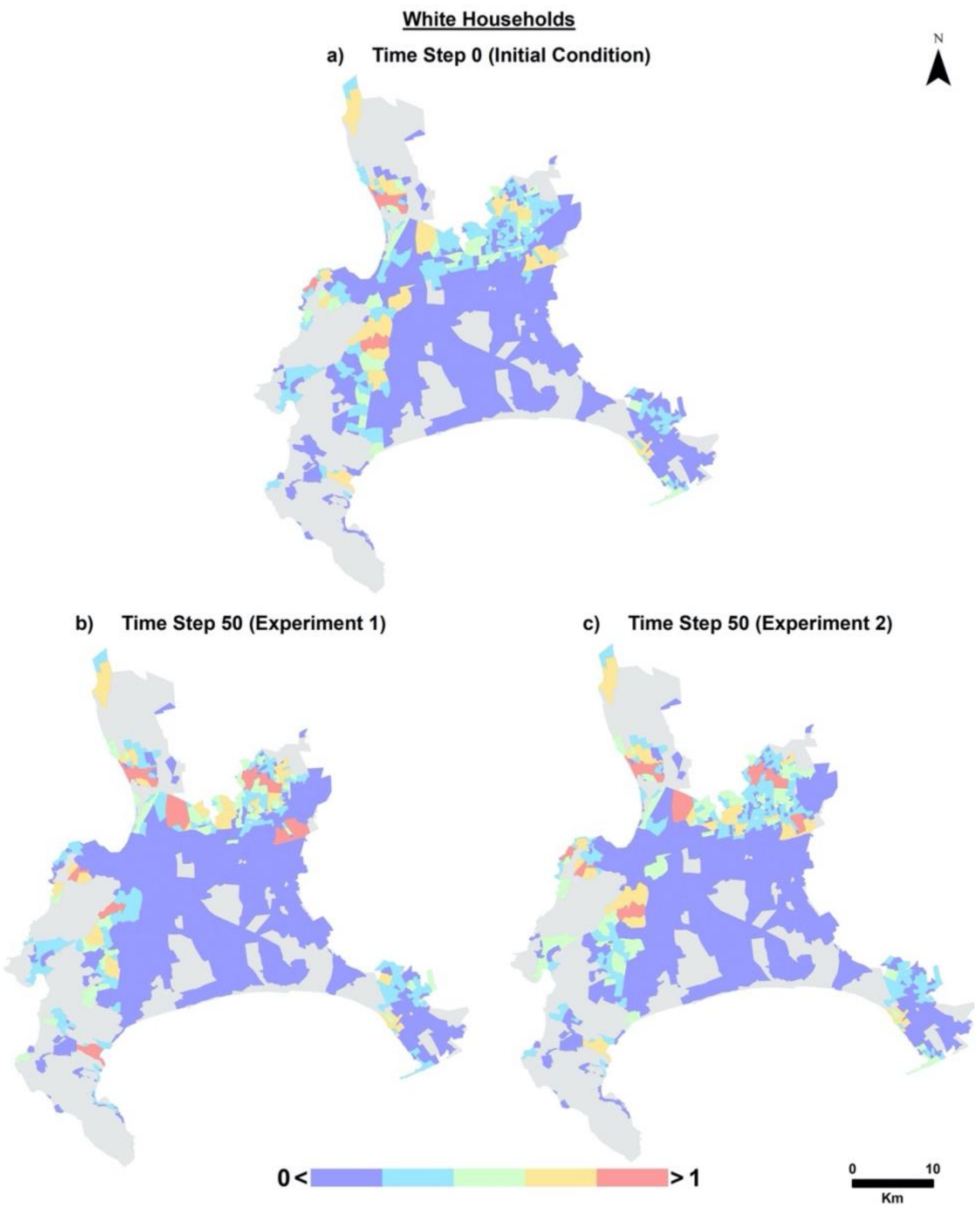


Figure 9.18: Maps Showing the Local Spatial Isolation of White Households at Time Steps 0 & 50 for Experiment 1 & 2. Both maps were generated by using 4 similar breaks (Manual classification)

In response to the research question for this second experiment, segregation did decrease slightly between the Black African and Coloured groups and more significantly between the White and Coloured groups. However, it was found that segregation increased between the Black African and White groups. This may be a result of evident self-segregation by the White group, increasing the existing and significant spatial divide between these two groups.

Appendix F shows the changes in diversity (entropy) levels between the start of the simulation (time step 0) and time step 50 of both experiments 1 and 2. A score close to zero (green) indicates a low level of diversity and a score close to 1 (red) reflects a high level of diversity.

9.1.3 Discussion

The profiles of the number of discontent households for each racial group for both experiments not only reflect the effect of their preference (PrP) levels for similar neighbours on their contentment, but also provide an indication of the level of segregation of these groups.

This is evident in the high level of discontent White households in the first experiment reflecting both a high PrP level and the fact that although this group is very segregated, households from other racial groups are present in the White neighbourhoods. However, a more rapid decrease in the number of discontent White households throughout the simulation of experiment one is noticeable, as more desirable locations are easily found. This undesirable occurrence leads to even higher levels of segregation. Although the Coloured group profile shows a similar curve, the decrease in discontent Black African households occurs more gradually, with a large number of households still discontent at the final time step of the simulation. This occurrence appears inconsistent with the findings in Chapter 6 where the Black African group was found to be generally very segregated but may be ascribed to the limited residential mobility of the Black African households. However, the rate of decline in discontent households may merely be indicative of the varying levels of segregation and is not as crucial as the difference in segregation when homophilic preferences and restrictions are altered.

The decreased PrP levels for experiment two result in an expected decrease in discontent households across all racial groups, but significantly for the White population. This occurrence may indicate that only a small percentage of non-White households are integrated into White neighbourhoods and that a decrease of only 20% for the White PrP level results in significantly less discontent White households. It highlights the findings of Chapter 6 where only the upper-income households of other racial groups are exposed to the White population.

It is evident from the spatial distributions of racial groups, obtained from the first experiment of the Racial Preference simulation exercise, that distributional changes have occurred in a similar manner during the simulation run with all three racial groups mostly clustering more in regions they predominantly occupy, regardless of differing PrP levels. Even the lower PrP level of 50% for the Coloured households resulted in noticeable segregation, as these households are also influenced by the higher preference levels of the Black African and White households. This is evident in the increased occupation of some Coloured neighbourhoods by Black African households in the first experiment. As with the first experiment, the limited residential mobility of the Black African population has a noticeable effect on the distribution of this group and results in numerous smaller clusters across the study area. The high PrP level of White households is evident in the receding of these clusters around the centre of the study area (adjacent to the Coloured regions).

The spatial distribution of all three racial groups in the second experiment reflects similar clustering compared to the first experiment, regardless of a decrease in the PrP levels for all three groups. This may be attributed to the fact that the residential mobility of the Black African group increased, allowing for a wider region to search for alternative dwellings. This is evident especially for the Black African group, with a decrease in dispersed households to the north and west of the study area. However, the additional clusters that emerged for the Black African households occurred either in racially diverse suburbs such as Woodstock and Observatory or predominantly White neighbourhoods. Nonetheless, it is evident that the distribution of the Coloured and Black African population remains segregated, as was found with the spatial segregation indices applied in Chapter 6.

Similarly, the clusters of Coloured households expanded into racially diverse suburbs in the north-west and predominantly White suburbs to the west of the study area. In contrast, the distribution of White households across the study area remained mostly unchanged apart from the regions where the non-White groups moved into these White suburbs and the White households receded. Consequently, segregation is maintained by the White population, regardless of the integration of Black African and Coloured households into the White neighbourhoods. The only areas where racial integration does occur are the suburbs highlighted in Chapter 2 and Chapter 6 respectively as grey areas during apartheid and racially even.

These two experiments show that a level of racial segregation persists, regardless of a decrease in PrP levels across all groups. Although a degree of integration is detected between the Black African and Coloured groups in the second experiment and also the occupation of White neighbourhoods by these two groups, the latter results in the White population receding and thus perpetuating segregation. While a general decrease in segregation is noted between the first and second experiment, it is interesting to find that segregation between the Black African and White groups increased even further. Consequently, it is evident that the role of policies in the promotion of racial integration is limited to the establishment of racially diverse residential developments and that the subject of self-segregation plays a predominant role in perpetuating racial segregation.

9.2 Simulation Exercise II: Income Constraint and Preference

Chapter 7 stipulated that the Income Constraint module was constructed on the premise that different income groups have different levels of either constraint or preference in terms of the neighbourhoods they reside in. The households of this module are divided into low-, middle- and upper-income groups with varying levels of restriction or preference. Economic restrictions represent the extent to which households are constrained from relocating to alternative areas and affect the low- and middle-income groups. In contrast, upper-income households have a preference level for neighbours of similar income status, rather than any constraint to their current locations.

9.2.1 Experiment 1: Baseline Income Constraint and Preference Simulation

Research Question: Given the current level of income constraint of the low- and middle-income groups and the homophilic preference of the upper-income group, will economic segregation persist in the study area?

Similar to the first experiment of the Racial Preference module (Section 9.1), the first simulation experiment of the Income Constraint module was undertaken for a baseline scenario and the constraint and preference parameters set accordingly for the relevant income groups. Hence, for this simulation experiment it was assumed that the findings of the isolation and exposure measurements for the income groups in Chapter 6 resulted from the degree to which households were either constrained (low- and middle-income) or the level of their preference for similar neighbours (upper-income).

Consequently, the *income constraint proportion* (IcP) for the low-income group was set to a level of 60% and a level of 30% for the middle-income group, reflecting the percentage of similar income type neighbours these low- and middle-income households are constrained to. The *preferred income proportion* (PiP) level for the upper-income households was set to 80%, indicating that this group prefers for at least 80% of their neighbours to be of a similar income group and reflecting the high level of isolation that was measured for this group. The residential mobility radius was set as follows: 2km for low-income households, 10km for middle-income households and 20km for upper-income households. The rationale for this is that the level of household income will affect the opportunities and constraints relating to residential relocation and effectively residential mobility.

Figure 9.19 shows the profile for each income group in terms of the number of discontent households with the desire to relocate to an alternative location. Both the low- and upper-income groups indicate a low number of households that desire to relocate and also a gradual decrease in these numbers, regardless of their high levels of constraint and preference respectively. This provides a clear indication of the high level of segregation already experienced between these two groups at the setup stage of the simulation.

In contrast, the middle-income group reflects a large number of discontent households at the model setup stage and a gradual decrease to time step 50. This is an interesting occurrence, given the fact that the middle-income group has a low level of constraint compared to the middle-income group and highlights the fact that the middle-income group consists of a large number of households which are spread across the study area.

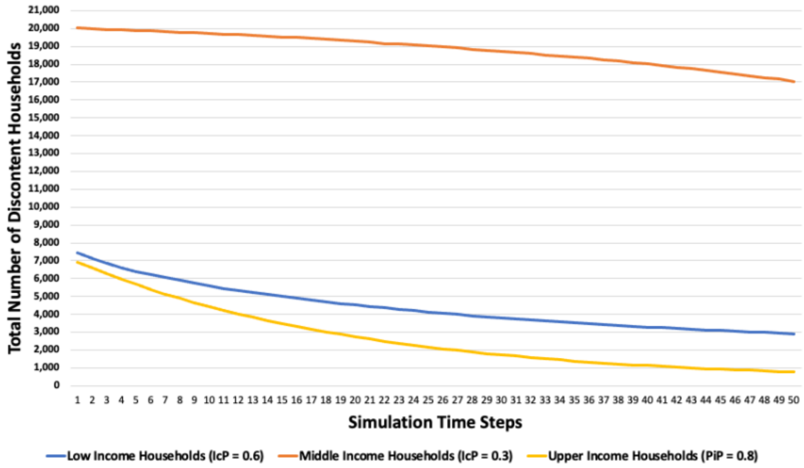


Figure 9.19: Number of Households of Each Income Group Desiring to Relocate (Average of 10 Simulation Runs)

The spatial patterns shown in Figure 9.20 indicate the distribution of low-income households at time steps 0 and 50 of the simulation. The clustering of households at time step 50 intensifies more prominently in areas where low-income households were already clustered initially (see Figure 8.13a), such as the central, southern, north-eastern and south-eastern regions of the study area. These are the predominantly Black African suburbs of Langa, Gugulethu and Delft and the Coloured suburbs of Manenburg, Bishops Lavis and The Hague to the centre of the study area and the Coloured suburbs of Tafelsig and Lavender Hill to the south. In contrast, more dispersed patterns emerged in the predominantly middle- and upper-income suburbs to the west and middle-income suburbs to the south of the study area.

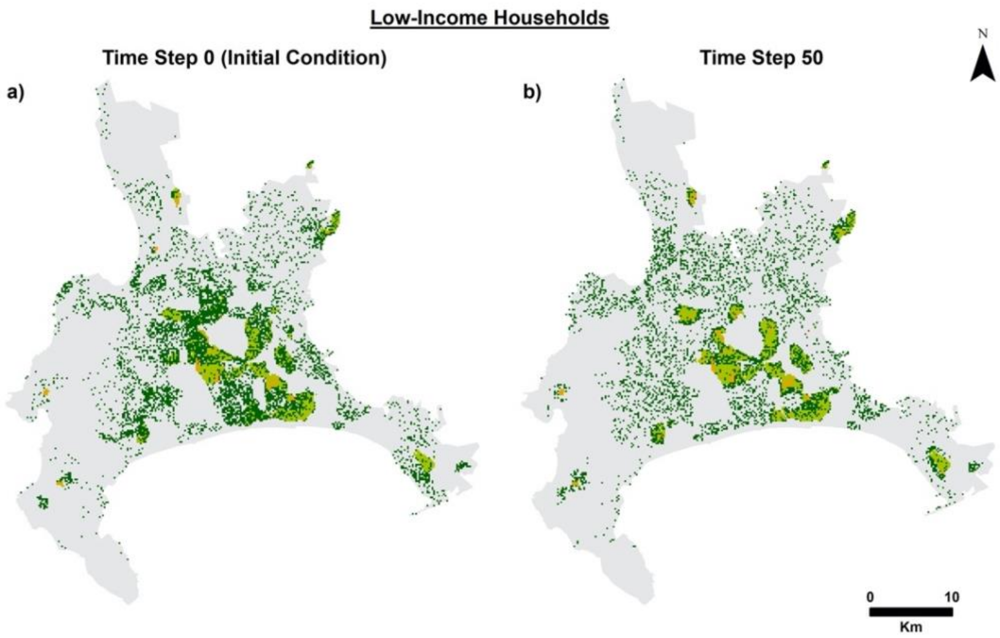


Figure 9.20: Maps Showing the Distribution of Low-Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.21 shows the spatial distribution for middle-income households at the start and last time step of experiment one of the Income Constraint module. Despite the small degree of clustering emerging to the west and dispersion to the south, very little significant change is detected between the setup stage and final time step of the simulation. This occurrence reflects the findings in Figure 9.19 of a high degree of discontent middle-income households. However, a decrease in clustering of middle-income households is noticeable in the centre of the study area and the south, which are predominantly low-income suburbs.

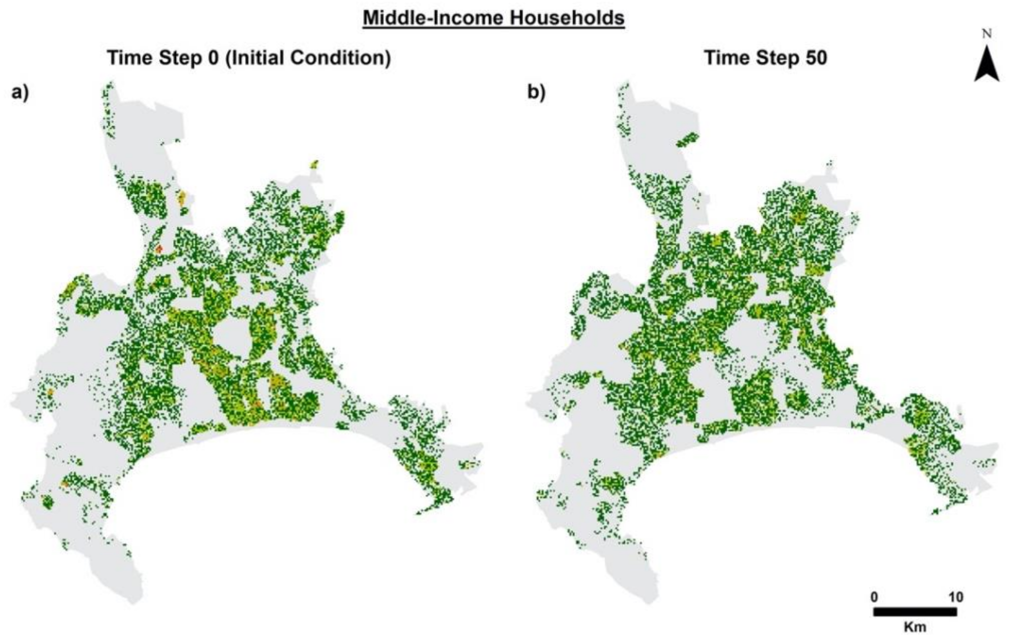


Figure 9.21: Maps Showing the Distribution of Middle-Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.22 shows the spatial distribution of upper-income households at initiation and time step 50 of the first simulation experiment. The predominant change noticeable in Figure 9.22b is the significant decrease of more dispersed households across the study area. The resulting pattern shows more concentrated clusters in the White suburbs of Joostenberg Vlakte and Zonnendal in the north-east, Richwood and Burgundy Estate in the north, Bishopscourt, Constantia Heights and Bel Ombre in the west, Steenberg Estate and Noordhoek in the south-west of the study area and Erinvale Golf Estate to the south-east. Hence, due to the high preference level of the upper-income group for similar neighbours these households self-segregated to a number of highly concentrated clusters. It is assumed that the dispersed upper-income households at time step 50 were either unsuccessful in finding a suitable alternative location to relocate to or that these households are still in the process of searching for such a location.

