A Geographic Information Systems and Cellular Automata-Based Model of Informal Settlement Growth

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Abstract

There exists a vital need to increase our understanding of the fast-growing informal settlements (IS) within the burgeoning mega cities of the less developed countries. Previous attempts have used descriptive speculation about underlying social, political and cultural forces, but they have not generated sufficient understanding to underpin useful and effective management policies. The result has been the piecemeal application of planning procedures and IS policies that were developed elsewhere, in developed nations. This thesis explains why such methods tend not to work within developing countries.

Nevertheless, recent progress in studies of complex urban systems conducted in developed countries, combined with the power of modern computer simulations, facilitates new insight into the dynamics of developing nations' IS. Accordingly, this research utilises a cellular automata model, which is formally joined to a Geographic Information System (GIS), to better simulate the spread of informal settlements in Yaoundé, Cameroon.

Similar approaches have been used, in part, to model the spread of planned settlements in cities such as Marseilles, Cincinnati, San Francisco, Washington/Baltimore and Lisbon, but they are unsuited to the capture of important dynamics and nuances of informal settlement growth within less developed countries. By contrast, the operational model proposed in this research is directly focussed upon the developing country context, and so can potentially lead to better understanding of the dynamic processes involved and the development of more systematic and effective policies for managing them.

Specifically, the proposed Informal Settlement Growth Model uses GIS to capture, generate and visualise spatial and temporal information, and then combines with a cellular automata program, in the form of a Visual Basic macro attached to a spreadsheet, to model informal settlement dynamics and so predict their future growth patterns. The model is innovative, free, entirely transparent, flexible, relatively simple and, consequently, laden with potential for furthering our understanding of the daunting informal settlements problem.

Statement of Originality

This is to certify that

(i) the thesis comprises only my original work towards the PhD except where indicated in the Preface,
(ii) due acknowledgement has been made in the text to all other material used,
(iii) the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Remy Sietchiping

Preface

Referred papers published and unpublished papers presented at conferences during the candidature as a result of the Ph.D research:

Refereed Papers

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List of Abbreviations

ANUDEM: Australia National University Digital Elevation Model

ASCII: American Standard Code for Information Interchange

BSQ: Band Sequential

BIL: Band Interleaved by Line

CA: Cellular Automata

CAM: Cellular Automata Machine

DEM: Digital Elevation Model

DUEM: Dynamic Urban Evolutionary Modeling

ESRI: Environmental Sciences Research Institute

FTP: File Transfer Protocol

GIS: Geographic Information Systems

INC: Institut National de Cartographie du Cameroun

IS: Informal settlement (s)

ISGM: Informal Settlement Growth Model

LDC: Less developed Country (ies)

LTM: Land Transformation Model

LUCAS: Land Use Analysis Systems

LUD: Developable Land Units

METROPILUS: Metropolitan Integrated Land Use System

MCE: Multi Criteria Evaluation

MIT: Massachusetts Institute of Technology

NGOs: Non Government Organisations

OOP: Object-Oriented Programming

RMS: Root Mean Square error

TIN: Triangulated Irregular Networks

TM: Thematic Mapper

UGM: Urban Growth Model

UNICEF: The United Nations Children's Fund

UNCHS: United Nations Centre for Human Settlements

USGS: United States Geological Survey

UTM: Universal Transverse Mercator

VB: Visual Basic

WHO: World Health Organisation

Chapter 1

Introduction

1.1 Research problem

The world population has more than doubled in the last 50 years, from 2.52 billion in 1950 to 6.3 billion in 2003. According to the United Nations Populations Division (2003), the world population will reach 8.9 billion by 2050, with 85% living in Less Developed Countries (LDC). In general terms, LDC are "late comers to the industrialisation process. They usually lack resources, savings and entrepreneurship, while having an oversupply of labour" (Sutiprapa, 1997, p.5). In this research, the terms 'Third World', 'Less Developed Countries' and 'Developing Countries' are used interchangeably. They all refer to the same type of national economy, "one that has yet to fully industrialise and where a large portion of the population continues to live in poverty. Inhabitants are likely to be very poor, perhaps living in a jerry-rigged shanty town-without benefit of water, sewers, or electricity-or maybe in slightly better, but still impoverished, accommodations" (Kaplan *et al*., 2004, p.399).

The United Nations Populations Division (2003) estimates that 98% of the world population growth is occurring in LDC. The rapid population growth and its concentration in cities are changing the spatial distribution of human settlements. This rapid urban phenomenon is particularly common in LDC in Africa, South America and the Asian continents. Africa for example, a continent where the vast majority of countries are considered 'less developed' has the highest regional population growth rate with 2.2% *pa* compared with the total world annual average of 1.2% pa. African countries will also account for 22% of the world's future population and by year 2050, will host 55%. However, even within these less developed continents, there are differences between the urban growth rates that highlight the rapidly changing and precarious situations some countries find themselves faced with.

A further significant feature of current and predicted human settlement is that most of it is occurring in urban areas, which absorb 98% of total growth in LDC. Significantly, more than 80% of new settlements fall into the informal category. That is, new settlements in urban areas which are essentially unplanned and do not respect formal planning regulations and markets (de Soto, 2000). These population and urban growth trends will enhance the exponential expansion of urban landscape and will also make the sustainable organization of the built environment more complex in cities. Research suggests that population growth and the subsequent associated spatial spread of the urban form will generate a predominantly self-replicating and uncontrolled growth that will only enhance the tendency of informal settlements (IS) to expand (Kaplan *et al.,* 2004).

The proliferation of informal settlements constitutes one of the most complex and pressing challenges facing developing countries. Some would argue that it represents a new urbanization challenge for cities in LDC (UNCHS, 1986; Satterthwaite, 2001; UN-Habitat, 2003). That is, 30-60% of urban settlements in LDC are informal (UNCHS, 1996; Fekade, 2000) and up to 80% of new settlements are created outside the official guidelines. Such guidelines, however, are often themselves ill equipped to address such rapid changes to the urban landscape. Furthermore, research shows that living conditions in IS are causing a direct and daily threat to the well being of the entire community and thus creating cities defined by poverty and often violence (Amis, 1995; Hope, 1996; Pugh, 2000; Jenkins, 2001).

It is clear that IS require greater recognition and improved responses. There is, however, a gap in the literature on understanding the future expansion and management of IS. In particular, the policies and tools available to predict their spatial extension and thus assist with important planning responses are limited (Abbott, 2002a). These limitations raise two important questions. First, where will the ongoing influx of people in LDC cities be settled? Second, what are the tools that can assist urban planners to respond adequately to the influx of people and the consequences their presence has on the landscape and urban form? While planning must be coupled with strong democratic governance and economic and social prosperity, it is a vital component in securing and creating sustainable cities.

To begin to answer these questions regarding the prospective expansion of IS and the challenges facing urban planners, it is important to briefly consider the processes and actors contributing to the proliferation of IS in LDC. Part of the issue is that in most LDC, the main instigators of informal settlement in urban spaces are local populations, (up to 92%) rather than the public sector or development agencies (Pettang, 1998). The rural incoming populations, for instance, create their own spaces, as no other housing is affordable or accessible. In doing so they disrupt, challenge and ignore town-planning routines and layouts. Another aspect of the complexity that defines IS is the apathy in public sector urban management practices. Additionally, it can be argued that the failure of city authorities to provide the necessary infrastructure and services for the effective development of adequate housing has caused informal dwellings to proliferate (Fekade, 2000). Such rapid and uncontrolled proliferation can therefore be articulated as the grassroots responses to settlement shortages in urban areas. In many LDC, it is almost as if the authorities are unprepared to face the significance of the problem and its effect on the future of cities (Smart, 2001). The decision-makers are unable or unwilling to provide the appropriate response to the settlement needs of many city dwellers. As a result, cities have rapidly expanded outside the planning context, making between 30% and 60% of urban areas in LDC 'informal' (Amis, 2001; UN-Habitat, 2001). Furthermore, city dwellers *design* their own settlements as they find themselves outside, or unrecognised by, formal planning regimes. This leads to massive demand for urban infrastructure, transportation and services.

So far, addressing IS has been dominated by quick-fix approaches (Jacopsen *et al*., 2002), whereby the strategies and policies implemented do not take into account the multiplication of similar IS patterns in the periurban areas. Current practices and strategies to respond to the expansion of IS are ineffective in the sense that they fail to curb or stop the proliferation of slums. Such inability, therefore, suggests the exploration of new approaches or tools that urban planners can use to improve the understanding and management of informal settlement growth.

The planning and development challenges posed by IS in LDC cities require new and innovative approaches. Previous and current research on IS in LDC are mostly descriptive and fail to consider the development of predictive approaches to anticipate the growth patterns of IS in order to design appropriate response and long term strategies to improve the management of fast growing cities (Abbott & Douglas, 2003). In this way, it could be argued that in LDC, the study of rapid urban changes suffers from a global and projective short-sightedness (Jenkins, 2001). Whilst this is partly due to the lack of research and implementation techniques, insufficiency and mismanagement of the resources allocated for planning and management purposes have also played an important part in the deterioration of the situation.

As a result, difficulty in recognising and predicting IS patterns and scale cries out for a new IS appraisal approach. An ideal illustration is Yaoundé, the capital city of Cameroon, which is growing rapidly and where unplanned developments are the rule and planned developments the exception. With more than 75% of urban areas recognised as informal, and 97% of new constructions being instigated by the informal sector (Pettang, 1998), there is a clear indication of ongoing expansion of IS in Yaoundé. In the context of Yaoundé, as in many other cities in LDC, town planning instruments are lacking, obsolete, and out of context. With the help of technology, new urban planning strategies incorporating IS could be designed, with emphasis focussed on criteria pertaining to the existence of IS and the development of scenarios of future (possible) distribution of slums.

Despite the *informalisation*[1] trend of urban areas in LDC, little has yet been done about developing a comprehensive predictive model of future distribution and expansion of IS. Although some studies have looked at ways in which urban dynamics in Developed Countries (DC) can be simulated and modelled by means of modern techniques, few studies investigating and reflecting the urban dynamics in the unplanned context of LDC have been reported. This represents a serious gap in both the literature and the application of urban planning in understanding and handling the unplanned developments and the living space of the majority of city dwellers in LDC. The informalisation of urban areas in LDC will become increasingly difficult to study and manage if traditional tools and methods are not replaced by new approaches.

[1] In this study, I will use the term *informalisation* to refer to the process of rapid expansion of IS in cities in LDC.

1.2 Aim and scope of the research

In light of the above discussion, this research aims to develop a new model capable of simulating the future expansion and distribution of IS in LDC. Whilst IS are the dominant urban landscape in LDC and exhibit complex unplanned features, understanding their characteristics and patterns has been limited, as discussed above, by the descriptive approaches and static representations adopted by much research and contemporary urban planning. One way of gaining a better insight into IS processes, behaviour and dynamics, however, is to embrace modelling technologies which use past and current IS patterns, physical and socio-cultural factors that generate IS patterns, then explore scenarios of future distribution (Torrens & O'Sullivan, 2001).

While it is recognised that models have their limitations in fully representing the complexity and contemporary nature of IS, new technologies, particularly computational and simulation techniques, offer possibilities to develop more relevant urban tools that can provide new insights into more complex geographical problems such as IS. It is recognised, for example, that a model cannot sufficiently capture all facets of political response to these situations nor policy approaches that might affect the expansion or management of IS. Nevertheless, recent progress in the study of complex urban systems and the increase in the power of the computer in modelling, offer opportunities to bring new perspectives into the study of IS. For instance, the Cellular Automata (CA) method in combination with Geographical Information Systems (GIS) has been used to analyse the urban dynamic processes in planned cities of developed countries. These technologies were usefully applied to model developed country cities such as Marseilles in France (Meaille & Wald, 1990), Cincinnati (White & Engelen, 1993), San Francisco Bay Area (Clarke *et al*., 1997), the Washington/Baltimore corridor (Clarke & Gaydos, 1998), Guandong province (Yeh & Xie, 1998), and Guanzhou province (Wu, 1998a). In this thesis, I wish to argue that with appropriate modifications, a similar approach and principle can be implemented to explore the dynamic process of IS in LDC.

Specifically, this research aims to integrate GIS and CA to investigate how IS in LDC emerge and grow. Two broad approaches will be used. First, the application of a GIS approach will seek to study the retrospective trends of IS. Second, a Cellular

Automata (CA) method will be used to calibrate historical growth patterns and to simulate future development processes. Since GIS often exhibits static features in the outcome of the model, the integration of dynamic CA properties will seek to build more relevant representations of IS which reflect the reality of fast changing urban landscapes in LDC. In particular, the goal of this integration is to achieve a more realistic predictive model of the future expansion of unplanned growth to assist urban planners and government understand and plan to reduce the growth of IS and ameliorate the associated economic, social and health issues.

The research will therefore propose an *Informal Settlement Growth Model* that will contribute to affordable strategic IS planning and management solutions. Specifically, the integration of GIS and CA may help in the simulation, visualization and modelling of unplanned settlements in LDC. This research will show that the dynamic visualisation of the simulation results will improve the understanding of how IS emerge and grow, and therefore provide more information for the better anticipation of servicing, economic opportunities and infrastructure responses before the emergence of IS. Ultimately, the application of the suggested tools could have important social justice outcomes by enhancing the management of complex urban forms through anticipation of unplanned areas and their impact upon the organization of urban space in LDC. In doing so, such approach would increase opportunities to improve the living conditions of future IS dwellers. It is worth mentioning that cities within LDC often exhibit peculiar local features in respect to IS characteristics, such as their size and the conditions pertaining to their emergence and growth. Therefore, the criteria and assumptions used in the application of the proposed model to Yaoundé, Cameroon, whilst not specifically applicable to all cities within LDC, nevertheless would be sufficiently flexible to readily accommodate adjustment to local contexts.

1.3 Research approach and questions

To achieve the research aim, this study is structured around the investigation of two research questions. First, are existing urban dynamics models appropriate to simulate IS emergence and growth in LDC? The following points will clarify this question:

a. What are the methods, techniques and resources currently available to explore urban dynamics in general and in LDC in particular?

b. Are existing urban dynamics models pertinent to the simulation of IS in LDCs' cities? Which rules and criteria can be utilised to depict, simulate and model IS in LDC cities?

c. How useful are the forecasting and dynamic visualization of IS models in raising awareness of issues inherent in IS rapid expansion?

Second, what are the potentialities of GIS and CA technologies in developing a dynamic model for visualizing informal spatial expansion in unplanned cities in LDC? The following sub-questions will elucidate this question:

a. How can historical and potential growth within unplanned settlements in LDC be documented via computer modelling technologies such as GIS and CA? What are the relevant variables in the context of IS?

b. What could be the contribution of the GIS and CA technologies in handling historical and predictive aspects of a proposed dynamic model?

To explore these questions, GIS and CA have been selected as appropriate methods to gain a better understanding of IS via a modelling approach. To date, some researchers have used qualitative and quantitative approaches to describe the problems facing unplanned areas in cities, but they have not placed sufficient emphasis on the prospective analysis of the phenomenon and how this could improve our understanding and response to IS (UNCHS, 1982; Abrams, 1996; Davey, 1996; Durand-Lasserve, 1996; Hope, 1999; UN-Habitat, 2003). This constitutes a current gap in the literature and in the practical capacity of governments and urban planners to effectively respond to the rapid expansion of IS. Likewise, quantitative and qualitative methods neglect the intrinsic rapport between time and space in dynamic environments, as well as the value of dynamic visualization. This thesis argues that GIS and CA can be integrated to capture and reflect the intrinsic IS dynamics and thus understand their prospective future growth patterns. The integration of GIS and CA enables the exploration of previous and current growth behaviour, and the capacity to suggest future distribution of IS. Moreover, the technique used in this research improves existing urban dynamics attempts in the sense that it highlights the spatio-temporal representation and dynamic visualisation of geographical systems. It also addresses the relevant socio-cultural factors which underpin the expansion of IS in LDC. The proposed model is an important step forward because it will show how GIS and CA can be combined to generate urban dynamics in an unplanned context.

1.4 Thesis structure

The following diagram summarises the structure of the thesis.

SECTION 1 (NON TECHNICAL)
Chapter 1: Introduction: Presents the context and the overview of the research. **Chapter 2: The problem:** Discusses the mechanisms of IS dynamics; assesses traditional methods for representing the growth of IS; and highlights the shortcomings of strategies and policies for IS management; suggests new methods for addressing IS expansion.
SECTION 2 (TECHNICAL)
Chapter 3: Current methods: Reviews the concepts, theories, practices and methods with an emphasis on combining CA modelling and GIS for visualization and animation. **Chapter 4: Previous work:** Assesses various models used in developed countries and their limitations in adapting in the context of LDC.
SECTION 3 (SYNTHESIS)
Chapter 5: Application of an existing model to Yaoundé: Presents an attempt to use an existing dynamic urban model in the context of LDC and reasons why its is unsuitable. **Chapter 6: A new model:** Draws on the material from the non-technical Chapters (One and Two), the technical Chapters (Three and Four), and the lessons from Chapter Five, to build the Informal Settlement Growth Model (ISGM) and apply it to Yaoundé. **Chapter 7: Evaluation:** Assesses the new model's strengths and weaknesses based upon four criteria: reliability, sensitivity, validity and utility. The main limitations of the ISGM are also discussed. **Chapter 8: Conclusions:** Provides a brief summary of the thesis, highlights the major findings, and suggests some recommendations for further research.

Hence, it is evident that the eight Chapters of this thesis fall naturally into three main sections: *non-technical, technical* and *synthesis*. Such a structure emphasizes how this thesis actually combines geographical analysis with modelling techniques.

Specifically, the non-technical Chapters (One and Two) provide a context, an overview, a review of the theoretical debates relating to IS and a description of urban planning responses. The technical Chapters (Three and Four) review the concepts, theories, practices and issues arising from IS mechanisms and current urban dynamics models and techniques. They advocate the integration of GIS and CA techniques for realistic urban modelling. The role of spatial models in urban dynamics is also assessed, along with the importance of dynamic visualisation or animation in urban modelling. Finally, the synthesis Chapters (Five, Six, Seven and Eight) join the non-technical arguments about urban dynamics and IS in LDC addressed in the non-technical Chapters with the issues and technologies discussed in the technical Chapters.

The distinctive Chapters of this thesis, therefore, begin with Chapter Four. This Chapter reviews existing urban dynamics models in order to evaluate their suitability for implementation in the context of unplanned developments in LDC. Since the research is focused on IS dynamics, Chapter Four also highlights the limitations of existing urban dynamic models in dealing with the spatial and temporal dimensions of rapid expansion of IS in the context of unplanned developments. Chapter Five then describes an application of an established urban growth model conceived for planned cities, and demonstrates why the model is not appropriate for simulating IS emergence and growth. Finally, Chapters Six, Seven and Eight describe, evaluate and review the development of a new model that can predict the emergence and growth of IS patterns in LDC. This model has been applied to Yaoundé, Cameroon.

Chapter 2

Exploring informal settlement dynamics and policies in the global context

2.1 Introduction

According to the United Nations Centre for Human Settlements (UN-Habitat, 2003), the world's population is now more than six billion, and with the current annual growth rate of 1.3%, seven billion will be living on earth by 2011. The world's population is, however, unevenly distributed amongst the regions. Some regions, of generally developed countries, are experiencing a decline of their population or slow growth, whereas developing countries (in the main) have rapid population growth. Research indicates that the World population growth is in fact being driven by Less Developed Countries (LDC), whose urban centres are now experiencing the fastest growth by comparison to developed countries (Kaplan *et al.*, 2004; Oucho, 2001). This rapid urban growth is correlated with rapid expansion of unplanned settlements to such an extent that Payne (2002) estimates that 837 million people are now living in informal settlements (IS). In 1988, Fernandes and Varley (1998) estimated that, in the 1980s 40% of city dwellers in Asia, Africa and Latin America, for example, lived in IS. The Global Urban Observatory (2003) now suggests that more than 60% of the urban population of LDC live in IS.

The rapid expansion of IS is not new. Since the 1950s, the amount of substandard housing and the number of informal dwellers have been growing continuously (de Soto, 2000). Furthermore, all indications point to a continued 'informalisation' of rapidly growing cities in LDC (Adeniji, 2000; Sanderson, 2000).

The aim of this Chapter is fourfold. First, to identify key theories and factors that explain the emergence and growth of informal settlement (IS) in LDC. Second, to discuss the nature and extent of urban planning policies in relation to IS in LDC. Third, to assess current tools urban planners in LDC use to address IS expansion. Finally, to develop a set of selection criteria that will help develop a model of IS growth in the context of these developing countries. In particular:

- The first section reviews the definitions related to unplanned and decayed settlements in urban areas to enunciate with a workable concept that will be used throughout this Chapter.
- Section two focuses on the emergence and the expansion of IS. The evolution of public policies of IS is also discussed. Based on the shortcomings of the previous policies and strategies, section three questions local and international responses towards IS.
- The final section of this Chapter assesses possible solutions that would assist urban planners in LDC to accommodate rapid expansion of IS. This section also covers spatial representations of IS and suggests an alternative approach that could improve current understanding of, and approaches to IS. This section also demonstrates how the limited planning tools and lack of proactive approaches constitute one of the main limitations of current IS responses.

Most of the examples used will be drawn from cities in LDC in Africa, South America and Asia to illustrate the role of IS in structuring contemporary urbanisation processes in those regions.

2.2 Informal settlement mechanisms

The definition of informal settlements (IS) varies widely from one country to another and depends on different parameters. Informal settlements are also known by different names. In French speaking countries for instance, they are referred to as *bidonvilles* or *elobis* (Cameroon), while in most English speaking countries, they are usually described as ghettos, shantytowns, slums or squatter settlements. In Latin America the terms *favelas* (Brazil), *barradas* (Peru) and *barrios* are frequently used. In South East Asia, the appellation also varies extensively from one country to another. For instance in Indonesia (and also in Malaysia), IS are known as *kampung* (a term associated with a village-type settlement in an urban or rural area), whereas in Pakistan, they are commonly known as *kachi abadis*. Administrative and legal officials often use terms such as illegal, irregular or unauthorised settlement; unplanned development, land invasion, and temporary settlement. In contrast to planned development, 'informal settlement' will generally refer to the non-conformity of urban land use to authorised practices with regard to access to land, land provision, building standards, standards of infrastructure and services. The term 'unplanned development' will be interchangeably used with IS. Occasionally, the term 'slum' will be used to stress the 'maturity' and the decay of a settlement. Similarly, 'squatter settlement' will occasionally be used to state the case where urban dwellers illegally occupy a property (land or building) designed for a specific use.

For this study, an informal settlement is to be understood as an urban residential area occupied by the poorer section of urban dwellers, in breach of urban planning regulations and where living conditions, services and infrastructures are below the legal and official standard (UN-Habitat, 2003). For the purpose of this thesis, the term 'informal settlement' is most suitable because it encapsulates all aspects of the topic from the regional, legal, administrative, socio-economic and physical perspectives.

Appendix 1 provides snapshots of some major characteristics and living conditions in IS. In general, there are several attributes that act as generative forces, and determine the emergence and sustainability of IS. Such attributes are related to their location, their socio-economic conditions, and their legal status, and will be discussed below.

2.2.1 Location of informal settlements

Informal settlements can be characterised by their site and situation. Usually, they are situated in location that are normally considered unsuitable for housing and urban development such as riverbanks, steep slopes, dumping grounds, abandoned or unused land, along rail networks, near industrial areas and market places, and in wetlands. They are also found in what might be considered 'unattractive' areas such as cemeteries, and close to waste disposal sites (Garr, 1996; Blight & Mbande, 1998). Overall, IS therefore flourish on marginal or any vacant and available urban lands. Natural hazard-prone areas of the city can also be correlated with the existence of IS. These risk factors include landslides, pollution and health hazards, fire and flooding, and ecologically unsuitable areas (Jenkins, 2001).

Although the location sites of IS can be generally identified, their situation in relation to other urban features do not seem to follow a particular pattern. Other situations for IS include marginal and unattractive lands such as marshes and slopes, marginal and abandoned lands such as railway setbacks, and industrial parks.

Despite the variety of situations that define slums and IS, they share common features such as overcrowding (for example in Nairobi, Kenya, high density 750 inhabitant per ha against 30 in planned development, (Alder, 1999)); inadequate and deficient infrastructure (e.g., water supply, sewage and drainage, sanitation, solid and liquid waste disposal, electricity, roads, health centres, and schools). Informal Settlements are also commonly characterised by the presence of spiritual and religious activities. For instance, Choguill (1987) demonstrates that religious and other places of worship are one of the rare and solid structures that are very much present in all IS communities. Recently, Berg-Schlosser and Kirsting (2003) have shown that religious groups are the second most important form that represents and reflects (after economic considerations) newly formed IS in many LDC cities. This research suggests that the religious factor is of paramount importance in structuring IS and can be used, along with other factors, in a modelling setting to predict the future expansion of IS.

While older slums are found in central city areas, new IS are more likely to develop in the periurban areas, or anywhere where vacant land exists. This knowledge of factors contributing to the location of IS is critical to the design of an informal settlement growth model. The understanding of the socio-economic conditions of slums and newly formed IS, can also assist in the formulation of the proposed model.

2.2.2 Social, economic and legal mechanisms of informal settlement

The socio-economic profile of informal dwellers helps clarify understanding of the actors in this informal environment that evolves outside the legal system and guides the formulation of IS growth models. Generally, IS represent a series of unorganised individual properties resulting from self-help strategies with no public assistance. Analysis of their socio-economic characteristics reveals that city dwellers living in specific IS have similar socio-cultural backgrounds (UNCHS-United Nations Centre for Human Settlements, 1982). The 1982 survey highlighted the social profile of an IS dweller as being a less educated and formally qualified, unemployed or low-income earner (working in the informal sector) who has often migrated from rural areas to the city for work; and who also spends over two-thirds of their annual income on food. There is also a correlation between urban migration and the ethnic composition of IS. Two illustrations are the Kibera slums in Nairobi (Kenya) founded by former

Sudanese soldiers, and the Dharavi slum in Mumbai (India), the "world's largest slums, where Tamil is spoken as the main language" (UN-Habitat 2003, p.27). Informal dwellers who are not 'newcomers', tend to have previously lived in IS (probably nearby) dominated by people from a similar ethnic, cultural or religious background. Similarly, new migrants to urban areas are more likely to settle in neighbourhoods with strong cultural, ethnic and religious ties (Ademola & Potter, 1990; Drakakis-Smith, 1981). Such trends suggest that established IS duplicate themselves and serve as a stepping-stone for the emergence of future settlements (Malpezzi & Sa-Adu, 1996). In that respect, the role of existing IS in an area, combined with cultural, ethnic and religious influences and composition are, critical in the future formulation of an IS growth model.

Datta and Gareth (1999) note that the IS dweller is more likely to own a house that has been built with the assistance of informal finance (such as borrowing from friends, informal credit, or help from friends and relatives). Despite the variety of types and quality of construction, most IS houses are built using local or salvaged materials, design and knowledge, in disregards of legal standards.

Another important factor is the intimate correlation between the urban informal economic sector, urban poverty and IS development (Sethuraman, 1981; Kengne, 1991 and 1998; Roubaud, 1994; UN-Habitat, 2003). Informal settlement also grows in parallel with the informal economic sector. In cities in LDC, popular market places are the breeding ground *par excellence* for the informal economic sector, where knowledge, skills and experience are not pre-requisites to access to the job markets, as they would be in the formal or public sectors. The informal economic sector in LDC is mostly concentrated in popular market places and small businesses in slums (Budihardjo, 1990; Kengne & Metton, 2000). Migrants to the urban areas have long fuelled the informal economic sector, with the urban authorities sometimes turning a 'blind eye' to the informal economy (Maldonado, 1995). While this situation has changed in the past two decades due to the economic crisis facing most LDC, the informal economic sector is still one of the last options left for other social groups such as school and university graduates, and laid-off workers from the formal sector to gain employment (Badshah *et al.* 1991; Kengne, 1996). This is an indication that many urban dwellers are entering the informal economic sector.

This intimate link between IS and the informal economic sector is further emphasised by Happe and Sperberg (2003) who show that the overwhelming majority of slum dwellers are active in 'multi-occupationality' (or many jobs) and that this relationship is growing concomitantly. Appendix 2 shows the growth in IS dwellers as a proportion of the total population in twenty selected cities in LDC. This continuous growth follows the same trend and rate as IS expansion (Penouil & Lachaud, 1986).

In terms of employment, the informal economic sector accounts for up to 70% of the national labour force, and contributes an average of 40% of the GDP in LDC (Kengne, 2000). Appendix 3 shows how, over the past three decades, the number of city dwellers employed in the informal economic sector has significantly increased in the majority of LDC. A recent report by the UN-Habitat (2003, p.xxvi) asserts that "the majority of slum dwellers in developing cities earn their living from informal sector activities located either within or outside slum areas". As previously stated, research shows that there is a clear correlation between these informal economic sectors, employment, market places and IS. It therefore appears that popular market places, where the informal sector is predominant, play an important role in the emergence, proliferation and consolidation of IS, and need to be incorporated in any simulation and model of IS growth.

Understanding the legal aspect of IS is also important for the appraisal of strategies and policies designed to 'contain' their expansion and in exploring why a predictive model might be useful to aid in that response. Researchers interested in IS agree on the unlawful status of IS, as implied by the terms used to define them (Arimah & Adeagbo, 2000; UN-Habitat, 2003). Informal settlements are referred to as *illegal* or *irregular settlements*, *squatting* and *unlawful occupation* (Fernandes & Varley, 1998). The illegal status of the settlements can manifest itself in three different ways.

In the first, the occupant of a given plot does not have a legal right to occupy the land. In such a situation, the illegal status expresses the non-recognition by the law of traditional ownership or other mutual arrangements by individuals that are not considered legally valid. Often, the occupants are not aware of the illegal status of their occupation of the property they are settled on.

The second type of illegality is usually known as *squatting*, which refers to the invasion and occupation of abandoned, or undeveloped buildings or properties. In this case the legal owner is known, but the apparent vacant status of the properties attracts the urban dwellers in need of housing. For urban policy-makers in LDC, squatters are subject to persecution, their shelter being demolished without any compensation, because they are considered to "violate legal regulations, which deprive legal owners of their rights…" (Pino, 1997, p.37).

The last category deals with non-compliance with building regulations and infrastructure standards. This situation is widespread in unplanned sections of the city. There is also increasing evidence that even planned areas in some LDC are slowly ignoring building regulations and legislation to a point where some sections of the city are gradually transformed into illegal dwellings, which could gradually evolve into, and become associated with, IS (Arimah & Adeagbo, 2000). The degradation or the informalisation of housing could also be the result of poor maintenance and management. The legal status is important to discuss because it determines and 'justifies' policies, interventions and attitudes towards IS.

2.3 Sustainability and theories of informal settlement

Informal settlements are prevalent features of urban form and landscape in most cities in LDC. It is common that formal and planned developments constitute the exception, while unplanned developments are the norm (de Soto, 2000). The scale of expansion of IS considerably outpaces urban planners and service providers. Urban theories attempt to explain how the informalisation of cities in LDC has emerged, and postulate on why IS are growing exponentially. To develop a comprehensive IS model, it is useful to understand the historical growth of IS and the theories that sustain their emergence and growth. These theories will assist to inform and design a sound IS model . This section first examines the spatial expansion of IS on the urban landscape, and then presents some informal settlement theories.

2.3.1 Expansion of informal settlements

UN-Habitat (2000) estimates that three billion city dwellers worldwide live in substandard conditions, associated with IS. In 2000, the World Health Organisation

(WHO) and UNICEF (United Nations Children's Fund) surveyed 129 large cities around the world and reported that the high population growth is directly correlated to the level and extent of IS. Figure 2.1 shows that although IS are a worldwide issue, they are still generally a developing country phenomenon, particularly in Africa, Asia and Latin America.

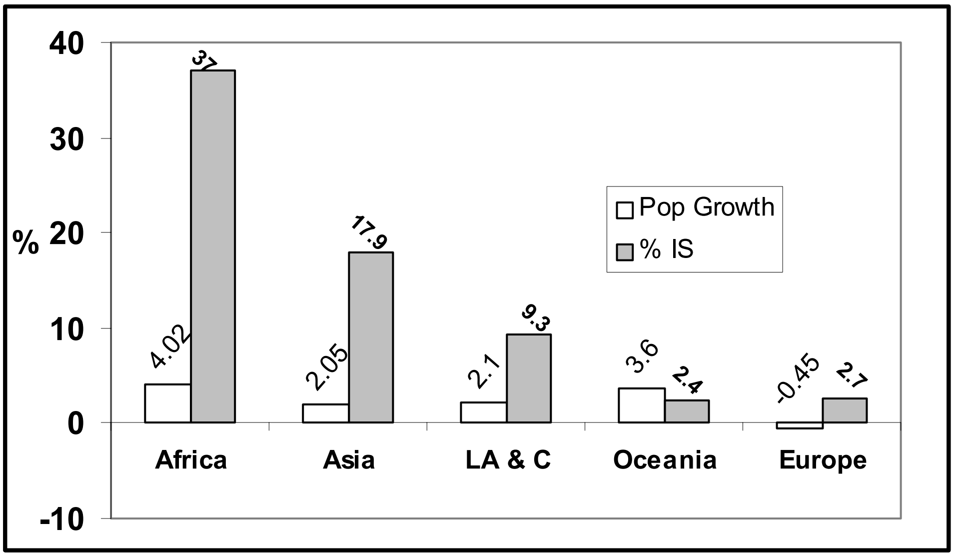

Figure 2.1. Population growth rates and proportions living in informal settlements: regional means for the largest cities (more than one million)

Source: WHO/UNICEF (2000)

Since the 1950s, the proportion of the population living in IS has not shown any sign of slowing down in most cities (see appendix 2). An earlier pilot survey of 14 cities in LDC by the UNCHS (1986) reported that IS housed between 32 and 85% of the urban population. The population growth in such cities is also very high (up to 14% per annum) (Stren & White, 1989). Hence, IS are spatially gaining momentum in large cities in LDC (Ogu, 1998, Patel *et al.*, 2001). Jenkins (2001) and UNCHS (1986) report that IS make up as much as 32% of Sao Paulo, 33% of Lima, 34% of Caracas, and 59% of Bogota in South America, and 44% in Maputo, 60% in Dar es Salaam, 70% in Luanda, and 85% in Addis Ababa in Africa. In some countries, slums constitute the essential characteristic of the urban landscape. The Global Urban Observatory (2003, p.81) for instance, reports the case of Ethiopia (99.4%), Chad (99.1%), Afghanistan (98.5%) and Haiti (85.7%).

One of the explanations for such growth and importance is that urbanisation in LDC was initially perceived as a mechanism to improve living conditions and the environment, especially for city dwellers with greater access to income. A corollary effect, however, was to induce significant migration from the rural areas to the city context where housing was not available or affordable to cope with the significant influx of people, thus contributing to the expansion of IS. Coupled with the continuous decrease and depreciation of competitive opportunities in rural areas, this means that rural populations have continued to move to urban areas (Rempel, 1996, Kengne & Sietchiping, 2000). Furthermore, these rural migrants are relatively young and lacking in skills demanded by urban labour markets, thus often increasing the proportion of urban poor.

Cities have since grown at such high uncontrolled rates that a combination of factors now explain why IS are the dominant land use pattern in most urban areas (Obudho, 1992). Insufficient urban infrastructure (especially housing) and services, the poor vision of city planners, the inconsistency of urban land use management, inadequate planning schemes, clashes of land rights, and economic crisis (e.g., structural adjustment and unemployment) all contribute to their growth. The impoverishment of city dwellers reflects on the quality of housing. The quality of settlements is one of the spatial expressions of the deterioration of the conditions in cities in developing countries. Even if the first objective of the migrant, or the city dweller with limited resources and skills, remains to earn a decent income, shelter is a vital necessity (Casinader & Ellepola, 1979). The problem facing the IS dwellers can be so acute that for them, informal land and housing markets are considered the only possible answer. A complicating factor is that the degradation of residential urban land use is now so acute that from the poverty perspective, there is enough evidence to support the argument that poverty is becoming more prevalent in urban areas than in most rural areas in LDC in highlighting the need for more innovative responses to IS issues (UNDP, 1991; Satterthwaite, 2001; UN-Habitat, 2003). Therefore, the amalgamation of shelters outside the official building schemes and regulations will develop into an IS, underlining the prevalence of unplanned developments as the new form of urban extension.

2.3.2 Informal settlement theories

In order to know what a dynamic informal settlement model must negotiate in predicting the distribution patterns of IS, it is important to understand some of the theoretical foundations of IS emergence and growth. The purpose of this section is to assess the theories behind spatial distribution and residential differentiation in urban areas. Informal settlement theories will shed light on why people live where in urban spaces, specifically, why and who lives in IS or slums, and why. Slum theories postulated for developed countries will be presented in order to show how they influence the formulation of IS theories in LDC.

It is worth mentioning that IS have long existed in Western cities, but with less amplitude than the developing cities are currently facing (figure 2.1). Theories to explain the emergence and growth of IS were proposed for developed cities and developing cities. According to the *residential differentiation* theory from the Chicago School in the 1930s *(*Burgess*,* 1925-as cited by UN-Habitat, 2003*)*, the city growth is shaped by the colonisation of 'quarters' or suburbs by various income and ethnic groups living in that city. Different social groups compete for the best 'location', and the weaker groups will occupy the least desirable urban space. This theory suggests that IS are the results of economic and social spatial segregation. This theory applies to developed cities and the context of developing cities is somewhat different from the formal and structured economies.

The *neo-liberal* (Alonso-Muth-Mills' model) view argues, however, that slums are the response to the housing needs of urban dwellers, especially those who cannot afford formal dwellings (Smith, 1980). Low-income urban dwellers can only afford cheaper housing in high-density areas with poor quality dwellings. This cheaper housing offsets other unavoidable urban living costs. Housing shortages and continuous degradation of environmental health prompted Abrams (1964) to suggest slum improvement programs that later underlined sites-services schemes. It can be argued that neo-liberal theory was enriched by Turner's (1976) discourse on 'freedom to build' and 'housing as a verb', which also influence the development of slum strategies such as security of tenure and regularisation undertaken in the 1990s (Pugh, 2000). Neo-liberal theory also contends that unplanned development emerges as the result of discriminatory or exclusive urban regulations, public spending and the spatial segregation of work places for rich and poor.

The *post-modern theories* of urban landscape perceive the existence of unplanned development as the product of skill and professional segregation of urban spaces (Flood, 2000). Urban dwellers seem to settle according to their professional skills and social status (Portes, 1972). Suburbs are classified according to their habitation by dominant groups such as rich, affluent professional groups (for example politicians and lawyers); the middle class; unskilled workers; informal workers; and the underclass urban dwellers. The UN-Habitat (2003) adds that "each has a clear part of the city to themselves, supported by housing and distribution networks, but overlaying each other rather than necessarily confined to clear quarters" (p.2).

Following these ideas, urban authorities in LDC perceive IS as problematic, and as a threat and a challenge to their long-term vision for the city. Various theories have been proposed as to why IS are predominant and problematic in LDC cities. One school of thought believes that urban authorities, along with land management practices and the urban planning scheme, have to be blamed for the informalisation of urban areas in LDC (Choguill, 1996; Fekade, 2000). This view advocates that "slums must be seen as the result of a failure of housing policies, laws and delivery systems, as well as of national and urban policies" (UN-Habitat 2003, p.5). This suggestion is based upon the inability of urban policy makers and planners in LDC to develop a comprehensive urban scheme that provides shelter to all city dwellers. Instead, housing schemes often target civil servants, higher income earners and those who are in the position of power. This is well illustrated by Aldrich and Sandhu (1995) who demonstrate that housing policies in LDC have been detrimental to a large section of urban dwellers, especially by 'excluding' the low-income portion of the urban population from accessing formal urban land and housing markets. In so doing, housing policies have contributed to the proliferation of IS in many LDC cities.

Another theory links the emergence and expansion of IS in LDC to political and historical factors, especially colonialism and postcolonial practices. For instance, Chandler (1994a; 1994b) claims that the existence of IS in LDC cities is the ultimate evidence of the inappropriate implementation of a western policy in a wrong context. The theory reflects upon the implementation of city planning schemes by some pre-colonial cities such as Kano in Nigeria. Similarly, Debusmann and Arnold (1996) argue that informal settlement problems arise from the way in which colonial and post-colonial politicians have spoken about customary land tenure and practice. They point out that colonial and postcolonial politicians’ language devalues and distorts customary tenure. As a result, the official discourse creates a "weak system of legal pluralism" (Debusmann & Arnold, 1996, p.228) in which custom is defined in opposition to, and as a pale reflection of 'superior' western law (Rakodi, 1995). As a result of such discourses, traditional claims to land use are undermined. Eventually, many indigenous farmers become gradually disinherited, 'landless', and those who continue to hold land become vulnerable to claims of politicians, or to new 'elites' with ties to the state (Hall, 1992). This theory can be extended to the inability of the political system to undertake democratic reforms and practices that could have led to a social justice in the distribution of wealth (Fanon, 1963). In that regards, de Soto (2000) points out that apart from the rampant poverty in LDC, the prevalent practices of corruption, dictatorship, poor governance, political and social instabilities and unrest and civil wars are some illustrations of the issues contributing to the proliferation of slums in LDC cities.