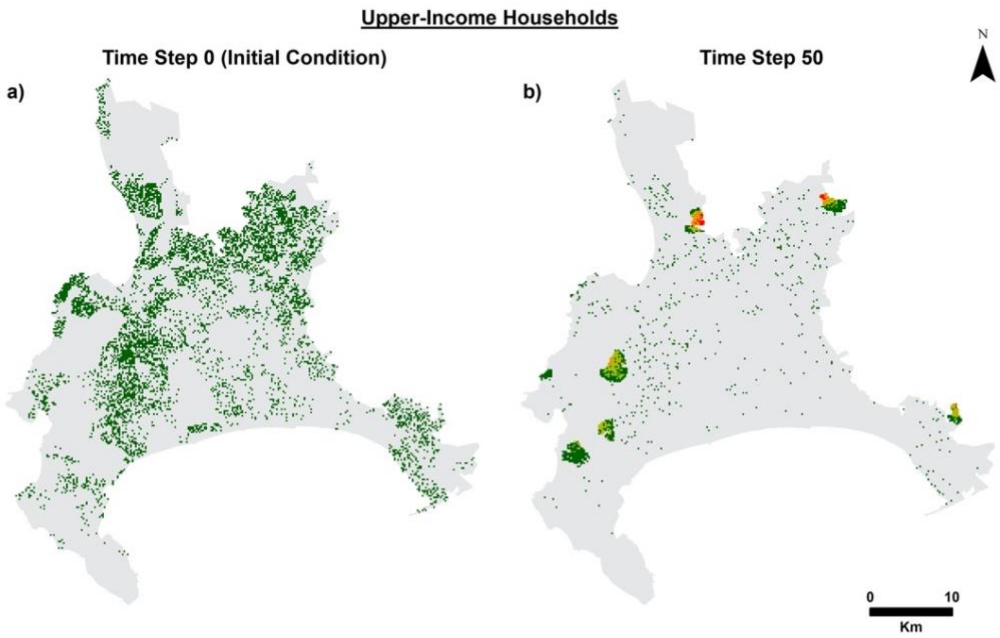


Figure 9.22: Maps Showing the Distribution of Upper-Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification).

The global isolation levels of the three income groups presented in Figure 9.23 reflects that although the upper-income group was least isolated at the setup stage, this level increased more rapidly than those of the low- and middle-income groups and may be assigned to the high preference level of the upper-income group. Similar levels of isolation and related increase is evident for the low- and middle-income groups. Thus, an increase in segregation among all income groups is evident in this simulation experiment.

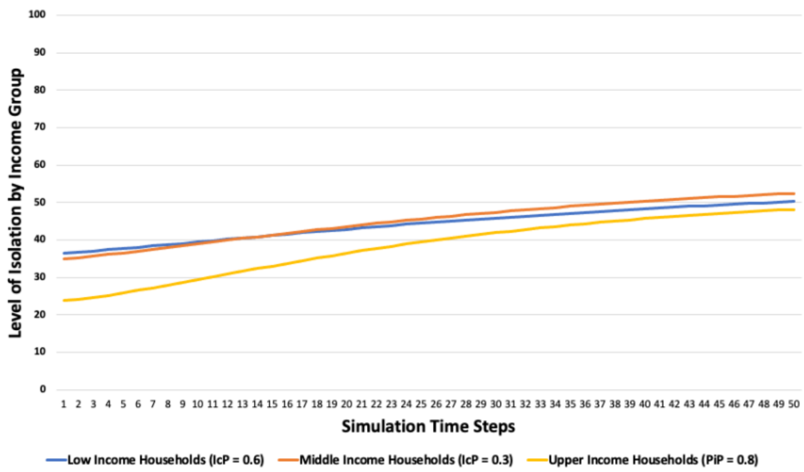


Figure 9.23: Levels of Global Isolation for Each Income Group (Average of 10 Simulation Runs)

Hence, the relatively high level of income constraint of the low- and middle-income groups and similarly high homophilic preference of the upper-income group resulted in an increase in economic segregation amongst the income groups in the study area. The most significant increase in segregation occurred in the upper-income group, where a high degree of self-segregation occurred.

Following on from Experiment 1 of the Income Constraint module, which presented an assumed baseline or 'what if' scenario of segregation dynamics in terms of income constraint and preference, Experiment 2 explores socio-economic segregation levels when real income integration policies are applied to the study area.

9.2.2 Experiment 2: Testing Policy for Residential Income Integration

Research Question: Will the implementation of policies, aimed at economic inclusion and the reduction of income constraint, encourage economic integration in the study area?

For the second simulation experiment undertaken for the Income Constraint module, the focus is on the objectives of residential socio-economic integration of the Cape Town MSDF. The promotion of economically inclusive and mixed income residential developments is reflected in all the District Plans for Cape Town and not only for the most segregated lower income suburbs.

Subsequently, the income constraint (IcP) or preference level (PiP) for each racial group is adjusted for this simulation experiment. With the Cape Town MSDF focussing on residential income integration through the development of mixed income areas, especially for low- and middle-income groups, the previous IcP levels of 60% and 30% of these two groups (respectively) are reduced to 30% for the low-income group and 20% for the middle-income group. With the upliftment of low-income communities in the more affluent suburbs through urban regeneration, as outlined in the MSDF Northern District Plan, the PiP level of the upper-income group is decreased from 80% to 60%. In addition, the residential mobility of the low-income households is increased from 2 kilometres to 5 kilometres. Apart from these changes, all other parameters remained the same as for the first experiment.

Figure 9.24 shows the profiles for the number of agents of each income group desiring to move at initiation and during the simulation run. Although the largest number of discontent households throughout the simulation again belong to the middle-income group, this number decreases more significantly to the final time step of the simulation. In contrast to the findings for the first experiment (see Figure 9.19), the low-income households reflect a lower number of discontent households than the upper-income group throughout the simulation and may be assigned to the low IcP (income constraint) level of the low-income group.

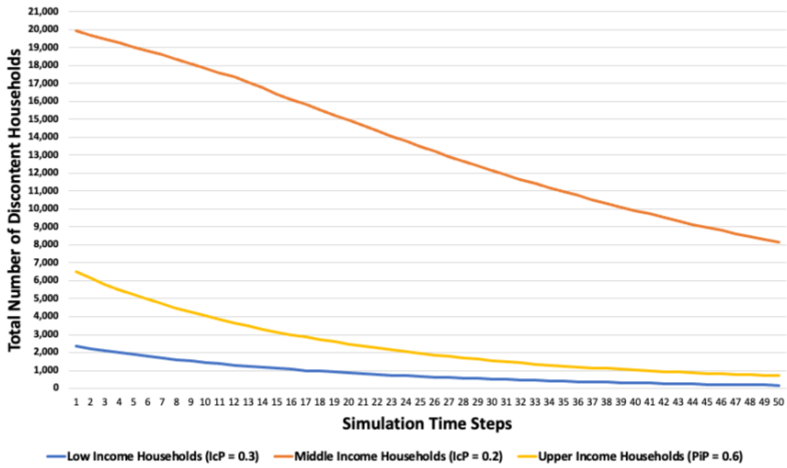


Figure 9.24: Number of Households of Each Income Group Desiring to Relocate (Average of 10 Simulation Runs)

Figure 9.25 shows the spatial distribution of low-income agents at time steps 0 and 50. Significant clustering occurred, in contrast to the findings in the first experiment, especially to the north and west of the study area. These clusters emerge regardless of the decreased IcP level for the low-income group and may be assigned to increased residential mobility for the low-income group. These clusters are evident in the predominantly middle-income suburbs of Woodstock, Brooklyn and Windermere to the north-east, Bellville to the north-east, Lotus River, Retreat and Grassy Park in the south-west and Kleinvlei and Palm Park to the west. The clusters to the north-west are located in the Black African township of Masiphumelele (see Figure 2.8) and Coloured township of Oceanview.

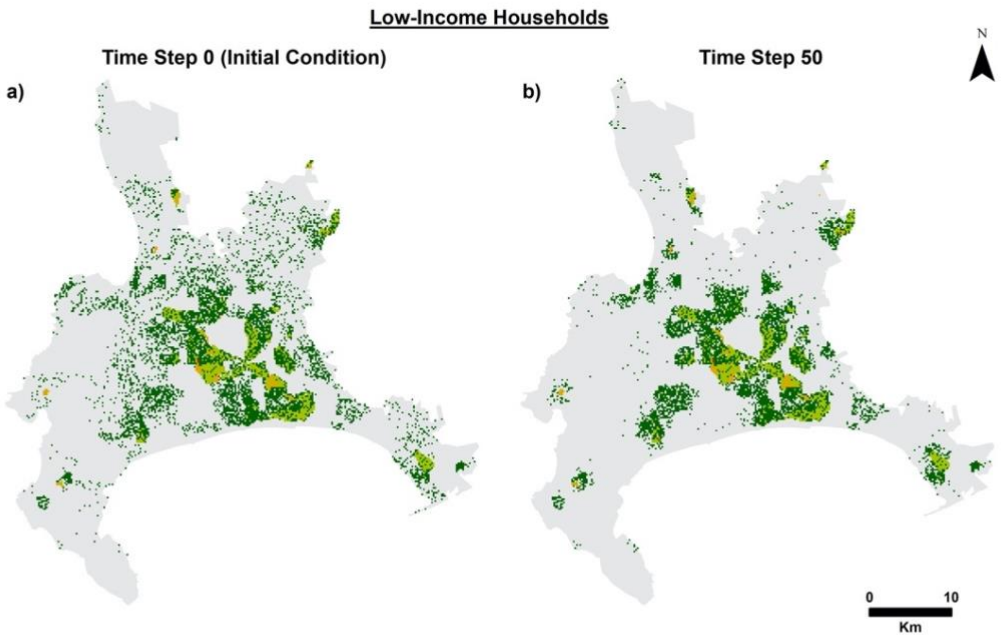


Figure 9.25: Maps Showing the Distribution of Low-Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.26 shows the spatial distribution of middle-income households and reflect little significant change in general from the findings in the first experiment (see Figure 9.21), apart from increased clustering is also evident to the north and west of the study area.

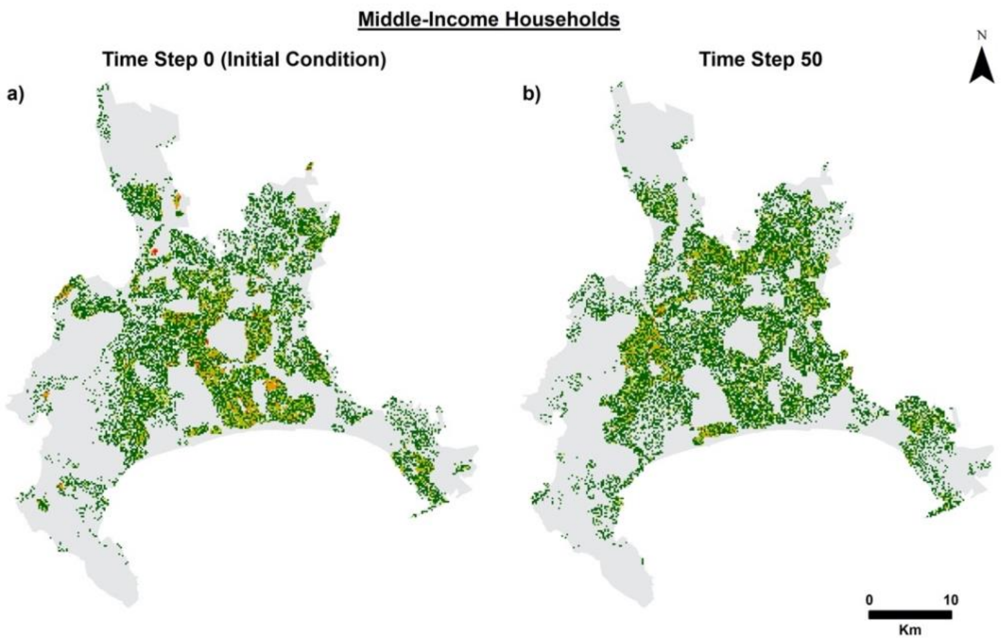


Figure 9.26: Maps showing the Distribution of Middle-Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.27 shows the spatial distribution of upper-income agents for the second simulation experiment. The clusters previously highlighted in the first experiment (see Figure 9.29) have increased in size, with the cluster in the north relocating eastward to the affluent White suburbs of Plattekloof, Welgedacht and Protea Vallei. Further clustering emerged along the coast to the north-west of the study area in the suburbs of Bloubergstrand and Big Bay and Sunset Beach, Camps Bay and Clifton to the west and Llandudno and Hout Bay to the south-west. All these suburbs are predominantly middle- to upper-income neighbourhoods, indicating some degree of upper-income households integrating more with middle-income households.

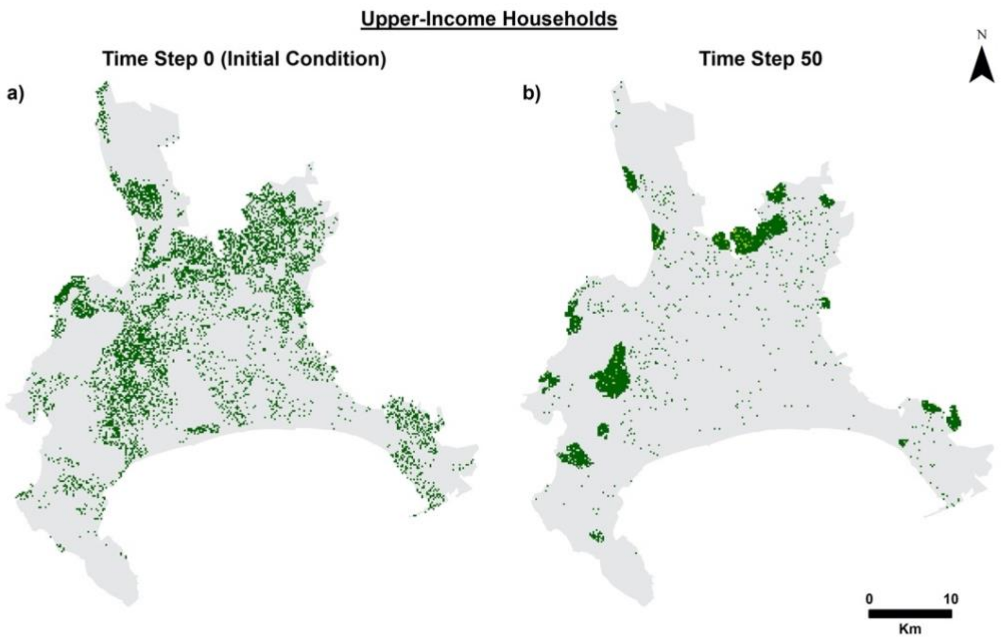


Figure 9.27: Maps Showing the Distribution of Upper-Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification).

Figure 9.28 presents the levels of global isolation for each of the income groups. It is evident that the profile of the low-income group reflects the highest level of isolation throughout the simulation. However, the profiles of all three income groups are very similar to the findings in the first experience (see Figure 9.23), reflecting a gradual increase in segregation to time step 50.

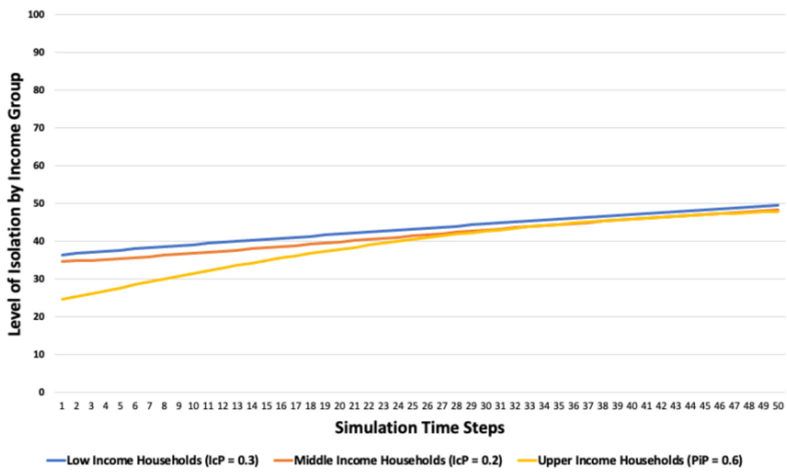


Figure 9.28: Levels of Global Isolation for Each Income Group (Average of 10 Simulation Runs)

Although segregation decreased noticeably between the low- and middle-income groups, the upper-income group remained highly segregated, even though the clusters are larger and less concentrated in terms of number of households. It is thus inferred that economic integration may indeed be orchestrated through the formulation of policies for economic inclusion and mixed income housing. However, these policies may have a limited effect on the homophilic preferences and subsequent self-segregation of the upper-income group.

Appendix G shows the areas in which change occurred in the spatial distribution of all income groups between the first and second experiments. In addition, Appendix H presents the change in entropy level distribution across the study area for both experiments.