There is a third view that suggests that the introduction of a new economic system has played an important role in the development of IS. This theory argues, for example, that the introduction of urban trade and income class subdivisions in new cities have translated into habitat discrimination and social exclusion (Huchzermeyer, 2002). Njoh (1999) also demonstrates that the failure of physical planning and spatial planning in Sub-Saharan Africa is largely correlated to the incapacity to integrate traditional and local socio-economic land values with the Western land management system (Njoh, 2000; 2001; 2003). This theory can be extended to the 'brown agenda' environmentalism theory that emerged from the 1992 Earth Summit in Rio de Janeiro, which advocates the sustainability of housing policies, environmental planning and management strategies, and interaction between various slum stakeholders (Kessides, 1997). Although current slum upgrading programs are taking on board the participation of various urban and slum stakeholders, the implementation of sustainability concepts along with the environmental planning and management schemes are yet to be considered in slum policies (Pugh, 2000).

A fourth view explains the emergence and growth of IS by the disequilibrium between demand and supply of urban commodities (land, services and housing infrastructure), particularly in relation to the sustainability and persistence of IS. Spatially, IS grow at least twice as fast as the urban growth rate as there is simply not enough infrastructure to cope with the demand for housing and services (Choguill, 1996). The theory postulates that while efforts are deployed to improve slums, new IS are mushrooming in other parts of the city as people create their own housing. Moreover, the theory points to the fact that some urban policies have been misconceived. Infrastructure and services upgrading programmes, for instance, do not make sufficient effort to make land available and accessible for future development (Kaplan *et al.*, 2004). Research also indicates that the priority of the city dweller, and especially that of informal settlers, consists of obtaining shelter, not basic infrastructure or legal rights, which are made less of a priority (Tarver, 1994). Under such conditions, it is therefore understandable that the main concern of informal settlers is the daily struggle to survive and this includes finding shelter at any cost. Consequently, the principle of supply and demand suggests that the spatial and temporal sustainability of IS is nourished by "the nature of governmental interventions or non-interventions and the actions and self-organization of those involved in the illegal practices" (Smart, 2001, p.31).

2.4 Evolution of public policies and planning responses to informal settlement

The plethora of explanations for the origin and growth of IS suggests that there is no single theory that can fully explain the emergence and the expansion of IS. However, despite differences in the theoretical explanations of IS emergence and growth in LDC, the implementation of public policies and planning responses have been somewhat similar across the regions and cities.

The assessment of policies and planning strategies implemented in relation to IS will serve as a benchmark on which the IS growth model will be built. It is important to have an understanding of the pitfalls and achievements of the past policies that will inform future strategies. In view of that importance, this section will review strategies that have constantly been undertaken to mitigate the socio-economic, physical and political impacts of IS. During the postcolonial period and particularly in the 1950s and 1960s, the issue of IS in LDC emerged as an important area for urban research (Mabogunje, 1990; Pugh, 1997). The current assessment of governmental attitudes and policies towards IS does not, however, take into account the pre-colonial and colonial periods. This section describes how urban authorities in LDC have adopted and shifted their approaches towards IS. Different countries and regions have implemented various strategies to deal with the expansion of IS. These strategies fall into four main chronological categories: *laissez-faire* attitudes in the 1950s and 1960s, sites-and-services programmes in the 1970s, slum upgrading in the

1980s, security of tenure in the 1990s, and *Cities Without Slums* action plans in the 2000s. This section reviews these four public policies, strategies and programmes that have attempted to address and contain the expansion of IS. The concept of each policy is presented along with its implementation, achievements and weaknesses in regards to long-term mitigation of IS. The assessment will later help the formulation of the IS growth model, and ascertain how this model might assist the conceptualisation of IS strategies which consider the future emergence and growth of IS in LDC' cities.

2.4.1 *Laissez-faire* and public housing: 1950s and 1960s

It is important to understand how IS was handled from the 1950s onwards, in order to comprehend how a proactive approach (through, for instance, a simulation method) could have assisted the management of IS. After the Second World War, many countries in LDC, especially in Sub-Saharan Africa, became independent. They inherited from the colonial powers an urban management system that was not in harmony with the local approach to land. In the 1950s, emerging towns in LDC were relatively small. Between the 1950s and 1960s, these towns experienced a massive rural migration (Rempel, 1996), which largely contributed to the rapid growth of what were previously small and manageable towns. Hardoy and Satterhwaite (1993) explain that urban authorities were falling behind in housing supply as well as the integration of established villages (now 'swollen' by urban areas). Eventually, the housing shortage generated two scenarios. Firstly, traditional villages that could not be remodelled to the planning standard, served as a benchmark for IS. Secondly, many urban dwellers, especially new migrants in the low-income category, could only find affordable shelter in marginal and unsuitable land around planned settlements.

With emerging cities growing fast, governments usually turned a blind eye to housing built outside the official regulation (Farvacque, 1992). In fact, policy-makers and urban planners regarded IS as a traditional form, a temporary situation, and thus a minor threat. As reported by Dwyer (1974), IS were tolerated and considered as a relic of 'traditional villages' in the process of being absorbed by the new urban development. In the master plan of Yaoundé in Cameroon, for instance, IS are referred to as traditional villages that need to be destroyed in the future and replaced by 'modern' infrastructure and services already available in public housing schemes (MINUH, 1982; World Bank 2002). Not surprisingly, these settlements remain today. Meanwhile, new IS established by recently arrived migrants were considered a temporary solution. Therefore, they were looked at with suspicion and hostility, although in the main they were generally tolerated (Smart, 2001).

Emerging and new urban centres needed the labour force from IS, which were the only places where many city dwellers could afford shelter. A situation initially considered as temporary became permanent, partly because IS dwellers could not afford housing or land in the planned areas. Similarly, public housing and welfare programmes (when they existed) were implemented in a discriminatory fashion, largely because the 'indigenous' political rulers, who replaced the colonial power, perpetuated the similar social and class divisions as the previous 'master' (Fanon, 1963). In fact, the main beneficiaries of public housing schemes were civil servants and middle and upper-income earners (Fekade, 2000). Moreover, nepotism, corruption, poor governance, and incompetence significantly contributed to the expansion of IS, and widened the gap between those who were in the position of power or had some sort of 'connections' and the rest of the urban population (Global Urban Observatory, 2003).

The survival of IS in the early 1950s and 1960s could also be explained by the relative availability of land for urban development. In the 1950s there was no shortage of urban land. This was enforced by the customary land tenure, whereby land was not considered as possessing a commercial value, but rather a social and cultural one. The introduction of new concepts such as monetary value and land registration, however, progressively influenced the traditional perception of land rights.

Politically, and particularly in the context of African cities, this period coincides with the attainment of independence. New local governments were preoccupied by the ideas of reconciliation, national unity, exercise of power and learning. In the learning process of managing modern and 'western' urban centres, urban planning policies and regulations were 'borrowed' from the colonial power, without consideration of local conditions (de Soto, 2000). Furthermore, urban control mechanisms were generally weak or ill-adapted to foresee the growing prospect of IS in the urban setting (Gaskell, 1990).

Another factor that helped IS flourish is related to inadequate urban planning regulations, such as building standards and the complexity of accessing formal urban land. On the one hand, the complexity of procedures to register urban land varied extensively in cities in LDC, although all were characterized by inefficiency, cost and long delay. For instance, the approval period could take three to four years in Peru (McAuslan & Farvaque, 1991), and two to seven years in Malaysia and Cameroon (Farvaque & MacAuslan, 1992). Appendix 4 provides more details on the waiting time to access public urban land in selected cities in LDC. On the other hand, Brennan (1993) reported that in the 1950s and 1960s, the building standard in many cities placed culturally inappropriate rules and regulations on individuals, for example, prohibiting the use of local materials for building. Furthermore, programs favoured public servants, and high-income earners. The majority of city dwellers who were not eligible (for instance not working in the public sector) for public housing or could not afford to be integrated into formal land systems, were left with the IS as their only realistic option.

Although the tolerance policy towards informal settlement was generally observed, there were also instances where IS and slums located close to the city centre were replaced by public housing schemes or other planned developments. In these instances, the occupants were evicted, and some moved further out of the city centre and rebuilt their lives in other new unplanned developments. Some did rebuild on the same site (Weru & Bodewes, 2001). Where demolition was not followed by relocation of all displaced persons, this usually led to an aggravation of the situation.

One of the drawbacks of such policies has been the dislocation of a population without having a workable resettlement programme for those whose 'properties' were dismantled. Smart (2001) illustrates how, since the 1950s, the destruction of informal dwellings and adequate relocation of residents (not owners) in Hong Kong has significantly reduced the number and the occurrence of IS. In contrast, Weru and Bodewes (2001) illustrate the case of Mitumba settlement in Nairobi which for many years experienced numerous demolitions, yet residents managed to resettle either on the same spot or near by. In this case, the displaced and homeless dwellers were left with no other option than resettlement by recreating IS. Apart from the obvious disruption that such uncertainties and upheavals caused to individuals, families and communities, this process was very costly for governments. Smart (2001) for example argues that the cycle of demolition and reconstruction of slums actually makes the cost of slum housing higher than in planned developments. It also costs the residents more to live in these areas. The UN-Habitat (1998) has shown that the cost of living is higher in IS than in planned areas, especially in relation to insecurity (tenure, social and economic), health hazards and threats, cost of commodities (such as electricity and water), and transportation. It could therefore be argued that developing a model that predicts the future expansion of IS will, for instance, assist urban planners in LDC to strategically create infrastructure and services that would ultimately avoid the costly cycle of demolition and rebuilding.

Public housing schemes also poorly performed in meeting housing demands in many cities in LDC. In that regards, Hope (1999) reports that public housing schemes across Africa as a whole provide less than 5% of housing needs. The failure of public housing can also be attributed to factors such as cost, socio-economic discrimination, inappropriate design, and ignorance of cultural context in housing planning schemes (Bourdir & Alsayad, 1989; Baroos & van der Linden, 1990; van der Linden, 1994; Malpezzi & Sa-Adu, 1996; Hope, 1999).

During the 1960s, IS gained momentum and dominated the urban landscape of most urban areas in LDC. International organisations then started to show some interest in confronting IS, especially, after the publication of de Jesus' book (1962) which gave a vivid account of the daily survival struggle in Brazilian *favelas*. With the support of international institutions such as the World Bank, UNCHS and Non Government Organisations (NGOs), governments in LDC moved a step forward and began to acknowledge the increasing influence of IS in the urbanization in LDC.

Overall it appears that between 1950 and 1960, most urban authorities in LDC adopted a *laissez-faire* attitude towards burgeoning IS. This policy fell short in many areas. It is clear that from the early stages of the expansion of IS, urban planners did not have the long-term vision and the tools to address and 'contain' the growth of, the then modestly-sized IS. It is now clear that urban effort and resources directed towards providing public housing have ended up being costly and have served only a small portion of urban dwellers (Adeagbo, 2000).

2.4.2 Sites-and-services: 1970s

The international community was concerned about issues surrounding the existence of IS, despite the tendency of LDC governments to overlook IS. These issues included environmental health, security, and the lack of basic infrastructure and services. Governments in LDC were now recognized as part of the problem in relation to improving the functionality of urban systems. This section will discuss the conceptualisation, implementation, and limitations of sites-and-services schemes in relation to long-term reduction of IS, which was the dominant approach adapted in the 1970s.

As rapid population growth and urban sprawl continued in LDC in the 1950s and 1960s, the tolerant attitude towards IS transformed traditional villages and temporary settlements into large slums. These slum areas gradually declined and were characterised by chaos and decay, and were seen to need 'urgent' intervention. Responses were mixed and often involved international organisations such as UNCHS and the World Bank. Some governments started to perceive these slums as an expression of urban planning failure, especially with regard to the beautification of towns. As discussed earlier, projects implemented through public housing schemes ended up being costly and were unable to supply sufficient dwellings. They marginalised the majority of urban dwellers, and ignored low-income urban dwellers and rural urban migrants who settled and generated unplanned developments.

During the 1970s, with the assistances of the international community, governments in LDC started to respond by trying to improve the services in slums areas. The World Bank suggested the 'sites-and-services' scheme. It targeted the poor and was conceived as the 'demolition' of slums, the 'relocation' of residents, and the provision of serviced land with the contribution of the 'beneficiaries' (World Bank, 1974; Agboda & Jinadu, 1997). The basis of the concept was the contribution of the beneficiary, as a means to acknowledge the capacity of low-income people to mobilise necessarily resources to self-finance their dwellings, based on the conception that low-income city dwellers have very limited access to formal credit and financial channels. Thus, sites-and-services scheme emphasised a notion of 'shared responsibility'. On the one hand, the government had responsibility for preparing the land parcels along with the provision of basic infrastructure for the qualified settlers (beneficiaries) either on freehold or leasehold tenures. On the other hand, it was the responsibility of the beneficiaries to build their house, using their own resources such as informal finance and labour, in order to access the services and infrastructure.

Sites-and-services schemes were advocated, financed and implemented by international institutions such as the UNCHS and the World Bank with three main objectives (Fekade, 2000). First, the programme intended to address the imbalance between planned development and unplanned expansion. Secondly, sites-and-services programmes aimed to improve socio-economic and physical and environmental conditions in deteriorated urban areas. Thirdly, the programme was economically motivated in the sense that the government would locate and subdivide a new area into plots and allocate services and infrastructure such as roads, power, water, drainage, and waste disposal. Afterwards, qualified residents would purchase the serviced plots at the market price, with the government recovering the cost of the investment.

The programme also put emphasis on the 'participation of the beneficiaries' (UNCHS, 1996) not only in purchasing the plot, but also in building the house in a set time frame according to the proposed models of housing and building. Whilst the sites-and-services scheme intended to improve the quality of environment of informal settlers and address the housing needs of low-income urban dwellers, the scheme's implementation was criticised for its many shortfalls. These included insufficient dwellings for low-income groups, the low number of beneficiaries, a lack of understanding and clarity around the role of the private sector, a lack of planning around the location of new serviced plots, low or non-existent standards, and failure to achieve cost recovery.

Sites-and-services schemes were also associated with partial or total clearance of the slums and their relocation to a serviced site (Mulwanda, 1989). This process actually aggravated the housing shortage (Hope, 1996), partly because there were not sufficient plots available to relocate those whose houses had been demolished. Hope (1999) indicates that less than 6% of intended beneficiaries in Kenya, Zambia and Zimbabwe actually benefited from the scheme for the paradoxical reason of affordability. Also, the transitional period between the demolition and the new establishment was not always well negotiated. Many evicted slum dwellers had difficulties accessing or being qualified for new serviced parcels due to lack of land titles and rights (the majority could not legally claim and prove their tenure right), illiteracy (most documents were written and they needed to fill out applications), corruption and bureaucratic hurdles (Malpezzi & Sa-Adu, 1996). These difficulties deterred and excluded many informal dwellers, who ultimately had to move to new unplanned areas. Eventually, middle-class and high-income land speculators and 'land grabbers' occupied the serviced plots, partly because they could afford the cost or could take advantage of corrupt practices (Jacobsen *et al.*, 2002). Moreover, sites-and-services schemes did not respond to the magnitude of the informal settlement problem because they ended up being costly while barely affecting the provision of affordable housing to the poor (Apiyo, 1998).

Land availability and accessibility were other difficulties in implementing sites-and-services projects. In Yaoundé for instance, less than 25% of city dwellers possessed an official land title (MINUH, 1990). Instead of improving the land supply (affordable and accessible), the government policy had long created an artificial 'stock' of urban land, aiming to avoid unplanned development. In the meantime, no alternative settlement measures were taken, such as servicing land prior to the arrival of housing clearance victims. Eventually, city dwellers were left with no other alternative than to occupy public land, with help from traditional owners and informal land developers. Undeveloped public lands were then occupied by city dwellers who progressively transformed the areas to IS. Therefore, not only those who were already established on the now 'public domain' became illegal settlers, but also the new settlers became 'squatters'. This process of occupying available land is important to understand, because it can be captured by a prospective IS growth model.

The role of the private sector in the dynamic of IS was highlighted during the implementation of sites-and-service scheme. In fact, the private sector appeared as the main driving force of the urbanization process in LDC, accounting for up to 95% of newly developed urban areas. Such a situation exists partly because business people (more than government or planning agencies) could foresee and exploit such 'booming' housing market sectors, often using unscrupulous methods such as bribery, corruption and political and social ties (Pettang, 1998).

Sites-and-services schemes required high housing standards and building quality on newly serviced plots, making the scheme unaffordable for the majority of low-income people (World Bank, 1974). Restrictive conditions were also attached to buildings and activities on the sites. For instance, commercial, livestock and agricultural activities were banned in the new development parcels (Peattie, 1982). These restrictions were in contradiction with living conditions in slum areas, where such activities were integrated into the living environment and constituted income sources for slum dwellers.

Sites-and-services projects also failed to achieve their cost recovery objectives. The primary reason was the financial burden that the beneficiaries were experiencing. People were expected to pay for the serviced parcel, build their house at the set standard, and support the cost of infrastructure and services such as electricity, water, and transportation. Some of these costs were new to the settlers, who had not necessarily been subject to them in their previous environment. Eventually, some settlers had to sell, abandon their properties to those who could afford to build to the required standards, or live in an incomplete dwelling. Some plots had to be taken from the initial owner and allocated to someone else.

As far as the government was concerned, the public budget allocated to these schemes was not always available to service IS sites, or new parcels. There was not always the political will and usually there was a significant delay in making serviced land available to the beneficiaries. At the same time, the support of international financing institutions progressively dried up (van der Linden, 1986).

Despite these weaknesses, sites-and-services schemes are credited with enabling shared responsibilities between the stakeholders (Drakakis-Smith, 1986). On the one hand, the programme emphasised the participation and the contribution of the beneficiaries to the resettlement process. Similarly, the programmes acknowledged and capitalised on the ability of low-income dwellers to mobilise informal resources. On the other hand, local governments were no longer acting as 'providers' but as 'facilitators', which saved them some resources. However, the magnitude of the negative impacts and shortcomings easily offset these positive aspects to a point where new strategies had to be introduced with the hope to curb the rapid and continuous degradation of slum areas. Overall, the implementation of sites-and-services schemes failed to address IS management issues and there was no provision for preventing or reducing the future expansion of IS.

2.4.3 Slum upgrading programmes: 1980s

In the 1980s, slum upgrading programmes were developed in recognition of the fact that the sites-and-services scheme was unable to absorb the expansion of IS (Payne, 1984). As new sites were created, the living conditions in newly created slums were deteriorating, thus leading to a vicious circle of unfinished informalisation. This section discusses the rationale behind the adoption of an upgrading programme, its main components, and its limitations in addressing long-term problems associated with IS. The discussion will provide another example of poor planning in relation to prospective IS, and will indicate how some sort of a model might have helped some of the shortcomings of these policies.

The idea of developing a slum-upgrading programme emerged from various sectors and was driven by a variety of motivations. In the 1980s, international organizations, especially the UNCHS and the World Bank, introduced upgrading programmes aimed at improving the general standard of housing, infrastructure and services in urban areas that were experiencing decay (Maitreyi, 1994). The upgrading policy was based upon a 'chain-system' principle whereby improving housing and services, was considered to ultimately alleviate the problems of IS. Furthermore, upgrading policies were thought to generate economic growth, and finally achieve social and spatial sustainability (Banes *et al.*, 2000).

Upgrading programmes differed from sites-and-services schemes in many aspects. For instance, in contrast to site-and-services approach, upgrading programmes occurred on site and did not necessarily require the eviction of residents or the destruction of shelters. This meant that a physical upgrading scheme emphasised the infrastructure and services of the slum environment in general, and did not necessarily transform the individual housing as a sites-and-services approach would have done. Moreover, slums upgrading programmes encouraged the use of local and affordable material, as well as accepting lower housing standards (Fekade, 2000). Upgrading programmes can also be credited with introducing the 'human dimension' to the interaction between the stakeholders. New concepts were introduced to the planning language such as empowerment, capacity building, and participatory planning. During the implementation of upgrading schemes, the term 'partnership' replaced the term 'beneficiaries' used in sites-and-services schemes.

Depending on the level of need and the context in which it was applied, an upgrading programme could have many components. At the lower end of the scale, upgrading schemes incorporated the creation of infrastructure and services. However, upgrading was also often concerned with the replacement of decaying infrastructure and the provision of new services and facilities such as running water facilities (generally communal water pipes), housing improvement, social support programmes (health, education, leisure and playing ground), municipal services, conservation of historical sites and cultural heritage, employment prospects, roads, services, buildings (schools and community centres), lighting and electricity, dust bin collection, and communal or public toilets (especially in India and Pakistan). Sometimes, facilities such as sewage, drainage and telephone services, as well as individual security of tenure, were considered in an upgrading scheme. For instance, the UN-Habitat (1999) reports the case of Manila in the Philippines where in the 1980s, an upgrading scheme negotiated a compromise with a private landowner. Instead of evicting the squatters, the landowner subdivided and serviced the land, whilst the squatter settlers paid for their serviced plots and improvements to their housing. The composition of an upgrading package varied extensively from one project to another, but the dominant factor remained that the improvement of infrastructure and services in the slum area in general were favoured, rather than individual housing development.

To some extent, slum upgrading programmes acted as an affordable option and reached a relatively large number of slum dwellers. For instance, Brennan (1993) reports that the implementation of an upgrading programme in Calcutta reached two million residents, while in Jakarta, 3.8 million people benefited from upgraded services and infrastructure. However, upgrading programmes had many shortcomings and failed to meet expectations. Generally, slum upgrading was criticised at four main levels: the negative role of foreign investments, the lack of socio-economic benefit, the low level of success in securing the tenure for slum dwellers, and the short vision of the programme.

Firstly, the programmes were implemented and financed by foreign agencies, which over time gradually reduced their financial support to the programme. For instance, the relative importance of the upgrading budget of the World Bank went from 42 % in the late 1970s to less than 8 % in the late 1980s (Brennan, 1993). Similarly, local government could not sustain the financial cost of upgrading. As the funding dried out, many programmes were suspended, and the lack of income meant that infrastructure and services could not be created, completed, sustained or maintained. Therefore the situation in slums not only rapidly deteriorated (Okpala, 1999), they did so to a point where the United Nations declared the year 1987 as the International Year for Shelter for the Homeless, as an affirmative act to tackle the housing needs of low-income groups.

Secondly, upgrading programmes did not produce the socio-economic impacts projected. For instance, when Amis (2001) reviewed upgrading programmes in Indian cities, he did not find any correlation with the poverty reduction, employment and land security, which the programme had aimed to achieve. Ironically, improving infrastructure and services had led to an increase in real estate value, thus encouraging land speculation. Low-income dwellers were, therefore, shifted out of the upgraded areas for the benefit of middle and high-class urban dwellers. The UN-Habitat (1999) illustrates this problem with the example of Dandora, a slum in Nairobi, where in the 1980s, the World Bank financed an upgrading programme. A survey in the area 10 years after the completion of the programme revealed that more than half of the current inhabitants were middle or high-income city dwellers, and were not resident at the commencement of the programme.

Thirdly, none of the upgrading programmes demonstrated any integration of security of tenure with employment or income-enhancing activities. There was no evidence from any of the upgrading programmes to support the argument that such a project could be duplicated elsewhere, nor sustained in the long term (Durand-Lasserve, 1996). Sehgal (1998) indicates that, instead, many associated negative factors jeopardised the sustainability and the success of upgrading programmes: local politics, corruption, conditions attached to foreign aid, the value of real estate and the location of a particular slum or squatter settlement.

Fourthly, upgrading programmes only reached a small portion of IS and did not develop into an ambitious project that could address the security of tenure in large scale IS. The upgrading of communal infrastructures and services did not improve individual dwellings. Therefore, on many occasions, the socio-economic and physical environment within the upgraded areas continued to deteriorate. The insecurity of tenure deterred IS dwellers' ambition to undertake housing improvements or upgrade individual shelter. The lack of security of tenure also inhibited the efforts of public and private service providers (such as electricity, water and telephone companies) to invest in unplanned areas. Moreover, the slum upgrading model did not address the issue of newly or emerging IS, nor did it provide a proactive approach towards the creation of future IS.

It appears that in order to improve conditions in established IS, security of tenure should be addressed, not at a small scale, but at the urban level. Developing a model that could consider grassroots interaction and behaviour, in order to project the future distribution of IS at the scale of the entire city, could have helped reduce their expansion. This new strategy should include all income groups, not only the poor in slums.

2.4.4 Security of tenure and massive regularisation of existing slums: 1990s

One of the major ways in which urban planning strategies have been improved around IS has been the development of practical mechanisms to consolidate and secure land tenure. In the 1990s security of tenure, also referred to as an *enabling* approach, was proposed and supported by international agencies, namely UN-Habitat, as a contingent measure to limit the eviction and demolition threat in slums (Jenkins, 2001). Although the informal settlers do not necessarily have the legal title over the land, they can undertake improvement on their properties without fear of eviction. The security of tenure approach also postulates that the availability of and the accessibility to urban land provides a sense of 'belonging' and brings stability to an urban area (Kombe & Kreibich, 2000).

The security of tenure approach derives from the fact that when the residents have the sense of appropriation, they also have the confidence, motivation and will to invest, upgrade or improve their environment (Kombe, 2000). The capability of low-income dwellers to significantly improve the quality of their environment can be illustrated with a project in Dar-es-Salaam whereby through securing the land, residents have the incentive and the motivation to clean up the neighbourhood (Durand-Lasserve & Royston, 2002). The regularisation of this informal environment helps address the problem of tenure insecurity in already established slums, which otherwise translates into a vicious cycle of construction, destruction, eviction and reconstruction. In Africa for instance, South Africa is leading the land regulation campaign by providing secure tenure with basic services to displaced IS dwellers. Before destroying a slum, the new government in South Africa allocates new plots with basic functional services such as roads, water and sewage (Masland, 2002).

The security of land policy, however, has two major limitations. First, this policy advantages land grabbers and informal 'conquistadors', rather than those who reside there. So, when regulation does occur, the conquistadors (who do not necessarily live in the settlement) will resell or rent the land to city dwellers, eventually at a higher price because the land value has increased with the security

(Fernandes, 1999). Therefore, informal settlers who failed to claim their land rights, or who were renting, will seek another site to develop or create slum-like settlements. Second, the implementation of security of tenure does not guarantee any long-term solution to the expansion of emerging and future IS. This is an important gap that the security of tenure policy has failed to address. Developing a model that can explore the prospects of future expansion of IS would have helped the post-ante measures to negotiate land rights and regulation.

2.4.5 Cities Without Slums action plan: 2000s

In 1999, the World Bank and the UN-Habitat initiated the Cities Without Slums (CWS) action plan, which now constitutes part of the Millennium Development Goals and targets. Specifically, the action plan aims at improving the living conditions of at least 100 million slum dwellers by the year 2020 (UN-Habitat, 2003). The main innovation in this policy is to move from the physical eradication or upgrading of slums adopted by the past policies, to deal with one of the fundamental reasons why slums exist in the first place: poverty. The action plan recognises that slums are largely a physical manifestation of urban poverty, and to properly deal with them future actions and policies should also act on aspects such as poverty reduction or eradication.

This holistic approach of CWS action plan is encouraging, but raises two important concerns. Firstly, the number targeted is far too modest to significantly change the number of IS dwellers by the year 2020. In 2000 it was estimated that 850 million people live in slums and it is projected that by 2020 about 1.8 billion will live in IS (UN-Habitat, 2003). Secondly, the CWS action plan does not articulate what measures should be taken or formulated to curb the emergence of new IS. Similarly, there is no provision or indication as to what actions various urban 'stakeholders' at all levels (local, national and international) should undertake to reduce, if not stop, the mushrooming of new slums. Unless these two concerns are properly taken on board, the ambitious 'City Without Slums' will end up as a slogan.

As outlined above, previous urban land management approaches failed to develop a contingent plan to prevent and anticipate the emergence of IS. The information further suggests that there was no collaboration between public land schemes and informal market providers. This lack of collaboration has inadvertently boosted the spread of IS (Durand-Lasserve & Royston, 2002; Payne, 2002).

2.5 Past and current informal settlement policies: limitations and new directions

The review of past and current urban policies and practices concerned with IS suggests that they are ineffective in reducing the expansion of IS. As argued above, one of the key generators of IS is non-availability and inaccessibility of planned urban lands. Approaches towards slum mitigation did not conceptualise the creation of conditions for all urban dwellers to access planned development, and to capitalise on urban properties. Moreover, previous urban strategies did not create favourable conditions for collaboration between all the actors in urban land and housing markets. This section discusses the motivations to consider a proactive approach towards the emergence of new IS.

2.5.1 Limitations of past and current informal settlement policies and strategies

In LDC, policies and strategies addressing the housing needs of urban dwellers, have been designed to fit specific urban groups, neglecting other social entities. In the 1950s and 1960s, for instance, housing policies mostly addressed public servants, middle and high-income urban dwellers. Concomitantly, low-income dwellers had little or no option than other creating their own space, known as IS. When the focus was turned on the IS, the response was too little and too late to effectively curb the informalisation trend. Similarly, the middle and high-income groups were left with limited access to planned urban properties. As a result, upgraded settlements targeting low-income people were progressively invaded by the wealthy. The low-income section of the population was thus pushed out of upgraded or newly planned developments. Sectorial urban policies, which so far address specific social urban groups, rather than considering the global needs of all urban dwellers, can only perpetuate the urban land crisis in LDC.

Additionally, informal settlement policies have been implemented with specific and often unrelated objectives, rather than using a more holistic approach towards urban systems. As the review has shown, previous IS policies have addressed specific physical components such as housing, infrastructure and services of the urban system, while other components (for example land issue and income disparity), have remained unchanged, decayed or become obsolete. For instance, the upgrading approach dealt with infrastructure and services, but housing continued to degrade and new IS were generated in other parts of town (Mason & Fraser, 1998). Such outcomes were a result of the fact that urban and slum strategies did not consider factors such as land availability, accessibility and rights. Similarly, sites and services schemes were implemented when planning instruments such as building norms, construction standards and planning regulations were inoperative, and governments had little willpower to make any changes to urban planning policies (Laquiem, 1983; Aldrich & Sandhu, 1995).

There is an urgent need, therefore, to develop a more comprehensive approach that addresses the urban housing crisis, not only in unplanned developments, but also in the broader context of the urban system. It is in that perspective that the UN-Habitat (2000) initiated the Global Strategy for Shelter (GSS) in an attempt to bring all the components of the urban system together, so that they would be considered in future urban housing strategies. The strategy also aimed to synchronise the need and demand for urban properties across socio-economic groups.

During the course of the conceptualisation and implementation of urban policies, especially those concerning IS strategies, many urban stakeholders and partners have been disregarded. In LDC, urban property stakeholders include public and governmental agencies, private land developers, NGOs, traditional landlords and councils. These urban actors do not cooperate in their interventions in urban property development. Instead, they behave as competitors and their approaches and interventions are overlapping and antagonistic. This lack of integration has resulted in the development of parallel and conflicting housing developments. For example, urban planning policies in LDC have all emphasised planned development. This has resulted in private urban property developers who end up controlling the largest portion of urban land stock and buildings (Jenkins, 2001). In Yaoundé (Cameroon), for instance, public urban housing consists of less than 3% of all housing stock, whereas the private sector controls more than 97% (Pettang, 1998). Urban housing policy and strategy could have been improved if potential synergies and partnerships between all actors in the urbanisation process were considered.

Previous and current policies and strategies have not yet suggested the necessary changes to legal and regulatory land frameworks, such as land markets, registry, land valuation and legal instruments, that could have facilitated land acquisition for all urban dwellers in LDC, especially those from lower socio-economic situations (Kironde, 2000). These changes could have helped capitalise and increase property value. Instead, planned urban land is very limited, expensive, and the access procedure is too cumbersome for low-income urban dwellers, thus excluding them from the limited planned developments. Generally, obtaining a legal land title in LDC involves a costly and lengthy procedure that could last up to ten years. As a result, *informalisation* of urban space in LDC is endemic to a point where "…it is the legality that is marginal; extra legality has become the norm. The poor have already taken control of vast quantities of real estate and production" (de Soto, 2000, p.30). It can therefore be argued that the failure to acknowledge and incorporate a large portion of informal real estate and properties creates "dead capital worth" (de Soto, 2000, p.32).

Therefore, two urban property market systems (formal and informal) coexist in LDC' cities with the informal sector driving the urbanisation process (Smart, 1986; Jenkins, 2001). There is a need to make property rights available for all, and enable all city dwellers to access property and add value to their wealth. Eventually, urban policies and strategies generate artificial land shortages in the formal sector, thus creating the breeding ground for insecurity of tenure, illegality, non-serviced settlements, decreasing urban land value, and the vicious cycle of poverty.

2.5.2 Lessons from urban slum policies: the way forward

So far, this Chapter has argued that informal settlement policies and strategies have been concerned with a 'quick fix-syndrome' (Jacobsen *et al.,* 2002) and have often lacked any long-term vision. The implementation of all the approaches discussed has proven ineffective in addressing the growing problem facing IS. Rather, the conception and implementation of slum and urban policies have largely fuelled the informalisation of cities in LDC (Bishwapriya, 1996). It is not surprising that "what is happening in most cases is the reverse: piecemeal, undirected or impractical policies that cannot be implemented or which, in practice, benefit only those in power" (UN-Habitat, 2003, p. 5). Despite the conceptualisation and implementation of these various policies, IS have not been eradicated, have kept expanding spatially, and urban planners are overwhelmed and ill-informed of the past, current and possible extent of IS:

> A major reason why local administrations in most cities have not coped successfully with growth is because they do not know what is going on in their local land markets. The information base in many cities lacks accurate, current data and land conversion patterns, number of housing units (informal and formal) built during the last year, infrastructure deployment patterns, subdivision patterns, and so forth. Often, city maps are 20 or 30 years old and lack descriptions of entire sections, particularly the burgeoning periurban areas (Brennan, 1993, p.80).

The review of these slum policies also highlights the fact that the implementation of each of these strategies has largely benefited the middle and higher income section of the society, not the low-income city dwellers as intended. This suggests that the shelter needs of middle and higher incomes section of the population have also not been fulfilled, and that they are best able to afford newly upgraded housing programmes. Not surprisingly, any improvement in the environmental conditions of the slums, initially directed towards low-income groups, has ultimately been taken advantage of by higher income groups, and the initial target groups have been shifted away from schemes such as sites-and-services and upgrading. Consequently, an increasing number of urban dwellers are now living in IS.

The review of informal settlement policies and strategies also reveals a constant lack of a proactive approach in the policy formulation and implementation. It has emerged from the previous and current policies that demolition without a clear and sustainable relocation programme usually leads to a cycle of construction-demolition, or a cloning of slums on an even greater scale. The trend is now towards far greater tolerance of IS.

Similarly, the review shows that in cases where security of tenure has been implemented, the owner, not the occupier of the land or house, benefited. This situation also fuelled the expansion of IS. As Smart (2001) demonstrates in the case of Hong Kong, when a relocation policy considers both the owner and the occupiers, the success rate is higher, as the role of land grabbers and other conquistadors will be significantly reduced. So far, actions undertaken to address the expansion of IS can be described as a 'Sisyphus stone', whereby the process results in a vicious cycle of eternal beginning.

One of the most effective ways to address the settlement crisis that affects the majority of urban dwellers in LDC is to develop tools that help represent the real picture of the spatial behaviour of unplanned developments (Brennan, 1993). Such tools would assist the development of a long-term strategic planning for IS management. It is also anticipated that such dynamic modelling of IS growth could make urban authorities more aware of the issues surrounding the spread of IS. With this increased awareness, decision-makers would be more willing to confront problems facing the urbanisation process in general and the informalisation of urban areas in particular. The next section discusses how the spatial mapping of IS can contribute to informing IS policies and strategies, as a prelude to a computer modelling approach.

2.6 Traditional spatial representations of informal settlement

During the past five decades or so, the informal settlement literature in LDC has been dominated by description and analysis (characteristics and strategies). Sometimes perceived by urban authorities as illustrating the failure of their urban planning effort, IS have long been considered as an 'anomaly' to be corrected (Rakodi, 2001). Moreover, the spontaneous and precarious characteristics of unplanned developments have contributed to their lack of representation in urban planning instruments. The precarious and spontaneous nature of IS has let urban planners and researchers assume that they cannot be 'planned' or 'predicted'. In this regard, Abrams (1996) indicates that IS has always been articulated as a 'temporal problem' to be dealt with in the near future. Urban authorities in many LDC for example, have constantly understated or overlooked the representation of IS patterns in formal planning documents (Abbott, 2002). These factors have affected the spatial representation of IS, and when it does happen, the representations of IS have always been static, despite their evolutionary and dynamic behaviour. For example, urban planning documents do not represent the IS category in the spatial distribution of past, current and future land uses. Rather, IS are usually labelled as 'undeveloped land' and therefore not recorded in official documents.

On one hand urban planning instruments emphasise the representation of planned developments, rather than unplanned developments. Such an emphasis can be partly explained by the way urban authorities have viewed IS as contrary to the aim of the planning exercise. It could also be explained by the fact that planning policies implemented in the Western context (with marginal existence of IS) are transferred and insinuated into developing country’s settings (with the preponderance of IS) without considering the local realities (Njoh, 2000; 2003). Planning instruments thus constantly omit the representation of IS.

Policies addressing IS issues have also neglected the role of spatial representation and the visualisation potential of IS in the formulation of their strategies. Given the spatial extent and the number of city dwellers living in IS in LDC, it is crucial to develop accurate, up-to-date mapping techniques to support decisions and policies (Mason *et al.*, 1997). The fact that there are common characteristics (see section 2.2) to IS that can be mapped —characteristics that might have been overlooked in previous and current IS policies— indicate that it is possible to grasp a better understanding of their spatial distribution and dynamics. Whilst a model will not be able to spatially capture all the components of IS strategies and policies that this Chapter has identified, which also underpin the expansion of IS, a model can well represent a significant proportion of issues such as how IS would occur on vacant and less valuable land, close to the existing slums, in proximity to transportation, near sources of employment and income (such as markets), and so on. This necessity to represent the spatial behaviour of IS in relation to other physical features is reinforced by the fact that IS are versatile and changing phenomena, and yet can be dynamically captured and represented (Abbott & Douglas, 2003). The capability and usefulness of dynamic representations of IS can be examined from three perspectives: traditional mapping, remote sensing, and simulation and modelling.

2.6.1 Mapping informal settlement

Traditional mapping techniques can be used to capture the distribution of IS in urban settings of LDC. Data is derived from sources such as fieldwork, census data and existing maps. Figure 2.2 shows how secondary source data can be used to map the evolution of land use in an urban area, highlighting the evolution of IS.

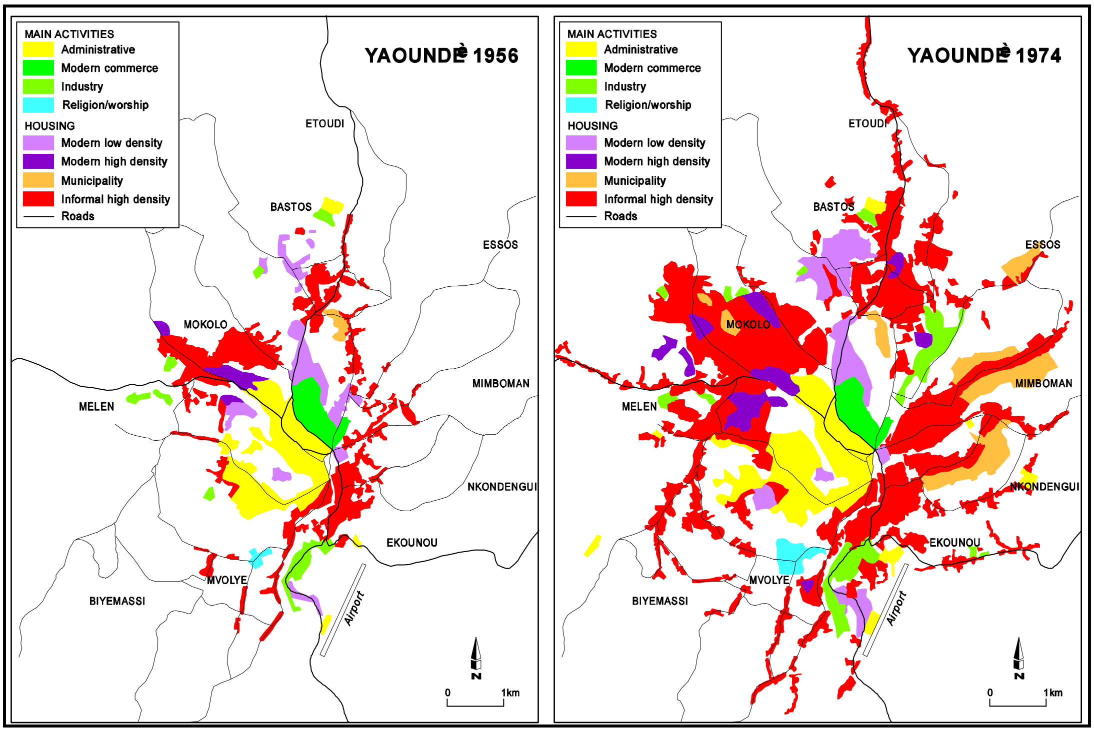

Figure 2.2. Example of mapping the expansion of IS using topographic maps: land use change in Yaoundé (Cameroon)

Source: MINUH, 1990

These data sources aid in designing a time-series map showing the historical evolution of urban land use. This traditional technique is, however, not very effective because it relies upon secondary information sources to reproduce the change in land use. Moreover, the approach is time consuming, error-prone, and the final map products are not always up-to-date. Similarly, this mapping approach is limited to past and known events, and the future prospects cannot be incorporated. Aerial photographs constitute an improvement on the use of topographic maps in monitoring the growth of urban IS (figure 2.3). Detailed maps are available in appendix 5.

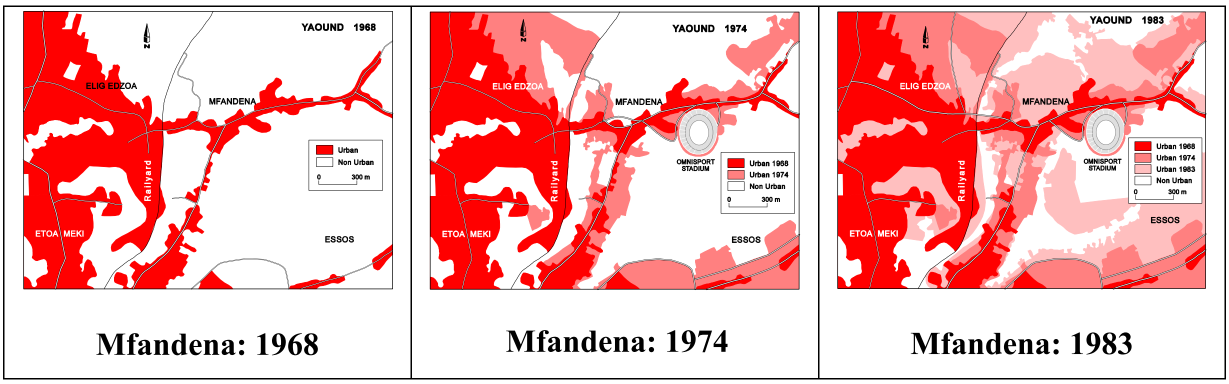

Figure 2.3 Example of mapping the expansion of urban IS using aerial photographs*:* Mfandena a suburb in Yaoundé, Cameroon, between 1968-1983

Source: INC, Aerial Photograph of Mfandena (Omnisport), Yaoundé

However, effective informal settlement decision support systems should be accurate, up-to-date, readily available and prospective. Traditionally cartography inadequately serves that purpose, because the product is often outdated. Remote sensing images can be used to address the need for up-to-date data sources for better management and monitoring of informal settlement dynamics.

2.6.2 Extracting informal settlement patterns from remote sensing images

Remote sensing technology consists of capturing earth information without being in contact with the object. In contrast to the previous technique, remote sensing images such as aerial photographs and stereo images, especially high spatial resolution images, provide a primary and more reliable data source for mapping IS (Dureau, 1997; Dare & Fraser, 2001). Remote sensing images are a valuable data source for informal settlement studies, especially for reconnaissance, identifying key physical characteristics and quick inventory and update mapping. For instance, stereo images are often used when precise measurements are required, such as, digital terrain model generation for flooding analysis in IS. In the context of informal settlement mapping, remote sensing offers two options: analogue data mapping and digital mapping (Mason *et al.,* 1998). On the one hand, analogue (or hardcopy) remote sensing data mapping such as aerial photographs, tends to produce hardcopy maps of a higher spatial resolution. Appendix 5 gives an example of mapping the evolution of a section of Yaoundé urban area using aerial photographs. This technique has the same disadvantages as traditional mapping techniques in the sense that it is time consuming, error-prone and out-dated. On the other hand, a digital (or softcopy) remote sensing mapping approach produces easily manipulatable maps, using automated extraction and identification or classification of features (figure 2.4). This approach could be very useful for decision support systems because maps can easily be made available (Mason *et al.*, 1997). These softcopy maps can easily be updated, and the approach is appropriate for rapid mapping, monitoring, and using change detection, for instance (Sietchiping, 2001a). Nevertheless, digital and analogue mapping do not address the future behaviour of IS.

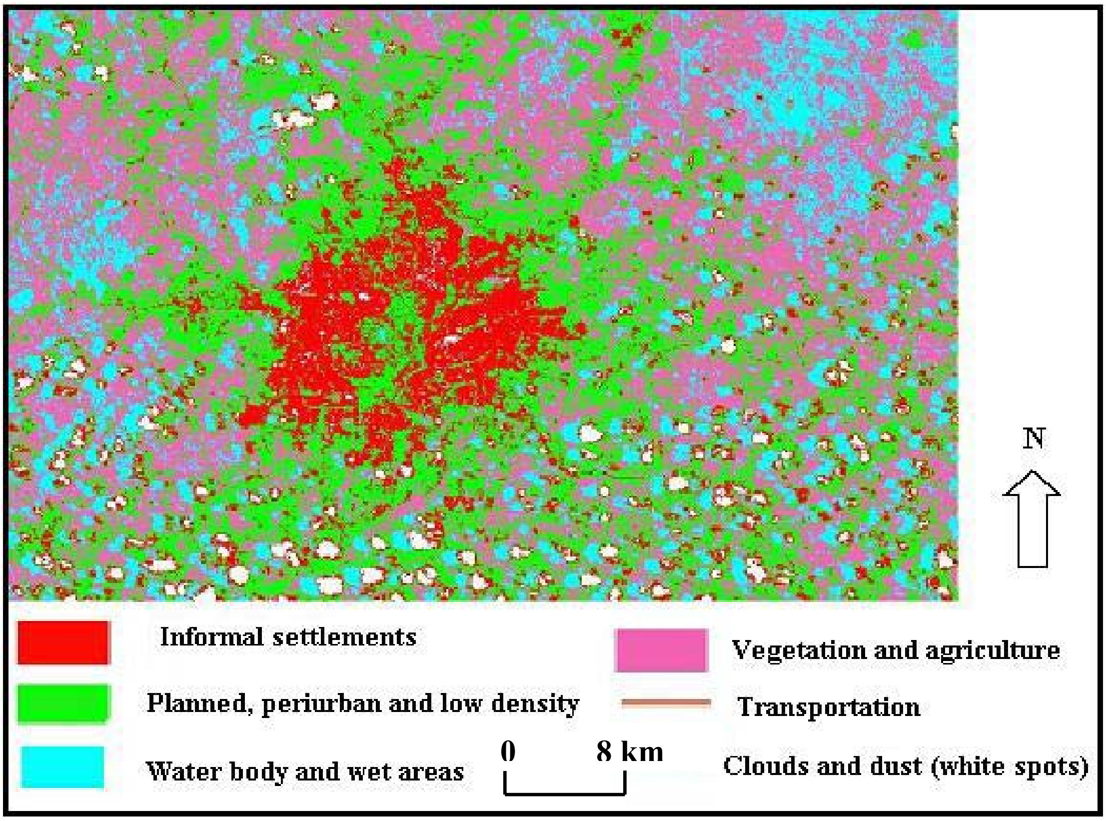

Figure 2.4 Using remote sensing for automated extraction of informal settlements

Source: 1988 Landsat TM image of Yaoundé (Cameroon)

2.6.3 Simulation and modelling techniques: the new direction

What this research suggests is that a long-term perspective and a proactive or anticipatory approach is required to predict where new IS will occur and to therefore act accordingly. As the review of the literature above has made clear, this new proactive approach supposes a good knowledge of factors contributing to the emergence of and growth of IS. These factors include transportation networks, sources and places of income and employment (e.g., market places), places of worship, existing IS, and the topography of the area. Knowledge about the long-term expansion of IS can be achieved using an approach that would clearly demonstrate historical trends while at the same time assisting in projecting the possible location of future IS patterns (Abbot, 2002a).

On the one hand, computerised Geographic Information Systems (GIS), a spatial technique, can greatly contribute to this IS representation process, especially helping with the organisation of data, for instance using an overlaying method, and establishing correlation between physical factors and the location of IS (UN-Habitat, 2003). As will be argued during this thesis, simulation of the historical expansion of IS can provide clues as to where future settlements will occur. On the other hand, the simulation and modelling techniques can be used to obtain new insights into the intrinsic correlation between the factors underpinning the expansion of IS and the processes determining their future location. One of the advantages of adopting the simulation and modelling approach lies in their capacity to incorporate the dynamic behaviour of IS and visually represent their expansion. This will help in designing a better and more efficient decision-support system and policies for managing IS in LDC' cities. Such a model could assist in the development of contingency plans to make land and housing available for and accessible to all urban dwellers.

2.7 Conclusions

Informal settlements have been described according to their physical appearance, environmental and health threats, compliance with law, and socio-economic mechanisms. It has been shown in this Chapter that there are many factors that have contributed to the emergence and constant expansion of IS in LDC' cities. These factors include population growth (associated with rural-urban migration, religious affiliation and kinship), accessibility and availability of employment, poverty, topography, land use status, transportation networks, availability of land, porosity of urban planning and policies, corruption, poor governance, and instabilities. The task is to incorporate, when possible, the factors identified into a model that could help investigate the dynamic expansion of IS.

The informalisation of urban areas in LDC persists despite the measures which have been taken and the attempts made to curb their expansion. The succession of policies and concepts has done little to find the right path to address the shortage of shelter and contain the expansion of IS. The chronological appraisal of these strategies has shown some variations, but it has been demonstrated that these measures perform poorly in reducing the spread of IS. The critical weakness of these policies is that conditions pertaining to the emergence and growth of IS were not incorporated in them. Moreover, all the five major approaches towards IS point to short-term and 'quick-fix' measures rather than the promulgation of a long-term vision for the prospects of IS.

The review of the literature has also made clear that it is becoming increasingly evident that urban authorities do not always have the means to appreciate the social and spatial scope of IS. One of the reasons is the lack of adequate land management instruments and mechanisms as well as appropriate appraisal tools. Developing a model is one strategy to address this weak urban land use management. It is clear that a proposed IS growth model would not intend to address other issues raised in the literature in regard to why responses to the expansion of IS have failed, such as the lack of political will, corruption, poor governance, social unrest, legal and policy impediments and funding issues. However, an IS growth model which outlines the context, could provide critical information to a range of key stakeholders for improved understanding and response to these complex urban dynamics processes that define many cities in LDC.

The scope of IS could be ascertained from historical trends in order to inform future perspectives, such as forecasts of spatial expansion. This thesis proposes to formulate a model that will show historical growth patterns in a city and develop scenarios of future IS distribution and hence aid the appraisal of spatial importance in unplanned development. The proposed IS growth model will also consider contributing factors in the emergence and growth of IS. Importantly, it will take into account socio-cultural factors along with physical and infrastructural components. The proposed model would therefore include transportation networks, existing IS patterns as well as IS dwellers' source or income and employment and general topography (terrain). Furthermore, by adding a dynamic visualisation component to the human and geographical dimension of unplanned developments, it is anticipated that one will gain better insights into the future distribution and development of IS. Compared to other approaches, the modelling and simulation approach will result in better-informed policies and facilitate the decision support process. The main challenge is, however, in relation to how to conceive, design and implement a model of IS growth. Can the dynamic representation and modelling of IS be achieved within GIS technology, in parallel with another technique, or through an integration framework incorporating both spatial techniques and simulation and modelling techniques? The next section will evaluate how the spatial techniques such as GIS can be used in combination with modelling and simulation techniques such as cellular automata to investigate the dynamic behaviour of IS in LDC.

Chapter 3

Conceptual framework for exploring urban dynamics: GIS and cellular automata-based models

3.1 Introduction

Urban simulation aims to improve the understanding of urban evolution and to predict urban changes. To do so, urban dynamics seek to represent evolutionary patterns of the city over time and space. It is generally argued that although traditional large-scale urban simulation approaches of the 1960s were based on solid theories, they had significant weaknesses such as poor handling of space-time dynamics, they were impractical, their representation of data was too coarse and their 'top-down' approach ultimately failed to reproduce realistic simulations of urban systems.

Urban dynamics modelling has gradually moved from theories based on static centralized approaches, to spatio-temporal and hybrid-system based theories. Models are now accounting for the complexity exhibited by urban processes, forms and systems. Indeed, the range of factors underpinning urban dynamics is now viewed as enriching the development of modelling approaches, and thus improving our understanding of urban changes. Current urban simulation approaches are taking advantage of progress in information technology, data availability and complex theories (such as cellular automata and artificial intelligence) to address the criticisms raised by previous urban dynamics modelling attempts.

To be useful and realistic, however, urban models require 'real-world' data such as existing spatial and tangible urban patterns that can be integrated and mapped in a modelling scenario. Geographic Information Systems (GIS) have emerged as a prime framework for the management of a range of spatial real world data. Efforts to use GIS as a modelling tool have, however, been received with scepticism, especially because GIS is rigid, has limited modelling functionalities, and poorly handles the temporal dynamic dimension. Cellular Automata (CA) that were developed in the 1940s to explore complex behaviour and systems, are now progressively being adopted and adjusted to address some modelling weaknesses reported in current GIS technologies. Urban dynamics modelling is, therefore, widely adopting a CA approach as a means of enhancement, especially when this approach is integrated with GIS (Torrens, 2002). There are instances were GIS and CA in combination have been used to explore, study, understand or inform urban dynamics, with variable results.

Chapter Two argued that the IS constitutes one of the most prominent spatial facets of urbanisation in LDC, and that policies and strategies to curb their expansion were largely inefficient. A model was therefore suggested as a means to improve our understanding of IS process and growth in LDC contexts. It was suggested that understanding the factors and theories underpinning the emergence and growth of IS can be used to develop a dynamic IS growth model that would ultimately assist IS policy and planning responses in LDC.

The purpose of this Chapter is to present the state of knowledge on urban dynamics, specifically in relation to modelling and simulation by means of GIS and cellular automata and their integration. Although GIS and CA have been applied in different fields of study (such as forestry, physics and biology) this Chapter will be limited to work conducted in the area of urban dynamics modelling. The scope of the theoretical and conceptual framework assessment will be on existing urban dynamics models, because using GIS and CA for modelling could provide new insights into the IS growth in LDC. In particular, this Chapter will demonstrate how the concept of urban dynamics has evolved and what approaches have been used to achieve better simulation and modelling. The ultimate goal is to demonstrate that the proposed IS growth model can expand on the previous GIS and CA based approaches.

Section one of this Chapter summarises the conceptual and theoretical framework of urban dynamics modelling. This section traces the origin and formulation of spatial models in urban studies. Traditional and current urban dynamics models are also assessed. Section two illustrates the role of visual dynamics representation in urban dynamics simulation. This section examines the weaknesses and strengths of dynamic visualisation and animation in the representation of spatio-temporal attributes of urban systems. Section three outlines the use of CA and GIS as urban modelling approaches, both separately, and in combination. This section demonstrates the advantages and limits of GIS technologies in urban modelling. It also gives a clear illustration of the role played by CA in improving the theory, as well as the hypothetical and operational components of GIS-based urban dynamics models. Close attention is paid to how appropriate integration of GIS and CA technologies can lead to better urban dynamics modelling, especially of IS.

3.2 Theory and models of urban dynamics

This section traces the roots of urban dynamics modelling and simulation, in order to provide an understanding of their theoretical context and limitations. In particular, it presents the state-of-the-art theories and applications of urban dynamics. The first part traces the roots of the spatial models in urban studies while the second gives an account of the traditional urban dynamics approaches. The last part outlines the new approaches towards urban dynamics and suggests that whilst existing models have advanced conventional modelling approaches, they lack a number of critical capacities which the IS model developed in this dissertation seeks to address.

3.2.1 Spatial models in urban dynamics

In geography, a model usually refers to a temporal and spatial representation of an spatial element in order to simplify its understanding. It is often argued that a model represents a useful tool to gain a better and rapid understanding and perception of the complexity of a system. In sciences, models are commonly used to simplify the representation and explanation of complex patterns. Models are now wide spread over many areas of study such as geography, sociology, economics, and geology. In particular, social sciences have embraced models in different studies such as migration, market forecasting, transport, land-use and urban changes (Couclelis, 2002). In geography, modelling has been specifically applied to the study of migration, population, business locations and pedestrian movements in cities (Torrens & O'Sullivan, 2001). Despite the use of models, affiliated and sub-disciplines in geography often adopt the meaning of the term 'model' to suit their field to such an extent that the spatial and temporal dimensions are sometimes left apart (Wegener, 2000). For instance, models and scenarios of population projections are not usually spatially explicit.

One of the advantages of spatial models is that they consider a space and its attributes within a discrete time frame. Incorporating space and time in urban dynamics modelling, however, has not always been easy. Usually, emphasis is placed on one set of elements (e.g., space in GIS) rather than the interaction of all elements within the system. The integration of space, time and attributes in building modelling is now increasingly preoccupying urban dynamic researchers because it is seen as useful path for system analysis and realistic model improvement. Efforts to develop appropriate theories to express spatial models have been enormous and there are many ways of classifying existing spatial models. Wegener (2000), for instance, distinguishes three groups of spatial models.

The first group constitutes scale, conceptual and mathematical models. A scale model replicates the earth's surface and some of its subsystems. Conceptual models express the functionality and the connectivity of a system using graphs, charts or words. Mathematical models explain the system using formulas. This type of model represents the way spatial models are formulated and is not concerned with the representation of real world and phenomenon, especially spatial.

The second category of models tends to provide solutions to concrete and specific problems. As a result, models are often divided into three main categories: deterministic, probabilistic or stochastic. Deterministic models rely on the interconnectivity of elements in a system to guide the solutions. Probabilistic models generate possible solutions to a given situation based on the probability of independent variables that are taken into consideration. Stochastic models use probabilistic models and use conditionality to propose solutions to a problem. This category is more concerned about the prescriptive, informative, utilitarian and operational sense of spatial models.

The third category of spatial models deals with the movement within a system. There are a number of types. A static model considers the system as in equilibrium with one single state. A dynamic model develops a multiple discrete or continuous timeframe within the system under investigation. Eventually, a spatial model, which treats time as discrete, is known as simulation. In this category, the time dimension is emphasised while the spatial dimension and theoretical contributions might be completely ignored.

There are many other possible classifications according to the field of research, the object of study, the techniques used and the applications. Not surprisingly, none of these single models or categories satisfactorily represented spatial dynamic patterns. Integrated spatial models have therefore been developed which encourage the use of more than two of the above models. The next section will describe these integrated models; discuss existing urban modelling theories, and highlight some of their weak points as well as the inspiration behind what is now referred to as traditional urban dynamics modelling.

3.2.2 Traditional urban dynamics model: breaking out of the 'black box'

The term 'black box' is commonly used to qualify the implicitness and equilibrium theory of initial spatial urban models (Torrens, 2002). This section analyses the rise and decline of the earlier urban dynamics models, revealing some of their strengths and weaknesses.

The work of Von Thünen in 1826, Ravenstein between 1885-89, and later Weber, Christaller, and Ulman pioneered spatial modelling in the social sciences. However, the earlier models were severely criticized as "largely descriptive" (Wilson, 2000, p.57), and treated the city as a centralized node with little interaction (gravity model) within the components of the zone or space. Also, traditional models were too coarse and lacked detailed data, their representation was 'primitive' (Wegener, 2000) and the elements of space were not interconnected.

In the early spatial models such as central place theory, attributes were treated separately and then aggregated. The area was usually considered to be homogenous, assuming that all the attributes of the space are evenly distributed within their respective areas. That is, the two dimensional modelling linked each component of the space with specific information, especially with the emergence of computing technology. In the 1960s, spatial urban modelling took advantage of advances in the computer sciences to develop coarse and empirical models from small scale to large scale. These models introduced new approaches to urban modelling. Yet, despite these advances, computer memory and speed slowed attempts to move from small to large-scale modelling. In the early 1970s, the impatience to see spatial urban models delivering a comprehensive understanding of the urban system raised instant criticism. It was in that context that Lee (1973) proclaimed the demise of large-scale urban models in 'Requiem for Large-Scale Models'. Lee's argument was based on the lack of computing power, size (from workstation to personal computer), and cost (manually programmed punch cards), availability of data and theoretical framework. Lee (1973) reported that urban models in the 1960s were unnecessarily complicated, expensive, data 'hungry', lacking transparency, mostly static, often unable to replicate their results, error prone and impractical.

Batty (1994) notes that in the 1970s, critics of large-scale urban models were nourished by the innovative approach that urban modelling brought into planning but there were still shortcomings. Firstly, urban planning researchers were divided over whether planning should be considered as science or design. Secondly, in the early geographical spatial models, such as Allen and Sanglier's (1979), the 'self-organization' concept was lacking. Finally, attributes and area were treated separately, and then aggregated. The area was considered to be growing homogenously.

Continued advances in computing technology later answered some of the issues raised by Lee (1973). Urban dynamics researchers were seeking possible integration and compatibility with other technologies and tools (Batty, 1994). In particular, progress in the theoretical and methodological frameworks of urban simulation was helped by computing technology and complex theory, which enabled them to respond to the criticisms of the earlier spatial models (Harris, 1994; Lee, 1994).

To correct these weaknesses, urban researchers developed a range of urban dynamics modelling theories. These include the Lowry gravity model of the early 1960s, entropy based spatial interaction (Wilson, 1970), random utility choice by Domencish and MacFaden (1975), bifurcation theory (Allen & Sanglier, 1978; 1979a), the multinomial logit model (Anas, 1983), and structural evolution (White & Engelen, 1993). Wegener (2000), however, notes that theories sustaining urban models were largely influenced by economics (especially market supply and demand) or transportation (origin and destination), rather than taking various components of the urban systems and subsystems into account. Previous urban models did not also consider a city as a decentralized system. Despite these deficiencies, this profusion of theoretical frameworks provided the necessary scientific benchmarks to develop comprehensive and operational urban models. Wegener (1994) gives a detailed account of operational and comprehensive urban system models. Twenty urban models were identified with different levels of sophistication and comprehensiveness. Of these, Wegener noted that only twelve could be considered as comprehensive and operational (applied in real cities).

Any theoretical exploration of the complexity of urban system requires clarity, precision and detail. In that way, urban dynamics modelling can achieve it goals. Forrester (1969) suggests that the logic, consistency and explicitness that is embedded into the modelling procedure, helps with understanding urban systems, and testing hypotheses. This allows urban dynamics modelling and simulation to ease the social misrepresentation of time, spatial relationships, space and its attributes.

In practical terms, it is vital for planners and decision-makers to have reliable, localized information and a broad knowledge of urban issues. That is, to ensure that the gathering of relevant information, and its dissemination, interpretation, analysis and presentation of urban issues and activities guides a well-informed decision. But traditional urban models fail to respond to the needs of urban planners and decision makers.

Since the 1970s, progress has been made in GIS technologies, which have served the cause of modelling techniques, especially in interconnecting and handling detailed and multiple elements of the space. In particular, computer speed and memory have fed the development of modelling techniques and representations. So has the availability and variety of GIS and modelling software. There has also been a significant shift from line command to 'clicking' function, which has made GIS more accessible to urban modellers

(Forrester, 1994). Computing power and speed have also provided answers to some of the criticisms raised by Lee's 'Requiem for large-scale models' (1973). These include computing power, size (from workstation to personal computer), cost and user-friendly programs (from manually programmed punch cards to menu-driven). Spatial urban dynamics models have thus revitalized both progress in computer sciences, and the input from others disciplines such as complex theories.

3.2.3 Towards urban geocomputation

Limitations noted in traditional urban dynamics models have led to the exploration of new ways and theories to respond to the critics. Current urban dynamics modelling borrows from other disciplines such as complexity theory, computer sciences and artificial intelligence to better inform urban dynamics theory and generate useful models (McDonnel, 2003). In particular, geocomputation (GC) has been advocated as a new urban dynamics paradigm, which conceives "modeling systems at the scale of individuals and entity level units of the built environment," (Torrens & O'Sullivan, 2000, p.11). Geocomputation has benefited from computer technologies and programming, data availability, detail and integration that have enabled the emergence of realistic and informed urban simulation and models (Openshaw and Abrahart, 2000). Urban models are becoming widely available and operational (Wegener, 2000), and one of the driving forces behind the revitalization of urban dynamics, is the contribution of complex theory.

Previous urban models represented urban dynamics as snapshots, rather than as a system evolving over time. Whilst spatial dimensions were well represented, the poor dynamic representation of urban space constituted one of the major limitations of previous operational urban models (Atkinson & Martin, 2000). In the literature, this weak temporal dimension was implicitly represented by one set of data used for simulation (one map), or there was a large gap between periods (e.g., ten year periods for census data). Representing urban change in that way was realistically and theoretically inappropriate, given the inherent complexity and multi-dimensionality that usually defined such changes.

The importance of dynamic representation and the ability to see and understand alternative development scenarios is well established in urban studies. For instance, a simulation "can serve as an accessible surrogate for the city's complex systems, extensive spatial structure, or environmental influences" (Decker and Lesser, 1993, p. 231). Making complex alternative scenarios accessible improves the role of parameters that influence the behaviour of urban systems. Improving the communication between researchers and stakeholders reduces confusion, increases trust, and results in more useful urban dynamics modelling (Forrester, 1994). The ability to package complex and multiple sources of information is now well handled by GIS and other representation technologies. For instance, multimedia and hypertext have been one solution to make the spatial and temporal information more interactive (Wiggins & Shiffer, 1990). Three-dimensional and four-dimensional (change across time), animation and visual representations are another means of quickly communicating complex geospatial data (Thurston *et al.,* 2003).

Research on visualization and simulation has a relatively long history in urban illustration, beginning with the use of ink-and-paper sketches to compare alternative developments. There is an abundance of literature that examines the perceptual and cognitive reactions to visual simulation (Craik & Feimer, 1987). Researchers in this area have examined the role and impact of photography, photomontage (superimposed images on existing photographs), audio/video imaging, multimedia approaches, and full-scale simulations, in which a life-size scale is used (Herzog, 1989; Orland, 1994). There is a consensus that the visualisation, simulation and representation of spatial and temporal urban features increase the understanding and perception of their intrinsic behaviour and processes (Card *et al.,* 1999; Thurston *et al.,* 2003). Researchers have also found that realistically simulated images cut across traditional cognitive boundaries and reach those who may not be as adept at processing more abstract two-dimensional imagery such as maps, plans, and blueprints. The use of these simulated images can thus serve to simplify the representation of complex dynamic features (Batty, 1996a; Bishop & Dave, 2001).

As computers have advanced in graphic representation and speed, researchers have found that image processing was the most effective method of portraying reality to a respondent's satisfaction (Kraak & Ormeling, 2003). There appears to be consensus that computer-based simulations are the next generation of environmental simulation because of the crisp and clear images that can be developed (Bishop & Leahy, 1989; Clarke *et al*., 2002). The extent to which computer-based simulations have been used in previous urban dynamics models has, however, been limited by computing power and processing speed.

3.3 Visual animation of urban dynamics

One of the purposes of urban modelling and simulation research is to improve visualisation, and convey a rapid understanding of complex systems. Visual representation and display of urban dynamics, for instance, are mental processes. The idea of urban simulation is not new in geography, as seen in a 1972 quote by Kamnitzer indicating that "this will permit an observer-participant to insert himself into a dynamic, visual model of an urban environment by means of a visual simulation system" (p. 315). The ability to create workable simulation models, and place them into the hands of practitioners has, however, been a much slower process. Traditional mapping techniques and display, rather than computer images, have long been recognised as useful tools for providing visual and scientific insights into urban systems (Hall, 1992; Wood, 1994).

With the emergence of computer-based urban simulation technology and the development of movie-making industries (Openshaw *et al.,* 1994), many researchers found the usefulness and appropriateness of using animation in the study of spatial and temporal urban dynamics. For instance, Lathrop and Hamburg (1965) used the animation of a series of map frames to visualise the growth of the city of Buffalo. The interest in using visual animation lies primarily in its ability to reveal essential patterns of a complex system from simple rules (Tobler, 1970). One of the earliest urban simulation models was based upon the concept of a 'movie'. This concept refers to the spatial and temporal changes in the state of the object under investigation.

Other issues exist that need to be considered in regard to urban simulation for the study of small and large-scale urban change. The time-series urban expansion of Detroit by Tobler (1970) reveals the potentiality of using simulation and visualization techniques to simplify the understanding of complex urban systems and processes. One of the common criticisms of Tobler’s movie and Lathrop’s animation was that they produced static displays of features (map series) or only a sequential time frame. In another instance, Moellering (1973a; 1973b) illustrated the impact of visual animation when he applied 'real-time' visualisation in the study of traffic accidents in Washtenaw between 1968 and 1970.

Since the 1990s, animation has become extensively recognised as a means to explore and represent complex urban forms and systems. Batty and Xie (1994) show how the exploration of cellular automata and fractals can expand urban dynamics modelling techniques and capabilities. They showed how CA gives the same consideration to space, time, attributes and the relationship that exists within spatial components. In another example, Engelen *et al.* (1995) used cell-based animation to demonstrate the socio-economic impacts of climate change. Along similar lines, Batty and Longley (1994) have used diffusion models to express the fractal form of cities. Despite the visual improvements made, however, these attempts were limited by the poor use of continuous real-world data.

From the mid 1990s, developments in spatio-temporal visualisation became more effective. Macagnano (1995) for instance, used a computer simulation to examine the effect of a hundred years flooding on a small town in South Africa to its community. Macagnano came to the conclusion that visual simulation is an effective tool to explain complex spatial concepts and to narrow down the cultural and communication gap between the researcher and the community. Meanwhile, at the University of California, Los Angeles (UCLA), an urban simulator was established that simulated cityscapes using a combination of computer-aided design and a Geographic Information System (GIS) interface. The models were specifically designed to aid in community-based planning. Although this application revealed some problems with computing speeds and there was some dissatisfaction with the simulated renderings, the overall capacity to develop alternatives was improved under this model, due to a clearer understanding of the impacts for a given development scenario, that could be delivered.

In the late 1990s, a research group in California's Silicon Valley achieved one of the most successful applications of urban dynamics animation using real-time data (Acevedo *et al.*, 1996; Clarke *et al.*, 1997; Clarke *et al.,* 1998). This multi-disciplinary team put together a simulation of Urban Growth Model[1] (UGM) that they tested on the San Francisco Bay Area to study the impact of human activities on the spatial organization of land use and change. To illustrate this change, the group first conceived a model of urban growth in the area. The data sources (old maps, land-use database, and remote sensing) of the period of 1820 to 1990 were compiled using GIS tools. The second step was to use CA to simulate the potential development of the future land transformations caused by human activities. Finally, the team developed a model of urban growth in a well-planned city based on GIS, CA and land cover modelling. This model simulates the growth of the area (as a movie) up to 2100, which can be visualised in real-time. The upgraded version of UGM, known as SLEUTH (Slope, Landuse, Urban extent, Transportation and Hillshade) has been applied to simulate urban dynamics in North American cities and in Europe (Silva & Clarke, 2002).

As visualization has become a valuable technique for representing urban dynamics, so have the formats for displaying animation of spatio-temporal files. These can range from desktop publishing formats (e.g., GIF and JPEG) to movie and virtual reality (Dorling & Openshaw, 1992; Whyte *et al.*, 1997; Longley & Batty, 2003). Although the use of computer simulations for planning is seen as the next wave of urban modelling (Klosterman, 1994), there is little consensus on the methodologies by which this will take place. Some researchers are sceptical about using dynamic visualisation because of the simplicity of some model and theory formulation (Torrens, 2002). In urban planning situations, however, these tools could be very effective and practical. Real-time urban animation remains therefore at an imperfect stage, but there is much hope for further research, especially in the area of incorporation and management of varied data sources with the assistance of spatial technology such as GIS.

3.4 GIS as spatial modelling technology?

This section first assesses the contribution of GIS technology in the development of realistic urban dynamic models and then discusses how an urban dynamics model can be incorporated into a GIS environment.

[1] More information on UGM and SLEUTH programmes is available at Project Gigalopolis website: http://www.ncgia.ucsb.edu/projects/gig/ (last accessed, December 16, 2003)

3.4.1 Role of computer and GIS technologies in urban dynamics

Geographical Information Systems (GIS) are computer-based supports (hardware and software) for collecting, manipulating, overlaying, analysing and displaying digital spatial information using software. GIS' represent spatial features as vector or raster images and products of the database processing can range from maps to images and virtual reality. Since the introduction of GIS in the 1960s, the scientific community and practitioners have adopted GIS technologies for their use in compiling, managing, and displaying spatial data. The data handling capacity of GIS is therefore critical for developing operational urban modelling. For instance, GIS technology can help organise and link the spatial factors of emergence and growth of informal settlements. Not surprisingly, GIS has been used in various fields of study. Applications now cover nearly all fields of the geographical sciences and studies.

Since the conception of GIS technologies, advancements in computing technologies have also accelerated the development of GIS functionalities and applications. The framework of GIS has progressively evolved first from mainframe and minicomputer environments, to workstations, and finally to personal computers (PCs), portable devices, internet mapping, and virtual GIS. GIS tool providers have seen a rapid change in the type of GIS products available. In particular, there has been a move from standard hardware development to software, to data provider and programming (Waters, 2002). GIS tools have also become more flexible in responding to clients' needs and specific problems. The last decade has also seen the development of macro languages embedded into GIS environments, and the trend is towards greater compatibility and flexibility of GIS software tools with popular external programming languages.

The considerable advances in computer technologies and capacity in the last four decades has also expanded the development of various GIS software. Despite the overall similarities in GIS software, however, the differences preclude the way spatial output is represented, as well as the emphasis put on operations, functionality, sophistication and the integration of the components of the system. Nevertheless, an essential GIS support system has many components (Heywood *et al*., 2002). Today's typical GIS software includes features such as:

- a database (layer and attribute),
- a management capability, a cartographic display system (access, edit and display),
- a map digitising interface or interconnection,
- a database management system facility (to input, query, manage and analyse the attribute data),
- a spatial analysis capability (for overlaying, network analysis, occurrence and correlation, and relationships between database and features),
- an image processing system (e.g., process and integrate remotely sensed data into digital spatial sources),
- a statistical analysis package (e.g., for comparative analysis), and
- a decision support system to guide the allocation of resources based on input .

An important question, however, is whether GIS can simulate and model complex urban dynamics, such as informal settlement processes.

3.4.2 GIS and urban dynamic modelling

This section assesses whether current GIS technologies have the means to deliver dynamic modelling.

Investigating the ability of current GIS technologies to execute urban dynamic modelling is critical for this research for at least two reasons. First, if GIS technology by itself were sufficient to develop urban dynamics models, the proposed informal settlement growth model (ISGM), would have a readily available framework, environment and interface to experiment on. However, if the GIS technology is not sufficient, then the proposed model would have to identify another technology that would complement the spatial handling capacity of GIS. To identify its usefulness, the modelling within GIS will be presented, followed by a review of some attempts at urban modelling within GIS.

GIS modelling usually points to the application of basic functions such as buffer, overlay, digital elevation model, and Triangulated Irregular Networks (TIN) operations

(Zeiler, 1999). GIS also uses equation-based functions such as layering, image calculators or map query products as modelling applications. One of the advantages of GIS is the opportunity it provides to represent and interrelate irregular spatial forms and patterns (Geertman & Van Eck, 1995). Some have argued that this gives GIS models a descriptive characteristic, and a decision-support system for spatial problem analysis (Burrough 1986; Cowen, 1988). There is scepticism, however, around GIS as a modelling tool in the sense that modelling is too loosely used in a GIS environment. GIS might not be, therefore, an adequate tool for simulation and modelling real-patterns and spatial processes.

Three main limitations have been identified. First, current GIS models are static and weak in handling dynamic representation of phenomena (Langran, 1992; Fedra, 1993; Longley & Batty, 2003). Secondly, spatial representation in GIS is a disaggregate of independent zones with sporadic links and casual relationships rather than a system with dependent and independent variables and attributes (Tobler, 1979; Raper, 1989; Couclelis, 1991; Wegener, 2000). The third handicap is the inability of GIS to perform complex numeric analysis and to process multidimensional spatio-temporal systems (Birkin *et al.*, 1990; Batty, 1992; Wagner, 1997; Couclelis, 2002), especially when dealing with large-scale data. There are also complaints that GIS is not flexible enough to adjust to user needs, while some of its operations and functionalities remain weak (Wagner, 1997; Fotheringham, 2000).

Nevertheless, there have been some attempts to develop spatial models within GIS environments, especially by adding functionality and more features. It should also be remembered that, forty years ago, modelling and simulation were not the prime motivations in developing GIS, but collecting, manipulating and displaying selected spatial data (Batty, 2002). There have been some attempts where GIS has been used as a source for modelling and forecasting urban dynamics. Meaille and Wald (1990) have applied the diffusion model to the study of the urban growth of Marseilles (France) for example. They used satellite images and raster GIS data as inputs for a predictive model of the spatial distribution of population. This model, however, failed to produce realistic patterns of urban changes in Marseilles.

In another example, Batty and Xie (1994a; 1994b) have linked model programming with a GIS package (ARC INFO^{TM}) to develop an urban dynamics model using a raster GIS display interface. They applied the model to the city of Buffalo (USA). Temporal and predictive dimensions were insufficient in this model and the analytical capacity of GIS was also weak. To improve the output of the model, Batty and Xie (1994a; 1994b) had to rely on external mathematical procedures to generate the model. This can be explained by the limited capacity and functionality of GIS packages and their macro-languages to fully incorporate a time dimension (dynamics). The results obtained by Batty and Xie suggest that GIS by itself is not sufficient to develop a dynamic urban model and a proposed IS growth model should be used in an additional concept outside a GIS environment.

The similar procedure of adding external programming capacity has been attempted on various occasions. The California Urban Futures (CUF) model of Landis (1994; 1995), for instance, combined GIS with expert systems to predict the location of growth patterns of San Francisco over a twenty-year period. Compared to previous GIS-based models, the CUF had reasonable spatial and temporal dimensions. The predictive and simulation components of the CUF were, however, coarse and unreliable. This example shows that the combination of spatial technologies such as GIS with a dynamic approach could ultimately improve the output of urban growth models. Thus, GIS alone does not have the capacity to produce a reasonable prediction of urban dynamics.

This poor modelling and simulation capacity of GIS has been echoed by many urban dynamics researchers, including Longley and Batty (1996, p.350) who clearly state that "GIS is not about modelling and simulation *per se*, nor is it about forecasting and design, prediction or prescription...[rather] it is an enabling technology…it is about representing digital data so that it can be stored, queried, and visualized in the most intelligent and relevant way". Still, innovations in information technologies point to a GIS which will continue to enrich its modelling capacity by becoming more flexible and user friendly; by integration with other technologies and approaches, and by expanding its legacies and functionalities for better applications. To achieve a reasonable urban dynamics models, however, GIS technologies have to be combined with other approaches. The literature suggests that some of the GIS' inabilities to handle dynamics modelling can be overcome by appending other techniques, such as cellular automata (CA), which have great advantages over GIS in performing dynamic simulations and modelling (Couclelis, 2002; Xia & Yeh, 2001).

3.5 Cellular automata and urban modelling

The review of the GIS approach has indicated that it does not have a dynamic modelling capacity. To achieve this thesis' aim of developing a realistic urban dynamic model, especially an IS growth model, it will be useful to seek the contribution of dynamic models that will supplement spatial models (such as GIS). Cellular automata (CA) are becoming increasingly used as urban modelling tools mostly because they are simple to build, flexible to formulate, and capable of generating complex patterns that can emerge from historical evolution trends through the diffusion process. Cellular automata, thus, appears to comprise a plausible additional conceptual framework able to complement the GIS ability to manage IS factors. Specifically, CA can assist the development of the simulation and prediction component of the proposed IS growth model, which can only be performed within a current GIS framework. This section will discuss the concept of CA and its theoretical formulation, and then present some examples of CA applications as an exploration of hypothetical urban modelling. It will finally present some examples and attempts at modelling real urban dynamics using CA.