9.2.3 Discussion

Similar to the experiments of the Racial Preference module, the profiles of the number of discontent households for each income group provides information on the level of segregation between these three groups. Regardless of the low level of constraint of the middle-income group and high degree of integration with the low- and upper-income groups, a significant number of discontent middle-income households is evident throughout the simulations of both experiments.

In contrast, the number of discontent low- and upper-income households are comparatively much lower in both experiments, regardless of the high constraint (IcP) level of the low-income group and high preference (PiP) level of the upper-income group. This occurrence highlights the findings in Chapter 6 on the high degree of segregation between these two groups and the fact that most of the low- and upper-income households are already situated mostly among their own income type. This is also evident in the second experiment, with the upper-income profile remaining mostly unchanged. Only the low-income group indicates a decrease in discontent households in the second experiment, due to the significant decrease in constraint.

The changes in spatial distribution of income groups in both experiments of the Income Constraint module occurred predominantly in the spatial patterns of the low- and upper-income groups. Even though the IcP level for the low-income group is high (60%) in the first experiment, more evenly dispersed patterns of low-income households are found in middle- to upper-income regions to the north and west of the study area. This may be attributed to the low level of residential mobility of the low-income group in the first experiment and thus the inability to move to an alternative low-income area. This is noticeable in the second experiment where the residential mobility is increased for this group and more prominent low-income household clustering is detected. However, these new emerging clusters are located in predominantly Coloured middle-income suburbs and this integration occurs due to the decrease in constraint for both the low- and middle-income groups.

Although the middle-income group shows no significant distributional changes in both experiments, the outcome of the first experiment shows noticeable dispersion of the clusters of middle-income households in the predominantly Black African suburbs to the south of the study area, with an increase in low-income households occupying these regions. This occurrence highlights the low level of exposure between the low- and middle-income group found in Chapter 6. With a decrease in constraint levels for the low- and middle-income groups, a degree of integration is evident among them in the three central and southern districts (Tygerberg, Cape Flats and Mitchells Plain/Khayelitsha/Blue Downs) of the council's MSDF (see Figure 9.1). These suburbs were identified as significantly segregated in Chapter 6, in terms of race and income. The MSDF also highlight these regions as "needy" socio-economic suburbs (City of Cape Town, 2018, p. 28). It was also found in both experiments that the cluster of middle-income households to the west of the study area extended into the predominantly White middle- to upper-income suburbs.

In contrast, the distribution of the upper-income group in both experiments shows significant clustering in the predominantly White neighbourhoods to the north and west of the study area and mostly segregated from both the low- and middle-income groups. A decrease in the preference (PiP) level of the upper-income group in the second experiment resulted in the initial clusters containing lower numbers of households and also expanding spatially to integrate to a small degree with the middle-income group in the White suburbs to the north and west of the study area. In addition, new upper-income clusters emerged in the predominantly White coastal developments at the north-western and western periphery of the study area. This phenomenon corroborates the findings in Chapter 6 on White income groups being more integrated to each other.

The experiments in this Income Constraint exercise show that only a decrease in the level at which low- and middle-income households are constrained to neighbourhoods of similar income will result in the emergence of regions where these two groups are more integrated. It also reveals that although middle-income households integrate more into predominantly upper-income suburbs, the consistently high level of preference for similar neighbours of the upper-income group results in persistent segregation between this upper-income group and the other two groups. This is also evident in the higher degree at which the isolation of the upper-income groups increased in both experiments, compared to the low- and middle-income groups. Thus, although mixed-income and inclusive housing schemes may promote integration, market driven residential development reinforces spatial and economic division.

9.3 Simulation Exercise III: Racial-Income Preference and Constraint

The history and physical form of the South African city was shaped by racial segregation, which evolved over time to manifest socio-economic exclusion and inequality (see Chapter 2). It was discovered through the application of segregation metrics to the study area in Chapter 6 that both racial and income-related dynamics still play a role in the persistence of segregation in Cape Town. The aim of this third simulation exercise is to explore the interrelated dynamics of racial preference and income constraint and whether the obtained output presents spatial distribution patterns that might contribute to the understanding of racial and socio-economic segregation. The objective is to explore further the findings that both the subjects of race and income play a role in persistent segregation in Cape Town and also to undertake a comparative analysis to explore whether the spatial distribution of income-by-race groups either resemble or differ from the patterns obtained from the separate Racial Preference and Income Constraint modules.

For the exploration of the combined dynamics of racial preference and income constraints, the third simulation exercise was undertaken in the same manner as the first two. Thus, two experiments were undertaken in which the parameters for residential preference and income constraint were combined in one simulation model. The household agents are divided into nine income-by-race groups, as studied with the segregation metrics in Chapter 6. Consequently, a Coloured household with a low-income (for example) would initially act in accordance with the constraint level that was set for low-income households and then to the residential preference parameter setting for Coloured households. The rules applied previously in terms of racial preference and income constraint/preference and also the parameters of neighbourhood radius and residential mobility remains unchanged.

9.3.1 Experiment 1: Baseline Income Constraint and Racial Preference Simulation

Research Question: Given the high levels of racial and upper-income homophily and income constraint, will the current level of socio-economic segregation persist in the study area?

The first simulation experiment undertaken for the Racial Income Module exercise applied the same default settings, used for the first two module exercises, to the combined parameters of racial preference and income constraint. For example, if the PrP (racial preference) level for the Black African group is set to 60% and the IcP (income constraint) level for the middle-income group is set to 30%, the Black middle-income group will reflect a PrP level of 60% and IcP level of 30%. All other parameters remained the same as before.

Figure 9.29 presents the profiles for each of the three income groups by race and in terms of the number of discontent households with the desire to relocate to an alternative location between time steps 0 and 50 of the simulation. The PrP and IcP/PiP levels for each group are also included for reference. The Coloured low-income group reflects the largest number of discontent households at the setup stage of the simulation and also throughout the simulation, regardless of a decrease in numbers towards time step 50. In contrast, the Black African and White low-income groups reflect considerably fewer discontent households and respectively a more gradual decrease and predominantly unchanged state between time steps 0 and 50, regardless of the comparatively high PrP and IcP levels of these two groups. This may be assigned to the high level of segregation between the Black African and White population and the fact that a majority of households already reside predominantly among racially similar neighbours.

The White middle- and upper-income groups also reflect a similar trend and comparatively high level of discontent households at time step 0, but more rapid decrease to time step 50 as alternative locations are easily acquired. The Coloured middle- and upper-income groups also reflect similar trends to each other, but a significantly lower number of discontent households at time step 0 and a more gradual decrease of these numbers to time step 50. The Black African middle-income profile is slightly higher but very similar to the Coloured upper-income profile, with the Black African upper-income group showing the least discontent number of households throughout the simulation. Again, the low number of discontent middle- and upper-income households of the Black African and Coloured groups, despite of their relatively high levels of racial and income preference, indicate an initial state of segregation in general among all other income groups by race.

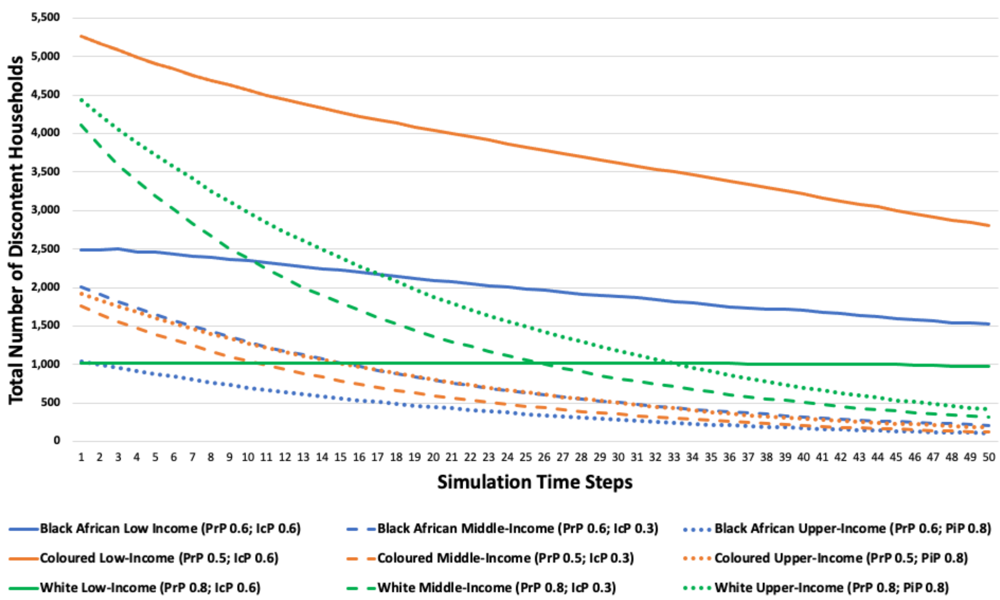


Figure 9.29: Number of Households by Income Group of Each Race Desiring to Relocate (Average of 10 Simulation Runs)

Figure 9.30 shows the spatial patterns generated in the simulation experiment for each Black African income group. The distribution of the low-income households at the last time step (see Figure 9.30b) reflect minor differences from the original pattern at the setup stage of the model (see Figure 9.30a), apart from clustering occurring to the west of the study area and dispersing slightly to the south. In contrast, the Black African middle-income group shows significant clustering at time step 50 (see Figure 9.30d), compared to an initial condition of both clustered and dispersed households across the study area (see Figure

9.30c). The upper-income group showed the most significant change (see Figure 9.30f), as a predominantly dispersed pattern of households at setup (see Figure 9.30e) resulted in significant clustering to the north and west of the study area. An interesting observation is that these clusters are quite segregated from the other Black African income groups in the study area. In contrast, the emerging clusters of low- and middle income Black African households are more integrated.

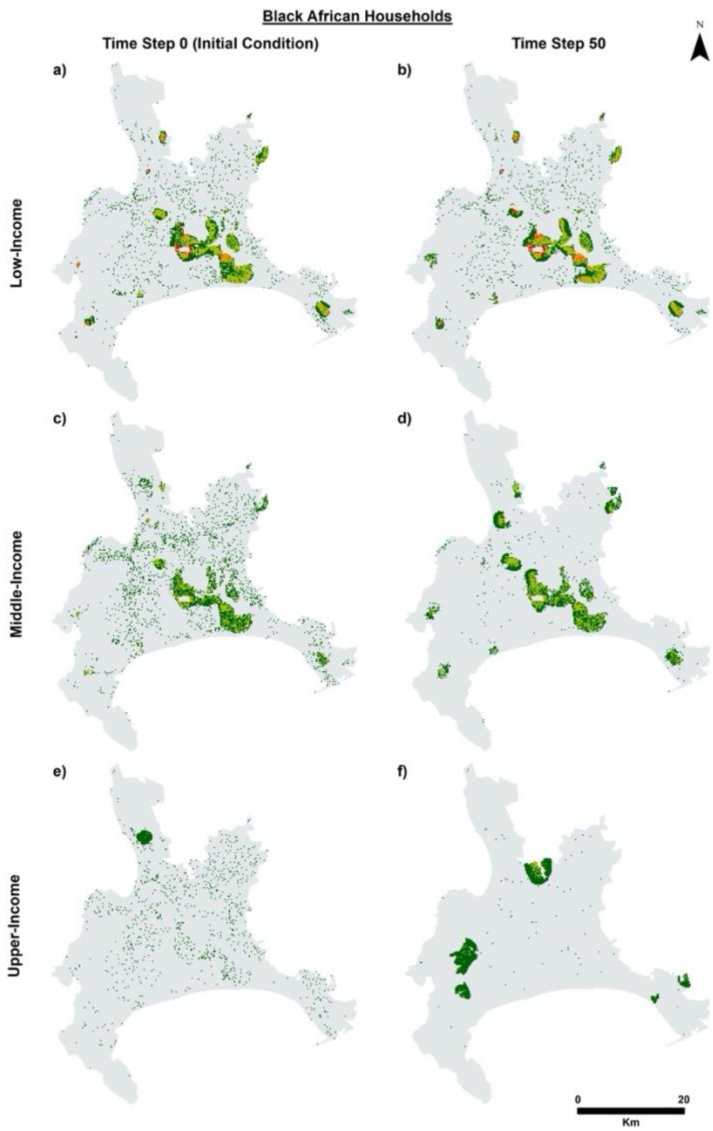


Figure 9.30: Maps Showing the Distribution of Black African Income Households at Time Step 0 and 50. All maps were generated by using 4 similar breaks (Manual classification)

Figure 9.31 shows the spatial patterns generated in the first simulation experiment for each Coloured income group at time steps 0 and 50. For the low-income households (see Figure 9.31b) the general distribution patterns remained mostly unchanged. However, four clusters of higher household numbers emerged to the centre and south of the study area. Most of the larger initial clusters indicate a degree of dispersion at time step 50.

In contrast, clustering increased across the study area for the middle-income group (see Figure 9.31d), with most of the previously dispersed households (especially in the predominantly White suburbs to the north) relocation to these clusters. The spatial distribution of the Coloured upper-income households reflects a similar pattern to the Black African upper-income group at setup stage (see Figure 9.31e) and time step 50 (see Figure 9.31f). Hence, the predominantly dispersed pattern at setup changed to a more clustered pattern to the north, west and south-east of the study area.

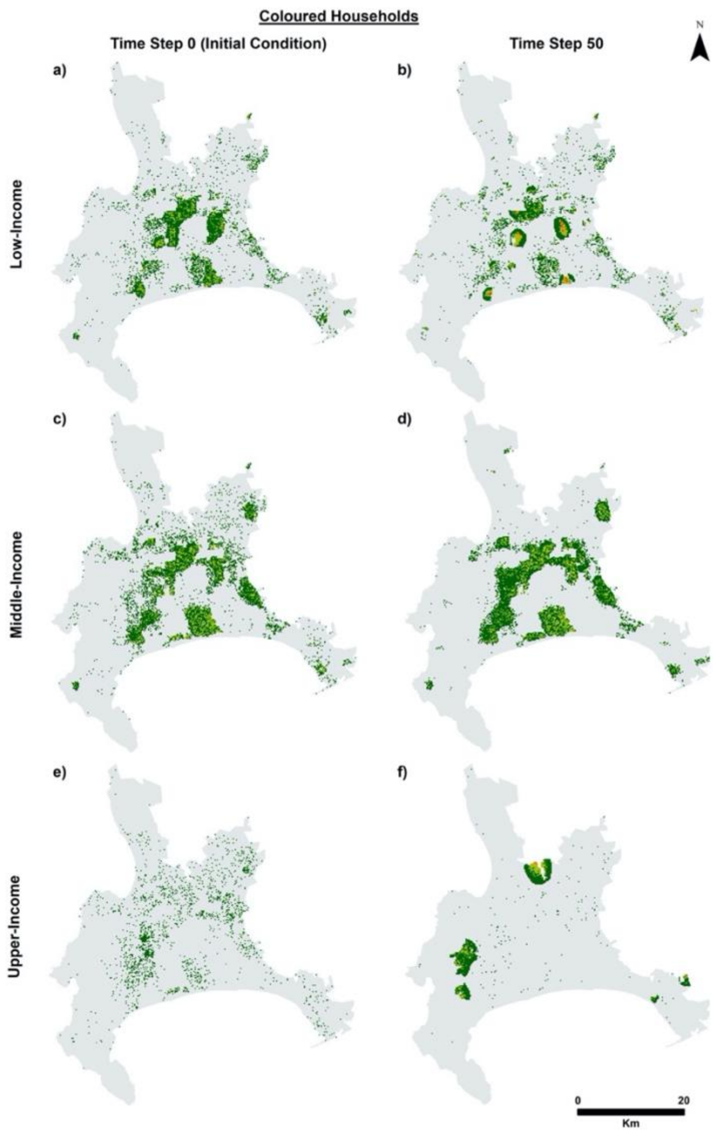


Figure 9.31: Maps Showing the Distribution of Coloured Income Households at Time Step 0 and 50. All maps were generated by using 4 similar breaks (Manual classification)

Figure 9.32 shows the spatial patterns generated for each White income group. The dispersed low-income group (see Figure 9.32a) reflects minimum change at the end of the simulation, apart from gradual clustering to the north and west (see Figure 9.32b). The distribution of the White middle-income group at time step 50 (see Figure 9.32d) reflects significant clustering to the north, west and south-east of the study area. Although the initial distribution of the upper-income group (see Figure 9.32e) is similar to the middle-income group, significant clustering occurs by the end of the simulation (see Figure 9.32f) and again in the same location as was found for the Black African and Coloured upper-income groups.