3.5.1 Concept of cellular automata

Cellular automata (CA) were originally conceived by Ulam ('cellular') and Von Neumann ('automata') in the 1940s to provide a framework for investigating the behavior of complex and extended systems (Schatten, 1999). Thus, a cellular space qualifies the basic component of the space, while an automaton is a self-organizing element that performs logical and continuous programmable instructions. The concept of a self-organizing system is central in CA urban dynamics modelling and it refers to the tendency for system structures to spontaneously develop ordered patterns, often on a large scale (Torrens, 2000; 2001). In its original format, CA can be understood as a mathematical idealization of physical and dynamic systems in which space and time are discrete, and physical quantities take on a finite set of discrete values (Semboloni, 2000). A cellular automaton consists of five main elements:

- A regular uniform and infinite 'lattice' or 'array' with discrete variables at each cell, (e.g., an urban space). Lattice space has *n* dimensions, but two-dimensional CA are the most common in urban dynamics simulation. Few urban studies have used three-dimensional CA (figure 3.1).
- A 'cell' is a subunit of a regular geometrical grid. While usually in a rectangular grid, a cell can be formulated as an irregular polygon, hexagon or a link. A cell (or a site) is a single element in the entire lattice (space). During the simulation (or the changing of state), cells react on the entire lattice, observing the same transition rules. Although representing only one state at the time, a cell encapsulates an infinite number of states variable, a geographical location and various attributes.
- A 'state' is a variable, which takes a different value at each site or time. It can be a property, a number or word (0 or 1, urban or non-urban). It can vary from two (Conway) to 29 (Von Neumann). The variables at each site are updated synchronously.
- The 'neighbourhoods'. In a grid, these are normally the cells physically closest to the central cell which might influence its value at the next step. During the simulation, neighbourhood cells act as immediate areas of interest or zones of impact for the central cell. The neighbourhood includes the cell itself. Many types of neighbourhoods can be identified including five for Von Neumann (figure 3.2) and nine for Moore (figure 3.3), which can also be extended (figure 3.4).
- Local or transitional 'rules' are a set of conditions or functions that define how each cell’s state changes in response to its current state and that of its neighbors. The future state of cells is determined by the transitional rules in a discrete time frame.

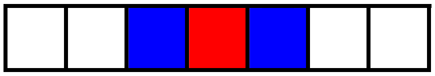

Figure 3.1: One dimensional CA grid with three neighbours on a lattice of 7 cells

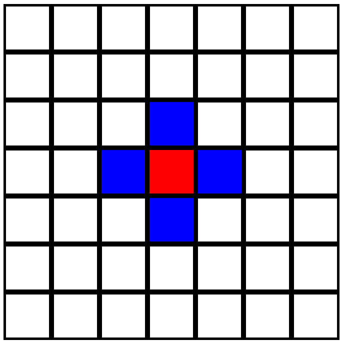

Figure 3.2: Two dimensional Von Neumann 5 neighbour possible cell

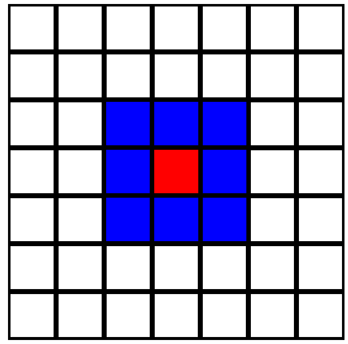

Figure 3.3: Two dimensional Moore neighbourhood grid cells, 7^2 possible cell states

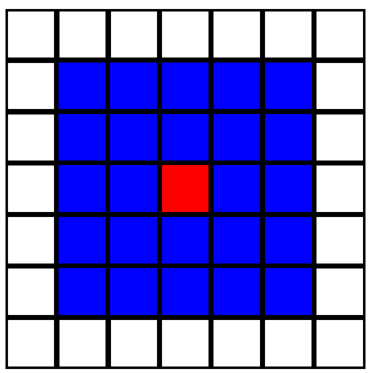

Figure 3.4: Extended Moore neighbourhoods

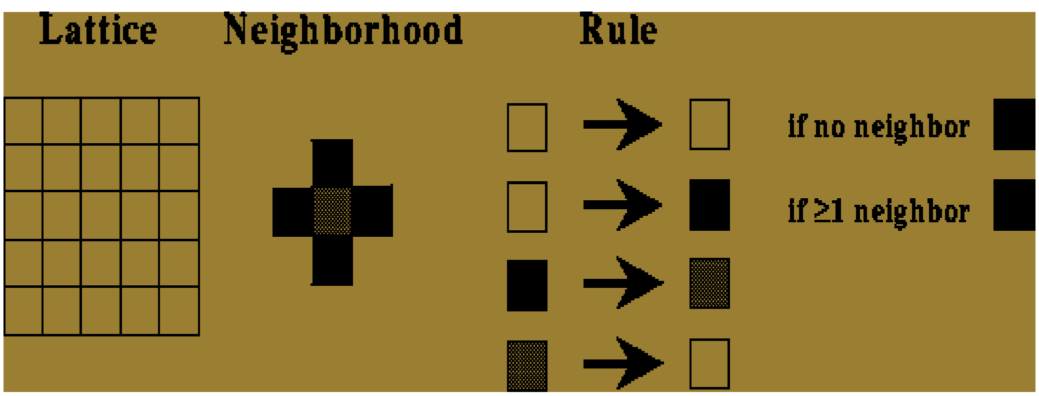

Figure 3.5: Cellular automata components: Lattice, Neighborhood, Rules and States

Sources: Figures 3.1-3.5 http://www.ifs.tuwien.ac.at/~aschatt/info/ca/ca.html (last accessed, December 17, 2003)

Other properties of CA include animation and dynamic visualization. CA behaves in accordance with the principle of 'think locally, act globally'. That is, it can encapsulate specific and smaller details that define the bigger picture. In relation to informal settlements modelling, CA will assist in developing a model that shows how the combination of different factors of IS emergence and growth interact and contribute to the future expansion of IS. As a 'bottom-up' approach, CA applications pay particular attention to detail and are spatially and temporally explicit. This capacity to integrate spatial and temporal dimensions makes CA appealing for the development of robust and reliable urban dynamics models. The urban dynamics modelling proposed for the development in this thesis has, therefore, many reasons to use CA to correct the weaknesses of traditional urban dynamics modelling. The potential for integrating CA with spatial technologies, such as GIS, opens up new possibilities to improve operational urban modelling, particularly with regard to the prediction of dynamic visualisation of informal settlement emergence and growth.

3.5.2 Limits and strengths of cellular automata

Conceptually and theoretically, a cellular automaton for urban studies has some limitations and advantages with regard to the development of an urban dynamics framework. This section first discusses some of the limitations of CA and how they can be overcome, and then expands on CA's strengths to improve 'real-world' simulation and modelling.

The original framework of CA is not appropriate to inform and support realistic urban dynamics (Wolfram, 1986). For instance, the overall original structure of CA is reported to have been too simplistic and constrained to apply in real urban applications (Sipper, 1997). Specifically, the original concept of cells as 'systems closure' is not considered suitable for urban dynamics studies because not all spatial patterns have a regular grid form (Batty & Torrens, 2001). Similarly, it is not reasonable to apply the idea of an infinite space plane (two-dimensional) and uniform regular space to the city because cities are not infinite, regular, or uniform. Moreover, the notion of neighbourhood is too coarse and does not take external factors and distance-decay actions into consideration.

Another criticism is that cellular automata only take a bottom-up approach, and account for local specificities that ultimately define the overall representation of the space generally. All constituents of urban systems, however, do not exhibit only bottom-up behaviour (e.g., urban planning decisions, national policies, macro-economy, and so on). Furthermore, CA is restricted to general rules and does not create its own dynamic. In real urban contexts, not all changes in the systems are driven by the same force or mechanism. It is clear that urban elements can react differently to general rules. However, these apparent rigidities of original CA architecture can be progressively turned into strengths to develops comprehensive models, especially when associated with other spatial tools.

Cellular automata were initially used to investigate emergent, complex and adaptive behaviour, especially self-organizing systems (Wolfram, 1984). Applied in urban dynamics studies, the CA framework is continuously amended and relaxed to generate realistic patterns. In the original CA, transition rules are universal and applied synchronically to all cells. In real urban processes and forms, however, no single rule governs the behaviour of the entire system. To solve the rigid transitional rules, urban dynamics CA transition rules are formulated using Boolean statements, and probabilistic expressions such as IF, THEN and ELSE. The flexibility thus gained in these expressions, simplifies the representation of more complex systems (Batty, 1996).

The simulation of urban dynamics is an area of research where CA has been recently implemented. Here, cellular automata represent a useful tool for understanding urban dynamics, improving theory, achieving realistic and operational urban models (White, 1998). White and Engelen (1993) have demonstrated that a cellular automata approach can lead to a better understanding of spatial patterns, as well as representing realistic patterns. In the spatial modelling perspective, the strengths of CA lie in their capacity to perform dynamic spatial modelling over a discrete and continuous Euclidean space. Similarly, CA have the ability to exhibit explicit spatio-temporal dynamics. Other work has shown how CA models can be integrated with other spatio-temporal models, to improve the representation of urban features (Bertuglia *et al.*, 1990; Bivand & Lucas, 2000; Openshaw & Abrahart, 2000). Finally, the flexibility of transitional rules embedded into CA architecture favours a better 'control' over the dynamic patterns that are generated.

The important role of using complex systems such as cellular automata to seek to discover, understand and explain how cities emerge and change is now well established (Couclelis, 1985; White & Engelen, 1994; Allen, 1997; 1999; Portugali, 2000). The introduction of CA approaches in geography is traced back to the work of Hägerstrand (1968) on diffusion models. In his representation of a society with a 'robotic life', Hägerstrand highlighted the major components of current CA architectures: discrete time and state, cell, neighbourhood, uniform transitional rules and lattice. The investigation of Hägerstrand was limited by the capacity of the simulation (less than 200 cells), yet it was theoretically and conceptually well formulated. Tobler (1970) went further to develop a forecasting model based on urban growth. He called it a 'computer movie' and the description was so close to the current cellular automata. In fact, Tobler's study laid the theoretical and conceptual foundation of cellular automata for future applications in geography. In 1979, he published a paper formalising the concept of CA, and opening the way for geographers to use CA for urban planning applications, spatial modelling and simulation. However, the temporal dimension of Tobler's CA was considered weak because the simulated maps developed for each year were very different from the reality map (Wegener, 2000).

Tobler's work was improved by Couclelis (1985; 1989; 1997) and Batty and Longley (1994), Batty and Xie (1997) who enhanced the theoretical and methodological aspects of CA for analysing and modelling complex urban dynamics. In the same spirit, Couclelis (1989) demonstrated how CA might be used as a metaphor to study how different varieties of urban dynamics that might arise. Couclelis claims that, although CA is not originally intended to produce realistic representations of urban dynamics, it can be reformulated and integrated with some spatial models to form better predictive models (Phipps, 1989). White & Engelen (1993; 1994) go further to advocate that CA is capable of generating real patterns of urban land-use change. In the following sections, two instances will be presented where CA architecture has been relaxed and used; first as a hypothesis to explore the urban dynamics of fictitious cities; and then in the simulation of real urban patterns (operational urban dynamics).

3.5.3 Hypothetical urban simulation with cellular automata

A number of researchers have shown how CA can be used to explore possible local and global urban forms, theories, patterns and processes (Batty & Longley, 1986; Batty & Xie, 1994; O'Sullivan & Torrens, 2000). Earlier CA models (such as Tobler's (1979) model of Detroit, and Couclelis' (1985) model of the behavior of developers in Los Angeles have been used to demonstrate how global patterns emerge from local transitional rules. This can be very useful as a pedagogical tool, especially when used as software or hardware. Cecchini (1996) for instance, demonstrates that CA can provide a comprehensive understanding of land use change in fictitious cities as well as in the coordination of urban subsystems and patterns.

In other examples, Batty (1994) applies CA to verify urban dynamics theories and to test some hypotheses of urban changes. Similarly, Semboloni (1997) assesses aspects of economic theory by applying CA to the simulation of urban form and growth in a hypothetical city. Benati (1997) also uses CA to simulate the location of competitors on a discrete and bi-dimensional market place using equilibrium theory. Phipps and Langlois (1997) apply CA to test the Von Thünen model in order to establish CA suitability for the interpretation of real patterns. Phipps and Langlois' work was interesting in the sense that it showed another way of understanding a well-established geographical model. The study, however, was not sufficient to bring out all the potentialities of CA for the sharpness of real urban dynamics. In another example, Wu (1998) and Batty (1998) have demonstrated how CA can be used to explore the development of polymorphous-polycentric cities. Cellular automata have also been used to investigate intra-urban land use transformations (White & Engelen, 1994) and long-term spatial urban sprawl (Batty, 1996). Portugali *et al.* (1994) have demonstrated how CA can be used to simulate spatial segregation between different social groups.

The attraction of CA in urban dynamics exploration has also seen the development of hardware, which has significantly improved the performance of modelling and simulation. For instance, the Cellular Automata Machine (CAM) along with soft-CAM (CA software simulators with parallel computing) was developed at the Massachusetts Institute of Technology (MIT) by Toffoli and Margolus (1987) and was reported to perform at least twice as fast as their GIS counterparts (Wagner, 1997). Both CAM and soft-CAM were, however, too expensive, which limited their access to other researchers (Hiebeler, 1991).

Batty and Longley (1986) propose a discrete grid to simulate the London land use map. Results are interesting and useful for the insight they provide into the nature and form of urban land-use dynamics. Similarly, Portugali and Benenson (1995) have demonstrated that CA can be relevant to investigate the dynamic migration trend of self-organizing cities. A Venice team (Cecchini & Viola, 1992; Cecchini; 1996) has used CA to simulate and predict urban structures and classes in 'fictitious cities'. This hypothetical model shows how various classes can be formed from CA. The work of Cecchini's team has led to the development of urban dynamics CA software. Known as AUGH! (Generalized Urban Automata with Help! On Line!), this software is a hypothetical exploration with limited capacity for real applications in urban modelling (Cecchini, 1996). However, the AUGH! model is too simplistic to provide realistic representations of urban patterns and forms therefore fails to address concrete issues.

One of the most significant improvements to CA models comes from Wu's work. Wu (1998a) applied CA in a generic city to highlight the fact that CA can significantly improve the understanding of growth patterns of polycentric urban forms. Wu and Webster (1998) also applied CA to explore the sustainability of urban forms. Two main difficulties have, however, limited these experimentations into real urban areas. First, the limited size of the space considered by CA software reduces the potentiality of these applications in real world situations. In addition, many of these applications are limited to 'two-states' behaviour, such as urban/non-urban, whereas urban systems can embed several states at a the same time (Batty, 2000). Second, real-world applications of Wu's model were limited due to difficulties experienced in spatially reflecting some fundamental formulations of CA. For example, the model did not address the concept of CA explicit representation of change of state based on general rules and attributes of the neighbouring elements. Likewise, the model failed to clarify the CA principle that global change is generated by local behaviour. In light of these key questions, researchers who are concerned about realistic representation have therefore had to readjust the fundamental structure and behaviour of CA, or seek alternative integration with other spatial models that can better handle real world data.

3.5.4 Representing real cities with CA?

To achieve the realistic representation of urban dynamics, the fundamental structure of CA as well as its general principles, is associated with neighbourhood rules using probability theory. Since the 1970s, CA has been regarded as a useful tool to simulate and model various urban systems and subsystems such as traffic, transportation, urbanization and land use changes. Although initial applications have been limited to test hypothesis, theories and generating fictitious cities, real applications have been rare. This is partially explained by the rigid conceptual framework of the original CA. In the 1990s, however, operational urban CA models started to emerge owing to the progress in conceptual urban CA, complexity theory, the development in the rapport between CA and real data interfaces, and computing power. Almeida *et al.* (2002) identify more than twenty operational CA models since the 1990s. In these latter reported cases where CA has been used to explore real patterns, some strict CA principles have been relaxed as a means of achieving more realistic simulations (Meaille & Wald, 1990; Clarke *et al.*, 1997; Wu, 1998; Almeida *et al.*, 2002a). This section reviews some examples of cellular automata urban modelling applied to real cities, highlighting the achievements made but also pointing out some of the models' fundamental limitations.

White & Engelen (1993) have used CA to explore the spatial structure and temporal dimension of urban land use and to test general theories of structural evolution. The cellular model generated patterns for each land use type, which are then compared with data from a set of US cities. The results showed good representations of actual urban form, suggesting that CA approaches make it possible to achieve a high level of realistic spatial data representation. In another instance, White *et al.* (1997), managed to implement CA to model and predict the land-use of the City of Cincinnati in USA. While these two models were successful on one level, they only covered a small area. Moreover, the size of some areas (like the CBD) appeared underestimated compared to other parts of the city. Furthermore, the models only deal with relatively little data and the prediction period was too short to be realistic (two simulations for the Cincinnati model), as one simulation represents more than a century of real time.

In Europe, Colonna *et al.* (1998) used CA and Rome census data of 1981 and 1991 to model the residential land use evolution. Whilst the model was able to provide an example of how to investigate the spatial dynamic of Rome, the application used few classes and data was calibrated on two sets of existing census data for a short period (ten years). This study also revealed that the ten years difference between the datasets could not properly reflect the dynamics of Rome. Furthermore, the work showed that the model did not fully perform to a point where patterns emerged from internal transitional rules, explaining why the authors reported a misrepresentation error of 4%.

Some researchers maintain that CA models alone can successfully simulate realistic urban dynamics (Wagner, 1997; White & Engelen, 2000). Urban simulation by means of CA is more relevant for theoretical and pedagogical investigation, rather than useful real world applications (Almeida *et al.*, 2002). Furthermore, many researchers in urban modelling suggest that CA should be integrated with other spatial techniques to improve real-world modelling applications (Batty & Xie, 1994; 1997; Couclelis, 1997; Xia & Yeh, 2001). One of the advantages resides in the CA model structure and real data manipulation through the integration of spatial modelling techniques. Batty *et al.* (1999a) have illustrated this point when building urban dynamics hybrid software that combines the strengths of both GIS and CA. Their DUEM (Dynamic Urban Evolutionary Modelling) software is written in C++ language and designed to achieve both hypothetical and realistic simulations. Even in cases where CA has been extensively used as an urban simulator, real-world (spatial) data has been able to be incorporated in some ways (Wu, 1998).

There is clearly a need to examine the underlying theory and utility of advanced generic urban simulations that can support bottom-up logic (cellular automata and agent-based models), consider bottom-up influences and cope with real-world data interchanges. (Batty & Jiang, 1999; Benenson, 1999). This can be achieved by designing 'hybrid systems' (Batty & Torrens, 2001) which might include Multi-agent simulation, CA and land use or transportation models. Again, all the urban dynamics experiments carried out using only a CA approach have performed poorly in generating realistic patterns. Some explanations can be related to the lack of input and output of attribute data into a CA framework, and the difficulty of capturing top-down approaches. Other reasons relate to the fact that, state-of-the-art computing systems have eclipsed theory building and much of the literature is simply descriptive, describing isolated examples of one-time applications. The trend is, however, to relax the initial principles and configurations of CA, by making them more sensible and flexible for realistic representation, and to integrate CA with other spatial technologies such as GIS. In light of the capacities of CA and in relation to its applications, the GIS contribution could consist of data input, manipulation and output, while CA could perform functions such as calibration, transitional rules, parametric analysis and other modelling functions beyond GIS capabilities.

3.6 Integrating GIS and CA for urban dynamics modelling

Operational and exploratory urban models aim to facilitate the representation of urban systems. Previous urban models, however, were unable to meet this aim and operational models were rare. On the one hand, traditional urban models have long been described as 'black boxes'. Their outputs were usually equations and too complex for the stakeholders who subsequently were reluctant to use them (Torrens, 2000). On the other hand, while technology has improved on the traditional urban models, many have failed to be operationally available.

Yeh and Xie (2001; 2003) have shown that GIS can act as an important tool to make better use of urban dynamics models like CA. The concept of integrating GIS and CA tools is based upon their similarities and the possibility of relying on each other to perform better modelling. For instance, a raster GIS structure is represented in a CA environment by the cells and lattice. CA and GIS are basically Euclidean (two dimensional) time-space model approaches but the notion and understanding of space can be quite different both in GIS and CA. This section extends the discussion on the similarities between CA and GIS and then explores the potentialities for a workable integration. After clarifying the theoretical framework for an integrated GIS/CA-based model, some examples are presented to illustrate existing approaches that claim to achieve better modelling of urban dynamics. The next section also discusses how the integration of GIS and CA could be implemented to achieve this thesis' aim to simulate the emergence and growth of IS in LDC' cities.

3.6.1 Reasons to link GIS and CA for urban dynamics modelling

A number of important points have been raised in the literature about the benefits of linking GIS and CA to improve urban dynamics modelling. GIS and CA are argued to have significant common features and complementary functionalities, and can therefore supplement and complement each other (Wagner, 1997; White, 1998). Couclelis (1985; 1989) discusses the theoretical considerations for the integration of GIS and CA as well as their potentialities in improving the quality of spatial urban dynamics models. Couclelis (1997) points out the 'natural affinity' between CA and GIS and advocates a more interactive and visual integration of GIS and CA to improve the patterns of realism in urban modelling and simulation.

Sui and Zeng (2001) recognize the interest of developing a GIS-based CA urban modelling and simulation. Some of the advantages these authors cite are that the bottom-up approach (CA) enables the incorporation of various local parameters into the modelling process in order to better represent their evolution. Furthermore, when a model is based on spatial data (GIS), it can take advantage of CA approaches and consider time, space and attributes in the formulation of scenarios. In doing so, subsequent models are more likely to generate realistic urban dynamics, correcting the static representation of GIS.

In many ways, the deficiencies of GIS and CA can be compensated by each other. For example, although the capacity of CA to explore complex systems is well established (Wolfram, 1984; Itami, 1994), its capacity to represent real patterns has still to be proven. In the case of GIS, its predictive and analytical capacities are insufficient to handle complex urban dynamics. The integration of the dynamic strength of CA with the good temporal and spatial representation found in GIS and remote sensing is, therefore, appealing as a practical means to achieve realistic representation. On the one hand, GIS has much to offer in this integration: pre-processing, sorting, storage and retrieval of data, database querying, graphical display, input and output editing. On the other hand, CA will provide the power and the speed for processing database analysis, temporal dimensionality (for instance by handling multiple iterations), the flexibility to assign transitional rules and definition of the spatio-temporal neighbourhood.

3.6.2 GIS and CA integration: Loose coupling versus strong coupling

Urban researchers agree on the principle, usefulness, and necessity to link CA with GIS to achieve more realistic and informed urban dynamics models. However, strategies are divergent in identifying the best way to achieve optimum results.

One approach consists of building a CA modelling application using the programming language within a GIS language protocol (Batty & Xie, 1994a; 1994b; Yeh & Xie, 2001). This option requires a certain level of familiarity with the programming language embedded in the GIS package in use. The flexibility of the language, however, is not always guaranteed and the scope for application of the skills learned in the process is limited.

Another approach to integrate CA and GIS is to develop a stand-alone CA program that can use data from GIS. Data interchange and compatibility can be achieved using file conversion protocols (Yates & Bishop, 1997). However, if the program cannot access and modify the data to and from the GIS environment, then the process of reformatting the input and output is not only more likely to mislead the representation, it could also be time consuming and error prone. For these reasons, 'loose' or 'tight' coupling are more likely to produce better integration models (Bivand & Lucas, 2000; Almeida *et al.*, 2002; Couclelis, 2002). These two techniques will be discussed below.

There are two dominant views that sustain the way in which realistic dynamics modelling could be achieved if GIS and CA are to be used simultaneously. The difference lies in the extent to which the integration is achieved. Coupling is attractive because of the continuos expansion of GIS technology, its interchangeability and interoperationality with other spatial platforms and technologies (Waters, 2002). Another advantage of coupling is the possibility it creates to use different tools (statistics, image processing, stand-alone programs, GIS platform, and so on) to process all the information (Almeida *et al.*, 2002).

The first view is constructed around the argument that GIS functionalities and capabilities should be extended to respond to a specific need. So, the integration of GIS and CA approaches will be successfully achieved through tight coupling. That is, new extensions, functionalities or dynamic tools are encoded into the GIS environment to expand its capabilities to perform tasks for which it was not originally designed. In the perspective of urban spatial modelling by means of GIS, the advocates of strong coupling support the view that future GIS should be equipped with spatial dynamics modelling functionality and capabilities (Raper & Livingstone, 1995; Mikula *et al.*, 1996). This can, however, be done another way around (Batty, 1998). The integration of CA and GIS can also be achieved by incorporating GIS functionalities into a cellular automata analytical engine, such as the CAM modelling machine developed by Toffoli & Margolus (1987), to enhance the simulation realism. Although models generated through tight coupling are often suitable for a specific application, they are poorly replicable in a different context. Moreover, spatial models developed within GIS remain less flexible and the capabilities of handling other modelling functionalities are weak. Thus, there are thresholds for the extension of CA or GIS functionalities and capacities. At least in the case of GIS, it is clear that the technology was not designed to perform complex modelling operations (Longley & Batty, 1996; Alberti, 1999; Alberti & Waddell, 2000).

Another view contends that if GIS and spatial modelling approaches are to be integrated, it should be envisaged in respect of the sole strength and contribution of each set of tools. This technique is known as loose coupling. Loosely coupled refers to the linking within GIS and CA, input and output data, functionalities and capabilities of the two technologies initially conceived to perform different task in order to enhance the final product. That is, each approach maintains its fundamental structure and functionalities and only contributes where it best performs. In the case of CA and GIS for instance, a loose coupling approach is the first pragmatic choice when it comes to dynamics modelling and simulation of real patterns (Clarke & Gaydos, 1998). In the event of loose coupling, there are many variants; from using GIS purely as the display environment, to a more expanded coupling where the contribution of GIS is much wider

(Batty, 1998). In a sharing task, GIS could act as a data management, storage, retrieval and static visualization interface, while CA would perform other functions that cannot or are less well handled by GIS, such as dynamic exploration and data analysis, interaction with commands and functions, weighting parameters, iterations, calibration, modelling, dynamic visualization and simulation. If the synergy task is not carefully defined, however, there is a potential risk of role conflict, and the possibility that the user might not have full control over the system and the data (Yeh & Xia, 2000). When this difficulty can be avoided, loose coupling can be considered as a flexible and adjustable integration strategy that usually leads to more realistic simulations.

The loose coupling can also be achieved through the development of a macro language. Conceiving and building scripting and macro languages could achieve optimum and flexible integration of CA and GIS. This supplementary programming task, which takes place outside the GIS and CA environments, is appealing because programming languages can be used and the knowledge gained could be re-used or expanded for other applications. Moreover, the scenario can be easily updated or adjusted. Also, many of these programs support conditional statements, Boolean expression ('if…then') iterations, calibration possibilities, and many other functions. In that respect, properties of Object-Oriented Programming (OOP) have been reported as appropriate for realistic urban modelling and simulation (Hill, 1993; Benenson & Torrens, 2004). For instance the SWARM[2] software tool uses OOP to simulate landscape behaviour based on the integration of GIS and CA (Wu, 1999). The integration can also be realized by creating a graphic user interface that gets its input from a GIS package to run a simulation based on a CA protocol (Wu, 1998a). All factors considered, it appears that the linkage between spatial models and modelling and simulation techniques can be better achieved through the loose coupling approach.

3.7 Conclusions

This Chapter has shown how urban dynamics has a long tradition in geography. Two main stages have emerged from the review of urban modelling research based on

[2] The SWARM project can be consulted at http://www.gis.usu.edu/swarm/ (Last accessed, 7/4/2003).

CA, GIS and their integration. The first period (from 1940s to 1990s) was the development of the conceptual and theoretical framework. The second period (since the 1990s) has been marked by the increasing interest diverted into the applications of dynamic approaches; first in fictitious cities, and then in real contexts.

In particular, the Chapter demonstrates that in the field of urban modelling, there is evidence of growing awareness that the concept of equilibrium is no longer sustainable, and the theory of complex systems (i.e. dynamics) is prevailing. The Chapter also contends that realistic urban dynamics models should consider the equal representation of space, time and other key attributes, and this can only be successfully conducted by the integration of many spatial tools. What is clear, however, is that avenues by which to achieve this coupling of technologies for realistic representation remain wide open for debate.

The second half of the Chapter illustrates how the improvement in computing and GIS technologies for the last forty years has helped development in the field of urban dynamics modelling and simulation. In particular, the Chapter argued that GIS is appropriate for urban modelling and simulation compared with CA, which although well suited, needs real-world data to generate informed and useful simulations. The characteristics of CA and GIS respectively have been highlighted as have their potentialities for integration for comprehensive and realistic modelling. Application of urban modelling dynamics has been presented using either GIS or CA alone or in combination of the two. It is apparent from the analysis that their integration is the way forward to gain better insight into the process and form of urban dynamics simulation and modelling.

After presenting the framework to build realistic urban dynamics, the next Chapter will review existing urban dynamic models to assess their suitability to be adapted for and implemented in an informal settlement growth model.

Chapter 4

Towards a methodology of selecting an appropriate predictive model

4.1 Introduction

Operational urban dynamics models seek to inform urban theory and to support urbanisation. Similarly, the incorporation of complexity theory and spatial dynamics methods is increasingly seeing the emergence of useful urban dynamics models, to the extent that the realistic simulation of urban growth is becoming more available. As a result, dynamics models now improve our understanding of the processes that underpin urban evolution and informal settlements (IS) and our ability to predict more accurately their spatial ramifications.

Chapter Two articulated the evolution of urban dynamics theories and practices. It highlighted the role of computer technologies, GIS and complex systems theories in the development of current urban dynamics models. It also demonstrated how GIS and cellular automata (CA), taken separately, would not be able to develop realistic urban dynamics. The Chapter also argued that the integration of GIS and dynamics models such as CA has emerged as an important path into the resurgence of urban dynamics fields. This new approach, embedding spatial and temporal dimensions, is progressively used, not only for pedagogical means, but also as part of a decision-support system. Not surprisingly, attempts have also been made to develop knowledge-based urban dynamics models, programs and software packages.

This Chapter will investigate realistic simulation properties of selected urban dynamics models and how useful they are for understanding urban and IS dynamics in LDC. In particular, the Chapter will look at the criteria to consider in relation to urban expansion and IS modelling. Arguments and methodology for selecting an urban dynamic model that could assist the prediction of IS are also outlined. The first section of this Chapter will assess general requirements for urban dynamics modelling. Section two will discuss the criteria to be used in selecting a given model for a specific application. Section three reviews the pedagogical and exploratory urban models packages. Section four considers operational urban models and their transferability to the context of cities in LDC.

4.2 Designing useful urban dynamics models: issues to consider

Urban study researchers have applied cellular automata to investigate various situations such as land use dynamics (White & Engelen, 1993; Cecchini, 1996; White & Engelen, 1997; Webster & Wu, 1999; 1999a), large-scale regional development (Semboloni, 1997), social segregation in urban space (Portugali, 2000), and urban growth and sprawl (Clarke *et al.* 1996; 1997). In all these instances, GIS played an important role in manipulating real world data. Although some of these applications highlighted the pedagogical and research contribution of cell-based models in geographical sciences (Couclelis, 1997; Batty, 2002), there has been an increasing research investment in developing cell-based models as prescriptive and useful tools for real world situations (Clarke & Gaydos, 1998).

Not surprisingly, the integration of GIS and cell-based approaches has enhanced the field of urban dynamics, planning, and decision-support process in the urban environment. Traditional models now help new urban dynamics approaches in areas such as improving the design of data manipulation and reinforcement of output visualisation. Nevertheless, designing models depends on factors such as the aim of the research, the scope of the question under investigation, the technical knowledge, data constraints, and the availability of resources and data. Models must also consider how to portray 'real-world' situations by choosing variables that control the behaviour of the urban system, and by establishing relationships between these variables. Some of the ongoing major issues with such models, however, are the inherent complexities and inconsistencies that emerge given that the choice and weights of these control variables are widely subjective. Despite these discrepancies, there are ways to contrast and gauge models that could be appropriate for exploring urban and IS growth in LDC.

4.2.1 Four types of urban dynamics models

Generally, urban system modelling is developed using four different sets of data: land use, transportation, economic variables, and environmental impacts. Modelling land use in urban areas uses many bi-classification categories (urban and non-urban) as well as detailed categories (such as residential, industrial and agricultural) and representation of subclasses like population density, type of industry and agricultural type, etc. The three levels of Anderson *et al.'s* (1976) land use classification are often used for modelling land use in the cities of developed countries. The higher the level, the more detailed, complex, realistic and prescriptive the model can be. Models such as Clarke's Urban Growth Model (UGM), the Land Transformation Model (LTM), and the Land Use Analysis Systems (LUCAS) use Anderson Level I whereas the California Urban Future (CUF) model uses level II.

On the one hand, urban economic models can project employment, population, wages rates, rents, incomes and prices. This modelling process relies on census data and different population projections to build the model datasets. On the other hand, transportation models use variables such as traffic flow, parking, urban trips, distance from and accessibility to services and facilities. Data is provided by surveys from primary sources. Environmental impacts models consider parameters such as flood plains, green space, natural habitat, natural resources, energy, water and air quality. PCRaster for instance, is designed to investigate urban ecology, hydrology and geomorphology.

Increasingly, urban system models are borrowing from each other (land use, economic variables, transportation and environmental impacts) to achieve spatially and temporally explicit and informed urban decision-support. Considering that urban systems are complex and made of various components (physical, human, network, activities, etc.), the ability of an urban model to incorporate an increasing number of variables of urban systems with appropriate relationships, is promising in terms of being able to better represent these urban complexities. Current urban dynamics models, such as UGM, LUCAS, TRANUS, *SmartPlaces*, and *What if,* integrate two to three sub-models. Recognising the variety of urban dynamics models emerging from various areas of interest and choosing the right model for a specific application is perhaps one of the most important but contentious debates in relation to predictive models.

4.2.2 Steps towards assessing urban dynamics: selection criteria

Five steps were followed to select the appropriate urban dynamics package that could be used to simulate the growth of IS in LDC. First, a specific research question related to urban dynamics in fast growing cities was developed. Second, detailed research questions were developed that captured the various facets and angles of the problem. Next, the availability and reliability of data for the study area was ascertained. This was an important step because the quality of the data input determines the output of the model. Access to modelling resources was then evaluated. This involved clarifying what type of equipment, materials and finances were available that could be used for developing the model within the prescribed time frame. Finally, one of the problems with current models is that they do not necessarily take account of the various angles and aspects of the prediction before their application to other contexts. Even though one model may not 'cope' with all aspects of the problem, it is important to outline all the main components of the issues under investigation, in this case IS.

It could be argued that this approach was cautious. Given that there is not a 'perfect' model, the approach attempted here aims to at least identify a model which has the capacity to produce realistic and informative representation of urban settlements. It would also be important to create a model that could be flexible enough to consider incorporating more variables and create interactions amongst variables and the components of the models as well as the feedback effect. One way to approach the selection of a model is to set up a 'checklist'.

The EPA’s review of twenty-two models is a useful starting point in selecting the most appropriate model (EPA, 2000) for urban and IS dynamics in LDC. The EPA’s main finding was that urban land use models should be selected on the basis of their ability to predict emergent patterns. That is, models should be able to predict new developments using relevant variables with logical rules or conditions of change. Specifically, the EPA found that twelve points should be considered:

1. The model's ability to generate **sound outcomes** for a given situation, especially those that will provide an informed answer to the research questions within the scope of the study.

2. The **resources** required and available to produce adequate results should also guide the choice of the model. The researcher should consider the investment needed in terms of software, hardware, training, labour, skills, and cost (time and money).

3. The model should provide enough **supporting documents** and tools to ensure easy understanding and operation. In particular, software-based models should provide an extensive and comprehensive guide for implementing the program. This could take the form of a help menu, tutorial documents, help contact, discussion groups and follow-up support.

4. The **technical expertise and knowledge of the user** are important prerequisites in the choice of a model. A prior knowledge of a system or program used by a model can ease the implementation and the interpretation of the results. A sophisticated model with new approaches and tools can sometimes deter the efficient application of the model. It is important and helpful if the user can get first hand information about the model and be aware of the technical prerequisites required to run the model. In this case, models that required technical skills such as programming in a specific language were not favoured.

5. The **data requirements** to produce a comprehensive output need to be considered. Given that gathering and preparing data input for a specific model can be time consuming, it was clear that the selection of a model that can be adapted to urban and IS dynamics in LDC must seriously gauge the data requirements and availability such as the level of disaggregation (i.e. size and resolution), type (e.g., land use type, transport, topography and economic), format, time-series (e.g., number of years and frequencies), number (i.e. minimum files needed to run the model), and so on.

6. The model's ability to produce output that will inform the research question or the decision-making process is also vital. This assessment is reflected in the ability of the model to reproduce **'realistic' simulations** tested by seeing if the

outcome generated can be convincingly compared, measured and calibrated with the existing situation. It was therefore important to select an operational model that would produce realistic outputs.

7. **Land unit resolution** was also important to reflect the reality of urban and IS conditions in LDC. Often, the input files required by a model can vary from detailed (e.g., 5m) to coarse (e.g., 200m) size and from a local to a regional scale. For this study, the choice of an urban model took into consideration the quality and availability of data, in favour of local models.

8. Depending on the objectives of the research, the **temporal dimension** of the output could also be important in the presentation of the results and thus in a model's selection. Models vary in their capacity to generate either single or multiple outputs. Because the proposed urban and IS model seeks to investigate spatio-temporal dynamics and trends, it is critical that the selected model has the flexibility and ability to perform multiple simulations and scenarios. Moreover, choosing an appropriate model can be directed by its capacity to correlate different components of urban systems such as transport, land use, environmental and economic factors. The more versatile, complex and detailed a model, the greater the likelihood that the model could be useful and appropriate to simulate urban changes and IS growth in LDC.

9. The **level of data linkage** was also considered. The potential for input and output data to be used by other platforms, tools or program is an important asset. Therefore, the flexibility of a model can be assessed by its ability to import and export data to and from different applications. This linkage can intervene at any stage of the model's implementation, from data preparation to output analysis and visualisation. This is important because the interoperability of the execution of the proposed IS model would make the model independent of software, output format and platform.

10. The ability of an urban model to **convey a clear and unambiguous message** to a general public should be regarded as a valuable asset. This is the case for models incorporating dynamic systems in their procedures. In many cases such as urban planning, urban models are used as decision-support tools. It is

therefore important to choose a model whose output clarifies public uncertainties and improves understanding of the IS behaviour. This clarification can be achieved through the dynamic visualisation of the emergence and growth of IS or via the development of different scenarios of IS dynamics.

11. The model's **ability to be implemented on other sites** should also be considered. In the process of selecting the model, emphasis was put on one that has the flexibility to allow the implementation to sites other than the one where it was initially developed, keeping in mind that if adjustments were necessary, they would be made following the same procedure as during the initial case study, without extensive modifications.

12. A model with a **wide and frequent application** in many instances was more appealing than a research-oriented model that is at an earlier stage of development. The advantage being that there is the possibility to reflect on other experiences and applications to improve the current study's results, resolve any difficulties as well as being able to compare results.

Whilst the EPA's checklist was useful, it was felt that specific selection criteria needed to be developed for this research. For instance, the EPA criteria were developed for planning agencies in the USA and other elements could be added to fit the context of cities in LDC. A new set of selection criteria were developed to apply to any future urban model that might be considered appropriate to simulate urban and IS growth in LDC. These criteria include temporal and spatial resolutions, level of disaggregation, flexibility, cost, accuracy and reliability.

4.2.3 Methodology for selecting and evaluating urban and informal settlement models in LDC

A review of the literature was conducted to identify existing urban modelling resources that have the potential to be used to simulate the emergence and growth of urban areas and IS in LDC. Two hundred and twenty four publications and web links were identified, and they were first screened for their relevance and the criteria described in section 4.2.2. The relevance of each model was related to its ability to address issues of urban dynamics, simulation and modelling under the criteria outlined above. Attention was given to models with 'real world' applications and which used a 'bottom-up'[1] approach to urban modelling, especially those which are cell-based and implement GIS components.

Using these criteria (real world, bottom-up, GIS and cell-based) narrowed down the results to sixty-two possible models that can be used or adapted to explore urban and IS dynamics in LDC. Models which exhibited only one component of urban systems namely, urban economic, environmental or transportation were not considered, because they will fail to capture the complexity of urban dynamics experienced in LDC. A higher level of urban model complexity is useful because it can simultaneously represent more than one component of the urban system. The level of complexity criteria brought the search result to eighteen urban dynamics models that will be discussed individually in this section based on four main criteria: spatio-temporal dimension, flexibility, accuracy and reliability, and cost, none of which were discussed by EPA.

1. The ability of the model to handle both the **spatial and the temporal dimensions** was considered. The temporal resolution can vary from 1 day to 100 years and can have continuous and multiple time steps or lag time periods. A model that can be adapted to the urban and IS in LDC should have a temporal resolution of 1 to 5 years, because this is a reasonable period where changes can be noticed. It is also important the selected model allows continuous and multiple time steps because IS expand continuously and could follow different stages. The spatial resolution embedded into a model can vary from 1 acre to 1 million km^2 and it is critical that the selected model does not recommend data that are too coarse or too disaggregated for the context of urban areas in LDC. Level of disaggregation refers to the temporal and spatial properties of input files required to run the model. This parameter was important because, in the context of urban areas in LDC, input data for a given model (type, size and format) could not always be reliable or available to produce reasonable outcomes. For instance, input data with a small cell size (m^2) or too coarse (km^2) would not be relevant to Yaoundé in Cameroon.

[1] A bottom-up approach is often associated with CA and suggests that the problem is split into subproblems (or individual entities) Each subproblem is addressed individually, and all of them are then combined to explain the general condition (problem). That is, the association of local conditions explain the general condition, or acts on the principle of 'from local to general' whereas the Top-down approach would act from 'general to local'.

2. The **flexibility of a model** depends upon its ability to allow the user to adapt the program to a specific need (Agarwal *et al.*, 2000). That is, some models still function as a 'black box'[2] not allowing access to their source code, and not enabling the user to comprehend how the process operates. Open source urban modelling, however, is useful to compare the modelling procedure (such as calibration, simulation and validation) with other users, and to make necessary adjustment to the program to fit the context or the objectives of the research. In contrast, models which are for instance rigid in the number and resolution of files necessary to run the model will be less favourable partly because of the peculiarly local features that IS exhibit in some cities in LDC. This review will consider models that are flexible in relation to their input datasets requirements (e.g., number, spatial and temporal resolutions). In doing so, the design of the IS growth model should be able to deal both with common characteristics of IS among LDC and allow adjustments to specific features peculiar to a locality.

3. **Accuracy and reliability of input data** will be assessed as important elements when selecting or designing operational urban dynamics models. This is important because the input and output data of proposed urban and IS should be sufficiently accurate, visually explicit, trusted, and can be made easily available to inform planners and decision-makers in LDC.

4. Other important selection criteria were the **cost and accessibility** of a selected model. This is because the research budget was limited and models that could be obtained free of charge were highly regarded.

Each selected model will be discussed separately, in relation to the model's theory and methods, its flexibility, the cost of the program, access to internal code, level of disaggregation of input, data requirements, and real world application. These factors will also be considered for the overall evaluation of our subsequent IS growth models.

[2] In a *black box* model, the program is executed without any capacity to understand or unravel its internal structure, especially the source code of the executed program. This concept of a *black box* is opposed to a '*white box*' or public domain software whereby a potential user can access and modify the program.

4.3 Urban dynamics models software: a review

A variety of urban dynamics models with different levels of complexity, structure and purpose have been developed. The purpose of this section is to use the selection criteria developed above, to assess the appropriateness of existing urban models to explore and simulate urban and informal settlement (IS) dynamics models for LDC. This section will review eighteen selected urban dynamics models and has divided the models into two main categories: theoretical or research oriented models and operational urban models. Each model will be evaluated and compared in regards to the set criteria as previously outlined. These criteria include data requirements, level of disaggregation, spatial and temporal properties, flexibility, applicability and cost. For each model, the main features are described, as well as some applications, illustrations, and web links or main references for further information. Each description also highlights the relevance of the model to be used in the exploration of urban dynamics in cities in LDC, as well as some of their advantages and limitations. The synthesis of this analysis and review is presented on table 4.1, followed by a detailed discussion on each model.

Table 4.1: Comparison and synopsis of potential dynamic models capable of implementation on informal settlement modeling

Model	Aim	Spatial Resolution	Temporal resolution	Dynamic visualisation	Real World Applications	Data Disaggregation	Free	More info (Ref & www)
DUEM	Modelling urban activities	Raster 30 x 30 m	Dynamic Discrete	**YES**	**NO**	Cell	**YES**	Batty et *al.*,1999
SWARM	Modelling multi-agents behavior	Discrete	Discrete	**YES**	**NO**	Agents	**YES**	Langton *et al*., 1995 www.swarm.org
Starlogo	Modelling multi-agents behavior	Discrete	Discrete	**YES**	**NO**	Agents	**YES**	www.media.mit.edu/starlodo/
SIMLAND	Land development	Raster	Variable	**YES**	**YES**	Regional	**YES**	Wu, 1998
Regional Urban Development	Modelling rapid urbanization	GIS cell-based	Discrete	**NO**	**YES**	Regional	**YES**	Xia and Yeh, 2001
TRANUS	Urban and regional modelling	GIS layers	Static Equilibrium	**NO**	**YES**	Local (intensive)	**NO**	http://www.modelistica.com/modelistica.html
Smartplaces	Modelling urban growth and planning decision	GIS Vector Layers	Variable	**NO**	**YES**	Local (intensive)	**NO**	www.smartplaces.com
What if?	Modelling urban policy and planning	Overlay GIS Vector layers	Variable: 5-10 years timeframe 25 years	**NO**	**YES**	Parcel: data intensive	**NO**	www.what-if-pss.com
METROPILUS	Modelling: land use, jobs, and household	Overlay GIS layers	Static equilibrium	**NO**	**YES**	Parcel	**NO**	Putman, 2001
CUF	Modelling Urban	Raster GIS	Annual Fixed	**NO**	**YES**	Household	**YES**	Landis and Zhang, 1998c

(California Urban Models)	policy and urban growth	(100 x 100 m) Bottom-up	timeframe 5-10 years Dynamic			Parcel		
LUCAS	Modelling land use and environment changes	Raster 90x90m cell	5 years increments 100 years	**NO**	**YES**	Parcel	**YES**	Berry *et al.*, 1996
LTM: **Land Transform ation Model**	Simulate land use change and Physical impacts	Raster cell (CA)	Variable 5-10 years increments	**YES**	**YES**	Parcel	**YES**	Pijankowski *et al.*, 1997
UPLAN: **Urban Growth Model**	Simulate urban sprawl and Development policies	Raster cell (50 x 50m)	Annual 50 years	**NO**	**YES**	Parcel Zone	**YES**	Shabazian and Johnson, 2000
UrbanSim	Land use, transportation Planning, Public policy Urban sprawl (Discrete choice)	GIS Vector-based and grid cells (150 x 150m)	Variable Annual, dynamic	**NO**	**YES**	Parcel; Data intensive:	**YES**	www.urbansim.org
RIKS projects: eg MURBANDY	Monitoring land use change	Raster (100 x 100m)	Annual Variable	**YES**	**YES**	Regional and continental	**NO**	www.riks.nl/

LandSim	Web-based urban sprawl simulation	Raster	Discrete	**NO**	**YES**	Parcel	**NO**	http://gis.kent.edu/gis/empact/
PCRaster	Environmental modelling	Raster GIS Cells (CA)	Discrete	**YES**	**YES**	Parcel	**YES**	www.pcraster.nl
Clarke' Urban Growth Models	Urban growth simulation	Raster GIS Cells (CA)	Annual Variable	**YES**	**YES**	Local and regional	**YES**	http://www.ncgia.ucsb.edu/projects/gig/
ISGM*	Informal settlement growth modelling and simulation	Raster GIS Cells (CA)	Annual Variable	**YES**	**YES**	Cell, local and regional	**YES**	Sietchiping, 2004

* The properties of the ISGM are developed and presented in the Chapters 6 and 7

4.3.1 Urban dynamics models: exploratory packages

This section will assess three dynamic systems models that have potential to be used in exploring real complex systems such as urban and IS in LDC. The first section assesses the Dynamic Urban Evolutionary Modeling (DUEM), a research-oriented project with an interesting approach to a specific need in urban modelling procedure, but which possesses some limitations for wider applications. The next two sections evaluate *Starlogo* and SWARM respectively, which are multi-agent modelling packages, designed to explore the behaviour of various elements of a system.

4.3.1.1 DUEM

Batty *et al.* (1999a) introduced the Dynamic Urban Evolutionary Modeling (DUEM) as a framework to use GIS input to simulate the location of urban activities. The DUEM uses CA functionalities to define rules and transition probabilities for each activity on a lattice as extensive as one million cells. The model has been applied to the town of Ann Arbor, Michigan in the United States using residential data for two time periods (two seeds-1980 and 1985) and the calibration using years 1990 and 1995. In Ann Arbor, Michigan, DUEM was applied to simulate how residential housing development processes induced urban changes between 1980 and 1995. The example of Ann Arbor uses a 3 X 3 Moore neighbourhood with a 30 m square cell on a matrix of 595 X 824 cells. DUEM is written in C++ and runs on PC for hypothetical simulation and real world applications. DUEM is a mathematically formulated program and any transfer to a different context implies the modification of its functions and formulas.

Overall, DUEM can be considered as a pedagogical and theoretical model that explores the advantages of using multiple seeds in the dynamics generation. DUEM was not effective for application to the urban dynamics of Yaoundé, however, because the theoretical settings and the data required (residential information) to run the model would neither be available nor reliable in cities in LDC such as Yaoundé. Also, extensive reformulation of DUEM assumptions and formulas would be necessary to adjust the model to the context of IS dynamics in LDC.

4.3.1.2 Multi-agent SWARM project

Langton *et al.* (1995) at the Santa Fe Institute (USA) developed *SWARM,* a multi-agent package simulation to investigate the behaviour and interaction between complex individuals and systems. As a bottom-up approach, a SWARM project is useful for modelling spatial agents' behaviour, and the temporal dimension of the modelling process is limited. One of the advantages of the SWARM project is that the source code is made available for open source code modelling (Minar *et al.*, 1996). To date, the SWARM project has only been applied in a pedagogical and theoretical context, and no urban dynamics application has yet been reported. The implementation of a SWARM model requires an understanding of C or Java programming, which is suitable for research and developers, but not for real world applications. SWARM is free software and more information on the project is available on the website[3].

4.3.1.3 Starlogo

Like SWARM*, Starlogo* is a multi-agent package used to explore the emergence of complex systems and the idea of competition amongst parallel and independent agents. Starlogo applies cellular automata on geographical features to assess the behaviour of hypothetical agents. Although Starlogo[4] is free, it was not suitable for exploring the emergence and growth of real patterns such as IS in LDC, specifically because it is an exploratory and learning package, especially designed to investigate how large-scale chaos or order patterns can emerge from simple rules. An urban and IS growth model, however, would be concerned with the interaction between constituents of a real system and the effects of local behaviour on the entire system.

Despite their sound theoretical basis and their free access, these three models are still at the experimental stage and it could require considerable effort to transfer the theory to an operational model, a task beyond the scope of this research agenda. The next section evaluates existing operational urban dynamics models to identify which one could be appropriate to simulate unplanned urban dynamics.

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[3] More information is available at http://www.swarm.org/ (accessed, 27/11/03).
[4] More information can be obtained at http://www.media.mit.edu/starlogo/ (accessed, 20/11/03)

4.3.2 Operational urban dynamics models

This section assesses the transferability of fifteen operational urban models to the context of urban and IS emergence and growth in LDC.

4.3.2.1 SIMLAND

SimLand[5] (Wu, 1998a; Wu & Webster, 1998) is a decision-making package, which integrates GIS Arc/Info, multicriteria evaluation (MCE) and CA to simulate constraints in urban land changes. It uses historical land use distributions to generate multiple scenarios of urban development in both the present and future. Three parameters control the growth: economic growth rate, regional variation, and policy control. SimLand is a user-friendly and fully automated standalone software program. As a driven commands program, SimLand enhances the visualisation and interpretation of the output.

Some interesting properties of SimLand include features such as the explicit integration and parameterisation of global effects with the local self-organisation mechanism of urban dynamics. This could be important to integrate both the top-down approach with a bottom-up approach that contributes to the emergence and growth of urban and IS in LDC. Similarly, SimLand is comparatively innovative in using structural indicators to validate the simulation scenario with the real situation. In doing so, Wu's model proposes a new approach to define transitional rules and to weigh up the set of parameters. This innovation is important because one of the intriguing phases in developing CA-based models is to define appropriate transition rules within the neighbourhood where changes will occur and to weigh their ability to influence the change. This approach could well inform future urban and IS dynamic models, especially in designing flexible transitional rules. Clarke and Gaydos (1998) for instance have used trial and fitting methods to ascertain the weight and refine the rules. Instead, Wu proposes a more structured method that is based on considering the importance of individual factors influencing the changes. He suggests that a method, called the 'analytic hierarchy process' be used where a consistent weight set is extracted through pair wise comparisons made by decision-makers in their consideration of each factor against one another. This method was used to develop the

5 More information on *SimLand* is available at http://www.soton.ac.uk/~fw/simland.html (accessed, 8/12/03).

transition rules for land development in the city of Guangzhou in south-eastern China where the neighbourhood is based on the nine cells *Moore neighbourhood*. The interest in this model is that it is an example where consistent weights are derived for the transition rules using substantive comparisons, which can be related to what we know about how land uses are developed.

Despite these features, SimLand was not relevant for the purpose of this study mainly because of the inability to access the source code. Also, the input data required could not be compiled in other cities in LDC such as Yaoundé, which may explain why SimLand has not yet been implemented in other cities.

4.3.2.2 Regional urban development: Xia and Yeh model

Xia and Yeh (1998) have built several GIS and cell-based models of rapid regional urbanization in southern China, Guandong province. They have also attempted to fit their models using neural networks methods to calibrate them (Xia & Yeh, 2001). One of the advantages of the Xia and Yeh's models is how land development constraints were assessed. They defined each cell as having a land development potential, which takes account of the extent to which land is constrained from development. Apart from binding constraints that restrict any land development, the cell size on which they are operating is such that only a proportion of the cell might be developed. This is an important development in the sense that it provides new insights into ways in which constraints can be handled in a CA-like modelling (Yeh & Xia, 2001). This feature is not often used or discussed in any of the previous models. The future urban and IS dynamic model could take advantage of such new development.

The main disadvantage of this model is that the cell sizes tend to be large (up to 100m). For dynamic simulation of urban and IS growth in LDC, cell resolution of less than 50m would be useful. Another constraint with Xia and Yeh's models is the size of the neighbourhood, which is fixed at the local level, thus not flexible enough to handle action-at-a-distance. These main limitations of Xia and Yeh's models make them an unfavourable candidate to be adapted to the simulation of urban and IS emergence and growth in LDC.

4.3.2.3 TRANUS

TRANUS[6] is a Venezuelan software package for modelling urban and regional development by means of integrating land use and transport models. *TRANUS* uses discrete choice and random utility theories. The program has been used since 1982 and now runs on a personal computer (PC) with a GIS interface. The aim of the software is two-fold. Firstly, TRANUS is intended to simulate possible impacts of applying particular land use, transport policies and projects. Secondly, the program is used to evaluate these impacts on social, economic, financial, and resource environments.

TRANUS is data intensive. Data requirements include: population, employment, land use status and price, transportation network information (such as capacity, distance, links, speed limits, and traffic cost). The output of the model could be the simulation of plausible interaction between the impacts of the location of activities, transportation and land use policies. The calibration of the land use module for instance is annually zoned and requires input data such as: annual employment categories, population composition for each zone, total land availability and value (for each year and zone).

For this study, TRANUS was not considered to be an appropriate package for three reasons. Firstly, the input data needed to run the model are too disaggregated and may not always be easily available for many cities in LDC. Secondly, the package is expensive and requires tedious and reliable socio-economic statistics, such as speed limits, which are not critical for the exploration and simulation of urban and IS growth in LDC cities. Finally, TRANUS not only relies heavily on transportation models, it is not flexible enough to allow the modification or addition of input parameters.

4.3.2.4 Smartplaces

Smartplaces[7] is a rural and urban planning decision-support package designed to assess the evolution of global environment and resources. Smartplaces aims to support

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[6] More information on TRANUS can be obtained at http://www.modelistica.com/modelistica.html (accessed, 14/12/2003).

[7] More information on *Smartplaces* properties can be found at www.smartplaces.com or at http://www.asu.edu/caed/proceedings99/RADCLIF/RADCLIF.HTM (accessed, 12/11/03).

planning processes, explore, design and modify, illustrate and evaluate planning scenarios with user-selected criteria and priorities. The program allows the user to set appropriate parameters to model economic development, land use change, land use evaluation and environmental assessment. Smartplaces runs on PCs and can accept various datasets such as scanned aerial photos, census population data, lines features (TIGER), AUTOCAD formats and *Arc View* files.

Smartplaces is not appropriate for modelling unplanned growth for the following reasons. The program is data intensive, and input data is too disaggregated. As a result the information required to produce a reasonable outcome would not be available and reliable for cities in LDC. The program is also not spatially and temporally dynamic. Moreover, Smartplaces is expensive and would therefore deter potential users.

4.3.2.5 *What if?* model

What if? is a software[8] package designed to support the planning policy processes based on projections of population, jobs, household structure, and densities. The software is inspired by the equilibrium theory of demand and supply and the idea of land use 'sustainability' (Klosterman, 1999). What if? is written in *Microsoft Visual Basic* and integrated into *ESRI MapObjects GIS*. Three land modules or assumptions regulate the program: suitability (supply), growth (demand) and distribution (allocation). In What if?, urban land use is made of three classes: residential (divided by density), commercial and industrial. What if? uses four groups of GIS layers: suitability layers (up to ten different subclass layers and multiples categories), allocation layers (up to twenty five), boundary layers (up to five), and display layers. Despite a vast range of possible layer input, one land use data set for one period is the minimum input file. Other GIS layers, such as topography (slope), socio-economic data and transportation, are optional. Better simulation results are, however, obtained by adding more layers into the model. To obtain a good suitability map for instance, at least three vector layers should be used.

What if? possesses some interesting properties. For example, the user can adjust the program and weigh the suitability according to a specific need. Also, the

[8] More information on What if? can be obtained at http://www.robbert.ca/index.html (accessed, 14/06/02) or http://www.what-if-pss.com/ (accessed, 14/11/03).

flexibility of What if? software lies in using available GIS data, as well as the expression of specific policy underlying changes and the type of land use. Another advantage of the model is its bottom-up approach and the ability to produce various scenarios of future development. Like *Clarke's Urban Growth Model* and CUF, What If? is calibrated on historical data. The results of a What if? simulation are a report and a set of projected land use maps obtained from three assumptions: suitability, growth and allocation.

On close analysis, What if? was not suitable for this project because the package is expensive, even though demonstration software was obtained on request. Also, What if? appears to be very disaggregated for this particular application. The spatio-temporal dimension of urban growth exhibited by the program is also not explicit. In other words, the program uses mechanistic GIS simulation by combining different layered information with growth estimation of various input variables. Moreover, What if? is a vector-based model with 5 year increments for not more than 5-time periods, and up to 25 years prediction. Informal settlements and urban dynamics in LDC could be better explored using a cell-based approach with a more flexible timeframe. Finally, What if? is rigid in the growth increments (5 years) and the prediction period. That is to say, it is not yet possible for the user to adjust parameters such as prediction years and timeframe.

4.3.2.6 METROPILUS

Metropolitan Integrated Land Use System (*METROPILUS*) aims to simulate the location of households and jobs, and model land use changes. Accordingly *METROPILUS* is structured around three integrated sub modules: residential location, employment and land consumption. The package requires intensive data input and uses GIS software such as *ArcView* interface for display. *METROPILUS* was developed in the 1970s, and since then, has expanded its performance and has been applied in more than twenty cities in the United States (Putman, 2001).

Unfortunately, in the context of this study, the software was not suitable for the following reasons: it is too expensive (more than US$100,000), data intensive, and its data requirements have applications limited to the USA.

4.3.2.7 Spatial land use policy and urban growth models

In the 1980s, John Landis developed one of the earliest GIS-based urban models known as the California Urban Futures Model (CUF). CUF uses GIS as an associated program to collect, store and display data such as spatial accessibility, development policies (regulations or incentives), built-up areas and developable land (suitability and profitability). CUF's approach uses the prediction of economic and population growth, based on historical trends. Historical growth patterns are calibrated for a fixed period to forecast urban growth for the same timeframe in the future.

Simulation within a CUF environment is explicit in the sense that disaggregated and multiple variables are used as the model inputs. These input files contain categories such as urban land use (residential, commercial, industrial, transportation, hydrology and public land), vacant land, digital elevation model and socio-economic information (population and job). Thus, the simulation is the result of the correlation values of a number of various variables. A map scenario is produced in accordance with the policy and GIS layer properties, such as environment, policy stipulation, market, and population density. That is to say, the simulation is not the influence of rules and conditions governing the emergence and the evolution of the system (as in the case of SIMLAND), but as in the case of What if?, is an overlay of growth projections embedded in input layers.

So far, three main versions of CUF exist which can be translated into its development phases. The first version, CUF1, simulated the impacts of urban policy options on the location, pattern and density of residential population dynamics in Californian counties up to 2010 (Landis, 1994; 1995). Unlike *METROPILUS,* the CUF1 is seen as an adaptable and a bottom-up approach in the sense that the population growth is estimated at the smallest unit, then aggregated to the regional level. CUF1 is composed of four sub-models: bottom-up population estimation, spatial database management, spatial allocation of developable land units (DLU), and allocation of spatial increment (Landis & Zhang, 1998b).

The second version, CUF2, has upgraded some of the initial features of CUF1. For example in CUF1, future land development is obtained by aggregating vector information of each developable land unit (DLU). Only residential land use is considered in CUF1. Whereas CUF2 uses 100 X 100 m raster grid cells, and accepts more land use and layers than the previous CUF1. Moreover, CUF2 integrates five sub-models: activity projection components, land use changes, spatial database, and simulation engine (Landis & Zhang, 1998a). The probability of land use change on each hectare cell is estimated using a multinomial logit function of variables such as accessibility, policies, neighbourhood characteristics, and historical behaviour.

The third version is known as the California Urban and Biodiversity Analysis (*CURBA*), which can be seen as a simplified version of CUF2 (Landis & Zhang, 1998c). *CURBA* uses *Arc View GIS* as the interface and proposes to assess the impacts of urban growth scenarios on the natural environment.

Despite the well-founded theory, the cell-based approach (CUF2 and *CURBA*) and features of CUF models, there are some difficulties in using them to explore urban dynamics in a context other than the USA (California). In the case of cities in LDC, the allocation sub-model in CUF cannot be performed because the information to estimate profitability of the DLU is neither available nor reliable. Furthermore, CUF was designed in the context of structured and planned development and reliable data sources, which is not the case in the context of unplanned urban growth. Although Landis and Zhang's models are non-commercial software, GIS datasets necessary to run the models are accustomed to the California area and can only operate locally on some computers at Berkeley University, California. Therefore, CUF could not practicably be used for other experiences outside the California area, where the model has already been implemented. Similarly, CUF models do not have a feedback effect. That is, the land allocation module of the model does not influence the land prices and the next iteration (Agarwal *et al.*, 2000).

4.3.2.8 Land Use Analysis Systems

Land Use Change Analysis Systems[9] (*LUCAS*) is another raster-based land use model aiming to identify a suitable area for new development (Berry *et al.*, 1996). The model investigates the implications of human action on the physical environment, using spatial stochastic distribution. LUCAS consists of three main modules: a socio economic module which generates the probability of land cover change; a landscape

9 More information on the program can be found at http://www.cs.utk.edu/~lucas/ (accessed, 16/11/03).

module which simulates the landscape evolution; and an impacts module which evaluates the effects of these changes on different species and their habitat. The model uses input data such as land cover maps, topographic maps namely a digital elevation model (DEM), socio economic data, population density, and transportation networks. The model uses 90m x 90m grid cells to predict future development for up to 100 years with 5 year increments. LUCAS simulates a series of maps comprising change processes, land use and effects on species and habitats. LUCAS uses GIS software, GRASS (Geographic Resources Analysis Support System), for display.

LUCAS was not suitable for this project for three main reasons: First, the temporal dimension is not explicit and consists of five-year increments. The spatio-temporal dimension is important for the proposed urban and IS growth model in LDC, because it should encapsulate the intrinsic spatial changes over time. Secondly, the spatial resolution is too coarse (up to 90m^2 grid cells), which is too large to capture the spatial distribution of most IS patterns in most LDC. Finally, LUCA*S* lacks a feedback loop effect and urban dynamics do not constitute its primary area of investigation. As stated, these features are important because the selected model should be able to encapsulate and display dynamic representation of urban and IS changes.

4.3.2.9 Land Transformation Model

The Land Transformation Model[10] (LTM) is a cell-based simulation model of land use change induced by ecological processes (Pijankowski *et al.*, 1997). The LTM uses GIS to simulate ecological and catchment changes. Changes are derived from transitional weighted probabilities obtained from environment behavior (drainage and topography), socio-economic trends (population and employment), and policy fluctuations (taxes and property rights).

The main attraction of the LTM is that the simulation can be executed from a parcel scale (30m x 30m) to a local level (1km x 1km) to forecast up to 50 years of land transformation with 5 to10 year time increments. The model also uses variables such as employment location, land use map (Anderson level I land use classification), population distribution, topography (digital elevation terrain-DEM) and transportation

[10] Further information available at http://www.ncgia.ucsb.edu/conf/landuse97 (accessed, 12/12/03).

data. The Land Transformation Model is more appropriate and often used for hydrology applications rather than urban dynamics modelling.

4.3.2.10 UPLAN: Urban Growth Model

UPLAN[11] (Urban Planning) is a raster-based urban simulation package that assesses land use change to generate development scenarios according to a set of decision policy rules. Written in *Arc View Avenue* script, this software displays the simulation result on the web using *Arc View Map Object*. UPLAN uses input layers such as urban land use (residential, commercial and industrial), population density, flood plain, DEM, socio-economic data, transportation, agricultural land, and 'protected' area to derive the suitability of urban growth (Shabazian & Johnson, 2000). Spatial resolution is variable (from 50m X 50m to 200m X 200m) and the urban sprawl simulation timeframe can go up to 50 years. The simulation space is divided into zones with various levels of attraction weights. The user can generate a growth scenario by allocating attraction weights to each zone. The simulation results could be used to assess human-induced environmental change of a particular development policy. UPLAN is a web interactive package for a rapid appraisal of implication of the application of a policy.

The package could not, however, be relevant for this study for three main reasons. Firstly, the framework of UPLAN is rigid and can be regarded as a 'black box'. The user is unable to make any changes (such as simulation period, number of variables and new rules) in the program. Secondly, the user can only enter the attraction weights for parameters already set again, limiting the capacity to introduce new elements. Finally, UPLAN is in its early stages and like CUF, applications are customised to the California region.

4.3.2.11 UrbanSim

UrbanSim[12] (Urban Simulation) is a semi-empirical software package using an object-oriented approach to model regional land use change and planning. The software integrates three sub-models: transportation, land use and public policy (Waddell, 2000).

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[11] More information available at htpp://snepmaps.des.ucdavis.edu/uplan (accessed, 23/06/02).

UrbanSim is designed as a tool for urban planners and policymakers. The model is based on the assumption that market prices are driven by customer choice. That is, the model is inspired by the discrete choice, behavioural, and economic theories, and integrates transportation and land use models. UrbanSim models use five main categories of input data: land use, transportation, employment rates, estates and environmental conditions. Specifically, UrbanSim is fed by data derived from assumptions such as the estimation of the population and employment levels, projection of the urban economy, future land use plans, projection of transportation systems, and the assumptions of land development policies (e.g., density threshold, environmental constraints, deterrent or incentive taxes and fees). Parcel information is obtained from census data, real estate and insurance companies. UrbanSim classifies each household by size, number of children, workers and income, estate size, employment sector and age of household head. Information required for each parcel is very detailed. For instance, each household (parcel) embodies information that can fit into employment sectors (twenty sub-sectors), estate development (twenty four categories), and land use categories (twenty five classes). UrbanSim uses GIS to prepare the input layers.

GIS vector layers are mostly constituted of parcel and city boundaries, slope, and traffic zones, whereas raster GIS layers are composed of aggregated parcels of 150m X 150m grid cells. After preparing the data for the model, the simulation is derived from the following four steps: scenario assumptions, runtime parameters, the model configuration, and event changes (policy, employment, environmental constraints and development).

UrbanSim then generates urban growth scenarios (based on the information provided) with optional user-defined temporal increments of 1 to 10 years and a projection period scale between 5 to 10 or 100 years (Waddell, 2001). UrbanSim can simulate situations such as changes in land use, number of new constructions, location of businesses, evolution of estate prices and the location of new development. Recently, UrbanSim has been empirically validated in Honolulu and the Eugene-Springfield area in the USA (Waddell, 2001), which provides an opportunity for its practical appraisal.

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[12] *UrbanSim* is a public domain program and can be downloaded free of charge at

From a positive perspective and as a spatial forecasting policy model, UrbanSim excels in its flexibility to disaggregate and integrate household, employment and land use information. The timeframe for simulation, and the interval period are also variable, which enhances its flexibility. Moreover, agents and actions are clearly defined and interact within the model. Simulation in *UrbanSim* uses the feedback effect, and the database is updated at each iteration. The output simulation is spatially and temporally dynamic, which is rare in many urban models. In addition, UrbanSim has a higher level of complexity since many components of urban systems are incorporated and interact intensively within the program.

Despite these attributes, however, the model is not suitable to simulate urban and IS in LDC for four main reasons. First, UrbanSim is mostly a vector-based model using assumptions and is based on top-down approaches to forecast possible urban changes and their implications. In the same way as CUF and What if? proceed, the simulation is the product of aggregated prediction for each input layer. This is unsatisfactory given that layers do not interact during the simulation process. Secondly, UrbanSim uses a high level of disaggregation for each of the five parameters used (household, job, land use, estate value, and policy). For instance, land use categories have twenty-five designed classes: 'undevelopable' (1), 'vacant developable' (1), Government (1), Industrial (3), Commercial (3), Residential (8), 'Mixed' (8). This detailed and structured data input makes the model more appropriate for cities in developed countries. Thirdly, the model is structured for a sample project and its datasets, and the required input data is difficult to compile for other applications such as unplanned developments in LDC. The time and knowledge necessary to prepare an appropriate dataset for the model limits its wide application. Fourthly, the dynamic visualisation of UrbanSim simulation is poor (Waddell, 2002).

3.3.2.12 RIKS projects

RIKS[13] (Research Institute for Knowledge Systems) has developed sixteen simulation projects (up to July 2002), with different purposes. Three were selected because they address urban dynamics modelling: RIKS, GEONAMICA and MURBANDY.

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http://www.urbansim.org/ (accessed, 30/11/03).

[13] More information on all RIKS projects is available at http://www.riks.nl/RiksGeo/Projects.htm or http://www.riks.nl/ (accessed, 15/05/02).

The first project, known as RIKS, was conceived as a theoretical investigation of self-organizing systems, rather than a realistic representation of urban dynamics. Compared with mechanistic GIS simulation such as CUF and What if?, *RIKS* uses CA and a ruled-based approach to explore the development of a disaggregated spatial model. The generic application known as cell city, was developed between 1990 and 1995 and used only a CA-like approach for urban dynamics.

The second project, GEONAMICA, couples GIS and CA to simulate disaggregated urban land use. This project did not undergo further development as initially planned.

The third project, Monitoring Urban Dynamics (MURBANDY), was developed with the participation of the European Union. The aims were to integrate disaggregated remote sensed data in a GIS interface with cellular automata for monitoring land cover changes in urban and peri-urban areas, to understand these changes and learn to forecast future changes. The application of MURBANDY was conducted for European cities with the aim of developing a generic European cities model based on transitional rules which are not sensitive to physical, cultural, social and historical differences. Rather, all cities were scaled at 1 ha cell (100m X 100m) and rounded on three spatially ordered parameters: suitability, accessibility and zoning.

In spite of their good design, these projects were not suitable for this research for two reasons. First, these projects were all customized for a specific application. RIKS projects were mostly designed to suit the customer's need. They therefore required the involvement of the developers or the team at each step of development and their possible applications. As customer-oriented programs, these projects could not be replicated. Secondly, in order for such projects to be successful, heavy funding schemes are necessary for a positive implementation of RIKS programs. This is because RIKS products and services are not fee free. This has been the case for other RIKS projects such as *SimLucia*, *RAMCO*, *Metronamica St. John's* and *Xplorah*.

4.3.2.13 LandSim 1.0: Urban growth simulator project

LandSim[14] (Land Simulation) is designed to simulate urban sprawl in the context of the USA in general, but specifically in the region of Ohio. The project uses environmental and land-use data for fourteen counties in the northeast Ohio region, to develop a web-based urban growth scenario. LandSim is a stand-alone simulation package, which projects residential, commercial and industrial expansion. LandSim is a *Visual C++* program, which could be loosely coupled to *Arc View*, *Arc Explorer* or *Arc Info* GIS software. The program accepts only *ascii* format and generates *ascii* files that should be converted into *ARC View* or *Arc Info* grid files.

The first version, LandSim *1.0,* is customised to accept input data with a header file having a resolution of 2200 columns by 2650 rows. This means that the data resolution is variable at the lower scale, but cannot be extended indefinitely. The program proposed four sprawl growth management strategies namely 'avoid farmland', 'use growth boundary', 'avoid non-suitable area', and 'use uncontrolled growth' (open space growth). Although the current dataset is for the northeast Ohio region, the simulation operates only on one township at a time, not on the entire region. Moreover, only the final year map is displayed, rather than the evolutionary process of urban dynamics. LandSim 1.0 is an attempt to develop an open source modelling using web-based simulation. Users can generate a sprawl growth scenario by visiting the website. Figure 4.1 shows a future land use simulation result for a county in North Ohio under the condition of urban sprawl on suitable land.

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[14] More information on program properties can be found at http://gis.kent.edu/gis/empact/ (accessed, 17/11/03).

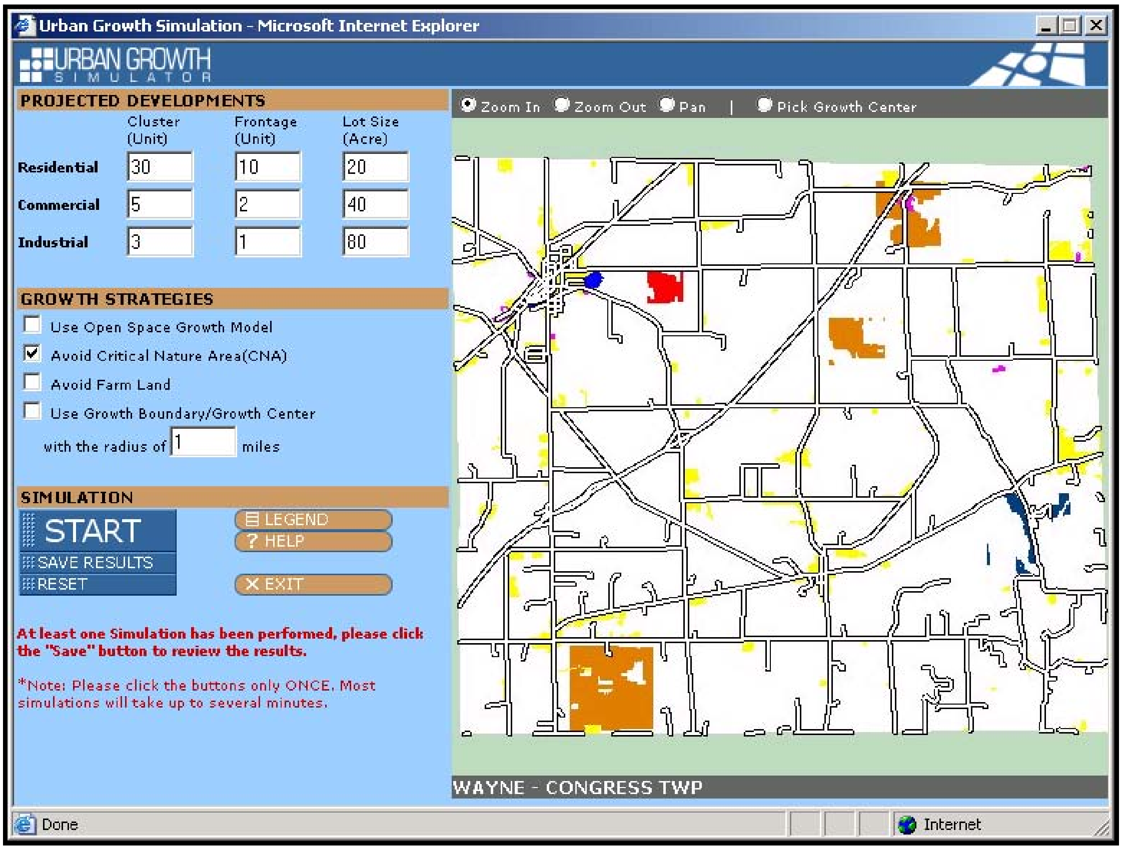

Figure 4.1: *LandSim* web interactive window
Source: http://empact.geog.kent.edu/ (accessed, 12/12/03)

Despite those merits, LandSim 1.0 is not suitable for modelling urban dynamics in other contexts, particularly cities in LDC, because the source code is not accessible, and therefore cannot be modified and can be seen as a 'black box'. The program is rigid and the user can only instigate minor adjustments to the system such as changing its weight, choosing management strategy, selecting types of development. Like CUF, the dataset is customised only for the Ohio region, which means that applications to different contexts are not feasible at the present stage. Moreover, the temporal dimension of the simulation is not explicit.

4.3.2.14 PCRaster

PCRaster[15] is raster GIS environmental software that models aspects such as ecology, drainage, rainfall, runoff, landslide hydrology and geomorphology (Griffiths & Collison, 1999). PCRaster applies the tight coupling of the GIS approach with cellular automata behavior (neighbourhood effects) to simulate landscape processes in a regular lattice structure of discrete spaces (Wesseling *et al.*, 1996).

The software is not suitable for urban growth modelling in LDC because it was expensive to purchase (US$2,000) and the source code cannot be made available for potential modification to suit these research objectives. Additionally, the dynamic visualisation of the output is poorly developed.

4.3.2.15 Clarke's Urban Growth Models

The Urban Growth model[16] (UGM) is conceived around the integration of GIS and cellular automata approaches. UGM is written in the C programming language and runs under UNIX. It is a geographical model using a spatio-temporal dimension, which aims to explore neighbourhood expansion (Clarke *et al.*, 1997).

UGM uses raster cells to simulate the urban growth transition from non-urban to urban land. Defining rules and weighted probabilities generates the growth. In UGM, local rules (roads, urban seed and slope), temporal factors (historical patterns) and random effects, governed *Monte Carlo* simulation. The software accepts two types of input files: images folder and schedules files. The images folder consists of six categories of *.gif* files that are fitted into the model. At least three urban maps and two road maps are acceptable, but only one slope map, one 'excluded' map and one 'hillshade' are required. Land use maps are optional. The schedule folder contains two types of files: the dates of all the urban and road maps. The spatial resolution of input files can range from 100m X 100m during coarse calibration to 30m X 30m at the simulation stage. The temporal dimension also varies extensively and depends on the user and the case study (from a few years to decades or centuries).

The simulation is controlled by five parameters, which carry respective weights or coefficients: slope resistance, road gravity, breed, dispersion and spread. The coefficient of each parameter is determined by running four rigorous calibration phases: coarse, fine, final and averaging best results. The weighted probabilities of each parameter are then used as input into the growth prediction. The simulation uses the feedback effect and bottom-up approach. Unlike other modelling packages such as CUF and *LandSim*, simulation in UGM produces annual maps of urban extension within the timeframe defined by the user. Similarly, UGM is spatially flexible, and

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[15] Background information on *PCRaster* can be found at http://www.pcraster.nl/ (accessed, 10/12/03)

some input files such as land use are optional. This series of maps can also be reclassified, compiled and visualised as animation products. Compared with PCRaster for instance, UGM has the capability to self-modify the five parameters and can model land use evolution.

The second and upgraded version of UGM is known as SLEUTH, which stands for *Slope*, *Land cover*, *Exclusion area*, *Urban extent*, *Transportation network* and *Hillshade*. These characters constitute the five main categories of data input. Whereas UGM was designed for local application, SLEUTH is more ambitious and claims to be used for forecasting urban growth at a regional and continental scale. UGM and SLEUTH have been applied in the study of many planned cities in North America such as San Francisco (Clarke *et al.*, 1997), Chicago, Washington-Baltimore area (Clarke & Gaydos, 1998), Sioux Falls, California, and Philadelphia (Varanka, 2001); Lisbon and Porto (Silva & Clarke, 2002) in Portugal (Europe); and Porto Alegre (Leao, 2002) in Brazil South America. (Figure 4.2 shows the simulation of San Francisco Bay area from 1800 to 1990.

[16] UGM and relevant source codes can be obtained free of charge at http://www.ncgia.ucsb.edu/projects/gig/ (accessed, 09/12/03). There is also a discussion group where users can exchange ideas.