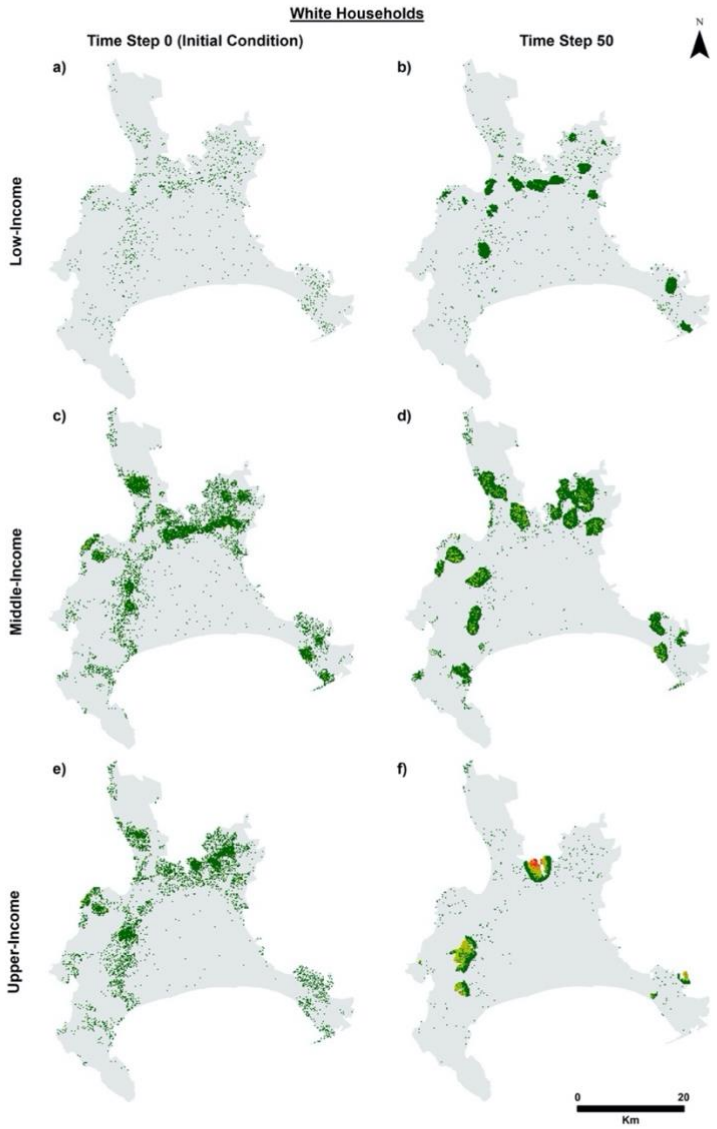


Figure 9.32: Maps Showing the Distribution of White Income Households at Time Step 0 and 50. All maps were generated by using 4 similar breaks (Manual classification)

Figure 9.33 presents the global isolation profiles for the income groups of each racial group in the study area. It is evident that the Coloured and White middle-income groups are most isolated at time step 0, with a gradual increase in isolation levels during the simulation run. In comparison, the Black African middle-income group is less isolated with only a slight increase in isolation between time steps 0 and 50. Although the Black African low-income group is second most isolated of all racial income groups at time step 0, the level of isolation remains mostly unchanged during the simulation. White low-income reflects the lowest level of isolation of all groups, both at time step 0 and throughout the simulation, regardless of gradual increase in isolation.

In contrast, the initial low level of isolation of the Black African and Coloured upper-income groups reflects a significant increase during the simulation and as a result are two of the most isolated groups at time step 50. Although the White upper-income group is more isolated than the other two upper-income groups at the setup stage of the simulation, a gradual increase results in this group being only slightly more isolated than the Black African and Coloured upper-income groups at time step 50.

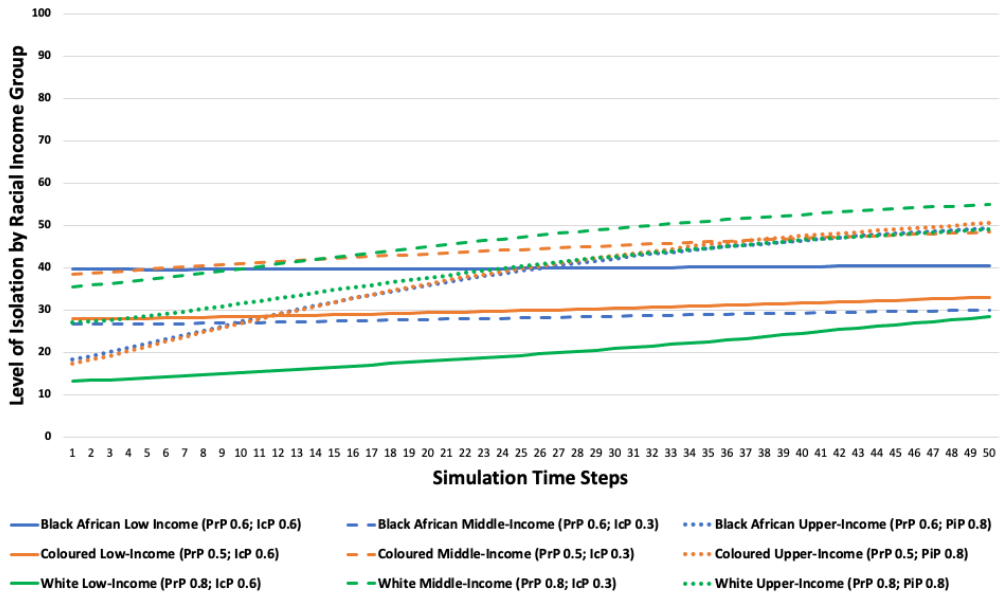


Figure 9.33: Levels of Global Isolation for Each Racial Income Group (Average of 10 Simulation Runs)

In response to the research question for this experiment, it is evident that socio-economic segregation persists. The Coloured and Black African groups are significantly segregated from each other, even though the low- and middle-income groups for each of these racial groups are mostly integrated. The White income groups are not only segregated from other racial income groups, but also from each other. However, the upper-income groups of all three races are the exception and quite integrated.

Following on from the baseline scenario set in Experiment 1, Experiment 2 explores segregation levels of the income groups of each race when the parameter settings of the Racial Preference Experiment 2 and Income Constraint Experiment 2 are combined.

9.3.2 Experiment 2: Exploring the Influence of Combined Income-by-Race Dynamics on Segregation

Research Question: Will the implementation of policies aimed at both the alleviation of poverty and reduction of homophilic preference, encourage socio-economic integration?

For the second experiment of the Racial Income module simulation exercise the racial preference (PrP) and income constraint/preference (IcP/PiP) parameters from the second exercises of the Racial Preference and Income Constraint modules (respectively) were combined. Table 9.1 provides the Black African income groups as example to present the mentioned combination of parameters:

Table 9.1: Combination of Experiment 2 Parameters of Racial Preference and Income Constraint Modules

<table>
<tr><th>Simulation</th><th>Group</th><th>Racial Preference</th><th>Income Constraint /Preference</th></tr>
<tr><td rowspan="3">Section 9.1.2
Simulation Exercise I
Experiment 2</td><td>Black African</td><td>30%</td><td rowspan="3"></td></tr>
<tr><td>Coloured</td><td>30%</td></tr>
<tr><td>White</td><td>60%</td></tr>
<tr><td rowspan="3">Section 9.2.2
Simulation Exercise II
Experiment 2</td><td>Low-Income</td><td rowspan="3"></td><td>30%</td></tr>
<tr><td>Middle-Income</td><td>20%</td></tr>
<tr><td>Upper-Income</td><td>60%</td></tr>
<tr><td rowspan="3">Racial Income Module
Simulation Exercise III
Experiment 2</td><td>Black African Low-Income</td><td>30%</td><td>30%</td></tr>
<tr><td>Black African Middle-Income</td><td>30%</td><td>20%</td></tr>
<tr><td>Black African Upper-Income</td><td>60%</td><td>60%</td></tr>
</table>

Figure 9.34 presents the profiles for the income groups of each of the three racial groups that are discontent at their current location throughout the simulation. The profiles for all three upper-income groups show little change when compared to the findings of the first experiment (see Figure 9.29), regardless of a decrease in PrP (racial preference) and PiP (income preference) levels for all three racial groups. In contrast to the first experiment, the middle-income groups show lower numbers of discontent households at time step 0 and a

more gradual decline in these numbers to time step 50, especially the White middle-income group showing significantly fewer discontent households at model run initiation. This may be ascribed to a decrease in both the PrP and IcP (income constraint) levels of all three middle-income groups.

The most noticeable change is a significant decrease in the number of discontent Coloured low-income households throughout the simulation of experiment 2, compared to experiment 1 (see Figure 9.29). Similarly, the profile for the Black African low-income group reflects a lower number of discontent agents and follow a similar trend. Again, this may be assigned to the decrease in PrP and IcP levels for these two groups. Although the White low-income group remains mostly unchanged at time step 0, a gradual decrease in discontent households is evident towards time step 50.

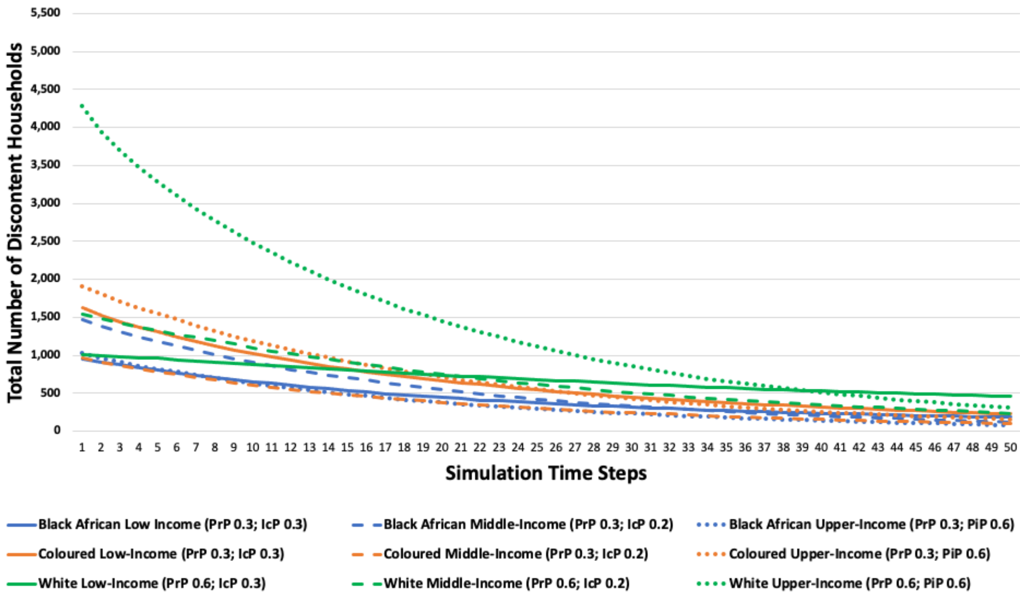


Figure 9.34: Number of Households by Income Group of each Race Desiring to Relocate (Average of 10 Simulation Runs)

Figure 9.35 shows the spatial patterns of each Black African income group at both the setup stage (time step 0) and time step 50 of the simulation. Although the distribution of the Black African low-income group (see Figure 9.35b) remains mostly unchanged in comparison to the distribution in experiment 1 (see Figure 9.30b), it is noticeable that the households that were more dispersed to the north and west of the study area in experiment 1 have decreased significantly at time step 50 of experiment 2. A newly formed cluster is also evident at the north west of the study area in the predominantly Black African middle-income suburbs of Maitland and Brooklyn.

The Black African middle-income group also shows the development of a cluster in the same location at time step 50, which extends to the south and the predominantly Coloured middle-income suburbs of Woodstock and Salt River, mostly Black African middle-income suburbs of Observatory and the White middle- to upper-income suburb of Mowbray. Further clustering is evident to the east of the study area in the predominantly Coloured middle-income suburbs of Kalkfontein, Highbury Park and Black African middle-income suburb of Happy Valley.

Although the predominant Black African upper-income household clusters to the north and west of the study area remained (see Figure 9.30d, experiment 1) at time step 50, further clustering emerged in the predominantly White upper-income coastal suburbs (identified in Figure 9.27) to the north-west and west of the study area and White upper-income suburbs of Noordhoek and Chapmans Peak to the south-west.

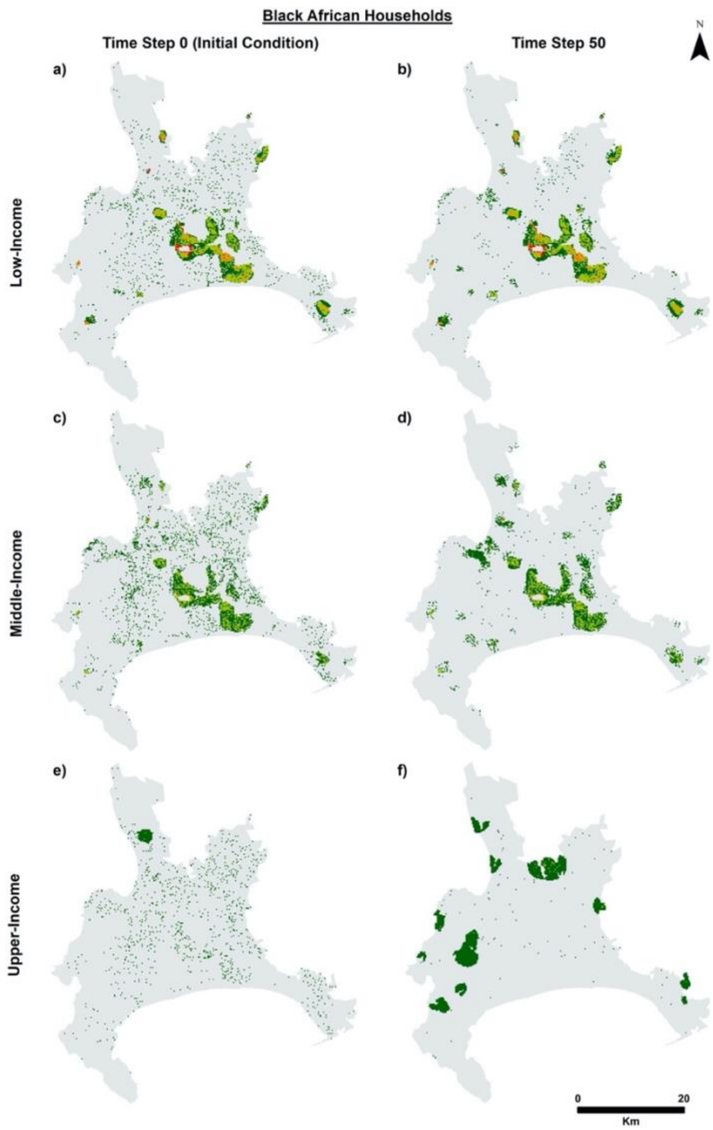


Figure 9.35: Maps showing the Distribution of Black African Income Households at Time Step 0 and 50. Both maps were generated by using 4 similar breaks (Manual classification)

Figure 9.36 shows the spatial distribution of Coloured income groups at time step 0 and time step 50 of the simulation experiment. The clustering of Coloured low-income households (see Figure 9.36b) are evidently more prominent, compared to experiment 1 (see Figure 9.31), especially in the predominantly Coloured middle-income suburbs of Tafelsig and Beacon Valley to the south [1], Lotus River and Lavender Hill to the south-west [2] and Windermere and Maitland to the north-west [3]. Although dispersion decreases for the Coloured middle-income households (see Figure 9.36b) it remains mostly unchanged compared to experiment 1 (see Figure 9.31d). The Coloured upper-income households (see Figure 9.36f) at time step 50 presents an interesting distribution, which is similar to the that of the Black upper-income households in the same experiment (see Figure 9.35f). The first experiment reflects a similar occurrence (see Figure 9.30f and Figure 9.31f respectively).

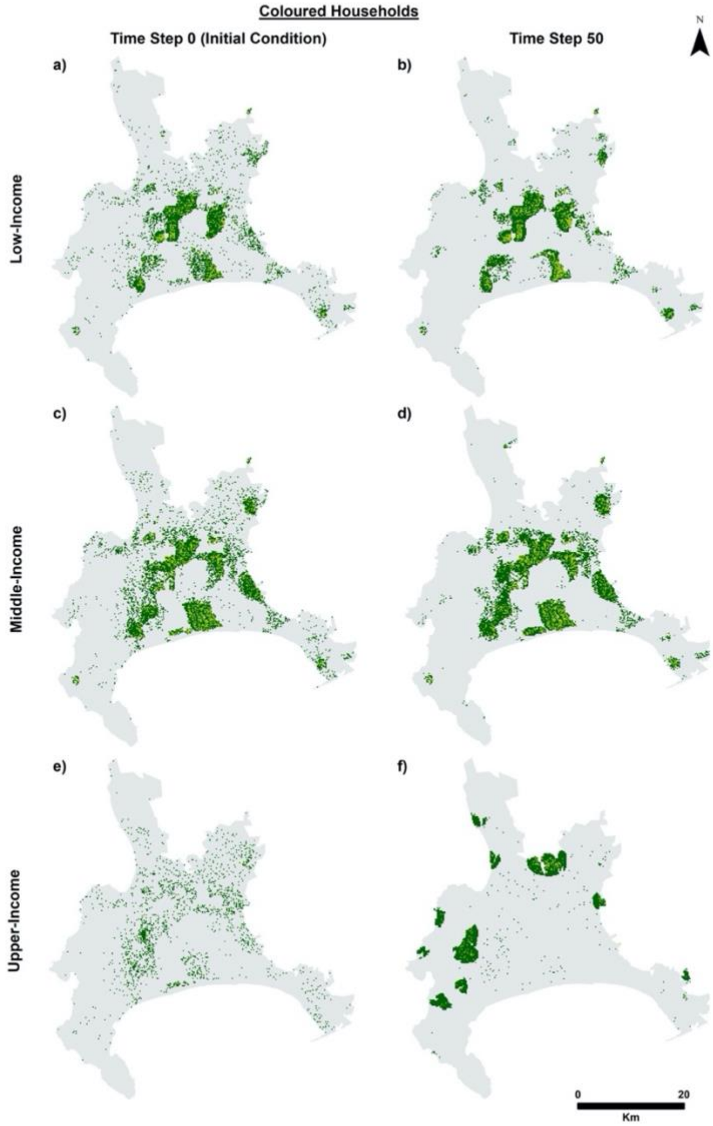


Figure 9.36: Maps Showing the Distribution of Coloured Income Households at Time Step 0 and 50. All maps were generated by using 4 similar breaks (Manual classification)

Figure 9.37 shows the pattern of spatial distribution of the White income groups and again at both time step 0 and 50 of the simulation. Although the predominantly dispersed White low-income households at time step 0 (see Figure 9.37a) were significantly more clustered at time step 50 (see Figure 9.37b), similar to the findings of experiment 1 (see Figure 9.32b), these clusters are situated at different locations than before. The cluster to the north-west is located in the White middle- to upper-income suburbs of Joostenberg Vlakte and Kraaifontein. The clusters to the centre of the study area are located in the predominantly

Coloured middle-income suburbs of Roosendal, Belhar, Bishop Lavis and Uitsig. The cluster to the west is situated in the White middle- to upper-income neighbourhood of Hout Bay and to the south-west similar income neighbourhoods of Sun Valley and Capri.