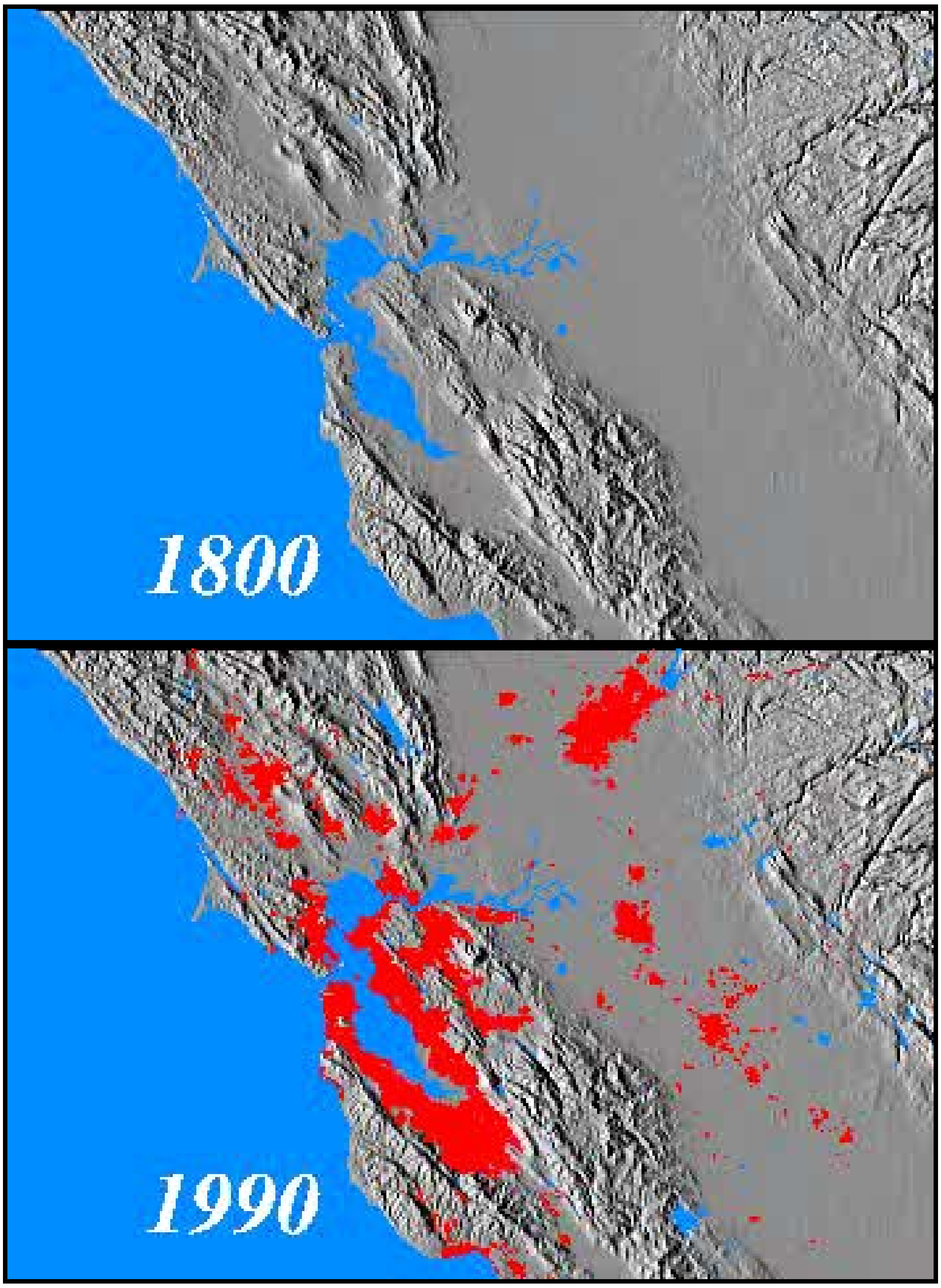


Figure 4.2: UGM has used factual historical data to represent the growth of San Francisco, USA

Source: http://www.ncgia.ucsb.edu/projects/gig/ (accessed, 09/12/03)

There are number of limitations to Clarke's model. First, it could be considered as deterministic, because the forecast relies on the historically known behaviour of each class or pattern. That is, the probability of a variable or change depends on the state of the similar classes in the previous years, and the control parameters the user has obtained from the calibrations. Second, although the model successfully handles spatio-temporal urban dynamics, it only models two states, urban and non-urban space, and does not simulate urban land use changes. Third UGM relies on the historical behaviour of spatial patterns and ignores other non-spatial information of urban systems such as economic and land regulation, employment, population growth, urban growth policies and socio-cultural influences. Instead, the program treats these variables as if they were embedded within space and time. Fourth, the program has a rigid number of input variables, which makes it difficult to adapt to the context of IS emergence and growth. Finally, using Clarke's model requires a general understanding of C programming, particularly if there is a need to modify the source code.

Despite some of the deficiencies noted in Clarke's model, UGM emerges as a serious option for modelling urban growth in Yaoundé, Cameroon, mostly because of the dynamic modelling, its availability, free access, flexibility in data disaggregation, rigorous calibration, and spatio-temporal data output.

4.4 Conclusions

Urban Dynamics models are shaped and bound by factors such as the developer's research interests and background, funding, data availability, and the scope of the study. It appears from the review of urban dynamics models that the high level of complexity exhibited by a model reinforces the likelihood for realistic representation.

Urban dynamics models assessed in this Chapter are constantly under construction (as illustrated by the creation of new versions, for instance in CUF and Clarke's models), sometimes over many years and have found ways to accommodate new objectives, changes to computer technology, the exploration of new fields, and the enhancement of their complexity. For example, CUF was originally conceived to predict developable land on a vector basis, while CUF2 incorporated new features and functionalities which handle cell-based modelling to explore urban growth.

This review has also revealed an emergence of a new trend in urban dynamics modelling. This new trend is related to the emphasis put on dynamic visualisation and animation using various media such as the internet (e.g., LandSim), and to the enhancement of level of complexity (e.g., What if?). The next area to consider is the Web and interactive modelling packages, rather than different pieces of hard or software. Open source web modelling packages such as UPLAN gives an indication of the 'new age' of greater accessibility, interactive visualisation and availability of community evaluation of urban dynamics simulation. One of the weak points of existing urban dynamics models remains their lack of flexibility in relation to the ability of the potential user to access and modify their source codes, so that input variables for instance can be adjusted. The review of the different models has also raised other points that must be considered in terms of assessing their applicability and suitability to the objectives of this study.

For example, the review of different models has shown that each model was conceived with specific objectives accordingly, application of the model to another context usually requires modification, and is also influenced by data availability; the flexibility of making necessary changes and the overall comprehensiveness of the model. In light of this, models that are not flexible enough in regards to the spatial and temporal resolutions, access and modification of source code, simulation timeframe and input data, are difficult to apply to new contexts. For instance, CUF and SimLand models are customized for one region; hence reducing the potential of being applied to other locations and situations. The review process has also highlighted that the cost of some urban dynamics packages would deter many potential users. This was illustrated with the cases of What if?, TRANUS, PCRaster and METROPILUS. Appendix 6 provides a synopsis of each model reviewed in this Chapter against the key selection criteria.

Based on the criteria developed at the beginning of this Chapter, it also follows that the choice of the model to be used to simulate urban and IS growth in LDC is directed to those which seek realistic representation and can handle complexity by integrating a vast range of data. Similarly, models that had reasonable spatial and temporal resolution, were flexible and sensitive to changes, freely accessible, and theoretically sound found favour. In light of the review and the positive and negative aspects of each model, Clarke’s UGM provided a solid framework to start sketching a GIS and cellular based model for simulating urban and IS in cities in LDC.

The next Chapter will demonstrate in more detail how Clarke’s Urban Growth Model was used to simulate the development of Yaoundé, Cameroon.

Chapter 5

Simulating and modelling Yaoundé urban dynamics using a conventional approach

5.1 Introduction

The complexity of urban and informal settlement (IS) dynamics can be explored using various approaches included modelling and simulation. Realistic simulation is, however, rarely achieved by existing urban dynamics models. This is because most urban models are too narrowly focussed according to developer's field of study, resources and data, and fail to replicate real-life situations within broader contexts. This research will attempt to use simulation and modelling techniques to investigate the spatial distribution and dynamics of unplanned developments.

As stated in the introduction, the premise of this research is that there is a strong case for developing realistic urban dynamics models to improve the understanding of complex systems such as cities in LDC. In the previous Chapter, eighteen urban dynamics packages were assessed in relation to criteria such as the objectives underpinning this research (Chapter One), the limitations in resources and the accessibility of the data required for the operation of the models. The review revealed some disparities amongst existing urban models. In reference to the key variables used to compare the selected models, Clarke's Urban Growth Models (UGM) emerged as the most promising package to help simulate urban growth in the context of unplanned development. In fact, compared to other models, UGM offers numerous advantages including the integration of GIS and 'relaxed' cellular automata, flexibility in data input and data disaggregation, rigorous calibration procedure, multiple spatial and temporal output products, accessibility to modelling source code, worldwide applications and user networking facilities, as well as availability free of charge.

This Chapter applies Clarke's Urban Growth Models (UGM) to investigate its applicability and capacity in capturing the urban dynamics of a fast growing city, Yaoundé. Specifically, by using UGM version 2.1 to generate urban dynamics models for Yaoundé, this Chapter will seek to achieve three main goals. First, the relevance of UGM software to IS will be assessed by evaluating its ability to generate urban forms and patterns that correspond to actual historical trends in urban growth. This will test the applicability of the assumptions underlying the model. Second, the application will be assessed in terms of its capacity to enhance the visualisation components of urban dynamics. The final goal will be to examine the possibility of applying UGM software to investigate informal settlement emergence and growth in LDC via the test case of Yaoundé. It is noteworthy that only background information of Yaoundé relevant for each application will be referred to.

The first section of this Chapter presents the UGM software, its theory, structure, data requirements and preparation in relation to the criteria developed in the Chapter Four. The second section describes the necessary steps to prepare data for the UGM and the different programs involved. The third section deals with the calibration procedure. The fourth section examines how the calibration results are used to simulate and predict future urban extension based on the case of Yaoundé in Cameroon. The dynamic visualisation that results from the calibration is also discussed. The last section presents the merits and limits of this urban growth model in relation to IS simulation.

5.2 Clarke's Urban Growth Model

As discussed in the previous Chapter, Clarke's Urban Growth Model (UGM) initially intended to model the urban extension of American cities has so far been applied to the simulation of several planned cities, particularly in the US including San Francisco, Chicago, Washington-Baltimore, Sioux Falls and the South Coast of California. This section attempts to apply UGM to simulate urban dynamics in an unplanned context in LDC. The model's theoretical basis is first presented, followed by the procedure for preparing data input for the model.

5.2.1 UGM theory and operation

Clarke *et al.* (1997) define the Urban Growth Model (UGM) as a GIS and CA-based model that is scale-independent. The GIS part of the model mainly contributes to the preparation and feeding of raster spatial data into the model, whereas the CA approach is used to define functions such as growth rule, simulation and prediction. GIS and CA are loosely coupled to predict urban land use change based on a three-step historical calibration. The model applies a series of universal growth rules on input files composed of slope, roads, urban extent, land use and excluded areas. Drawn from CA behaviour, the universal growth rules are randomly applied to cells, each of which is synchronously updated at each time-step. Growth rules were initially devised to simulate bush fire propagation (Clarke *et al.*, 1994) and later modified to simulate urban growth (Clarke *et al.*, 1996). In the case of urban growth, rules are guided by factors that are embedded in the space. The model uses the *brute force calibration*[1] approach to identify the best-fit score for each of the five urban growth coefficients: diffusion, breed, spread, slope resistance, and road gravity. The final stage of the calibration produces a single score for each parameter that is then used for prediction and simulation.

UGM is written in the C language and executes two loops. The first loop performs *Monte Carlo* iterations on historical input maps, whereas the second loop executes growth rules on a single year. The starting urban growth year is known as the *'seed'*. A potential urban cell is randomly selected and then the growth rules used to assess the urbanizing potential for neighbouring cells within the lattice.

5.2.1.1 Model's theory

The model assumes that state transitions between iterations are governed by local rules related to slope resistance, proximity to urbanised cells, and proximity to the transportation network. Five factors control the behaviour of the model: diffusion, breed, spread, slope resistance and road gravity. The *diffusion* or *dispersion coefficient* controls the random selection of cells for possible urbanisation at the next iteration. The *breed* parameter introduces the probability that a cell, under a spontaneous growth condition, becomes a new centre for the spread of urbanisation. The *spread coefficient* calculates the probability that such a growth centre will create new urban cells in its adjacent neighbourhood. The *slope resistance* factor evaluates the topographic constraint governing the development of new urban cells on steeper slopes. The *road gravity* coefficient estimates the probability of new urban cells forming along the communication networks (e.g., road). The values of these factors

[1] Brute force calibration refers to the estimation of values for each parameter from known historical growth patterns.

are entered into the model during the calibration. Appendix 7 describes the function of each coefficient in detail.

When the calibration is running, all the five growth control factors are then weighted by probabilities that encourage or slow the growth cycle, according to four growth phases: *spontaneous, diffuse, organic* and *road influence*. Figure 5.1 illustrates the four growth types.

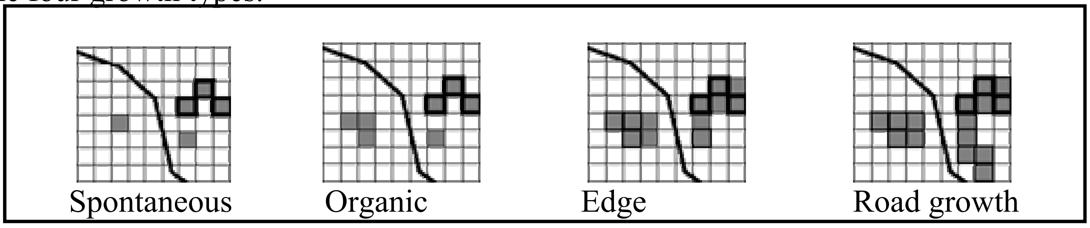


Figure 5.1 Four types of growth implemented by UGM

Source: Project Gigalopolis website: http://www.ncgia.ucsb.edu/projects/gig/v2/About/gwSelfMod.htm (accessed 20/06/02)

These four growth factors are applied to the last simulated urban area, and then updated at each iteration. Specifically, *spontaneous growth* occurs when a given non-urbanized cell falls in the adjacent neighbourhood of an already urbanized cell. This then affects the urbanization of the surrounding cells. Spontaneous growth function expresses the probability of the random formation of new urban areas. Defined as cellular automata, this function means that any non-urbanized cell in the lattice has a chance to be urbanised at the next iteration, and its probability updated at each time step due to a self-modification factor.

Diffuse growth anticipates the emergence of urban cells in areas that are likely to become urban, even if urban cells do not surround them. Also known as edge-growth (for their CA properties), diffusion propagates growth on the edge of an urban seed or on the new urban centres generated by spontaneous growth. Basically, if a non-urban cell has at least three neighbouring cells that are urbanized, then it may be urbanised at the next time step, depending on slope and spread coefficients.

Organic growth expresses the tendency of the city to spread from the urbanised area to the non-urban and non-excluded areas of the lattice. This also refers to the probability that a new spontaneous growth cell will become a new growth centre.

The r*oad growth* factor estimates the probability of urbanisation along the communication infrastructure networks, taking into account connectivity and accessibility. The probability of a cell being affected by road growth is weighted by three coefficients: breed, road gravity and dispersion.

5.2.1.2 Operation of self-modification automata

Self-modification is another important function in the behaviour of the system. Self-modification is a cellular automata behaviour, which grades all the input according to the following criteria: critical high, critical low, boom and bust. Self-modification first sums up the four growth types (spontaneous, organic, diffuse and road factor), then starts to decrease or increase the three growth control parameters (diffusion, breed, and spread). The system will experience a rapid expansion or 'boom' when the growth parameters are multiplied by a value greater than one. Alternatively, when the area (cell) is saturated or inappropriate for urban development, growth will slow down (decrease) or 'bust'. This decrease is obtained when the system multiplies the growth parameters by values of less than one. As the urban development 'consumes' constructible areas over successive iterations, the area becomes saturated and the 'boom' (coefficient greater than 1) factors — those coefficients greater than 1 — progressively reduce while the 'bust' factors — those coefficients less than 1 — are expanded. This principle can be applied to simulate urban extension in any given section of an urban area.

Some constraints are introduced to the system to avoid uncontrolled exponential growth. For instance, as the communication network expands, so does the road gravity factor (the urbanization effects on cells close to roads). As shown in figure 5.2, growth can be graded from rapid to 'little or no'. Figure 5.2 also illustrates the evolution of the scores of each coefficient as the simulation progresses. For instance, the slope resistance factor decreases, as the number of urban cells increases. This reflects the fact that steeper slopes are gradually urbanised at a later stage of the urbanisation cycle, especially when the amount of land available is decreasing.

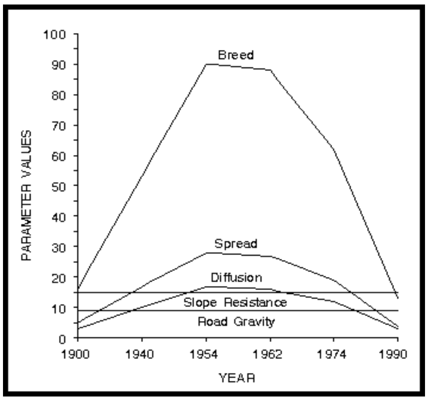


Figure 5.2: Self-modification operation in UGM
Source: Project Gigalopolis: http://www.ncgia.ucsb.edu/projects/gig/v2/About/gwSelfMod.htm (accessed 20/06/02)

Self-modification also controls the behaviour of the cells according to the overall state of the region. That is, the parameter values decrease progressively from the beginning of the expansion. By introducing some constraints, self-modification prevents the system producing an exponential or a linear growth trend.

5.2.2 Data required by the model: the case of Yaoundé

Data preparation is one of the most critical steps for successful implementation of the UGM. The program accepts the input of six *.gif* greyscale format datasets that represent slope, road, urban, *hillshade*, excluded and land use. The land use map is optional and was not used in the present application. For the process to run effectively, all images should have particular properties. All greyscale maps must have identical spatial resolution — that is, the same number of rows and columns for each dataset. Likewise, only binary data maps are appropriate. Moreover, maps must be in raster or grid format and should respect the UGM naming code. The number and function of input files can, however, vary extensively from one application to another.

5.2.2.1 Data preparation and input

Map source data is prepared for input in the following manner. One *slope* map is required and can be obtained from any mapping program which provides digital elevation model (DEM) functionality. Each slope cell should be classified as a percentage (0-100%) of the slope. The slope data for Yaoundé was obtained by combining digitised contour lines at 10m intervals, with 23 spot heights and rivers. To perform this task, the ANUDEM (Australian National University Digital Elevation Model) was used, not only to obtain a DEM but also to derive the *hillshade* and *excluded* maps. The ANUDEM was used because it has the capacity to generate a more accurate DEM than that generated by other available software (Hutchinson, 2001). For instance, *slope* and *hillshade* generated in *ArcView* will usually change their values when exported to another platform such as *Idrisi*. Moreover, only *themes* (not views or images) are exported from *ArcView*, while *Idrisi* files preserve image values and properties before and after export to a different program. Yet, ultimate accuracy could not be achieved. Nevertheless, after several attempts to generate a DEM in *ArcView* and *Idrisi*, the *ANUDEM* was finally very effective for eliminating spurious sinks on the DEM, adjusting digitising errors and integrating all layers (namely water, contour lines and spot height). The later were used to obtain a more accurate DEM of Yaoundé. ANUDEM generated a DEM of Yaoundé in *ASCII* format which was then exported to *Idrisi*, firstly to derive and classify the maps at various resolutions (200, 100, 50 and 30m), and secondly to be converted into *.gif* files ready for uploading to UGM. The ANUDEM-generated DEM is in *ASCII* format, which is then classified and converted into greyscale as shown in figure 5.3. It is worth noticing that the ANUDEM produced a slope map that emphasises hills and slopes. As will be shown later, the slope factor is marginal in the performance of UGM in Yaoundé in comparison with Western cities in general.

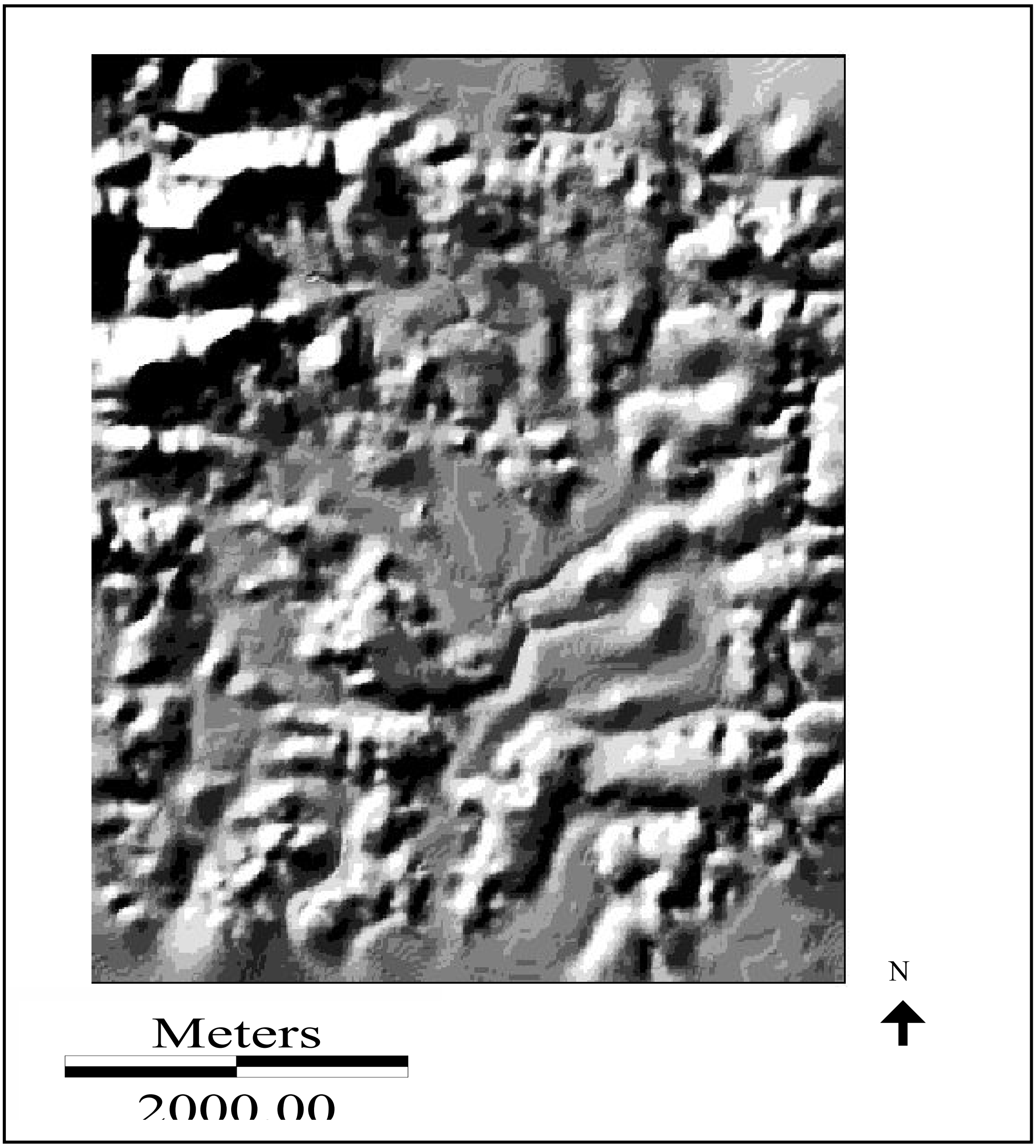


Figure 5.3 Sample of classified slope map

UGM requires a minimum of four urban maps at different dates. During the calibration, the starting year for the urban *seed* is used as the genesis of the calibration, whereas other urban year patches are used to control the calibration and to identify the appropriate coefficient for the prediction based on historical growth trends. Apart from the general properties of the UGM files described above, urban files should be in a binary format (urban and non urban) and can be classified as follows: each pixel with a value of zero (0) is non urban and all other pixels (values 1 to 255) are classified as urban. Following this principle, five urban maps were derived from land use and urban planning maps of Yaoundé. Figure 5.4 shows the five urban maps used for the calibration. Urban areas of Yaoundé were captured at five periods.

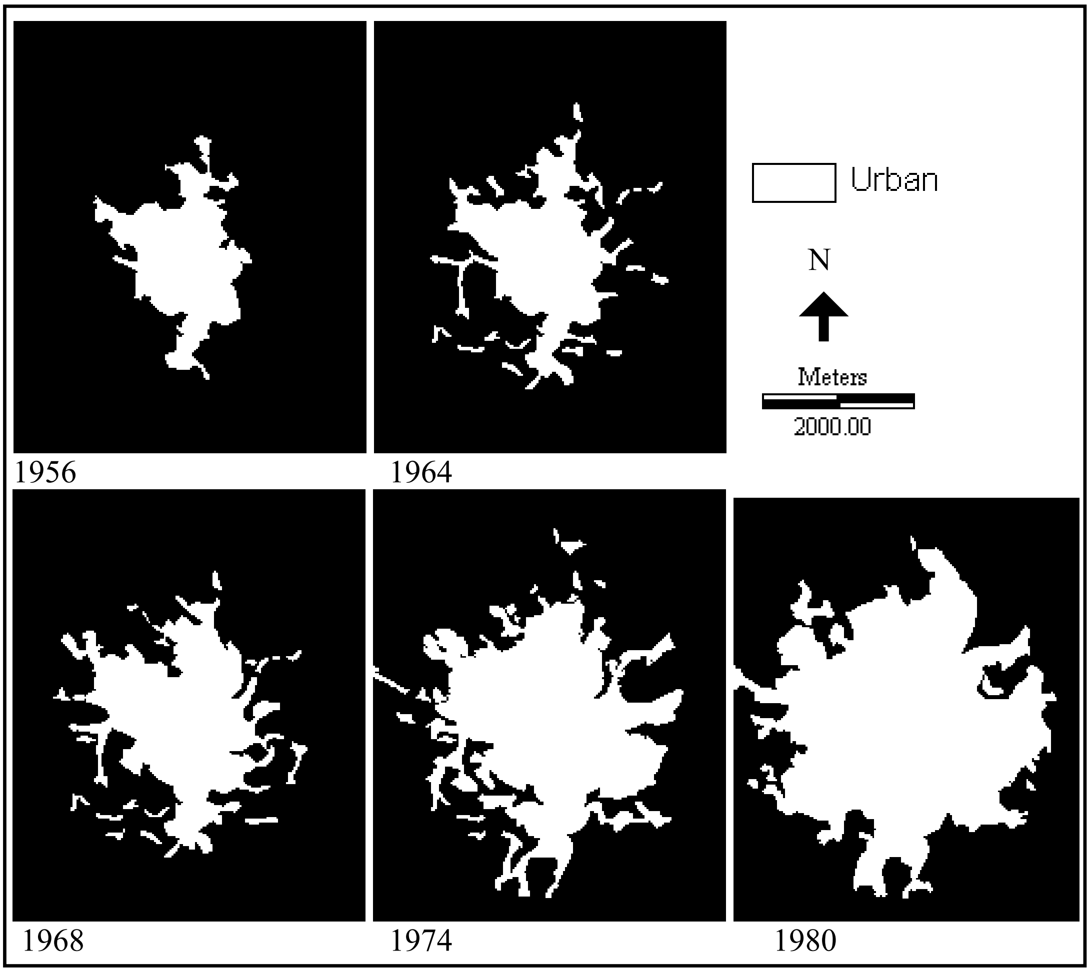
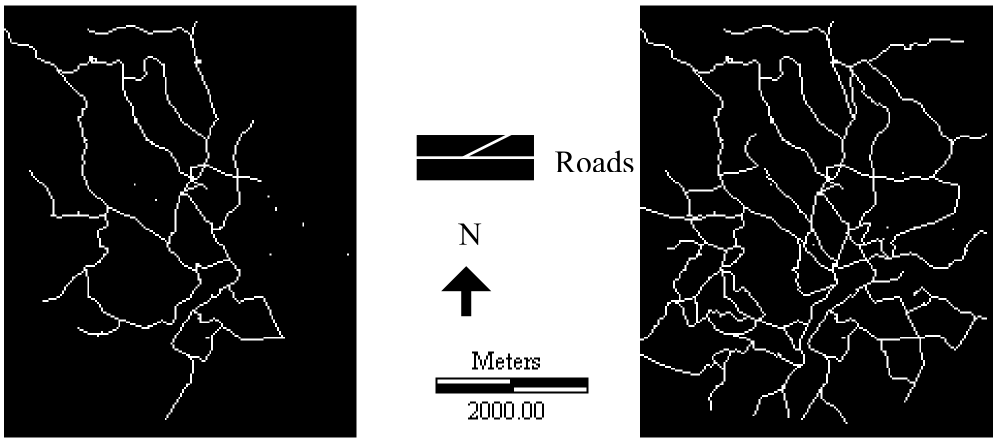


Figure 5.4: Five steps in the urban growth of Yaoundé: 1956, 1964, 1968, 1974 and 1980

The program requires one *excluded* map, which encapsulates all areas that cannot be subjected to urbanisation, such as parks and important water bodies like the ocean. The *excluded* map was obtained following a similar procedure for the slope map. Again, the cells were classified as binary with a cell of value 0 that being open to urbanisation, while cell values of 1 to 100 were excluded from the urbanisation process. *Excluded* areas are avoided during the calibration and simulation and thus no change can occur to cells in these areas. However, considering that the urbanisation process for Yaoundé, was not significantly restricted by the presence of any major physical feature, there was no excluded area identified. All cells on the excluded map therefore bear the value 0.

At least two transportation maps at different stages of city development are necessary for the program to calibrate growth. Unlike urban layers, transportation maps can contain projected routes. The program uses the *road gravity* variable and assumes that better accessibility and connectivity to the road network attracts more urbanisation. In the UGM, roads can be weighted according to their level of accessibility and importance as high, medium, low or none. In the application to Yaoundé, all roads carry the same weight because only major roads were selected for the modelling. Figure 5.5 shows two instances of road development used in the application of UGM to Yaoundé.



1956 1974

Figure 5.5: Sample transportation maps used for the calibration

The program requires one *hillshade* map that acts as a background image for the simulation. The Hillshade map is prepared in accordance with the requirements, such as spatial resolution, for other input data. Apart from the physical aspects already included in the hillshade map, other stable features, such as a water body, could be added to increase the visual realism of the simulation. However, all hillshade cells should have a nil value (0) so that the file will remain constant during all the iterations and simulations.

Once all the maps required by the model have been obtained, the next step is to clearly define how to prepare them in an acceptable format for the program.

5.2.2.2 Preparing data for the urban growth of Yaoundé

In the case of Yaoundé, urban maps were obtained by using *ArcInfo* to digitise the urban areas depicted on various topographic maps in five different years: 1956, 1964, 1968, 1974 and 1980. The significance of these years is as follows: 1956 signifies the emergence of Yaoundé as a town and is the earliest reliable representation of the extension of the city. The years 1964 and 1968 represent the post-independence period of rapid urbanisation of Yaoundé, although it still remained the political capital of the French speaking part of Cameroon. The year 1974 represented the post-unification of French and English speaking parts of Cameroon, with Yaoundé as the political capital. The year 1980 is relevant in that, significant expansion was mapped in this year and published in Yaoundé town planning documents of 1982. (Franqueville, 1984). Subsequent to 1980, official source maps were not available, consistent and accessible to the author, and thus prevented the testing of UGM in relation to urban expansion post-1980 data. This data was not critical for this experimental research because the program uses background information to simulate future urban extent (although it could be an issue in other LDC if data gaps exist). The simulated map can then be compared with any recent map to evaluate the accuracy of the prediction. The derivation of more recent maps from statellite imagery will be discussed in section 5.4.2.

Roads were digitised at three stages of their development (1956, 1968 and 1974), all deriving from two official urban planning documents for the years 1963 and 1982 at a scale of 1/12500 (MINUH, 1990). Rivers, contours, spot heights, and other formats were compiled from a topographic map of Yaoundé at a scale of 1/12000. Santoir and Bopda (1995) provide a comprehensive coverage of Yaoundé's river system, road network and physical form at a scale of 1/12500. All these layers were digitised using *Arc Info*, then exported into *Arc View* for georeferencing, analysis and editing.

Hillshade, *slope* and *excluded* maps generated in *Arc View* were, however, distorted and the pixel values changed when maps were input into UGM 2.1. To solve this problem, *ANUDEM 4.6.2* was identified as the most reliable software to produce best-fit *hillshade*, *slope* and *excluded* maps needed for UGM. In fact, the program generated more accurately regular grid-based digital elevation models (DEM) and drainage systems by automatically interpolating and correcting anomalies from input files (Hutchinson, 2001). The input files for the DEM of Yaoundé, which consist of spatial data such as elevation points (or spot heights), contour and streamlines, were used to generate hillshade, slope and excluded ASCII files. These ASCII files were then imported into Idrisi to be converted into bitmap format, then finally converted into *gif* format using Microsoft Image Composer. Table 5.1 explains the level of intervention required and the role of each program involved, in the preparation of the input files.

Table 5.1 Software and programs used to generate the urban growth model of Yaoundé

	Task	**Input**	**Output**
ARC INFO	Digitising maps	Maps sheets: topographic maps, historical urban maps, atlas plates	Arc coverage maps: road, contour, land use, river, spot height, boundaries,
ARC VIEW	Analysing, Georeferencing, Editing	*Arc Info* Coverage files (vector) ANUDEM *ASCII* files	Shapefiles Raster files
ANUDEM	Generate DEM	*Arc View* files (contour, river and spot height) ungenerated arc files	DEM Raster files
IDRISI	Create hillshade *Slope* and *excluded* files Convert into cellular automata readable files (live = 0 and dead= 1-255); Convert all files into raster format	ANUDEM and Arc view files	Hillshade, slope and excluded generating CA files with 2 states (0 or 1) Raster files
Microsoft Image Composer	1-Convert images into .GIF files 2-Renaming the files to the UGM 2.1 conventional name	Idrisi .Bitmap files (slope, excluded, hillshade) *Arc View* files (urban, roads	UGM conventional files
UGM 2.1	Calibration (coarse, fine and final), sorting best results, simulation	11 .GIF images renamed according to UGM requirements	Calibrations, predictions 3125 iterations/maps
Excel	Sorting calibration results	Calibration statistics	Selection of best results

When the maps were ready, they needed to be checked for consistency and agreement with regard to spatial resolution, temporal evolution and projection. The next step was to prepare a similar set of input files at different resolutions to be used during the calibrations and prediction. Because running the calibration at a fine resolution takes a great deal of time, the program breaks the calibration down into three steps: coarse, fine and final. Accordingly, four sets of input files were prepared for the simulation of Yaoundé. These were 200m cell resolution for coarse calibration, 100m for fine calibration, 50m for final calibration and 30m for prediction. Figure 5.6 shows an example of the input file at four different resolutions.

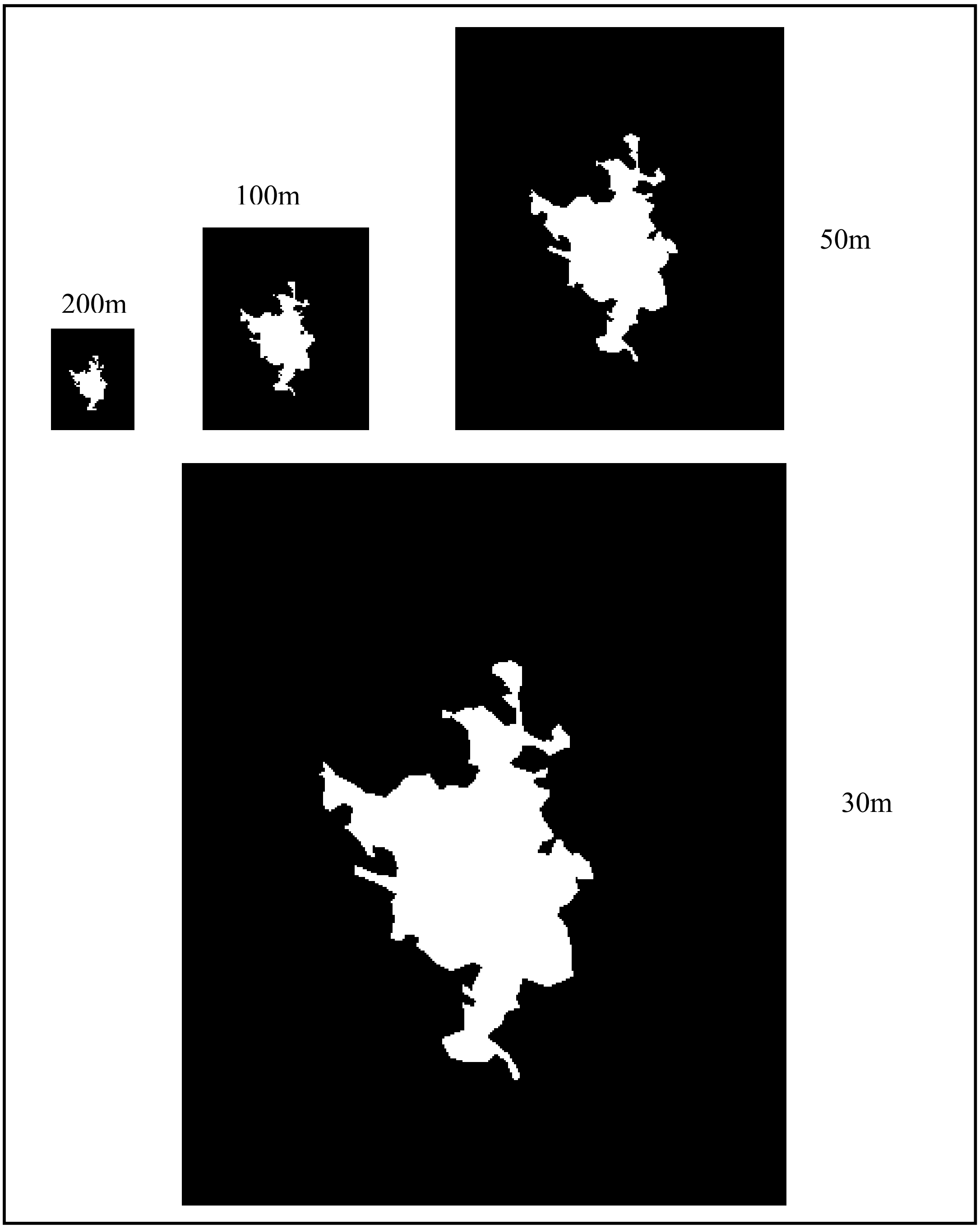


Figure 5.6 Example (urban extent 1956) of different image resolution (spatial) used during the calibrations of urban growth in Yaoundé[2]

[2] For simplicity, clarity and space reasons, map elements such as legend, north arrow and scale bar) will be purposely omitted on the forthcoming maps.

In this application, each set contains eleven input maps: five urban maps (1956, 1964, 1968, 1974 and 1980), three transportations maps (1956, 1968 and 1974), one *hillshade*, one *excluded*, and one slope map. S*chedule files* also needed to be prepared for the input folder. Once all maps satisfied the UGM format, the next step consisted of naming each file in accordance with UGM's coding convention.

5.2.2.3 Naming files for the UGM application

The program will only read input files with specific coding names and appropriate dates. All maps should be in greyscale and GIF formats. Specifically, all input urban and transportation maps must respect the following convention: <*location.type.year.gif*>, where *location* refers to the area of study and may also include an indication of resolution, with a length of up to 100 characters being permitted. The *type* indicates the data type (string) such as *urban*, *roads*, slope, *hillshade* and *excluded*. The *Year* indicates the year to which the data relates, displayed in four-digit format. For example, a 1956 urban map of Yaoundé with 100m resolution was written as *yde100.urban.1956.gif,* whereas a 1956 road map of Yaoundé with 100 m cell resolution was renamed *yde100.road.1956.gif*.

Additionally, *excluded*, *hillshade* and *slope* maps had to respect the following naming convention: <*location.type.gif*>. Thus, *excluded*, *hillshade* and *slope* maps of Yaoundé with 50m resolution were respectively renamed *yde50.excluded.gif*, *yde50.hillshade.gif* and *yde50.slope.gif*.

Apart from naming input maps prepared for the program, two *schedules files* have to be created either inside or outside the UGM in order to store the result of the calibrations and simulation results. Files created outside UGM program should be regrouped into two separate folders: the first folder is coded *urban.dates* and the second folder, *roads.dates*. All files should therefore be named and organised accordingly so they can fit into the program. Table 5.2 summarises the input files created and used, as well as their function in the model.

Table 5.2: Eleven files and two 'schedules' files used in the Yaoundé urban model

Data	Naming code	Nb of layers	Nb of classes	Note
Urban	Yde100.urban.1956.gif Yde100.urban.1964.gif Yde100.urban.1968.gif Yde100.urban.1974.gif Yde100.urban.1980.gif	5	2 each (urban and non urban)	The model will calibrate the 5 different stages of the urban development. Two images can be used but the program is more effective with four or more urban images.
Roads	Yde100.roads.1956.gif Yde100.roads.1968.gif Yde100.roads.1974.gif	3	2 (roads and non roads)	At least 2 sets of transportation networks (rail, roads and others) files are required. Their dates are independent from the urban maps.
Slope	Yde100.slope.gif	1	0-100	Weights the resistance probability of a slope. Slope: the average percent slope of the terrain is derived from a DEM Values: 0 - 100
Excluded	Yde100.excluded.gif	1	1 (non excluded area)	2 classes (excluded and non-excluded) Excluded Areas: water bodies and land where urbanization cannot occur (e.g., protected areas, sea, etc.)
Hillshade	Yde100.*hillshade*.gif	1	1	Use as aesthetic background only
Urban dates	Urban.dates	1	N/A	This folder is created directly into the *data* directory in UNIX. It lists all (5) urban files Or this UNIX command can be used: *ls –1 yde100.urban.*.gif > urban.dates*
Roads dates	Roads.dates	1	N/A	This folder is created directly in the *data* directory in UNIX. It lists all (3) road maps

Although the UGM is free to download, it runs only on UNIX machines. So, UGM was downloaded from the *Gigalopolis* website (http://www.ncgia.ucsb.edu/projects/gig/index.html) onto a SUN (SOLARIS) Micro Systems machine at the Department of Geomatics, University of Melbourne. The program UGM2.1.tar.gz was unzipped and compiled using GNU CC. A simulation test was run using demonstration data to ensure that the program was fully operational. Although the UGM model was executed under a UNIX environment, the outputs had to be transferred into a PC via *file-transferred protocol* (ftp) for further analysis and interpretation by other programs such as *Idrisi* and *Microsoft EXCEL*. After the simulation test, all the files prepared for modelling Yaoundé urban growth were uploaded to their respective folders in UGM to operate the calibrations.