The findings for the White middle-income group (see Figure 9.37d) reflect clusters that are in similar locations as found in experiment 1 (see Figure 9.32d), but more expansive and connected to form continuous bands especially to the north and west of the study area. Most of these clusters are situated in predominantly White middle- to upper-income suburbs. Another noticeable difference to the distribution found in the first experiment, is the emergent cluster of White middle-income households to the west of the study area and in the predominantly White middle- to upper-income neighbourhoods of Greenpoint, Sea Point and Fresnaye.

The distribution of White upper-income households (see Figure 9.37f) reflect the same patterns of clustering that was found for the Black African and Coloured upper-income groups. Hence, the clusters to the north and west of the study area, reflected in experiment 1, not only expanded slightly but also had additional clusters emerge on the north-western and western coast and same locations as the Black African and Coloured upper-income groups.

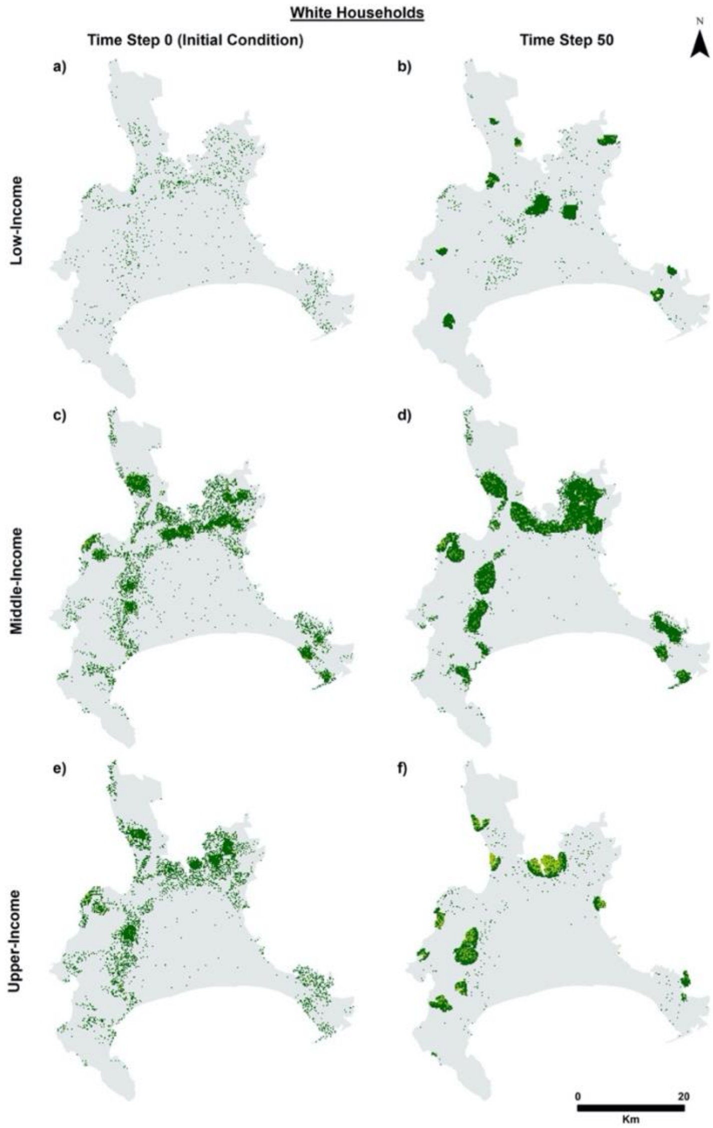


Figure 9.37: Maps Showing the Distribution of White Income Households at Time Step 0 and 50. All maps were generated by using 4 similar breaks (Manual classification).

Figure 9.38 shows the profiles for the level of isolation for each income group by race. In general, the profiles of all income groups are similar to those found in the first experiment (see Figure 9.33), with only a few noticeable differences. Although most profiles show slightly lower levels of segregation at time step 50, the Coloured low-income and White middle-income groups reflect an increase in segregation, with the latter the most segregated income group at the end of the simulation.

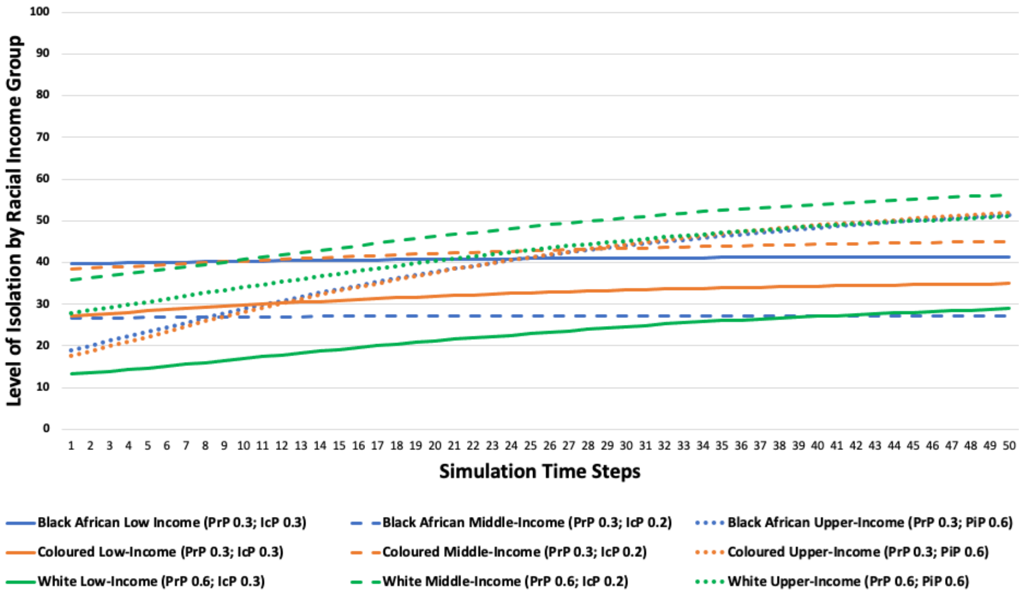


Figure 9.38: Levels of Global Isolation for Each Racial Income Group (Average of 10 Simulation Runs)

It is deduced from this experiment that policy formulation for the alleviation of poverty and reduction of racial homophily alone would not succeed. Limited change in segregation levels and spatial distribution occurred between the first and second experiment, indicating that there are factors at play beyond the dynamics included in the model. These external factors, such as racially mixed and economically inclusive housing projects, would prompt socio-economic integration.

Appendix H presents the changes that occurred in distribution of the income groups for each of the three races in both the first and second experiment. Appendix I shows how the distribution of diversity levels among the racial income groups changed during each of the simulations of experiments one and two.

9.3.3 Discussion

The profiles indicating the number of discontent racial income groups throughout the simulations of the two experiments reveal a number of interesting findings. Firstly, the profiles of the upper-income groups for all three races remained predominately unchanged between the first and second experiment, regardless of the decrease in racial (PrP) and income (PiP) preference levels for all three groups. Similar to the first experiment of the Racial Preference exercise, the comparatively high number of discontent White upper-income households at the beginning of each simulation and the significant decrease in this number by the end of the simulations respectively indicate the high level of segregation of this group, confirming the findings in Chapter 6. In contrast, the significantly smaller number of discontent Black African and Coloured upper-income households and gradual decrease of this number may suggest that these two groups are already predominantly located in desired regions, apart from a small percentage.

The significant decrease in discontent White middle-income households, regardless of a small decrease in PrP and IcP levels, may suggest that a higher level of integration between the White middle-income and other income groups existed initially. Similarly, the White low-income group reflects slight change between the first and second experiments, regardless of the comparatively high PrP level of this group in both simulations, suggesting an initial state of higher segregation. In contrast, the higher number of discontent households of the Black African and especially the Coloured low-income group in the first experiment reflects the level of integration of these groups with their respective middle-income racial groups that was revealed in the income-by-race measurements in Chapter 6.

Generally, the spatial distribution of the income groups for each race reveals enhanced visual clustering between the two experiments, especially for the low-income groups where increased residential mobility in the second experiment allows for a larger region to find more satisfactory location in. The initial spatial distribution patterns suggest that the low- and middle-income households are more integrated for each of the Black African and Coloured groups, but that significant segregation persists between these racial groups. This corroborates the findings of low exposure between the four groups of Black African and Coloured low- and middle-income in Chapter 6. Even though the White low- and middle-income groups are less integrated with each other, both these White income groups are also noticeably segregated from the income groups of the other races.

The spatial distribution of the upper-income (racial) groups reveals an interesting finding in that all three racial groups reside in the same regions in both experiments, even though these regions differ slightly between the two experiments. The only noticeable difference between these clusters is the intensity (number of households) of the White upper-income group being considerably higher than those of the Black African and Coloured upper-income groups. This phenomenon reflects the findings in Chapter 6, in that the upper income groups are racially more integrated than the other income groups.

In combining the parameters of the Racial Preference and the Income Constraint modules, these experiments corroborate the findings of the combined income-by-race segregation measurements of Chapter 6 by revealing finer details regarding the levels of segregation between racial and income groups in the study area. Firstly, the findings of the two experiments of this simulation exercise show that the upper-income group in Cape Town is racially integrated, but significantly segregated from other income groups. Secondly, the low- and middle-income groups are integrated for each of the Black African and Coloured communities, but racially segregated from each other and the White income groups. Thirdly, the second experiment shows that the only degree of racial integration between the Black African and Coloured groups occurs in the suburbs (‘grey areas’) that were integrated even during apartheid. Finally, the results for both experiments reflect a persisting main cluster of high concentration Black African low-income households that remained unchanged, regardless of a significant reduction in both PrP and IcP levels.

9.4 Overall Discussion

The aim of the simulation exercises and related experiments undertaken in this chapter is two-fold. Firstly, it presents an exploratory study of the dynamics of race and income and the role both subjects play in the persistence of segregation in Cape Town. Secondly, it enables the exploration, by means of what-if scenarios, of a city council policy for the promotion of integrated socio-economic urban development.

The empirical application of the District94 model for Cape Town demonstrated an expansion of the Schelling segregation model as exploratory methodology for studying and understanding better the role of race and income in the phenomenon of persistent segregation in Cape Town. Furthermore, the testing of different what-if scenarios enables the exploration of the dynamics of race and income. The implementation of the three modules of the District94 agent-based model allowed for the simulation of racial and income household dynamics, separately and combined, in terms of neighbourhood preference and constraint respectively. This enabled the revelation of varying emergent properties between the separate studies of race and income and the exploration of income by race, which corroborated the segregation measurement findings.

The alignment of these findings between the spatial segregation measurements and simulation model for Cape Town revealed that race still plays a significant role in the persistence of segregation in Cape Town, but that the subject of income is the dominant factor in perpetuating segregation in the study area. This conclusion proves the hypothesis of this thesis that both the subjects of race and income continues to play a role in the persistence of segregation in Cape Town.

Nonetheless, the replication of dynamics in a geographical system remains quite challenging (Heppenstall et al., 2011) and the limitations of the District94 model is acknowledged hereinafter. Although the model represents a geographical (urban) system, incorporating empirical GIS spatial data for the study area, geographical context is limited to the spatial extent of the study area and census enumeration boundaries. The random placement of agents within census enumeration areas also result in the lack of finer scale behavioural data (Batty et al., 2003; Torrens, 2014).

A lower level of abstraction was considered to provide for the ability of theoretical exploration of racial and income dynamics. As the District94 model is an expansion of the Schelling model, the individual consideration and choices of the household agents for desired residential locations are dependent only on the composition of a location's neighbourhood, in terms of race and/or income, and not regarding the nature of the area. Interaction between household agents is also limited to the preference for a specific neighbourhood composition, in terms of race or income. Agent interaction with the simulation environment is limited the identification of residential regions.

The choice of parameters and variables for the model was predominantly aligned and limited to that of the Schelling segregation model but were further expanded on various assumptions, in the interest of enhancing the realism of the model. Firstly, the 'probability of households moving' that allows for only a specified percentage of the total number of households in the study area to be considered for a simulation is a random selection of households across the study area. As empirical data is not readily available on this subject, the percentage specified for this research study was assumed. Secondly, the 'movement radius' at which each racial or income group can search for an alternative dwelling location was based on theoretical findings, concerning the residential mobility of different ethnic and income groups. Finally, the universal 'neighbourhood radius' assumed that households would not only consider the composition of their immediate neighbours in reality when considering how satisfied they are with their residential location, but rather the wider neighbourhood. This composition of a particular neighbourhood is also limited, in that it only refers to either the racial or income group households belong to.

Empirical calibration of the District94 simulation exercises proved to be challenging, due to the lack of relevant empirical data. Consequently, an indirect calibration approach was undertaken whereby theoretical findings and the results from the segregation measurement study were respectively used to identify the behaviour and the degree of preferences or constraints of the household agents. A level of congruence was identified between the simulation results and the results from the segregation measurements, supporting the relevance of the District94 model as an exploratory methodology for studying the dynamics of racial and socio-economic segregation in reality in the city of Cape Town.

Chapter 10

Conclusion

The persistence of urban segregation remains a pervasive and problematic feature of cities, especially in the South African context. As a consequence of entrenched residential segregation by race since its establishment, perpetual socio-economic disparity remains a challenging trait of the contemporary city of Cape Town.

The aim of this thesis is to contribute a better understanding of persistent segregation in the city of Cape Town through an exploration and analysis of the spatial extent of racial and socio-economic segregation and the role these subjects play as driving forces of persistent segregation in the city. This research study facilitates a convergence of expanding research on the measurement of spatial segregation and computer simulation of urban segregation by proposing the combined application of segregation metrics and agent-based modelling techniques for studying racial and socio-economic segregation in a quantitative manner.

This chapter concludes the thesis and is composed of three main sections. Firstly, the main contributions of this thesis are discussed. This is followed by an outline of the limitations experienced concerning the methodologies applied to this research. The third section presents a discussion on potential future work, building on this research study.

10.1 Contribution of the Research Study

The contributions offered by this thesis concern three main subjects. Firstly, further theoretical understanding of the complex and interrelated dynamics of racial and socio-economic segregation in the City of Cape Town was presented. Secondly, a quantitative exploration of racial and socio-economic segregation patterns in the study area was undertaken through the application of spatial indices. Thirdly, the simulation of segregation dynamics (in terms of racial residential preference and economic constraint) was provided through the application of an agent-based model as most suitable tool to explore these dynamics. The following three sections discuss the contributions to these three subjects respectively:

10.1.1 Complexity of Segregation Dynamics in Cape Town

The formulation of a literature review on the complexity of urban segregation in the City of Cape Town in Part 1, which studies both the interrelated and evolving dynamics of racial and economic segregation, presents a contribution in itself as the subject has not been studied in this manner previously. In contribution to the large body of literature on the persistence of segregation in Cape Town, this research offers new perspective by applying a complexity theory approach to study the dynamics of racial and socio-economic segregation and the resulting persistence of the phenomenon.

The consideration of complex system properties such as emergence and self-organisation in the context of urban segregation offers an alternative assessment approach to understanding the complex interrelatedness of the subjects in an urban environment that perpetuates segregation. Hence, the combination of discussions on the dynamics of racial and socio-economic segregation in Cape Town and the complex nature of these dynamics is deemed as useful reference material for future studies on the subject.

10.1.2 Spatial Measurement of Segregation

The review in Chapter 3 of the studies undertaken on the measurement of segregation in the South African context and more specifically Cape Town revealed that these studies mostly concern the aspatial measurement of racial segregation. Consequently, this thesis contributes to this body of work in more than one manner.

Firstly, it offers a spatial measurement of segregation in Cape Town through the application of spatial indices to better understand the dynamics of segregation beyond the boundaries of the geographical units that are applied to measure segregation and also to explore the interaction between the different groups that are studied. These spatial indices also provide the advantage of not only presenting segregation in Cape Town at a global level (summarising the degree of segregation for the whole city), but also local levels of segregation that assumes the spatial change of segregation across the study area.

Secondly, the measurement of segregation not only focussed on the racial groups of Cape Town, but also the different income groups residing in the city. The aim of this exercise is two-fold: to understand the segregation level and distribution of different income groups in the study area and also to enable a comparative analysis with the racial group distribution in the city to identify potential similarities.

Thirdly, the spatial measurement of segregation in Cape Town was also undertaken for the combined dynamics of race and income. Exploring the levels of segregation and exposure between 'income-by-race' groups revealed finer trends in segregation dynamics that were not possible to infer from studying the segregation of race and income separately. Hence, although the levels of racial segregation in the study area were found to be higher than that of socio-economic segregation, the unpacking of these subjects revealed additional dynamics and makes a contribution to existing research on segregation.

A comparison of the findings of these measurements to the historical context of segregation in the study area provides proof of the emergent properties of racial and socio-economic segregation in Cape Town. The segregation measurements for Cape Town also provided a means of comparison for the outcomes of the simulation model.

10.1.3 Agent-Based Modelling of Segregation

Although the dynamics of segregation in the city of Cape Town have been broadly studied in a theoretical and statistical top-down manner (see Chapter 2), hardly any consideration has been given to the complex nature of socio-economic interaction at a neighbourhood scale. Consequently, opportunity existed for this research to formulate a bottom-up approach to explore how spatial segregation patterns at a city (macro) scale are potentially influenced by the complexity of residential decision-making, adaptation and interaction of households at a neighbourhood (micro) scale.

In this thesis, the development of the District94 simulation model for the study area of Cape Town allows for racial and socio-economic segregation to be studied as a complex system through the application of agent-based modelling. It offers a different perspective from which future planning policies and related initiatives could explore segregation dynamics and subsequently formulate more inclusive urban development. Based on the seminal work of Thomas Schelling on segregation modelling (discussed in Chapter 4) and the adaptation of the Schelling segregation model, the District94 model in this thesis contributes a new empirical approach to studying urban segregation dynamics spatially and at a local scale in Cape Town.

10.2 Limitations of the Research Study

This thesis sought to apply, in conjunction, two approaches to the exploration of persistent segregation dynamics in the City of Cape Town. Hence, further to the descriptive presentation in Part I, of the way in which persistent segregation evolved from racial to economic disparity over time, Part II presented techniques for measuring segregation and a methodology of simulation to explore the complexity of persistent segregation. However, both these approaches presented certain limitations in relation to data availability and methodological procedures during the course of the research study. Although these subjects are extensive and intricate detail is beyond the scope of the thesis, this section provides a brief overview of these limitations and their impact on the development of the thesis.

10.2.1 Data Availability

Both the measurement and agent-based modelling of segregation in this thesis was predominantly guided by the availability of relevant data for the study area and effectively also limited by it.

The acquisition of the latest and most relevant census data for Cape Town proved to be a challenging and arduous process. Consequently, the only manner in which this data could be obtained was by receiving the database for the 2011 census for South Africa from Statistics South Africa. This database and related datasets were received on four compact discs by post for home installation and extraction. Further correspondence was then required to ensure that database functionality is understood.

Obtaining the same datasets for the 2001 census in a usable format proved to be more problematic. Although the acquisition of numerical census data on race and income was possible, it was not achievable to attain a combined dataset for income by racial group for the 2001 census during the data acquisition phase of this research study. The GIS dataset for the 2001 census (at sub-place enumeration level) also proved to be unfit for use as multiple geometry discrepancies were identified. These issues impacted the research study, as no potential existed for the execution of a comparative analysis of the census data for 2001 and 2011.

10.2.2 Measurement of Segregation by Income

The application of income data to the study presented limitations that are important for consideration, as discussed in Chapter 6 .

Firstly, the manner in which enumeration was undertaken for household income in the 2011 South African census resulted in the ‘No Income’ classification consisting of both households with no income and households not willing to disclose their income. Consequently, this classification was unfit for use in this study and omitted, resulting in a degree of uncertainty presented in the fact that households with undisclosed income are excluded.

Secondly, although the eleven census income classification brackets were generalised into three categories of low- middle- and upper-income, in accordance with the classification of the 2016 socio-economic profile study for Cape Town by the Western Cape provincial government (Western Cape Government, 2016), it is important to recognise that income in any census is a continuous variable and not discrete such as the variable of race or employment, for example. Therefore, it should be noted that the definition of what constitutes as low-, middle- or upper-income is unclear and would vary, consequently resulting in different outcomes of the measurements undertaken in this study. Consequently, the variable of income only served as proxy for socio-economic status in this thesis.

The conclusions drawn from the segregation measurements that were undertaken in this chapter are based on the assumption that the categorisation applied by the Western Cape provincial government does in fact represent low-, middle- and upper-income households in reality. However, this categorisation reflects a significantly large middle-income category for Cape Town and as a result the measurement findings were impacted in terms of the degree of isolation/exposure of the middle-income group to the other groups and also the influence the middle-income group has on the findings for the other income groups. For example, the level of isolation of the low- and upper-income groups could be underrepresented, due to the size and distribution of the middle-income group.

10.2.3 Exploratory Agent-Based Modelling

It is widely acknowledge that one of the major challenges in agent-based modelling and the simulation of real world phenomena is to progress from the theoretical and experimental application to more empirically-based research (Berger and Schreinemachers, 2006; Janssen and Ostrom, 2006; Stanilov, 2011). Although the simple District94 model is only a small step in this direction, numerous related challenges and limitations were experienced.

10.2.3.1 Modelling Households and Human Behaviour

Agent representation presented the first limitation in modelling households in the study area. The sheer number of households in the study area demanded that only a sample of this total number of households is represented in the District94 model. Thus, the study lacks the possibility of a comparative analysis between the sample population and the population size in reality. It is also acknowledged that sampling presents its own limitations in terms of representing agent behaviour at a basic level. The classification of household agents in terms of race and income is based on the census data provided for the head of a particular household. Consequently, a household with a Black African head would be classified as Black African. The same rule was applied to the level of income of a household's head.

It is important to emphasize that although agents in the District94 model represent households, which in effect are human micro-systems relying on human decision-making to govern behaviour, the decision-making undertaken in the model is simplified and consequently limited, not taking into consideration the complexities of human thinking, subjective decisions or important causal relationships (Crooks et al., 2018). A further limitation is the absence of data on household decision-making and related behaviour, which complicates the processes of model verification and validation.

10.2.3.2 Modelling Geographic Space

For the representation of geographic space in the District94 model the ability to import GIS data for the extent of the study area, the residential zones and the respective census areas provided a great benefit. However, the application of GIS data to incorporate geographically explicit space to the District94 model presented a number of limitations.

The pixel-based foundation of the agent-based model's simulation environment does not represent vector data effectively. Issues were also experienced in terms of depicting aerial census units that are smaller than a single grid cell. Furthermore, the introduction of agents to the relevant geographic areas in the model environment presents limitation in the sense that the grid cells contained in a census area do not represent the detailed layout of the same census tract and related residential units in reality. Consequently, even though the correct sample of households is assigned to its relevant census area, the introduction of agents to these areas occurs randomly with several agents potentially present in a single grid cell. This effectively reflects the same problem of aggregation in studying census data spatially.

The consideration of scale posed another limitation in the construction of the District94 model. Given the fact that the spatial segregation measurements in Chapter 6 were undertaken at a metropolitan city-wide scale and the intention is for the model outputs to be studied in conjunction with these measurements, an exploratory agent-based model had to be constructed for a large (metropolitan) scale residential system. Little guidance was available in the development of the model, as these larger scale systems are still fairly rare (Benenson et al., 2002; Mathevet et al., 2003). Consequently, the modelling of larger scale dynamics based on a more detailed representation of processes at a smaller scale were simplified. Ettema et al. (2005) emphasized the fact that such an undertaken will pose various other challenges in terms of data and model architecture.

10.2.3.3 Model Evaluation

It is widely acknowledged that the evaluation process of agent-based models is very challenging and there is also no formal methodology for the evaluation of agent-based models and the description of related processes and terminologies. Furthermore, the evaluation procedure of models often requires adaptation to a particular application and relies heavily on data availability and knowledge of the system.

As discussed in Section 4.4.1, the fact that the model is a simplification of reality makes it impossible to exhibit all the characteristics and dynamics of the system and phenomenon of segregation in reality. Another challenge was the difficulty in acquiring suitable data for a systematic validation approach (see Section 10.2.1). The lack of usable numerical and spatial (GIS) data for the census year of 2001 did not allow for the undertaking of an efficient validation process.

10.3 Future Work

Throughout the development process of the research in this thesis, various opportunities for future work became evident. This section considers the potential work that can be undertaken beyond this research study.

10.3.1 Segregation Measurement Expansion

10.3.1.1 Segregation Measurement over Time

The limitation of efficient data for the census year of 2001, as discussed in the previous section, is a major subject for consideration, due to the fact that it constrained options for the analysis of segregation in the study area and also the undertaking of a sufficient model validation process. The most important subject to expand on in future is the acquisition of satisfactory data for the South African census year of 2001, which will allow for the measurement and exploration of racial and socio-economic segregation over time in the city of Cape Town.

Consultation with Statistics South Africa (the national statistical service of South Africa) will ensure that the relevant numerical census data is obtained in terms of race and income by household (at sub-place level for 2001), especially for an analysis of the combination of income by race. Furthermore, the issue of multi-patch census tracts needs to be addressed in the 2001 census data. For example, where several detached census tracts represent one census tract code. This occurrence will prove to be problematic for the spatial measurement of segregation that is applied in this thesis, as this method relies on the establishment of a census tract centroid from which bandwidths are generated (discussed in Section 3.2.2).

10.3.1.2 Segregation Measurement of Income

The limitations presented in Section 10.2.2 on the application of income data and subsequently the measurement of income segregation provides for further consideration. Firstly, additional analysis of the 2011 census data is required to minimise the uncertainty presented by the 'No Income' classification, which consists of both households with no income and households not willing to disclose their income. Census indicators such as employment status and housing (dwelling type) and also general household surveys, undertaken by Statistics South Africa, will be useful in establishing whether households have no income.

Given the fact that income only serves as proxy for socio-economic status in this study, methodologies should be considered to mitigate the limitations presented in the measurement of income and related comparability over time. Socio-economic status could be established through the measurement of census indicators, such as education, income and occupation. In addition, a longitudinal study will benefit from the application of data from the South African National Income Dynamics Study (Department of Planning, Monitoring and Evaluation, n.d.), which would allow for the analysis of socio-economic class and also economic mobility.

10.3.1.3 Segregation Measurement of other South African Cities

The occurrence of racial and socio-economic segregation is not unique to Cape Town. Due to the shaping of the South African city by the dynamics of forced historical division, the phenomenon of persistent segregation is also evident in other cities in the country. A valuable contribution to the exploration of racial and socio-economic segregation will be to apply the methodologies of segregation metrics and related simulation to the City of Johannesburg especially. Johannesburg does not only provide a different spatial formation that would present varying results, but theoretical background reflects that it is also inherently a more racially integrated city than Cape Town.

The acquisition of numerical and spatial census data for the City of Johannesburg, similar to the racial and income census data obtained for Cape Town, will allow for the spatial measurement and modelling of racial and income dynamics in Johannesburg and a comparative analysis with Cape Town to be undertaken.

10.3.2 District94 Model Expansion

Further to the completion of the development and implementation of the model architecture, opportunity exists for the extension of the model, especially concerning the model environment, agent properties and interaction variables. The following subjects were considered, in terms of their relevance as extended features to the current District94 model:

10.3.2.1 Introduction of Dwelling Types

Although the current model consists of residential areas, potential exists for the addition of dwelling types and consequently dwelling size (as a property). The application of single residential, general residential and mixed-use information will provide for the specification of single detached properties, group housing and flat residences respectively. This will allow for the opportunity to explore how households potentially upgrade their living arrangements over time, which is a factor that might influence their decision-making.

10.3.2.2 Introduction of Neighbourhood Characteristics

In order to formulate simulation experiments that are best suited to assist city authorities in the reduction of segregation, specific externalities could be incorporated into the model to provide an incentive for certain groups to move to more integrated neighbourhoods. It is not only important for the local government to alleviate economic constraints, but also to promote social integration. To study economic restrictions, racially mixed housing projects such as Delft South (Oldfield, 2004) and Westlake in Cape Town, where the lives of racially mixed inhabitants are based locally in terms of economic, physical and social space (Lemanski, 2006d), could be introduced to simulation experiments.

Lemanski (2006d) highlighted that residential space is not the only sphere of social and racial change in post-apartheid South Africa and that contexts such as schools, churches and shopping centres offer spaces for integration. Ibraimovic et al. (2017) found that, beyond racial preferences, different racial groups reflect different sensitivities to location characteristics. For example, the quality of schools strongly influences the neighbourhood choices of all racial groups in Cape Town, while the negative effect of crime on neighbourhood choices impacts Black Africans particularly (Ibraimovic et al., 2017). The importance of homophilic preference and whether it could be reduced could thus be studied through the introduction of these factors to a simulation experiment.

The above is encapsulated in the suggestion by Ibraimovic et al. (2017) that preferences for both ethnic and non-ethnic location characteristics should be applied to agent-based models, which describe agent behaviour rules over their decisions of residential location. The conclusion that a high degree of heterogeneity in ethnic preferences show a degree of willingness for racial residential mixing advocates the need for ethnic preferences to be considered in the formulation of policies for improved racial integration. Hence, the authors suggest that these models would be useful for testing different policy measures, the development of different scenarios and predicting its impact on future dynamics of ethnic segregation (Ibraimovic et al., 2017).

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10.3.2.3 Exploration of Urban Expansion

The introduction of real data for various planned development scenarios will allow for the potential testing of changes in household movement dynamics. Hence, different future development projects may be introduced at the setup stage of the model and the potential change in household decision-making compared to the current urban residential footprint of the District94 model.

10.3.2.4 Household Dynamic Expansion

The dynamics of the study area's population can be expanded through the implementation of life cycle evolutionary processes (birth and/or death occurrence). This may tie into the introduction of dwelling types and sizes, as the large household (family) may seek a larger dwelling than the potential apartment choice of the young or elderly couple.

Although the interaction structure of the District94 model is localised, with the happiness and preferences of households depending heavily on their immediate surroundings at any stage, the potential exist for a more non-localised approach. For example, households may form communication networks whereby they are potentially informed of more satisfactory neighbourhoods elsewhere in the study area and not in their immediate surroundings.

The heterogeneity of household agents may be extended through the addition of variables that differ across the population. The heterogeneity in residential preferences of households will significantly affect the simulation outcome. Hence, the decision-making dynamics of the large family household (potentially seeking a large dwelling) may differ extensively from the household of a young professional couple (potentially seeking a smaller apartment close to business or commercial node).

Although the District94 model draws on the theory of stochastic dynamical systems by varying the preferences of different groups, further stochastic variants may be introduced. This can occur in the form of probabilistic spatial architecture where binary neighbourhood acceptance is extended with the potential for closer neighbours having a stronger effect on household decision-making than ones further away.

The simplified decision-making processes applied to the District94 model limits consideration of the complexities of human thinking and subjective decision-making. The enhancement of human decision-making could be considered through the potential application of a behavioural framework. Crooks et al. (2018) highlight that the role of theory and the manner in which agents are represented in a model are both connected to the embedded actions and behaviours of agents. The authors argue that the application of behavioural frameworks, whereby the behaviour (specified by a relevant theory) is built into the agents, is not sufficiently considered by modellers.

10.3.3 Model Evaluation Enhancement

Overcoming the limitation of inefficient census data from 2001, as outlined in Section 10.3.1.1, will also allow for a more sufficient model validation process. Model validation is the process undertaken to ensure that the output of the simulation is a suitable representation of the real system and thus considers whether the model dynamics are similar to the dynamics observed in reality (Gilbert, 2008; Feitosa, 2010). A set of experiments could be undertaken to provide retrospective validation of the model by simulating the segregation dynamics of Cape Town during the period of 2001-2011. The objective of retrospective experiments is to replicate past states of the studied system based on retrospective data and thus calibrating a model by tweaking its parameters in a manner that would reproduce a known (past) state of the system (Feitosa, 2010).

10.3.4 Model Application to other South African Cities

Although the dynamics of persistent segregation in the City of Cape Town formed the scope of this thesis, similar dynamics are evident in other South African cities. An extension of the exploration processes of the thesis (in terms of modelling racial and socio-economic segregation) towards other South African cities will present an interesting study to accompany the segregation metrics study of these cities. Furthermore, adaptation of the model to explore similarities and differences between the South African context and other Third World cities may add value to the exploration of the phenomenon of segregation and the persistent nature thereof.

10.4 Closing Summary

This study contributes to an existing body of exploratory quantitative research on persistent urban segregation through the combined application of spatial segregation metrics and agent-based simulation. The analysis of the subjects of race and income in this manner presents a new perspective on the complex dynamics of the phenomenon of persistent segregation in Cape Town, especially concerning the role played by race and income in persistent segregation.

The work undertaken in this thesis contributes to the ultimate goal of enhancing understanding of the extent to which residential segregation is being perpetuated by race and income in the city of Cape Town. Through the measurement and analysis of the distribution and spatial relationship of racial and socio-economic segregation in the city. Applying spatial segregation indices to unfold the combined dynamics of racial and socio-economic segregation in Cape Town revealed that although segregation remains predominantly racial, income disparities contribute significantly to the persistence of segregation and add complexity to the phenomenon. This was particularly evident in the occurrence of racial diversity being limited to the upper-income communities, while the middle- and lower income groups are racially more segregated.

The development of a spatial agent-based model for Cape Town provided for the exploration of the dynamics of persistent segregation and how race and income contribute to this phenomenon in the study area. The District94 model contributed to the (static) analysis of the segregation indices by offering an adaptation of the Schelling segregation model, enabling the exploration of dynamic rules producing racial and socio-economic segregation patterns. Furthermore, the discovery of emergent distributional patterns of income groups by race incite further exploration.