The purpose of running a calibration test is to check the quality of the input data prepared for the Yaoundé model. If an error message ('bug') is generated, this means that the input files do not fit the program format. Error messages are generated partly because of incorrect naming codes, and images with different pixel resolution. If the error is corrected (or no error is identified), then the program is ready to start the calibration.

5.3 Calibrating urban growth models

In modelling real cities, calibration is employed to find suitable value parameters so that the simulation can best-fit subsequent development stages. Unfortunately, there is no universally applicable method of calibration due to the variety of situations encountered. For instance, Wu and Webster (1998) use multicriteria evaluation to heuristically define the values of parameters for CA-like simulation. On the other hand, Clarke et *al.* (1997) consider that visual tests are useful to establish parameter ranges and to make rough estimates of parameter settings. They argue that randomly changing its value and holding other parameters constant can also identify the value of the final coefficient. Elsewhere, Clarke and Gaydos (1998) suggest that calibration can also be done by statistically testing the observed values against those expected. This method is to find which set of parameters produces the best-fit, within a reasonable computing time. Coefficient values obtained from calibrations are then used for prediction (Silva & Clarke, 2002; Yang & Lo, 2003). It is worth noticing that although calibration is very important in urban modelling and prediction, it remains a complex and specialised topic that is not central to the concern of this thesis.

In UGM, the purpose of the calibration is to gauge if the model can successfully replicate the historical urban expansion as presented in the input files. The statistical values which best-fit the historical expansion, are chosen from all the possible iterations generated by the calibration. The accurate values are then used to predict future urban growth patterns. This calibration approach is known as 'brute force calibration' (Clarke *et al.,* 1996). In UGM, calibration proceeds by progressively reducing the coefficient increments of input parameters, while increasing the spatial resolution at three calibration phases: coarse, fine and final.

5.3.1 Running the coarse calibration

Coarse calibration is the first level of narrowing down the values of each of the five input parameters (road gravity, slope resistance, spread coefficient, breed coefficient and diffusion coefficient). To reduce the computation time, large increments are used for each coefficient. At this primary stage, the program considers all possibilities (from 0 to 100), with a large increment of 25. Similarly, coarse calibration uses a low spatial resolution such that the program recommends ¼ of the full size image. In the case of Yaoundé, images were prepared at different resolutions (200m, 100m, 50m and 30m). The set of images with 200m resolution was used for coarse calibration, together with the location (*Yde200*), the seed number (1000), the *Monte Carlo* iteration (4) and echo parameter (0) as shown in table 5.3.

Table 5.3: Input scores at the coarse calibration phase

```
<<<<<<    Urban Growth Model 2.1      >>>>>>
Program Options Available:
To use existing 'calibrate' file
 To create new 'calibrate' file
              (a copy of 'calibrate will be in 'calibrate.bkp'
To restart the program from where a modeling run crashed

Enter program Option: 1

Enter 1 to calibrate, 2 to predict, or 3 to test: 1

Enter location string for file format prefix: yde200

Echo: 0

Enter random number seed > 0: 1000

Enter monte carlo number of times: 4

Enter initial diffusion coefficient: 0
Enter diffusion coefficient increment: 25
Enter final diffusion coefficient: 100

Enter initial breed coefficient: 0
Enter breed coefficient increment: 25
Enter final breed coefficient: 100

Enter initial spread coefficient: 0
Enter spread coefficient increment: 25
Enter final spread coefficient: 100

Enter initial slope resistance coefficient: 0
Enter slope resistance coefficient increment: 25
Enter final slope resistance coefficient: 100

Enter initial road gravity coefficient: 0
Enter road gravity coefficient increment: 25
Enter final road gravity coefficient: 100
```

When all these values are fed into UGM 2.1, the coarse calibration starts. Different scores but no image file is produced by a controlled loop, which repeatedly executes each growth history retaining statistical and cumulative data for the Monte Carlo application. In the case of Yaoundé, the coarse calibration ran for 45h29m43s. The operation executed 3125 iterations and generated *.log* files such as *control.stats*, *param, calibrate*, and *run.time*. Appendix 7 provides an exhaustive definition and description of all the files generated during the calibration. Although no image files are generated at this stage, the most important of these files is the *control.stats* which exhibits thirteen different output classes for all the iterations, as well as values of the five growth control parameters (*diffusion*, *breed*, *slope resistance*, s*pread* and *road gravity*). *Control.stats* file contains the calibration results that provide clues as to which statistical values will best-fit the historical trend. To find out which iterations are most suitable, the results of the *control.stats* should be sorted.

5.3.2 Selecting the 'best' results of the calibration

The aim of sorting the 'best' results is to narrow down the range of coefficients broadly captured during the coarse calibration, while still keeping the number of Monte Carlo runs low. Sorting is the procedure of reviewing and selecting the most successful iteration coefficients, (for instance 3 to 20 out of 3125 iterations during the coarse calibration), to be used at the fine and final calibrations. Best results are considered as likely values, which are quantified, compared and used to statistically test changes observed (historical patterns) with those expected (simulated). The higher the value, the more accurate the prediction for that set of iterations.

Sorting best results consists of reducing the range of all possible values to scores that are positively and efficiently correlated with the historical growth patterns. Similarly, sorting best results implies the selection of some of all the variables of the calibration results (recorded in *control.stats* file). All thirteen variables can be equally weighted to select the more likely combinations. But this depends on the purpose of the calibration, and later on the simulation. Clarke and Gaydos (1998) suggest that the best parameters for urban simulation are derived from the classes in which predicted coefficients are correlated (high *r-squared* values) with values computed from the historical map layers. These classes are *compare*, *r2pop*, *r2edge* and *r2cluster*. The first three of these parameters are expressive enough to give an idea of the simulation output. For instance, the class *Compare* gauges the output of the actual urban pixels with the predicted number of urban pixels, then *r2pop* compares the fit between the actual and predicted number of urban pixels; whereas *r2edge* shows the fit between the actual and predicted shapes of the images. The calibration results can be sorted either within or outside UGM. In the case of Yaoundé, both of these procedures were implemented.

An attempt was first made to sort all the calibration results by *best-fit*, directly within UGM 2.1 using the command *reweight*, following this path

<<<Utility + copy files into Reweight Directory + Data + Control.stats + set the weight in weightfile + run reweight>>>

Unfortunately, the program returned errors and could not perform the reclassification task. Configuration or algorithm problems are possible explanations.

A second attempt was made to sort and highlight only the 10 best-fit calibration results from three selected classes, within the UGM program, by implementing the command

<<<Data Directory + sort –r control.stats + head>>>

Again, the output was not satisfactory.

As another option, the calibration results (*control.stats.log* file) were exported outside the UGM program (using *ftp*) in order to perform the statistical analysis. *Microsoft Excel* was chosen because it has the capacity to analyse tables and perform multiple functions such as flexible and multiple sorting and classification. To do so, the extension of the *control.stats* files was changed to *.xls* then opened within *Excel*. In *Excel*, the command *sort* is used to rearrange the table in order to select the fit classes (results) for the next step, using the three categories: *compare*, *r2pop* and *r2edge*. Table 5.3 shows an example of sorting of best results using *Excel spreadsheet*.

Table 5.4: Using *Excel spreadsheet* to select best calibration results

Coarse calibration (Yde200)
All Results

integr	Compare	r2pop	r2edge	r2cluster	mean-clus	leesalle	av-slope	pct-urb	x centre	y centre	s dist	lan use	diffusion	breed	spread	slope rest	road grav
0.003	0.9992	0.8898	0.8081	0.3185	0.5142	0.4998	0.2108	0.8898	0.5524	0.6686	0.7336	1	50	1	100	100	100
0.0001	0.9992	0.8851	0.8007	0.2855	0.5874	0.499	0.0115	0.8851	0.3875	0.5077	0.7259	1	50	1	100	50	25
0.0037	0.9982	0.9054	0.8222	0.3634	0.5075	0.4477	0.2321	0.9054	0.5703	0.6547	0.7616	1	100	1	25	75	75
0.0009	0.9982	0.8816	0.7895	0.3002	0.5874	0.4916	0.0865	0.8816	0.4937	0.5631	0.7214	1	50	1	75	1	75
0.0001	0.9981	0.8852	0.8063	0.3191	0.3145	0.5007	0.0442	0.8852	0.2092	0.4108	0.7266	1	50	1	100	25	1
0.0105	0.9979	0.9099	0.8326	0.4044	0.2674	0.4495	0.8844	0.9099	0.7185	0.6409	0.7692	1	100	1	25	50	50
0.0078	0.9978	0.913	0.8265	0.4053	0.5075	0.4451	0.6797	0.913	0.3596	0.6532	0.7723	1	100	1	25	1	75
0.0018	0.9978	0.8902	0.8054	0.3139	0.397	0.4882	0.2714	0.8902	0.4331	0.5503	0.7379	1	25	25	50	1	50
0.0001	0.9973	0.8934	0.8096	0.3278	0.5995	0.4916	0.0081	0.8934	0.2789	0.8119	0.7407	1	50	1	75	75	100
0.0161	0.997	0.8948	0.8176	0.295	0.5603	0.4986	0.9822	0.8948	0.7081	0.5793	0.7411	1	50	1	100	100	50
0.0002	0.9967	0.9063	0.8206	0.3743	0.5075	0.4446	0.4959	0.9063	0.0166	0.5693	0.7625	1	100	1	25	25	100
0.0017	0.9959	0.9123	0.8321	0.3893	0.2674	0.4463	0.5644	0.9123	0.2365	0.5147	0.7729	1	100	1	25	1	50
0.0075	0.9959	0.9108	0.8294	0.4143	0.5075	0.4469	0.3762	0.9108	0.661	0.6102	0.7709	1	100	1	25	75	50
0.0036	0.9958	0.8806	0.7987	0.3445	0.2038	0.4993	0.5403	0.8806	0.7499	0.5701	0.7193	1	50	1	75	50	25
0.0016	0.9956	0.9035	0.817	0.3594	0.2674	0.4486	0.1608	0.9035	0.7749	0.6054	0.7568	1	100	1	25	75	1
0.0054	0.9955	0.9083	0.8229	0.403	0.2674	0.4439	0.8371	0.9083	0.4576	0.565	0.7659	1	100	1	25	25	25
0.0085	0.9949	0.8876	0.7967	0.323	0.3533	0.457	0.9438	0.8876	0.6614	0.573	0.7335	1	50	25	25	100	100
0.0019	0.9947	0.8875	0.7961	0.3532	0.4444	0.4917	0.2477	0.8875	0.4151	0.5164	0.7289	1	50	1	75	100	50
0.0002	0.9946	0.9113	0.8283	0.3929	0.5075	0.4451	0.0603	0.9113	0.1546	0.5684	0.7698	1	100	1	25	50	25
0	0.9944	0.8843	0.7969	0.3155	0.4112	0.4878	0.003	0.8843	0.2342	0.6002	0.7258	1	50	1	75	50	75
0.0017	0.9942	0.9045	0.8166	0.3805	0.2674	0.4429	0.3888	0.9045	0.333	0.5693	0.7587	1	100	1	25	50	1
0.0099	0.9927	0.881	0.7977	0.3382	0.4444	0.4929	0.815	0.881	0.7162	0.5182	0.7203	1	50	1	75	1	50
0.0047	0.9926	0.8937	0.8195	0.3282	0.4538	0.4989	0.5487	0.8937	0.4532	0.5295	0.7397	1	50	1	100	75	100
0	0.9925	0.9026	0.8197	0.3467	0.4112	0.4644	0.003	0.9026	0.1146	0.5539	0.7594	1	50	25	25	75	1
0.0042	0.9922	0.8925	0.8146	0.3404	0.5075	0.5046	0.9267	0.8925	0.2517	0.4384	0.7366	1	50	1	100	100	1
0.004	0.9916	0.8786	0.7997	0.3319	0.3785	0.5038	0.5036	0.8786	0.5462	0.5191	0.7175	1	50	1	100	50	1
0.0006	0.9909	0.8868	0.7989	0.34	0.3633	0.4895	0.0393	0.8868	0.9501	0.537	0.7325	1	25	25	50	1	25
0	0.9909	0.8826	0.7934	0.3737	0.1706	0.4848	0.003	0.8826	0.8521	0.6321	0.7263	1	25	25	50	50	100
0.0054	0.9907	0.8835	0.7919	0.3185	0.3236	0.4923	0.6341	0.8835	0.6145	0.6201	0.7238	1	50	1	75	25	75
0.0006	0.9906	0.9101	0.82	0.4026	0.5075	0.4457	0.077	0.9101	0.2892	0.5456	0.7675	1	100	1	25	1	100
0.0011	0.9905	0.8794	0.7992	0.3345	0.4444	0.5118	0.1922	0.8794	0.3269	0.5263	0.7174	1	50	1	100	75	1
0.0004	0.9903	0.9072	0.8219	0.3828	0.5075	0.4453	0.033	0.9072	0.4117	0.5876	0.7651	1	100	1	25	1	1
0.0003	0.9902	0.887	0.8137	0.3187	0.4311	0.5026	0.3178	0.887	0.0604	0.4867	0.7296	1	50	1	100	100	25
0.0003	0.9899	0.9102	0.8258	0.3952	0.2674	0.4473	0.0409	0.9102	0.4663	0.5863	0.7678	1	100	1	25	50	75
0.0019	0.9898	0.9104	0.8272	0.3786	0.5075	0.4473	0.8869	0.9104	0.0721	0.6789	0.7682	1	100	1	25	25	50
0.0014	0.9897	0.8929	0.8002	0.2963	0.5142	0.4837	0.2097	0.8929	0.4937	0.4039	0.7412	1	25	25	50	50	50
0.0032	0.9894	0.9102	0.8226	0.3965	0.5075	0.4449	0.3106	0.9102	0.376	0.6	0.7667	1	100	1	25	50	100
0	0.9893	0.9215	0.847	0.3238	0.5075	0.412	0.0045	0.9215	0.0001	0.4758	0.7891	1	50	75	1	25	100

The calibration scores were sorted by the likeliness of the iteration to produce reasonable input parameter values for the fine calibration. Ten best results were then recorded (see table 5.4) to derive the parameter range that will be used as input for the next phase. In the case of *diffusion*, good results were obtained for parameters ranging between 50 and 100. The *breed* remains constant at 1 suggesting that the increments chosen for *breed* could not capture different score at all range of iterations. At the next calibration phase, the increment could be modified to optimise or test the validity of the constant. Meanwhile, *spread* is more likely to produce a good result when it is calibrated from 25 to 100.

Table 5.5: Ten best results of the calibrations results, by *compare*, *r2pop* and *r2edge*

Iteration/ parameter	1	2	3	4	5	6	7	8	9	10	Total range
Diffusion	50	100	100	100	100	100	100	100	50	50	50-100
Breed	1	1	1	1	1	1	1	1	1	1	1
Spread	100	25	25	25	25	25	25	25	100	100	25-100
Slope	100	75	50	25	1	75	25	50	50	25	1-100
Road Gravity	100	75	50	100	50	50	25	25	25	1	1-100

The *slope resistance* and *road gravity*, however, varied all along the classes. There could be a number of reasons for this. The most likely explanation would be that the *breed* parameter had less control on the urbanization of Yaoundé than the road gravity, *diffusion* and the *spread*. In light of this, input variables should be narrowed down during the fine calibration to obtain reasonable values for each category.

5.3.3 Fine calibration

Sorting *control.stats.log* from coarse calibration reduces the coefficient values for each parameter that can now be used during the fine calibration. The purpose is to narrow down the selection and to achieve better combinations with a smaller range of parameters (for example an increment of the 5 to 10 instead of 25 used for coarse calibration). The number of *Monte Carlo* iterations will also be increased to improve image matching. During the fine calibration phase, Yaoundé images are resampled to a spatial resolution of 100 meters.

The *data* directory was cleared of all the *.log* files, to contain only the image files required for the fine calibration (*.gif* files), and other *schedules* files. The input procedure is identical to that described above for the coarse calibration. Visual comparison of the output revealed that the input score failed to capture satisfactory parameter scores for the projected urban areas. In fact, after sorting the best results, best-fit scores obtained for *compare*, *r2pop* and *r2edge* classes were below 0.888. The input calibration values were therefore modified, and the fine calibration was run once again using the values in table 5.6.

Table 5.6: Input scores at the fine calibration phase

```
<<<<<<     Urban Growth Model 2.1       >>>>>>
Program Options Available:
To use existing ‘calibrate’ file
 To create new ‘calibrate’ file
                (a copy of ‘calibrate will be in ‘calibrate.bkp’
To restart the program from where a modeling run crashed

Enter program Option: 1

Enter 1 to calibrate, 2 to predict, or 3 to test: 1

Enter location string for file format prefix: yde100

Echo: 0

Enter random number seed > 0: 1000

Enter monte carlo number of times: 6

Enter initial diffusion coefficient: 5
Enter diffusion coefficient increment: 5
Enter final diffusion coefficient: 25

Enter initial breed coefficient: 0
Enter breed coefficient increment: 10
Enter final breed coefficient: 40

Enter initial spread coefficient: 10
Enter spread coefficient increment: 10
Enter final spread coefficient: 50

Enter initial slope resistance coefficient: 20
Enter slope resistance coefficient increment: 10
Enter final slope resistance coefficient: 50

Enter initial road gravity coefficient: 0
Enter road gravity coefficient increment: 10
Enter final road gravity coefficient: 40
```

After three attempts, the input values produced output scores that were close to the input files. Scores of 0.999 were recorded for the *compare*, *r2pop* and *r2edge* classes. Although the *diffusion* and *breed* coefficients and their increments were significantly reduced, the *spread*, *slope* and road coefficients and their increments did not vary as much. Nevertheless, the number of *Monte Carlo* runs was increased from 4 to 6. This time, the calibration ran for 78 hours, 37 min and 15 seconds and generated 11 664 iterations. The length of the calibration could be explained by the high number of iterations, the lower number of increments and the workload on the server where the data were stored and computed.

The fine calibration result contained in the *control.stats.log* file was then exported into *Microsoft Excel* for sorting as described above. The best results of the fine calibration were sorted and best-fit values for five control parameters were ranged as follows:

Breed: 1-40
Diffusion: 5-25
Spread: 10-50
Slope: 20-50
Road: 20-40

Although the range of values for each coefficient was still broad, the final calibration will aim to narrow this down further.

5.3.4 Final calibration

We have just seen that the fine calibration produced a large range of scores for the control parameters. The aim of the final calibration is now to use the classified best-fit values obtained from the *controls.stats* file of fine calibration, to investigate the closest coefficient for each of the five parameters. Also, the increment will be significantly reduced from 10 and 5 at the previous stage to less than 3 during the final calibration. Yaoundé images with 50m spatial resolution are used for the final calibration. The same procedure was followed as described at the previous calibration phases, but the input values were adjusted as shown on table 5.7.

Table 5.7: Input scores at the final calibration phase

```
<<<<<<    Urban Growth Model 2.1      >>>>>>
Program Options Available:
(1)   To use existing 'calibrate' file
(2)   To create new 'calibrate' file
               (a copy of 'calibrate will be in 'calibrate.bkp')
To restart the program from where a modeling run crashed

Enter program Option: 1

Enter 1 to calibrate, 2 to predict, or 3 to test: 1

Enter location string for file format prefix: yde50

Echo: 0

Enter random number seed > 0: 1000

Enter monte carlo number of times: 10

Enter initial diffusion coefficient: 5
Enter diffusion coefficient increment: 5
Enter final diffusion coefficient: 15

Enter initial breed coefficient: 1
Enter breed coefficient increment: 5
Enter final breed coefficient: 20

Enter initial spread coefficient: 10
Enter spread coefficient increment: 5
Enter final spread coefficient: 35

Enter initial slope resistance coefficient: 20
Enter slope resistance coefficient increment: 5
Enter final slope resistance coefficient: 50

Enter initial road gravity coefficient: 20
Enter road gravity coefficient increment: 5
Enter final road gravity coefficient: 40
```

The *control.stats* file of the final calibration was exported to *Microsoft Excel* and sorted according to the same protocol as that used for the fine calibration. This time the twenty best-fit iterations indicate the following coefficient ranges for each of the five parameters:

Breed: 1-20
Diffusion: 5-15
Spread: 10-35
Slope: 30-45
Road: 20-30

These scores mean that the coefficient margins should be further reduced to identify the exact value *per* parameter. Running an averaging best results module in UGM will achieve this reduction.

Averaging best results thus used the best-fit results obtained after running the final calibration. The input scores for the final averaging best results were as follows:

Breed: 10
Diffusion: 12
Spread: 25
Slope: 42
Road: 20

This time, however, the increment was set at 1 for all coefficients. The results obtained were then used for the next calibration phase of simulation and prediction of urban growth in Yaoundé. For the prediction, the model used input maps resampled at 30m resolution.

5.4 Simulation and prediction

The previous section has shown that successful simulations can be obtained by gradually modifying the parameter values of CA models, rather than totally changing them. The calibration method used here to identify adequate change is based on the assumption that historical patterns and trends tend to guide the direction of future expansion. This section will first demonstrate how calibration scores for each parameter have been used to predict the future expansion of Yaoundé urban area. Second, the overall simulation results derived from the application of UGM will be used to discuss a plausible future expansion of Yaoundé.

5.4.1 Plausible future expansion of Yaoundé

So far, the program has produced only statistics that have been analysed to identify best-fit coefficients for each class. The simulation and prediction phases will now generate annual colour images for the stated number of prediction years. The procedure used to create such predictions for the case study of Yaoundé, is described below.

The prediction of Yaoundé's urban extension, uses the same input sources as in the *averaging best results*. Beginning with the year 1980, the Yaoundé model ran

100 *Monte Carlo* iterations in 8h24m51s. The Program simulated the future expansion of Yaoundé's urban area from 1981 to 2030. The simulation produced a series of annual maps that were then imported into a *Gif Animator* to generate an urban growth animation (Sietchiping, 2001a). Figure 5.7 illustrates the prediction results at 10 difference instances of the simulation. Each simulated image is coloured and illustrates three main states: first, the original status or *urban seed* (light yellow), then the present level of urbanisation (in red), and finally, the future urbanisation areas at different levels of potentiality (green)[3].

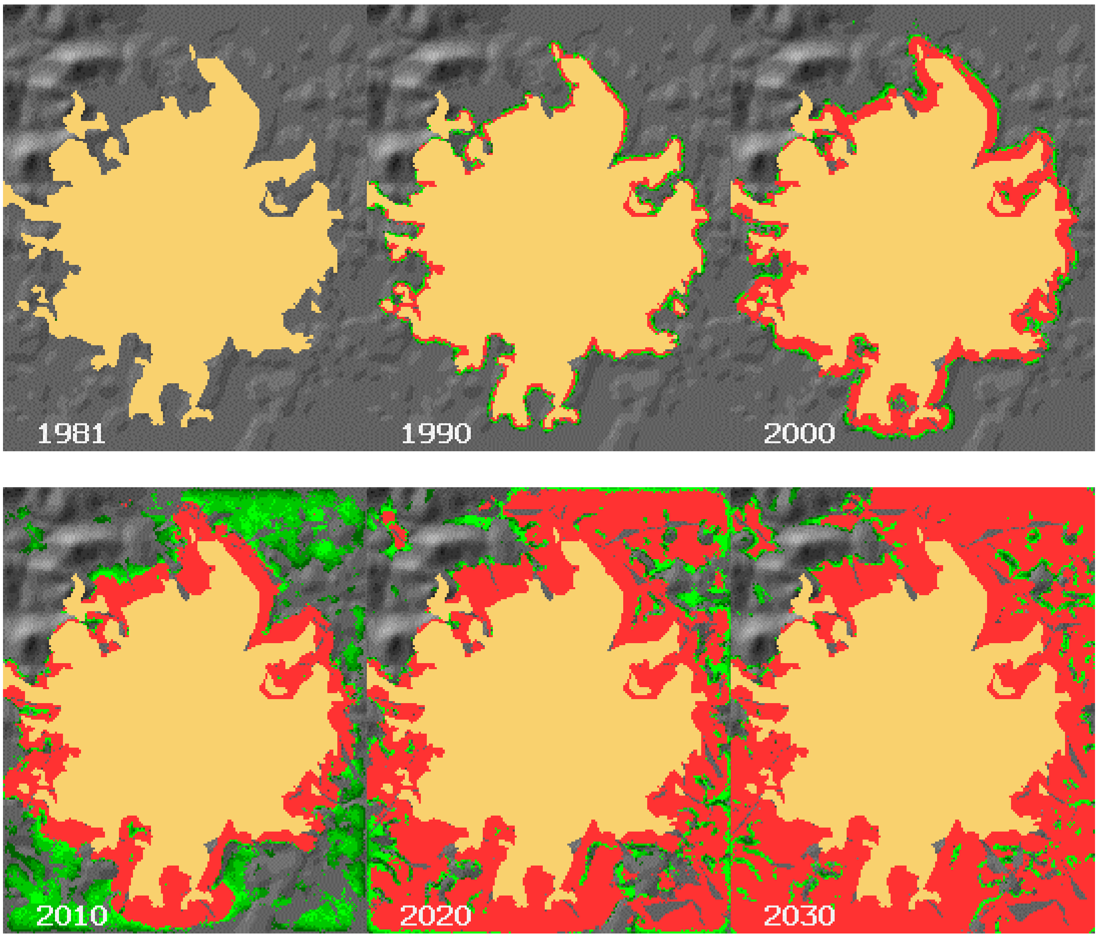


Figure 5.7: Results of the simulation of Yaoundé urban extension: 1981-2030

Each map also shows the simulated year, and a background map for illustration. The first frame (1981) shows the first simulated urban extent. No significant change is noticeable. The rest of the frames show new urbanised areas

[3] Note that for simplicity, clarity and space reasons, map elements such as legend, north arrow and scale bar) are purposely omitted on these maps and the next to follow.

(red) and probabilities (green) of a cell to be urbanised at the next iteration (year), with light green having the highest potentiality to be urbanised and dark green the least potentiality. Grey areas contained cells that have a negligible chance of being urbanised at future iterations. Table 5.5 details the colour scheme finds in simulated images.

Table 5.8: Colour scheme interpretation of simulated maps

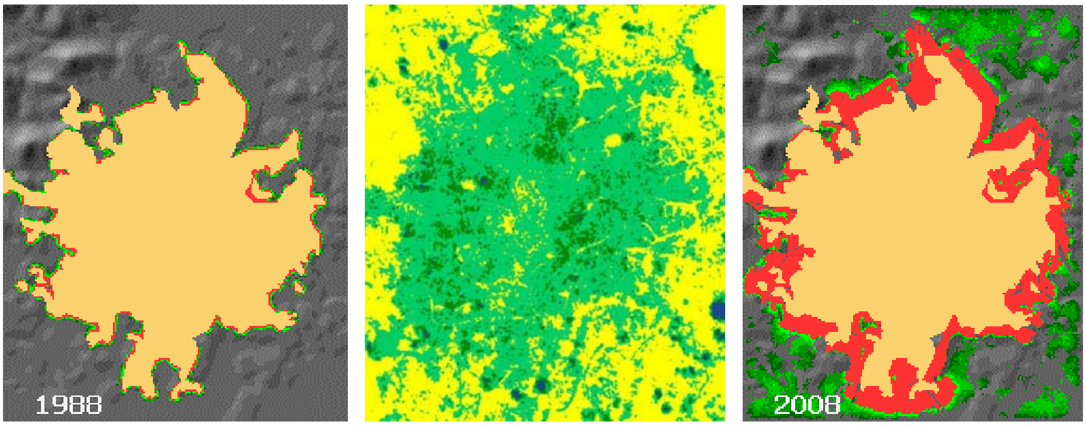
Code	Colour	Description
1		Existing Urban Areas (*urban seed*)
2		-60% Probability of Urbanisation
3		60 - 70% Probability of Urbanisation
4		70 - 80% Probability of Urbanisation
5		80 - 90% Probability of Urbanisation
6		90 - 95% Probability of Urbanisation
7		95 - 100% Probability of Urbanisation
8		Background image

5.4.2 Reliability of the simulation

This section assesses the model's results with the reality or observations of Yaoundé urban growth. Overall, the simulation of Yaoundé's urban area can be described as successful with some defining features. For instance, the simulation reveals the importance of the effect of road attraction on urbanised cells. The urbanisation process, however, is quite slow during the first 15 years, and the boom occurs half way through the simulation time, and is especially evident during the last 15 years of the prediction period. Similarly, in the north-west section of the Yaoundé map, the probability to urbanise emerges in the year 2006 with a new urbanised centre starting to form and cluster five years later.

The simulated urban area also spreads without discrimination to the surrounding area. This is due to the neighbourhood properties of the cellular automata embedded into the model. In addition, slope areas, such as the northwestern part of the city, demonstrate some resistance to urbanisation at the early stage of the simulation, and will progressively be colonised as the developable area diminishes. The slope effect is also reflected in the rapid rate of urbanisation in the monotonous terrain such as in the south and northeastern parts of the image. A satellite image improves the visual comparison between the simulated map and the reality on the ground.

A landsat thematic mapper (TM) image of Yaoundé was used to test the best-fit and the realism of the simulation of the model. A 1988 landsat TM image of Yaoundé was purchased from the United States Geological Survey (USGS). The image was rectified, georeferenced, and resampled at 30 m to conform to the input records used for the simulation. Bands 4, 3 and 2 were then combined to produce a classified urban land use (Sietchiping, 2003). The classified urban image, highlighting urban and non-urban space, was then used to verify the realistic trend and simulation products of UGM. Figure 5.8 illustrates the comparison of the classified remote sensed image of Yaoundé (1988) with simulated extension suggested by the urban growth model at two instances, 1988 and 2008.



a. Simulated map: 1988 b. Landsat image: 1988 c. Simulated map: 2008

Figure 5.8: Visual comparison of simulated maps and a landsat image of Yaoundé

The visual comparison of predicted growth and real urban extension in 1988 reveals some discrepancies in the simulated years. For example, the comparison of simulated growth (UGM) with real expansion in 1988 (landsat image) shows that the simulation urban growth did not exactly match the spatial expansion of Yaoundé (Sietchiping, 2003a). Considering the projected maps, it appears that the first ten years of the simulation produced very little change, while between 2020 and 2030, the spatial expansion was very fast (boom). Due to the fluctuation of the growth rate, the simulated dates did not correspond to the real patterns. There was at least 13 years difference between the suggested date and the possible matching period.

The simulation products pointed to the fact that the spatial expansion of Yaoundé was mostly influenced by the physical landscape and the road networks. It is therefore fair to say that in UGM2.1, *slope* and *road* are the main driving forces behind urban growth. This assumption was verified in the case of Yaoundé, where the overall simulated urban areas corresponded to the general pattern of the city growth, despite the year difference. To further illustrate the importance of road and topography, the calibration and simulation have highlighted the influence of the road network on the overall expansion of Yaoundé, especially along the main road directions northeast and south of the city. Since the Yaoundé model did not gauge road accessibility, the road gravity assumption was defined by the function of connectivity. In Yaoundé, new urban developments tend to be influenced by accessibility to road and topography. For instance, moderate slope at the south and east of the map, were the earliest areas to be urbanised by the model, and in reality, they constitute one of the most dynamic urban fringe developments in Yaoundé. On the other hand, the mountainous areas in the western part of the map were least attractive to urbanisation. The hilly terrain encountered in this section of the city largely explains the slow spatial extension. Therefore, as postulated by the model, the simulation was sensitive to the slope resistance and road gravity factors.

The model also performed well in reproducing the patterns and clustering tendency of Yaoundé's growth. That is, the spread of urban areas could be simulated with reasonable accuracy. Even though, the simulation was misled by the neighbourhood effect of the cellular automata and the historical calibration approach adopted by UGM, the model picked the general form and tendency of Yaoundé's spatial expansion. Accordingly, the dispersion function defined by the spontaneous growth, performed as expected by the model. Section 5.5 discusses the possibility of implementing UGM to simulate informal settlements in LDC.

5.5 Discussion and conclusions

The aim of this Chapter was to apply UGM to predict the future expansion urban area in Yaoundé, Cameroon. Datasets of Yaoundé were prepared according to UGM conventions to investigate probable spatial urbanisation. Considering modelling and simulation as an abstraction of the real world, the results of the simulation can be considered to be satisfactory. For instance, multi-date images produced were used to enhance the visualisation of urban dynamics. In doing so, the model has provided a good opportunity to develop a visual animation medium (or movie) of the simulation products, which substantially adds value to the representation of urban systems.

There were a number of difficulties that emerged during the implementation of the UGM on Yaoundé. For instance, preparing datasets for the urban growth model was a time-consuming task. Just as GIS and CA are loosely coupled within UGM, the preparation of datasets involved a vast range of programs and software outside the UGM program. Great care and patience must be taken to achieve qualitative and quantitative input files (to be used during the calibrations), especially during the preparation phase and when switching from one program to another. Whilst the procedure was facilitated by the instructions available at the UGM website[4], calibrations within UGM used thousands of iterations, and thus ran for several hours on a high-speed computer. In the case of the Yaoundé urban growth model, calibrations were executed during the weekend (from Friday to Monday) using up to 90 % of the memory, then continued during working hours on *renice* (low-priority) mode on a Solaris machine. The fact that UGM2.1 runs only on UNIX machines constrains the user by limiting access to the appropriate terminal. It also means that the user has to learn how to operate the UNIX system[5]. Similarly, the output files were exported to different programs for further analysis that created many backward and forward operations between SUN and PC terminals, using *file transfer protocol* (ftp). On some occasions, the program crashed and the operation had to be cancelled and started all over again which added to the overall timeframe.

Another issue that emerged was the reliability of UGM's assumptions. Some of the UGM assumptions proved theoretically questionable, especially for cities in LDC. While urban growth rules were, for example, controlled by physical and environmental factors such as topography, social considerations were not part of the growth scenario. Moreover, input factors incorporated into the model were not sufficiently and theoretically explicit enough to sustain the urban dynamics perspectives. This is because UGM implements an urban theory that ignores other components of urban dynamics such as socio-economic behaviour. As such, the

[4] http://www.ncgia.ucsb.edu/projects/gig/index.html (Accessed 16/11/03)

[5] The later improved version of the UGM 2.1 (known as SLEUTH-Slope, Landuse, Exclusion, Urban extent, Transportation and Hillshade), now runs on an *Intel* based PC using the cygwin UNIX emulation software. Such platform versatility was not available when the UGM was implemented in this research.

model identifies four factors of urban growth (road network, past urban spread, slope terrain and non-urbanisable areas), and the future expansion of the city is correlated with this historical growth path. Even here, only two factors (road and slope) effectively influenced the urban expansion. This conception of urban changes is not sufficient to extrapolate and track the constant mutation of urban systems and especially informal settlements, because emergent behaviour or modifications cannot affect the growth rules or patterns. This urban theory vacuum in UGM, suggests that UGM would be more appropriate for environmental change modelling than urban dynamics (Arthur *et al*., 2000; Pontius Jr., 2000; Pontius Jr. & Schneider; 2001).

As far as urban dynamics studies are concerned, the type of input parameters in UGM could also be questionable. The topographical input factors for growth scenarios —for instance, the importance of topography relative to social factors— are over-emphasized. Other researchers have articulated the importance of integration of socio-economical parameters into dynamic models. Varanka (2001), for example, echoes the voice of urban ecologists that "…if system change is to be cumulative, it is necessary that culture, population, territory, and organization all advance together" (Berry & Kasarda, 1977, p.15). Considering the significance of socio-cultural and economic factors in the emergence and growth of IS, it is critical that urban dynamics models find means to include both physical and socio-economic considerations into the simulation process.

A further limitation of the UGM model related to the flexibility and number of parameters the program can accommodate. In that regard, only such aspects as best-fit and scores of input parameters (road, slope, and urban) could be modified. Furthermore, the overall number and quality of these input files were set and could not be modified. This meant that only the five known and defined historical and topographic factors could be used to determine urban growth in any city, which would be unlikely to succeed, given the conditions pertaining to the growth of IS. Likewise, the *Monte Carlo* approach does not allow alternative outcomes during the prediction because the calibration is based on historical patterns. That is, the model is not sensitive to change introduced sometime in the future (simulated images), because UGM draws information from known historical patterns or rule-based models only.

Finally, in the UGM, the state of the cell at the next iteration is derived both from the actual growth process and the historical state of the adjacent cells or space. However, it is well known that the CA neighbourhood could be expanded to include a larger neighbourhood (Batty & Xie, 1994; White *et al.,* 1997). This extension of CA neighbourhoods remains a contentious issue because some researchers (especially in computer science) argue that only 4-cell and 8-cell 2-Dimensional could be considered as a CA model.

From these limitations, it could be argued that the application of UGM2.1 to explore Yaoundé's urban expansion replicated an historical trend by using the data and factors available and required by the model. It failed, however, to extrapolate future possible conditions that might arise simultaneously from the urban system's evolution and socio-economic behaviour. This constitutes an important shortcoming given the role of socio-economic and cultural factors in the urbanisation processes in LDC. The UGM program is therefore not suitable for simulating more than two urban or zoning classes, nor for modelling a mutation of planned urban cells to unplanned cells or *vice versa*. Likewise, the single excluded layer is static and changes cannot be introduced at a later stage of the simulation. So, only immutable features (stable lakes, rivers and sea surfaces) can be considered as excluded. In the case of Yaoundé for instance, informal settlements (IS) gradually gain ground along riverbanks, lakes or parklands considered as unbuilt areas, as well as any vacant land.

In sum, this means the model is less likely to produce reasonable development scenarios in LDC, unless subsequent changes are made in the source codes. As already suggested, changes can only be implemented on the coefficients, rather than the choice of input files. This constitutes a major limitation for the UGM as a possible option for building a flexible and informed urban dynamics model for LDC.

Despite the solid conceptual framework, the UGM is theoretically and practically less effective in simulating IS emergence and growth in LDC context. For example, the theoretical foundations of urban extension in planned cities in developed countries differ from the LDC conditions (see Chapter Two). Similarly, the UGM does not take into consideration socio-economic factors that significantly contribute to the growth of IS. It is therefore clear that there is a need to develop a generic model that can help investigate the emergence and expansion of IS in LDC.

The next Chapter will discuss how an integrated GIS and CA conceptual framework similar to, but also distinct from the UGM program, can provide an alternative Informal Settlement Growth Model (ISGM), and thus address the limitations of urban dynamics models.

Chapter 6

A proposed informal settlement growth model

6.1 Introduction

Urban dynamics models are available for cities in developed countries and their review has shown that to some extent they can be adapted to model urban growth in Less Developed Countries (LDC), but not uncontrolled settlements. While informal settlements (IS) are growing fast, very little attention is paid to approaches and tools for exploring and informing their dynamics. It is also clear that governments and urban planners have a very limited knowledge of the possible future directions of IS, thereby rendering ineffective the current management of uncontrolled settlements in cities in LDC.

Research shows that IS are now widespread (an average of 60% of urban settlements in LDC are informal) and constitute one of the most dominant urbanisation features in LDC (UN-Habitat, 2003). Yet the representation and forecasting of the probable expansion of IS has been largely neglected in urban planning schemes (Chapters Four and Five). Chapter Two reviewed different measures and attempts to curb the expansion of IS, and demonstrated that these measures barely achieved their aims partly because decision makers and urban planners do not possess the tools to explore the expansion of IS. Planning strategies and policies are developed as a reaction to the existence of IS, rather than proactive measures based upon a clear understanding of the process and the behaviour of the system.

In this Chapter, I postulate that by predicting where probable IS will occur over a certain time period, based on known variables (except future transportation networks, markets and places of worship), it is possible to better design and implement efficient management strategies that will overcome some of the shortcomings of IS. This then raises several important questions. What tools can be utilised for such a process and how they can be used to support the decision-making dynamics? How can stakeholders be encouraged to manage IS development challenges using a continuously enriched body of IS mechanisms knowledge, instead of proposing ready-made expert solutions?