Although the spatial measurement and agent-based modelling of segregation in this thesis presented a simplification of very complex dynamics in reality, it allowed for a different approach to the quantitative examination and analysis of dynamic processes of segregation in Cape Town. This thesis demonstrates that, while segregation in Cape Town is a legacy of the exclusionary mechanisms of apartheid, contemporary processes of segregation can only be completely understood by looking at the combined effect of race and income.

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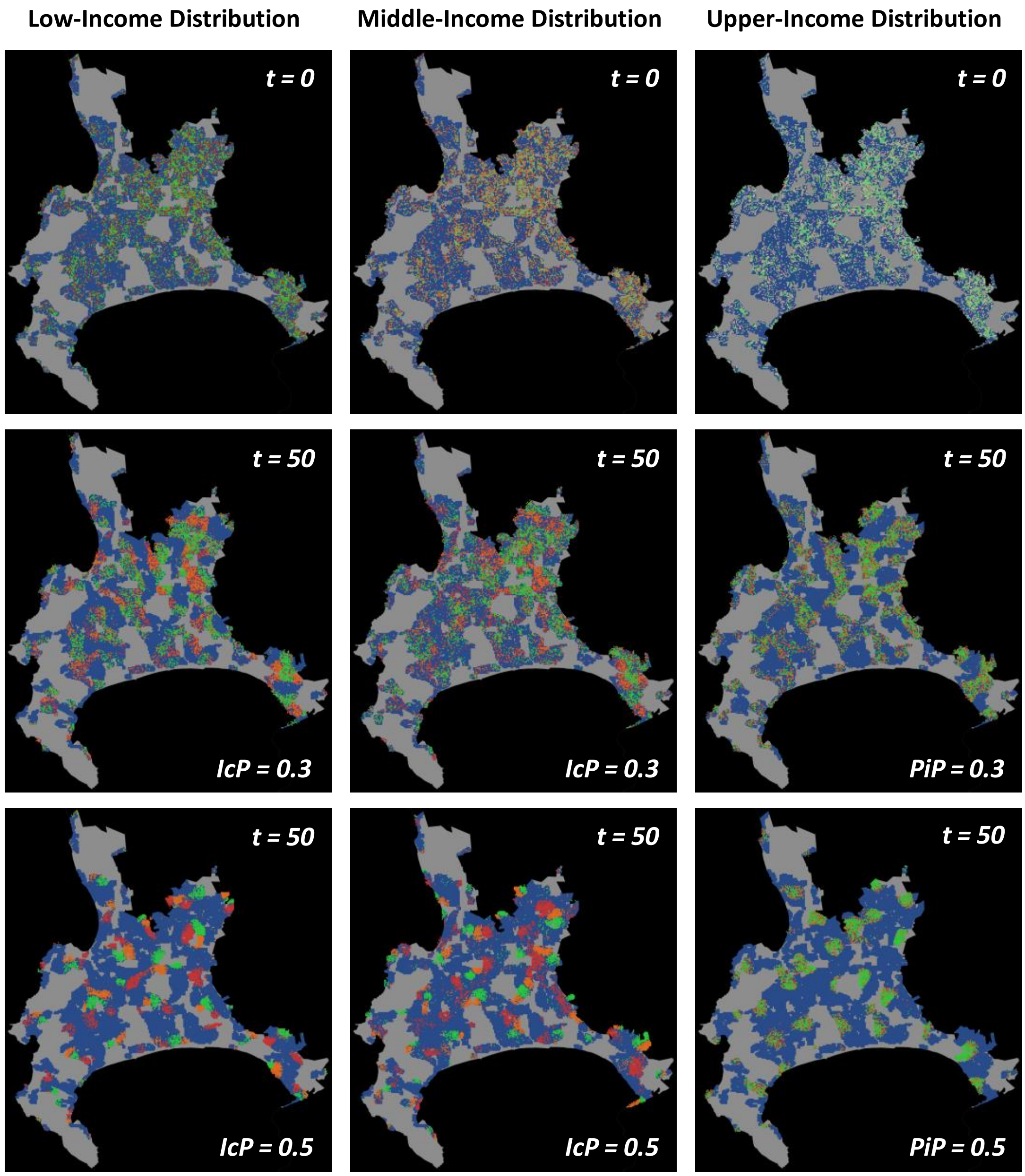
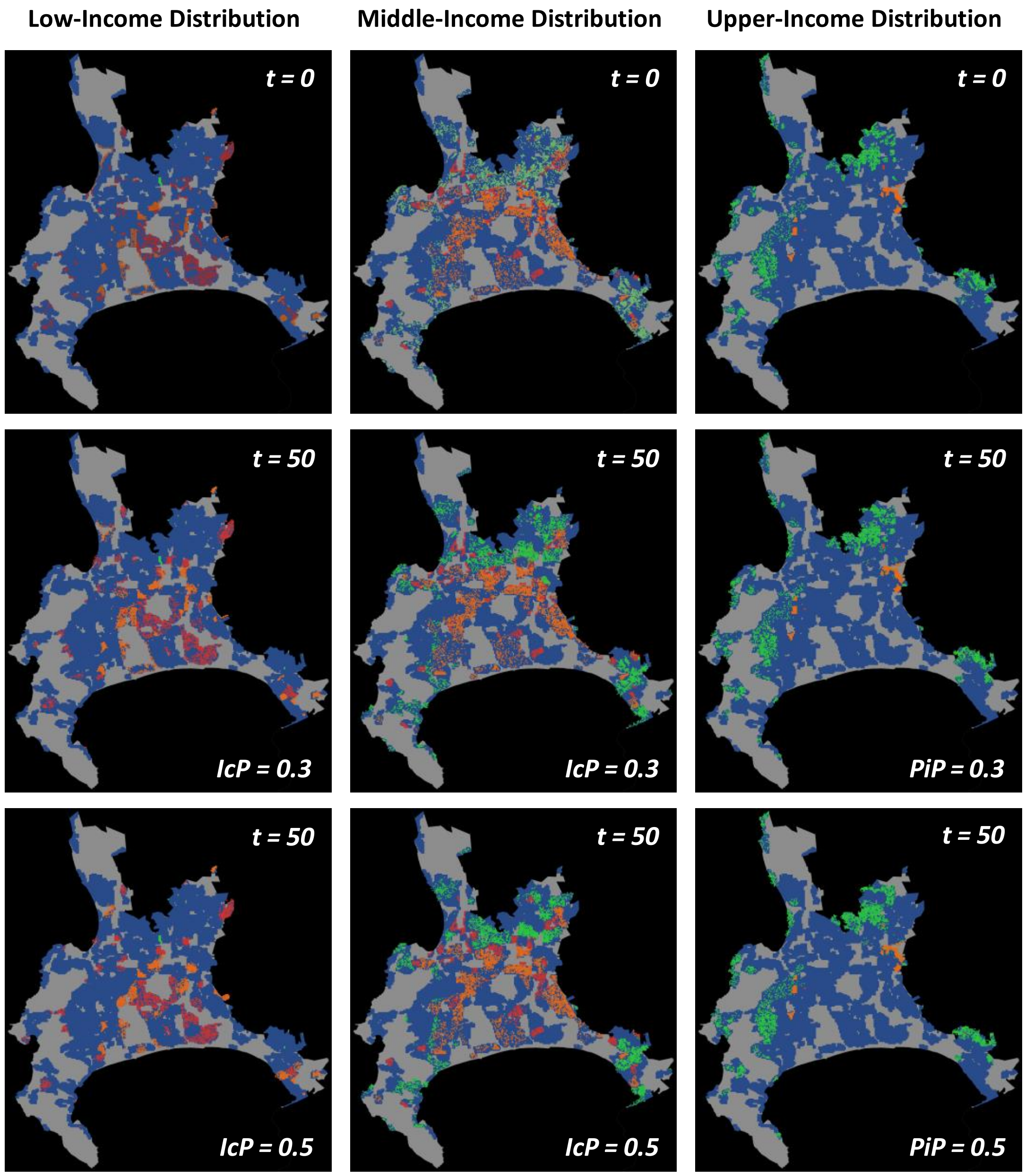
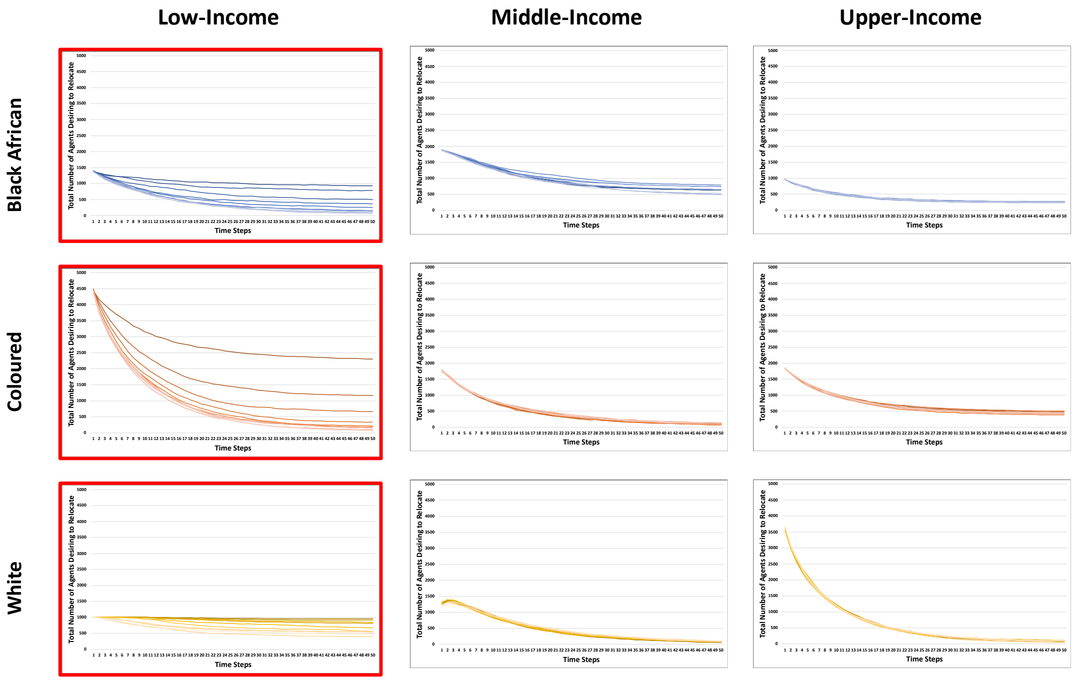
Appendix A - Initial Conditions Sensitivity Analysis for Racial Income Module (Complete Integration)



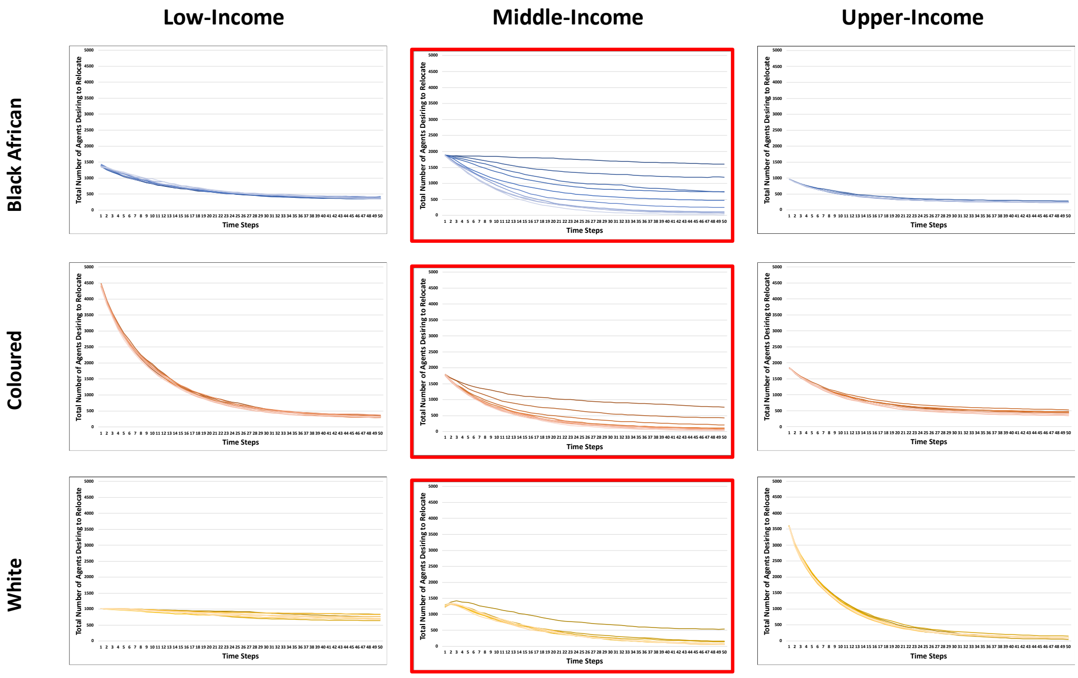
Appendix B - Initial Conditions Sensitivity Analysis for Racial Income Module (Complete Segregation)



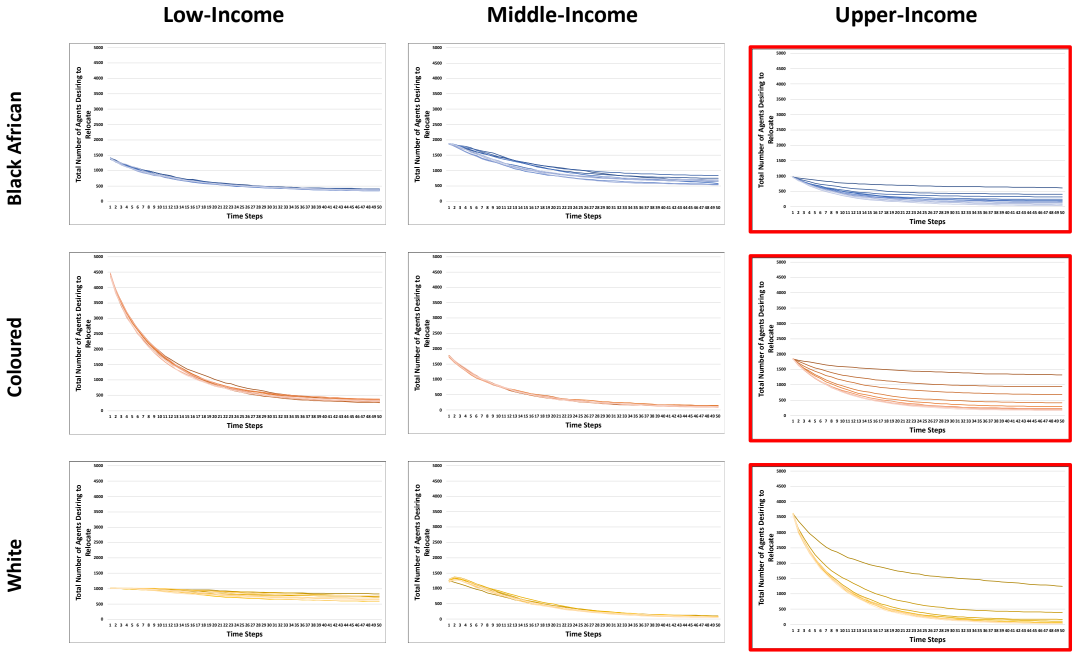
Appendix C - Residential Mobility Sensitivity Analysis for Racial Income Module (Low-Income)



Appendix D - Residential Mobility Sensitivity Analysis for Racial Income Module (Middle-Income)

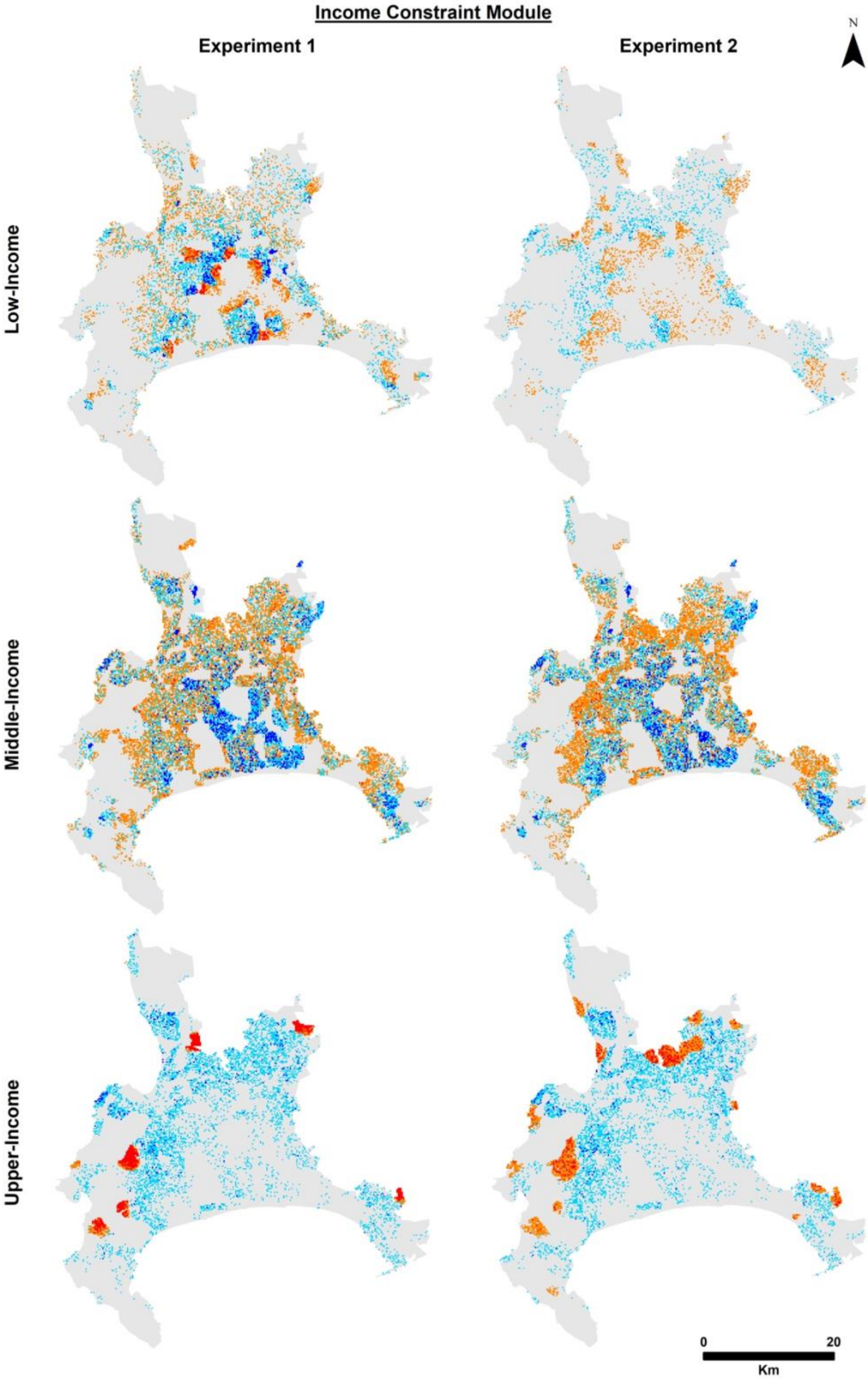


Appendix E - Residential Mobility Sensitivity Analysis for Racial Income Module (Upper-Income)

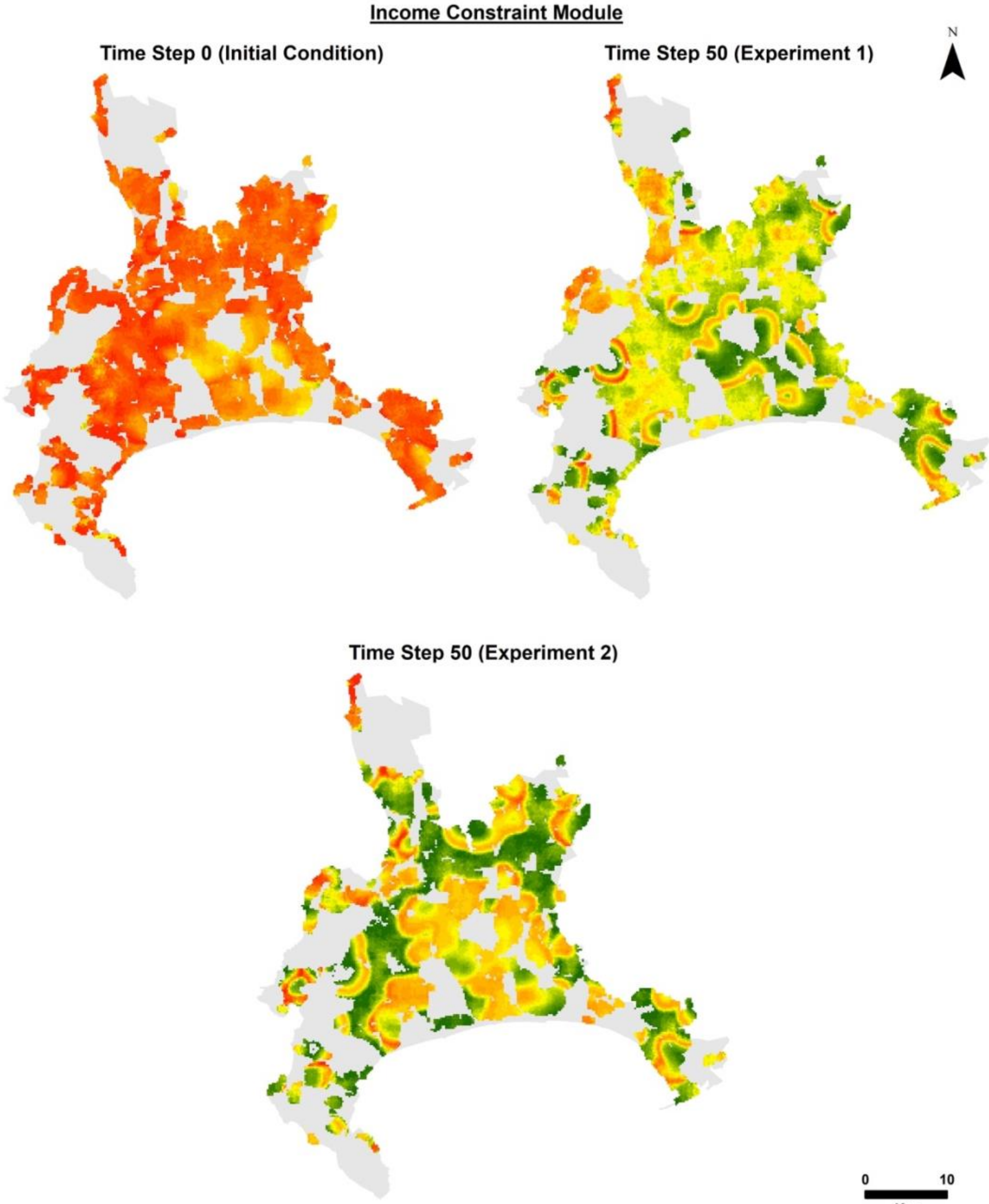


Appendix F - Spatial Entropy Level Change for Racial Preference Module

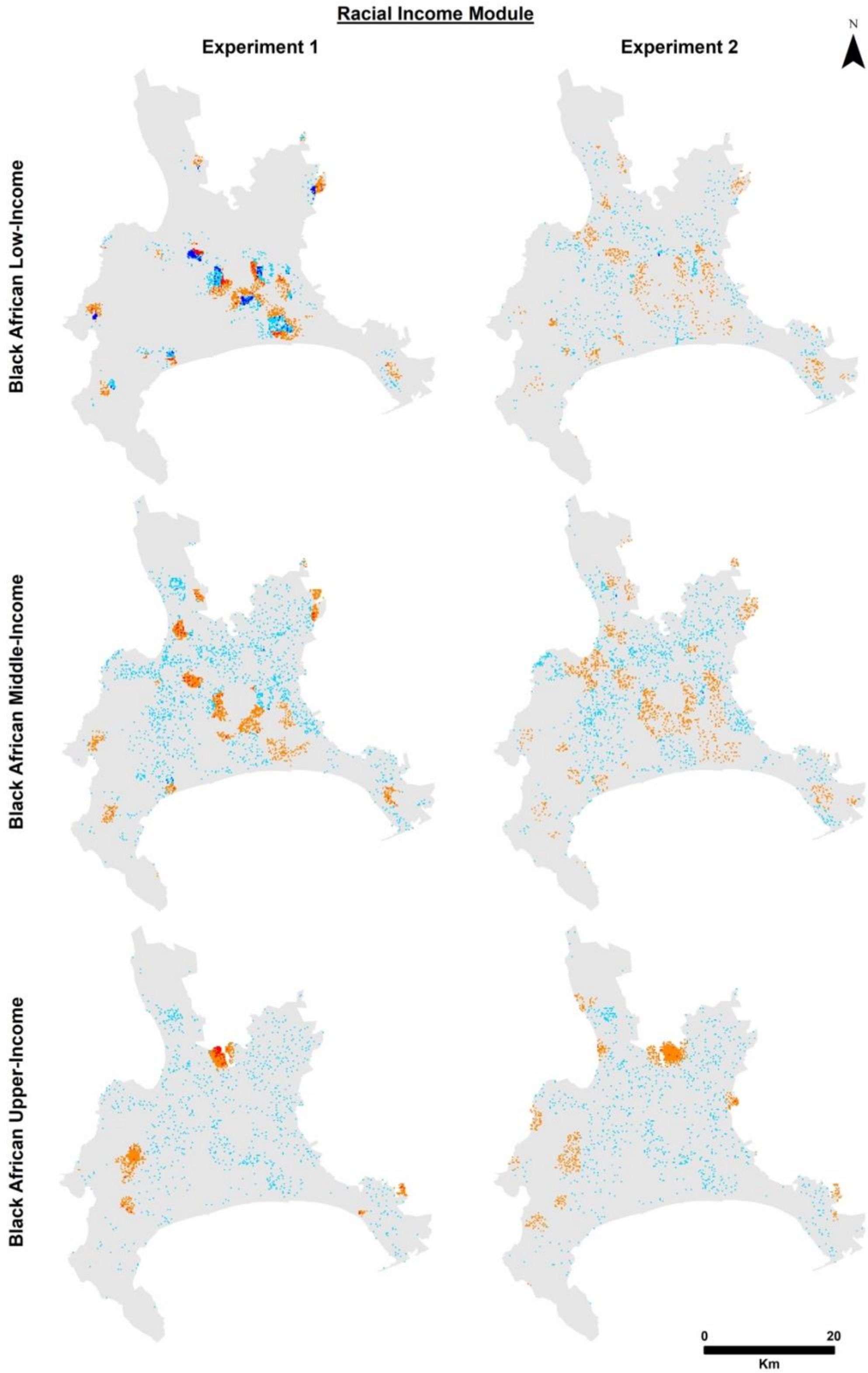
Appendix G - Spatial Distribution Change for Income Constraint Module

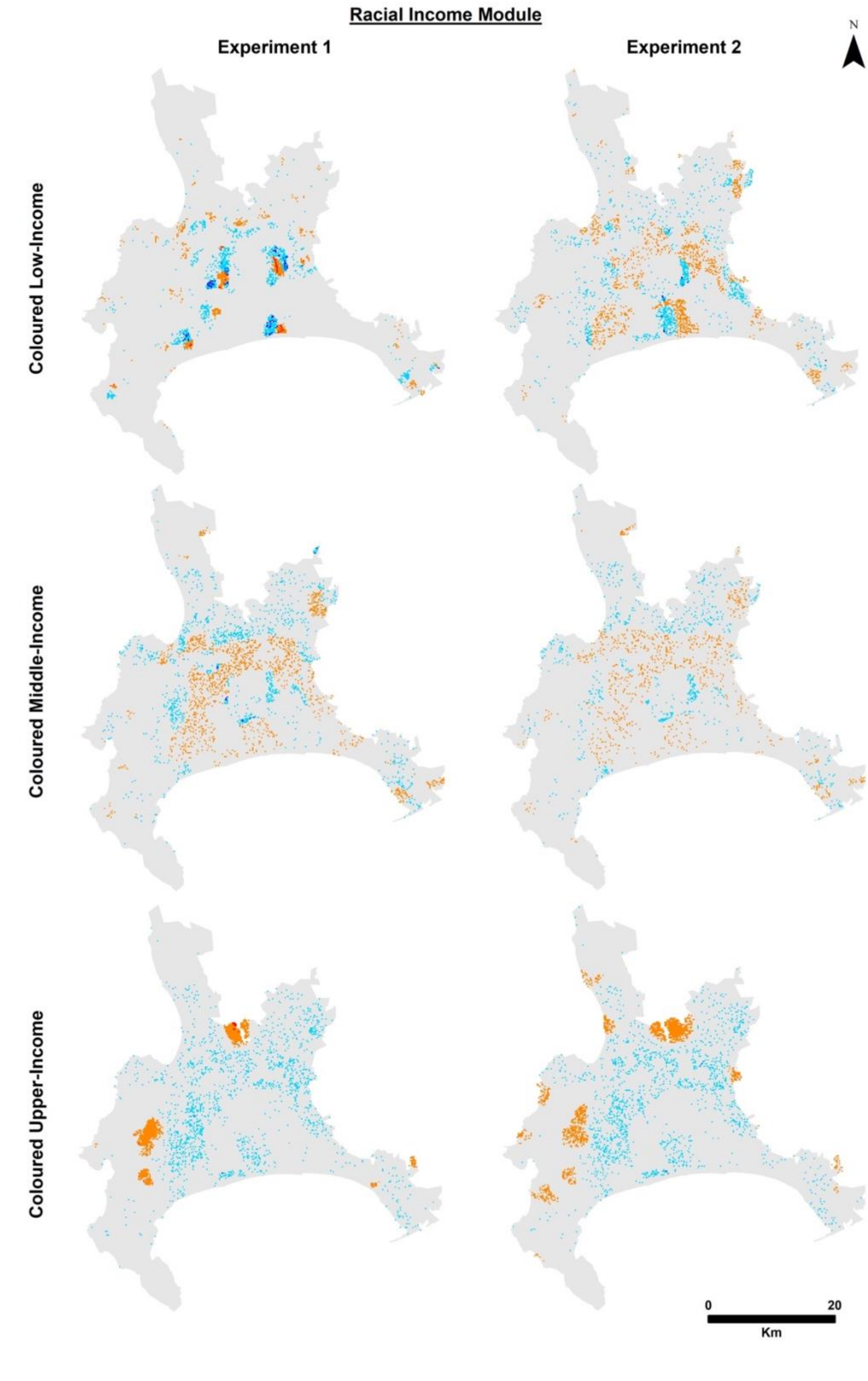


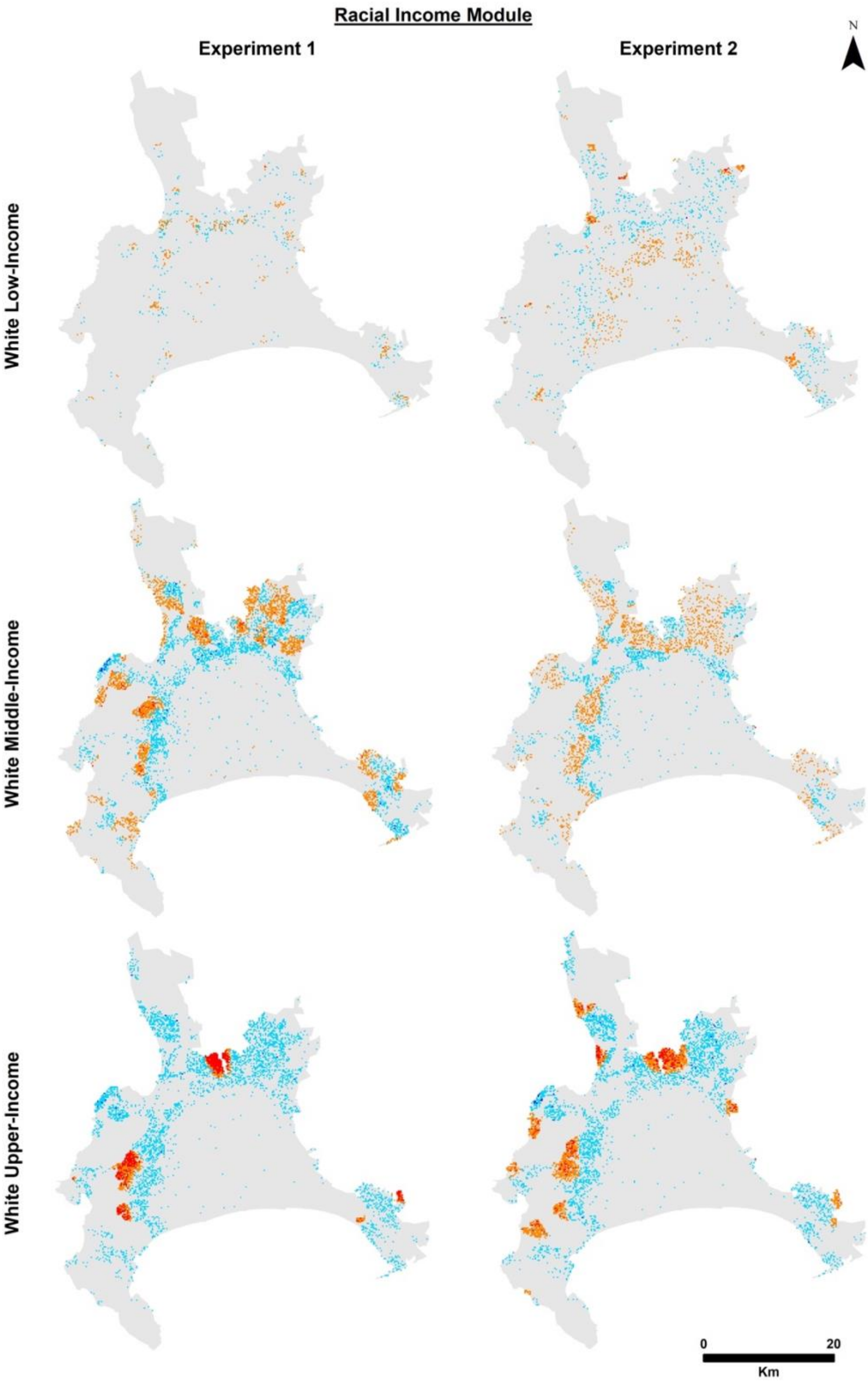
Appendix H - Spatial Entropy Level Change for Income Constraint Module



Appendix I - Spatial Distribution Change for Racial Income Module




Racial Income Module
Experiment 1
Experiment 2
N
Coloured Low-Income
Coloured Middle-Income
Coloured Upper-Income
0
20
Km



Racial Income Module
Experiment 1
Experiment 2
N
White Low-Income
White Middle-Income
White Upper-Income
0
20
Km

Appendix J - Spatial Entropy Level Change for Racial Income Module