This research uses an experimental approach in which, based on a shared conception of the known conditions pertaining to the emergence and expansion of IS, along with the evolution of past and current situations, the urban stakeholders (urban planner, decision maker, IS dweller, infrastructure and services providers) can use a model to engage in a process that can incorporate both prediction and simulation. There are numerous advantages in using prediction and simulation in IS management.

One of the purposes of using simulation and prediction in the model is to test some IS hypotheses and contribute to answering some *what if?* questions (contingent predictions) using different parameters and scenarios. Thus, this Chapter discusses how an IS model can be constructed, its different modules (structure) and functions, how to test possible scenarios by changing variables and their interrelationship.

This Chapter proposes an *Informal Settlement Growth Model* (ISGM) based upon the conceptual framework of Geographic Information Systems (GIS) and cellular automata (CA) discussed in Chapter Three. The ISGM is specifically aiming to:

- enrich the discourse around urban dynamics and the prediction of IS expansion in LDC cities;
- accompany and support the urban planning decision-making process;
- provide a framework for discussion amongst urban stakeholders on how to handle the rapid expansion of IS;
- simulate spatio-temporal systems behaviour of IS under various conditions and scenarios ;
- enable new discoveries about IS functioning by means of computer based experiments.

To achieve these objectives, a series of GIS maps and databases of a case study city (Yaoundé) are developed, and a CA model with a *Visual Basic (VB) macro* is programmed. The CA model is loosely coupled with a GIS interface to model IS expansion. Among other functions, the VB macro transforms the maps in the GIS database into *ASCII* (American Standard Code for Information

Interchange) formats, records and performs CA-like rules, and then links the output of the simulation to a GIS interface.

The first section of this Chapter presents how the ISGM model was conceptualised and built. The main features of the model are also highlighted. Section two explains the ISGM Visual Basic macro. Section three discusses the data requirements for the model. The data preparation for the model and the selection of the variables for data input are also discussed in this section. Section four presents a case study city (Yaoundé, Cameroon) where the ISGM is tested. Section five shows some sub-model development, and presents how the model predicts IS. Section six elaborates on the dynamic visualisation of the model outputs.

6.2 Designing the Informal Settlement Growth Model (ISGM)

This section first provides the background to the concepts, assumptions and rules used in the ISGM, and then enumciates how the model was initially configured.

6.2.1 Concepts, Assumptions and Rules

A review of urban dynamics models (Chapter Four) reveals that no existing models could be fully adapted to investigate the rapid expansion of IS. This point was made strongly in Chapter Five. Therefore a flexible model was proposed that would suit the conditions of expansion of IS in LDC.

There are at least three motivations to develop an IS Growth Model (ISGM). Firstly, an ISGM will improve the understanding of the intrinsic behaviour of IS dynamics where formal data is lacking. Secondly, likely future expansion of IS can be explored based on the knowledge of historical expansion, coupled with selected key conditions and parameters underpinning the emergence, existence and expansion of IS (UN-Habitat, 2003). Thirdly, the properties of ISGM, especially its ability to generate different scenarios and parameter weightings, coupled with the opportunity for the user to animate multiple outputs, would make it a useful tool to guide governments and urban stakeholders in their decision making process.

The ISGM draws its origins from the concept, theory and technologies of both cellular automata (CA) and Geographical Information Systems (GIS). The development of the model is inspired by existing urban dynamic models such as those developed by Clarke and Gaydos (1998), Batty *et al*. (1999a; 1999b), and Yeh and Xie (2001). Following the adoption of similar principles, ISGM loosely couples GIS and CA technologies to predict the patterns of emergence and growth of IS. The ISGM takes the approach further by incorporating various GIS data formats (point, line and polygon) to make the modelling process transparent and flexible. The proposed model does this in a number of ways.

On the one hand, the ISGM features the main components of cellular automata such as: lattice or grid space, cells, state, neighbourhood and iteration rules. Specifically, the ISGM is conceived on cellular automata principles whereby the changes operate on a pixel or cell-based grid square space. The multiple states are synchronously updated in discrete time steps according to generic rules. Accordingly, the previous states of the neighbouring cells determine the state of each cell at a given iteration. The ISGM uses *Moore*'s extended neighbourhood and can accommodate an unlimited number of rules. More importantly, the cellular automata developed within ISGM is innovative in the sense that it is considerably relaxed by incorporating functions such as threshold, constraints, probability factors, attraction variables and edge shaping factors.

On the other hand, ISGM uses GIS technology at two critical instances of the operation. First, to prepare data needed for the model (Chapter Five), and secondly to act as the interface to display the results of the simulation. The ISGM provides an option to the user to specify the GIS interface to be used for the output file.

Basically, the ISGM is organised around some general assumptions of IS growth rules that can be fine-tuned to suit local conditions while at the same time, maintaining the general conditions that pertain to the emergence and growth of IS. These assumptions are drawn from the knowledge and discourses on IS discussed in Chapter Two, as well as the CA and GIS approaches. For the Yaoundé simulation, some of the assumptions governing the conditions and behaviour of the model included:

1. The model's space is made up of a two-dimensional matrix of square, equal-sized cells;
2. It accommodates an unlimited amount of input data with the same format and properties;

3. Each layer consists of at least two states (e.g., road and non-road);
4. Each layer is in raster format and each cell has a unique identification number (ID) because changes operate at a cell level;
5. Changes operate only on vacant land on the defined matrix;
6. Cells change according to predefined and homogeneous rules;
7. Changes operates on a 4 x 4 extendable matrix Moore neighbourhood;
8. Each layer has a unique identifier (e.g., water: 20, vacant land: 1). This allows the macro program to read and convert the value of each land use category into *ascii* format, as well as set up the spatial neighbourhood filters in a logical way;
9. The selection of any one cell is random, but any cell across the complete grid can be chosen;
10. If a cell's neighbourhood does not contain at least one IS cell, a new IS cell cannot emerge. This condition prevents IS emerging in an isolated area, and it also generates consolidation of IS patterns;
11. Existing, other land use classes do not change within the model as currently configured, and so IS resulting from the decaying of planned developments is beyond the scope of the ISGM. That is, all new IS occur on vacant land. However, using the same ISGM, Wyatt *et al.* (2002) demonstrated that it is quite possible for an ISGM to take into account the conversion of planned developments into IS;
12. No cell 'dies' after emerging. That is, it evolves and maintains its state. This condition suggests that an IS cell cannot return to its previous state or mutate to another land use type once created. This rule is in line with the spread and consolidation of IS patterns observed within cities where unplanned developments prevail.

Based upon these assumptions, one of the most important conceptual aspects of the ISGM is to develop IS transitional rules. This operation consists of defining CA-like conditions under which the cell should behave on the matrix at each time step. Probabilities are used to do this — that is any new IS cell is generated with a user-defined probability. The probability depends on two conditions: (a) the stages of growth the model is in, and (b) the properties of the surrounding cells (land uses). Specifically:

1. If a vacant cell is located on a high slope, then its probability of becoming an IS cell at the next iteration decreases (*bust* factor);
2. If a vacant cell is located close to (e.g., less than four extended neighbours away from) a road, river, market place, worship place or low slope cell, then its probability of becoming an IS cell increases by a user-defined value (*boost* factor);
3. If a vacant cell is close to both rivers and one or more roads, its probability of becoming an IS cell becomes even greater;
4. The probability of IS emerging on vacant land is either *boosted* or *inhibited* by the type of dominant cultural and ethnic group located within its neighbourhood.

These general rules govern the operation of the Visual Basic macro. Apart from the parameter values that can be modified, the model provides numerous possibilities for fine-tuning the rules so they can be adapted to a specific condition as well as to improve its accuracy.

The GIS and CA concepts, along with these assumptions and probabilities-based rules, serve to frame the proposed model. To be operational, the model underwent several instances of refinement and modification to increase its simulation capacity and test the validity of its assumptions. The next section presents some of the steps used to configure the model.

6.2.2 Initial configurations of the ISGM

Having conceptualised the ISGM at a theoretical level, the next step is its development at the operational level. The VB version of the proposed model is the result of several attempts at using *strong coupling* GIS-CA in an *Idrisi*™ environment.

Initially, various options offered by Idrisi™ software were utilised. In fact, Idrisi™ *32 Release Two* suggested two cellular-like operations: an exclusive cellular automata operation known as *cellaton*, and blended cellular automata with *Markov* operation otherwise known as *CA_Markov*.

The cellaton operation proposes a user-defined *filter* (conceived here as the *rules*) and a *reclassification* file to operate the CA principles such as *neighbourhood* effect and the *states*. The user can then use the filter and the *reclass file* module in Idrisi^{TM}, to run a user-defined number of iterations on a classified (land use) map. The cellaton operation in Idrisi^{TM} has the advantage of an unlimited number of definitional rules, states and iteration outputs, thus making it an attractive platform to interact with and to display the output of a cellular automaton program. The cellaton process was applied on a classified map of Yaoundé, the case study site. A number of limitations were noted. From the application, it appears that the CA option offered by Idrisi^{TM} is basic and acts as a 'black box'[1]. The user has limited opportunities to control the behaviour of the simulation and cannot amend it to accommodate multiple layers. It became evident that the user could not customise the model to a specific context. Similarly, the input parameters could not be weighted to reflect the importance of each variable. Therefore, the results were not satisfactory.

Afterwards a combination of cellular automata and *Markov* classification, known in *Idrisi^{TM}* as CA_Markov was tested. The CA_Markov combines the *Multievaluation Criteria Evaluation* (MCE) and *Multi-Objective Land Allocation* (MOLA) routines to assess the suitability of a land category and then assess the allocation of changes based on the weight of each variable on a single input layer. The concept was appealing because, unlike cellaton, the CA_Markov operation offers the advantage of being able to assign the level of importance to each input variable and then observe the changes. It soon became apparent that the CA_Markov procedure in Idrisi^{TM} remains at the development stage, and therefore could not offer any reasonable result. Moreover, the CA_Markov could not accommodate multiple layers. To efficiently address these limitations, a Visual Basic programme was written that would be flexible enough to capture the complexity of IS. The next section will present the main modules of the ISGM written in Visual Basic macro.

6.3 Writing the ISGM with *Visual Basic* Macro

A range of programming languages, including Java, C and Visual Basic, could have been used to write the ISGM. Java and C (and C++) were identified as powerful

[1] In modelling, the term '*black box*' is used, in opposition to '*white box*'. White box denotes the transparency, accessibility and the ability to actually modify the source codes of a modelling programme to suit individual needs.

programming languages, but they require a level of programming skills that were beyond the capabilities of the author. Due to limited familiarity with these two languages and limited support from staff members who were not familiar with the *Java* and *C* languages, it was concluded that gaining proficiency in *Java* and *C* would require an extended period of time. By contrast, the Visual Basic (VB) macro language is reasonably easy to learn, write and modify. Moreover, support staff members were available who could advise in VB programming. More importantly, VB has the ability to call the functions (and thus integrate wider) mapping and GIS software such as Idrisi™. Visual Basic is also a cross platform language, appropriate for prototyping (e.g., using macro), and can be supported by almost any GIS environment. By adopting compact codes that have multiple functions, the VB macro uses less computing space and runs faster. These corrective measures were adopted when writing the ISGM VB macro to mimic CA-like behaviour. These functionalities and abilities of VB will thus enhance the usefulness, flexibility, portability and cost of the proposed IS growth model.

The CA-like behaviour of the ISGM is written in Excel™ macro language, from the same family as Microsoft Visual Basic. Unlike other CA-like models, the ISGM is *transparent* or a 'white box' in the sense that one can access and modify the line commands, record new macros, and check the consistency of the ISGM codes. The Macro language code for the ISGM is a standalone programme that utilises a GIS interface to display the results of the application. For this application, Idrisi™ was used as the display interface, because of its ability to preserve the properties of the input and output files. Similarly, Idrisi™ offers the possibility of calibrating, validating and statistically comparing the output of the simulation (if the last option was adopted).

The CA macro language developed for the ISGM is fully explanatory. A full draft of a version of the ISGM VB macro is available in appendix 8 and on the CD attached at the back of this thesis. Figure 6.1 provides a simplified representation of the five main modules of the ISGM.

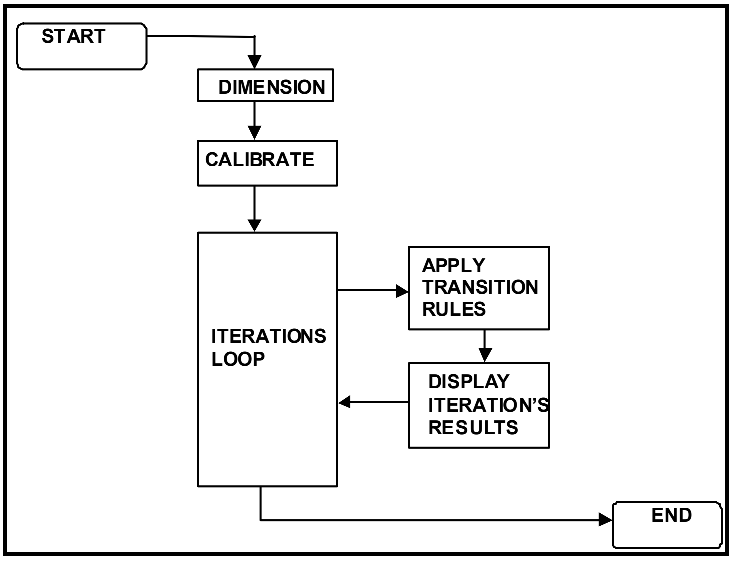


Figure 6.1: ISGM: summary of the five main modules

The following paragraphs explain step by step how the macro works and the execution of the main modules of the model. The ISGM is divided into five main modules: dimension module, calibration, iteration loops, transitional rules, and display of simulation results as illustrated in figure 6.2.

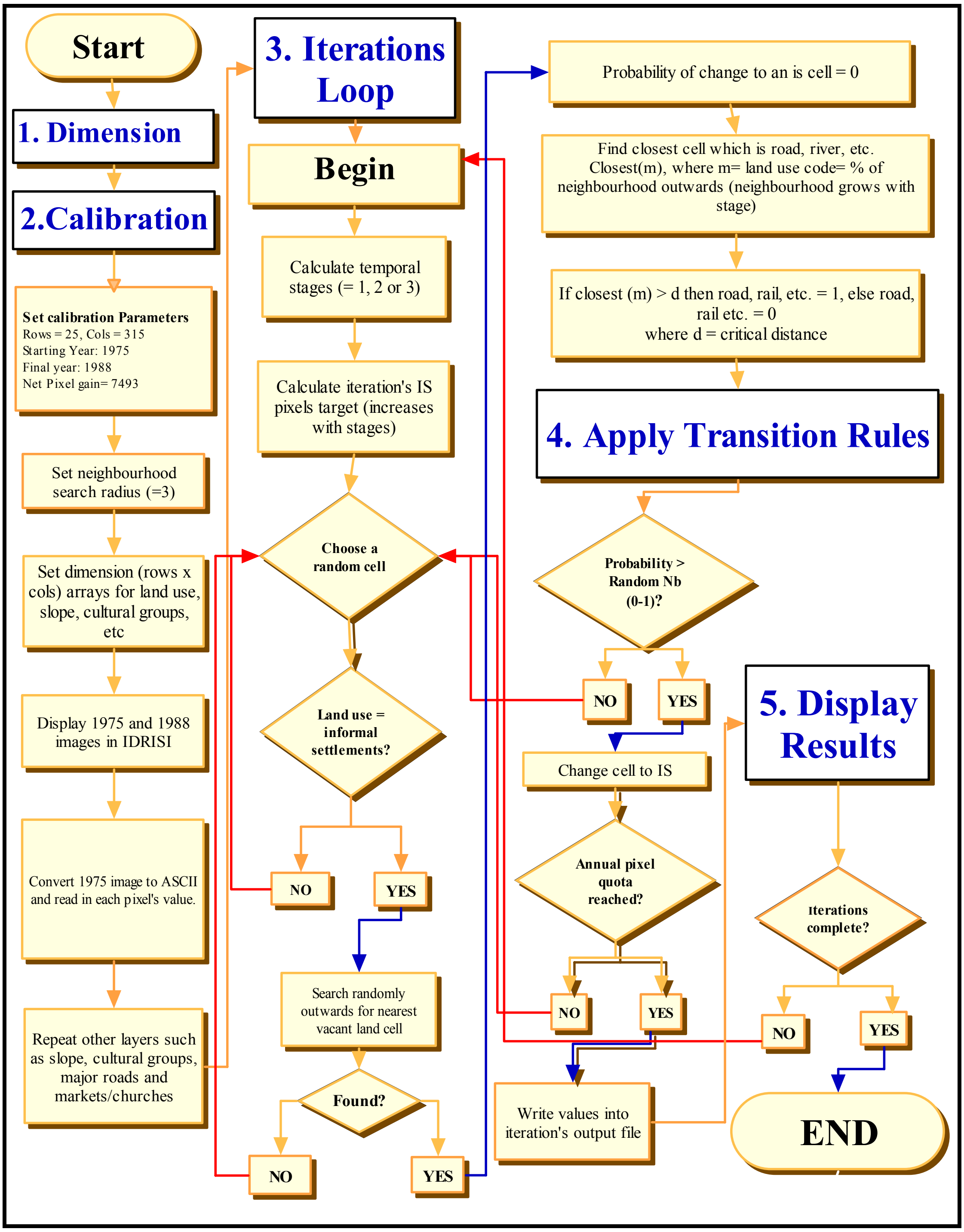


Figure 6.2: Sequence of operations and detailed flowchart of Informal Settlement Growth Model execution

6.3.1 Setting the dimensions of the ISGM

The dimension module declares and defines the conditions of operations of each variable. Two statements are defined in this section. The first statement stipulates the nature of the *CA VB macro*. The second statement lists the files used in the model and defines the type of files compatible with the model, as well as the identification (ID) of each land use category used in the model. The next section deals with the model calibration module in ISGM.

6.3.2 Calibration of ISGM

The second module of the ISGM sets the calibration method and the model parameters. The user defines five main parameters: the *image map* (rows and columns), the *base_ year*, the number of iterations, the neighbourhood size and the nett_ pixel_ gain. **First**, the image map parameter sets the dimensions of the ISGM lattice in a number of columns and rows. **Secondly**, the user defines the starting year for the calibration. **Thirdly**, the user declares the number of iterations. Here the iteration refers to the number of time segments (in this case years) into which the period, between the *base_year* and the final year, will be divided. The number of iterations can also be set to coincide with the number of simulated output map layers. **Fourthly**, the user defines the size of neighbourhoods for the looping at different stages. The dimension of each encoded input layer is also set. ***Finally***, the ISGM calibration module requires the user to state the nett_pixel_gain value, which is the number of additional IS pixels for the simulated class between the base_year and the target_year (last iteration). The ideal value is obtained by subtracting the number of the IS cells of the base year from the number of IS cells of the final year. The nett_pixel_gain value can however, be modified to simulate different scenarios.

Additionally, the macro sets the conditions under which the nett_pixel_gain value will be equally distributed in relation to the number of iterations, known here as the *annual_target*. The annual_target therefore, is a constant that divides the expected number of new IS cells by the set increment or iterations. The user can, however, add extra line commands to *bust* or *boost* the pixel allocations according to specific years, or to set the *annual_target* according to the growth rate or different stages of growth. For this application, the *annual_target* is refined to the number of development stages (this model defines three stages of IS development).

When the calibration parameters have been declared and verified, the macro can now proceed to perform the following three simulation steps. The first operation consists of locating the user-defined GIS environment in which the output of the future operations will be displayed. It is recommended that all files or layers are located in the same directory. When using Idrisi™, the working directory is defined as a configuration parameter within the Idrisi^{TM} programme. The macro retrieves the specified working directory and uses it as the location to access the input files (and later store the outputs).

At the next step, the macro displays the base and final year on the nominated GIS interface, with the user defined colour palette. It is recommended that a colour palette be created to clearly define and emphasise the most important aspects of the map, which the default colour palette in many GIS interfaces cannot guarantee.

The final step automatically converts the base_map into ascii file format so that the results of the simulation will be recorded as the values, therefore making them readable from the *Macro* programming code. After the base_year map is converted into ascii format, the macro can then read in values. All the input files or layers (except the target_year) are also converted into ascii and their values read.

It is worth mentioning that the ISGM underwent a series of improvements. Commands and functionalities have been gradually added to the model. One of these improvements was to automate the conversion from raster image to ascii format. Previous versions of the model were not automated and the format conversion was operated manually. The VB ISGM has run approximately 38 versions. When all the map parameters are successfully verified, set, displayed, converted and read in ascii format, the macro then moves to run the iteration loops.

6.3.3 Iterations looping in ISGM

The ISGM runs five loops within the map lattice. First, the **iterations loop** checks the user-defined number of iterations, which corresponds to the number of different temporal growth stages. This is a master loop, which controls the other loops. The iteration loop will also execute two other functions: (a) verify the conditions to change from a vacant cell to an IS cell; and (b) check the quota for each iteration and record the value into the output file. The transitional rule module changes those vacant cells that satisfy the rules and the defined probabilities into new IS cells. The new IS cell created during this iteration is then added to the count to update the nett_pixel_gain quota. Additionally, the transitional rule module verifies the stock of new IS cells created during the iteration. If the quota is not reached, the macro runs over the iteration loops to locate an eligible random cell, to which rules and probabilities will also be applied. Alternatively, if the iteration quota is reached, the macro then proceeds to record the values of the iteration.

After each iteration, the **annual change loop** resets the changes to zero. When the annual iteration is set to zero, the **random cell loop** continuously checks the map to locate a random cell starting from the first column, and then the first row. When a random cell is not found, the **non-changing cell loop** sends the operation back to the random cell loop. Otherwise, the macro proceeds to search for the cells at the edge (neighbourhood) of an existing IS cell. This operation prevents IS cells from emerging in proximity to other land use classes, unless they are surrounded by at least one IS cell. Finally, the **neighbourhood loop** searches for changeable cells at the proximity of all the land use categories present in the database, based on the user-predefined number of the neighbourhood.

It is worth mentioning that there is no limitation on the size of the neighbourhood. A bigger neighbourhood, however, will increase the running time of the macro. A two-bands neighbourhood for instance, randomly examines the properties (changeable or non-changeable) of each pixel, and counts the number of pixels within each land use category to make one of the following two decisions. If the cell is not an IS cell, another random cell is selected. If the randomly selected cell is an IS cell, then the macro proceeds to search for the properties of the cell adjacent to the IS cell. If the cell adjacent to the IS cell is not a vacant cell (changeable cell), then another random cell is selected. However, if a vacant cell is found in the neighbourhood of the IS cell, the macro then moves to identify the land use categories in the neighbourhood to set the probability of change. That is, the probability that a vacant cell will be converted to an IS cell increases not only with the number of 'trigger' land use categories (for instance, major road, low slope and market places) in the neighbourhood, but it also increases according to their proximity and frequency. When the macro has checked the properties of the land use categories surrounding the selected cell, it then moves to implement the respective transitional rules.

6.3.4 Executing transitional rules in ISGM

The rule module of the ISGM is designed to execute the transitional rules and to check the probability of change. It is worth remarking that the ISGM is based on multiple criteria and categories that define the conditions and probabilities under which an IS cell can be created. Combining *If statements* (conditional statements) with the probabilities provides the flexibility to include an unlimited number of rules that will govern the transition from one land use category to another. That is, the application of transitional rules and their probabilities are carried out almost simultaneously. In ISGM, the definition of rules ranges from simple to complex, and can incorporate multiple categories and probabilities. Only the imagination of the user can limit the number of transitional rules. There are, however, two points that are worth mentioning.

On the one hand, the probabilities for each factor or parameter reflect the relative likelihood of occurrence for single or multiple conditions. There are two levels of probability: general and local. General probability equally applies to the entire lattice, stages and parameters, whereas local probability declares the condition for a specific rule to be implemented. Each of these probabilities is ranged from less than 0 (no chance) to 1 or 100 (perfect chance). If the probability is equal to or less than 0, then the macro proceeds to choose another random cell. If the contrary is true, the macro will then change the vacant cell to an IS cell, if the iteration quota has not yet been reached. The ISGM also implements positive and negative weights of evidence parameters, which are associated with the probability. The positive weight of evidence or *boost* refers to the attractiveness of the variable to the IS. The greater the value of the boost factor, the greater the likelihood for the emergence of an IS cell in the neighbourhood. For instance, to test a road-driven ISGM, the probability boost of *roads* is increased to the maximum, whereas the weight of other factors is significantly reduced or ignored.

On the other hand, the negative weight of evidence or boost factor indicates the repulsiveness of the variable towards IS. The *boost* and *bust* factors are used to establish the transition probabilities, based upon the CA principles, namely the state and the neighbours.

The rule module executes single or multiple rules. One of the limits of multiply encoding, however, is that the last probability always overwrites the previous probabilities. This pitfall can be corrected by adding probabilities for each variable. By doing so, it is relatively easy to weight the contribution of each variable to the model, unlike when using a simple *Markov model* (also known as 'weights of evidence' based on Demster-Shaeffer theory), where the probability does not change over time. That is, the ISGM performs a random selection of suitable IS cells and their probabilities are altered over three stages. In total, 10 general rules are executed in this module, looking at the probability of, and the proximity to the following variables: major roads, slope, cultural groups, river, market place, place of worship, rail line, airport runway, proposed ring road, and excluded areas. To simulate a road-based ISGM for instance, the *general probability* is set at 0, and then the *local probability* for *roads* is set at 1 (or 100%), and the rest of the attribute rules present in the model are ignored. Similarly, a combination of variables in the rules module leads to the development of an ISGM based on probabilities of each input variable to trigger the emergence of IS.

One of the advantages of using VB macro is that the user can enter the program code and implement either one or an unlimited number of probabilities and rules. The programme code that implements the probability or rule counts can be activated by removing the comment marks, or ignored by reinstating them. The application of different rules and probabilities produces a range of results that are defined and specified in the display module of the macro.

Finally, the transitional rule module registers the total values of changes occurring during the iteration into the ascii output file. The output file for the iteration is now updated and the macro can display the results of the simulation.

6.3.5 Display and visualisation of ISGM results

This module sets the overall outcome and displays the results of the simulation. More specifically, when the simulated maps are created under the conditions described above, the output is recorded and ready to be displayed. The proposed model gives the option to specify the format, the size of the map, the number of output maps, and the heading for each map. The generated maps are converted to the user-defined display map format and stored in the designated working directory.

Unlike other urban dynamics models (except the UGM), the ISGM offers the flexible and automatic display of the outcome of the simulations (as they become available) in different formats, such as the default GIS environment that was used, or one of a range of graphic formats like *GIF, JPEG*, *BMP*, and *TIFF*. Similarly, the user can choose to alter the size of the input layers or define new format sizes for the simulated maps. The simulated maps can also be displayed on a user-defined colour palette. Additionally, the user has the option to declare which iteration will be displayed (for instance, all results, every second, third, and so on).

The macro also has a provision to delete irrelevant maps, and to adjust the IS quota if the programme is encountering difficulties. An additional command line adds a user-defined time frame (in this case annual change) and the title on top of each simulated map. The final command automatically displays the simulated maps onto the specified GIS interface (in this case Idrisi™). The entire code of the ISGM is available in appendix 8.

6.4 Preparing the data to test the model

This section outlines the test case of the Informal Settlement Growth Model presented in the previous sections, and applies it to a real world situation. The first part introduces the test environment, Yaoundé, and briefly describes the processes of IS growth it has experienced. The second part presents the data used for the simulation, and the data preparation.

6.4.1 Location and urbanisation processes in Yaoundé

Yaoundé, the second largest city (after Douala) and capital city of Cameroon in Central Africa (figure 6.3) was chosen to test the model.

Figure 6.3 Location of Yaoundé, Cameroon in Central Africa
Source: http://www.map.freegk.com/cameroon/cameroon.php

Yaoundé is selected for two main reasons. Firstly, the population of Yaoundé has drastically and consistently increased during the last fifty years. Yaoundé emerged from successive colonial 'masters' who 'took turns' in ruling Cameroon between the 19th and 20th century. The Germans 'founded' Yaoundé in 1889 initially as a military post, which was later transformed to the capital of the French administered Cameroon until the independence of the country in 1960. Up to the Second World War, Yaoundé was considered as a village with little urban infrastructure or urban characteristics (Franqueville, 1984; World Bank, 1995). From the 1950s, the population of Yaoundé rapidly grew, partially due to rural migration (the civil war or independence war created insecurity in rural areas between 1950 and 1960), and the emerging urban patterns and services of the new political capital. Figure 6.4 shows how the population of Yaoundé, grew from 59,000 in 1956 to 300,000 in 1976 to an estimated 1.6 million in 2003 (MINPAT, 1993; Bopda, 2003).

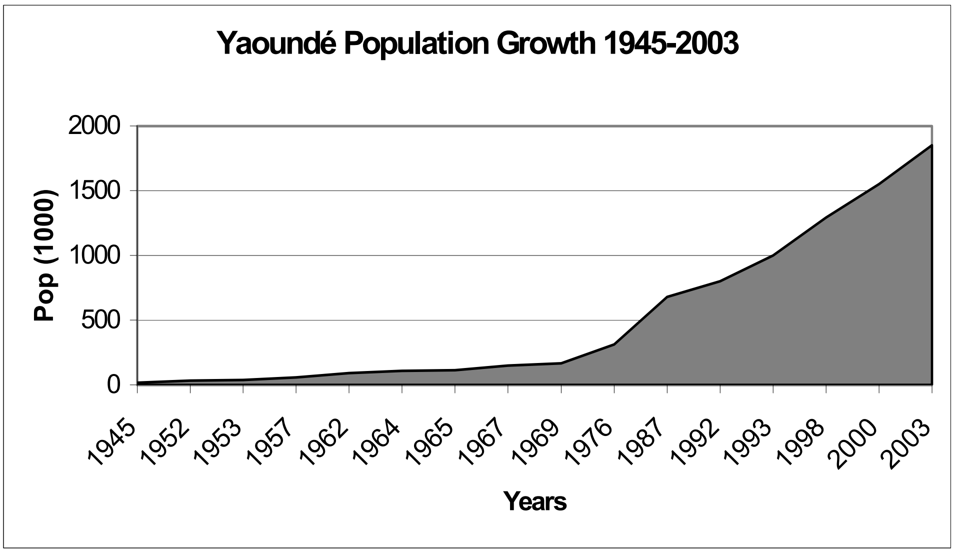


Figure 6.4 Population growth of Yaoundé, 1926-2003
Source: Franqueville, 1984; MINPAT, 1993; and Bopda, 2003

For the past fifty years, the population growth rate of Yaoundé has been one of the highest found in African cities. The growth rate was above 9% per annum between 1950 and 1990, and averaged 7.5% between 1980 and 1990. Since then the population of Yaoundé has continued to grow at an annual rate of at least 6.5% (MINUH, 1990; Kengne & Bopda, 2000; Bopda, 2003).

Secondly, the urban space of Yaoundé has increased almost tenfold in less than five decades (figure 6.5). With an urban area of about 1,500 ha in 1956, Yaoundé covered 5,300 ha in 1980 and about 14,000 ha in 2000 (Franqueville, 1984; Sietchiping, 2003a).

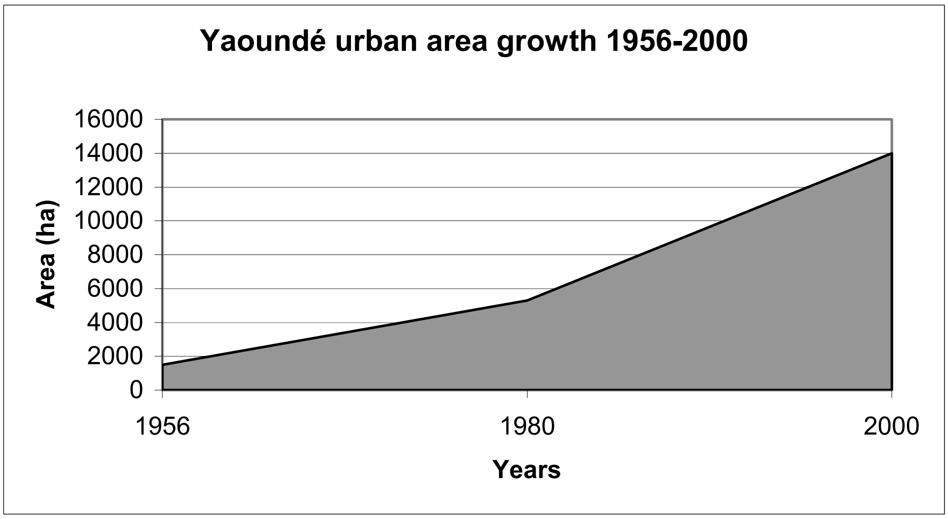


Figure 6.5 Yaoundé urban area growth: 1956-2000
Source: Franqueville, 1984; MINPAT, 1993 ; Tonyé *et al.*, 2000 ; and Sietchiping, 2003a

It therefore apparent that the urbanisation process in Yaoundé is dominated by two main factors: high population growth and the *informalisation* of urban space. One of the most noticeable features of Yaoundé urban landscapes is the long tradition of the predominance of IS (Franqueville, 1984). Figure 6.6 shows the evolution of IS in Yaoundé between 1956 and 1974.

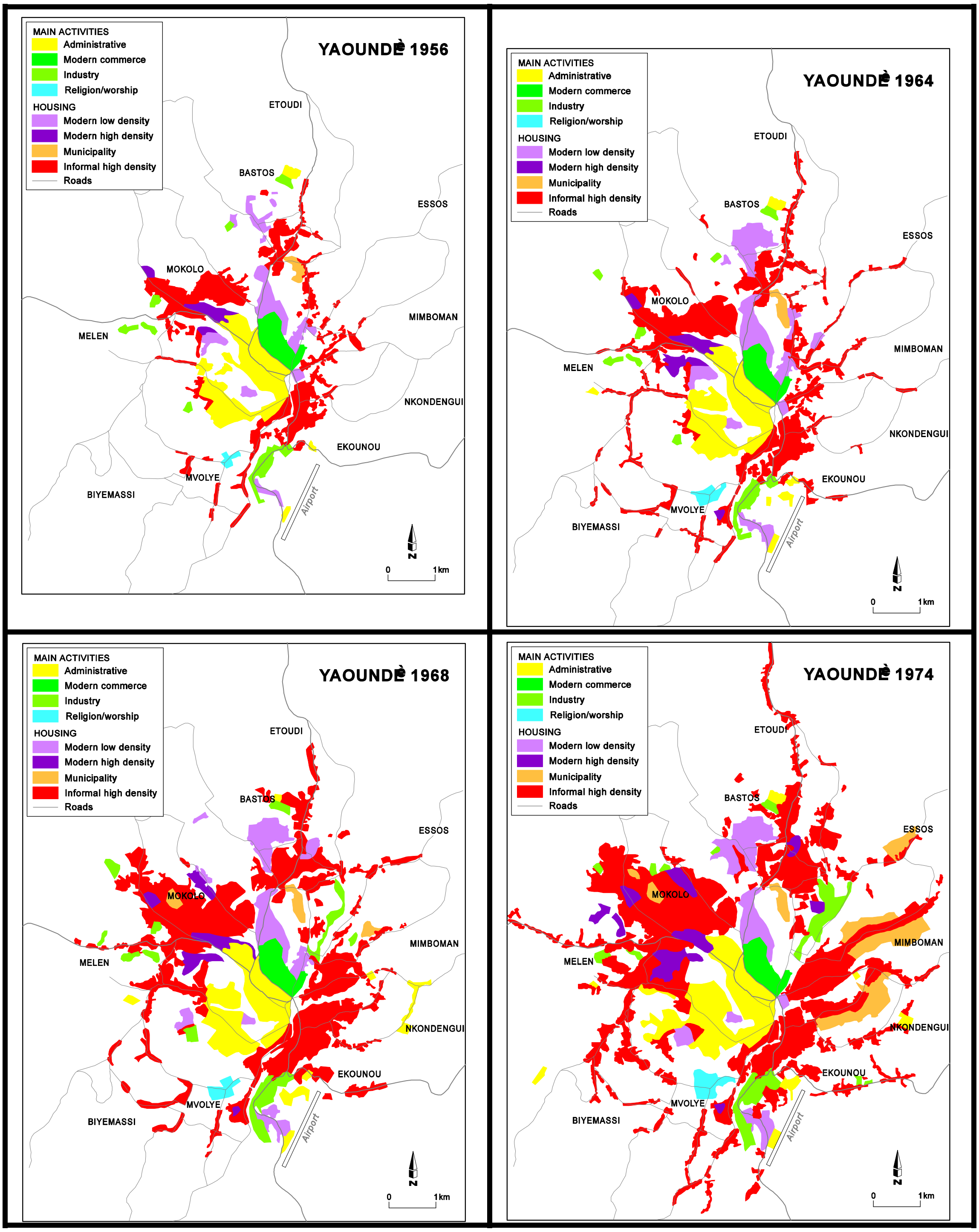


Figure 6.6 Evolution of informal settlement patterns in Yaoundé: 1956-1974
Source: MINUH, 1990

Recent studies show that in Yaoundé, 80% of settlements are informal and accommodate about 85% of city dwellers (MINUH, 1990; Pettang *et al*., 1995; Sietchiping, 2001b; Bopda, 2003). Similarly, the informal market represents more than 80% of housing stock (Pettang, 1998), which means that in the context of Yaoundé, new urban land uses are more likely to expand through the informal mechanism (provision, finance, construction, allocation, etc.). Three main types of housing can be identified based on the density of the built-up area per hectare and dwellers per unit: low density planned developments in wealthy areas, medium density in municipality or community housing for city public servants, and high density unplanned developments for the majority of the population. Figure 6.7 shows the distribution of housing densities in Yaoundé. This study focuses on the expansion mechanisms of the IS category, which constitutes the most dynamic land use in Yaoundé in terms of land acquisition, spatial densification and numbers of actors.

Informal High Density In Yaoundé, almost 80% of settlements are informal and accommodate about 85% of the population. The informal market represents more than 80% of housing stock as evident in *Mokolo* (below) and its surroundings.	**Municipal Density** Planned municipal housing satisfies less than 8% of housing needs. Their surroundings are being encroached upon by illegal housing such as *Essos*(below).	**Low Density** Less than 2% of Yaoundé dwellers can afford housing in planned, low density, high standard residential settlements such as *Bastos* (below).
		

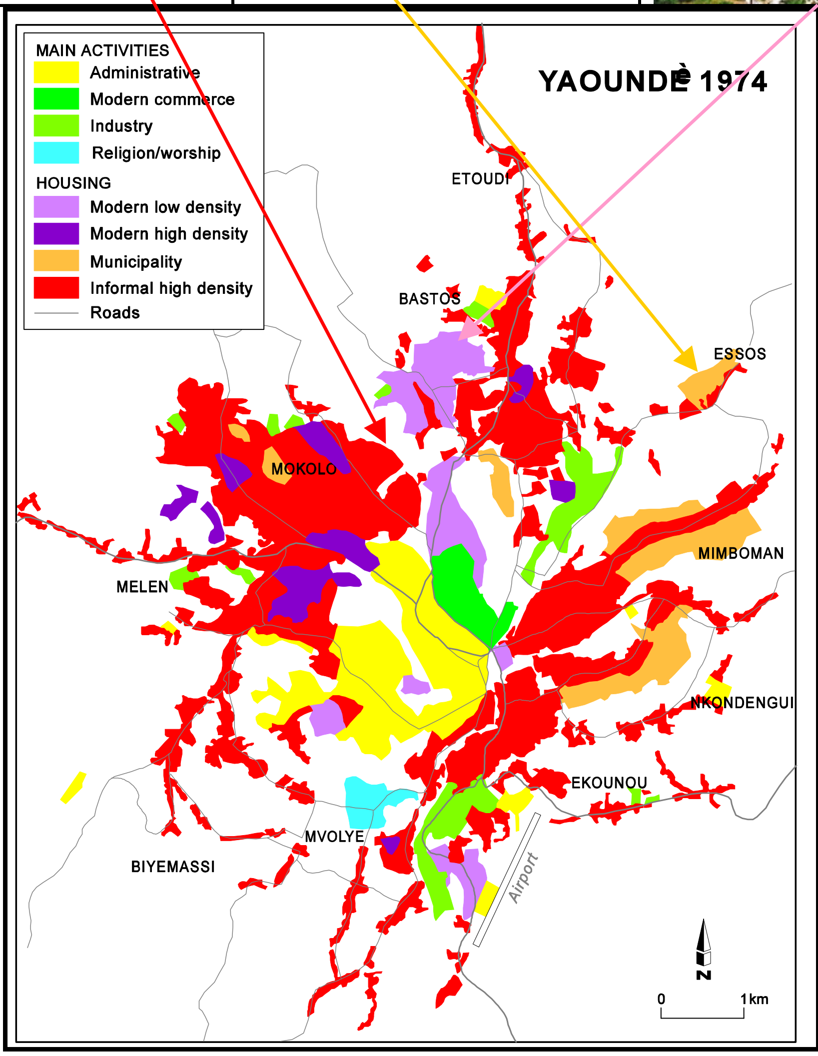


Figure 6.7 Urban residential housing density in Yaoundé (1974)

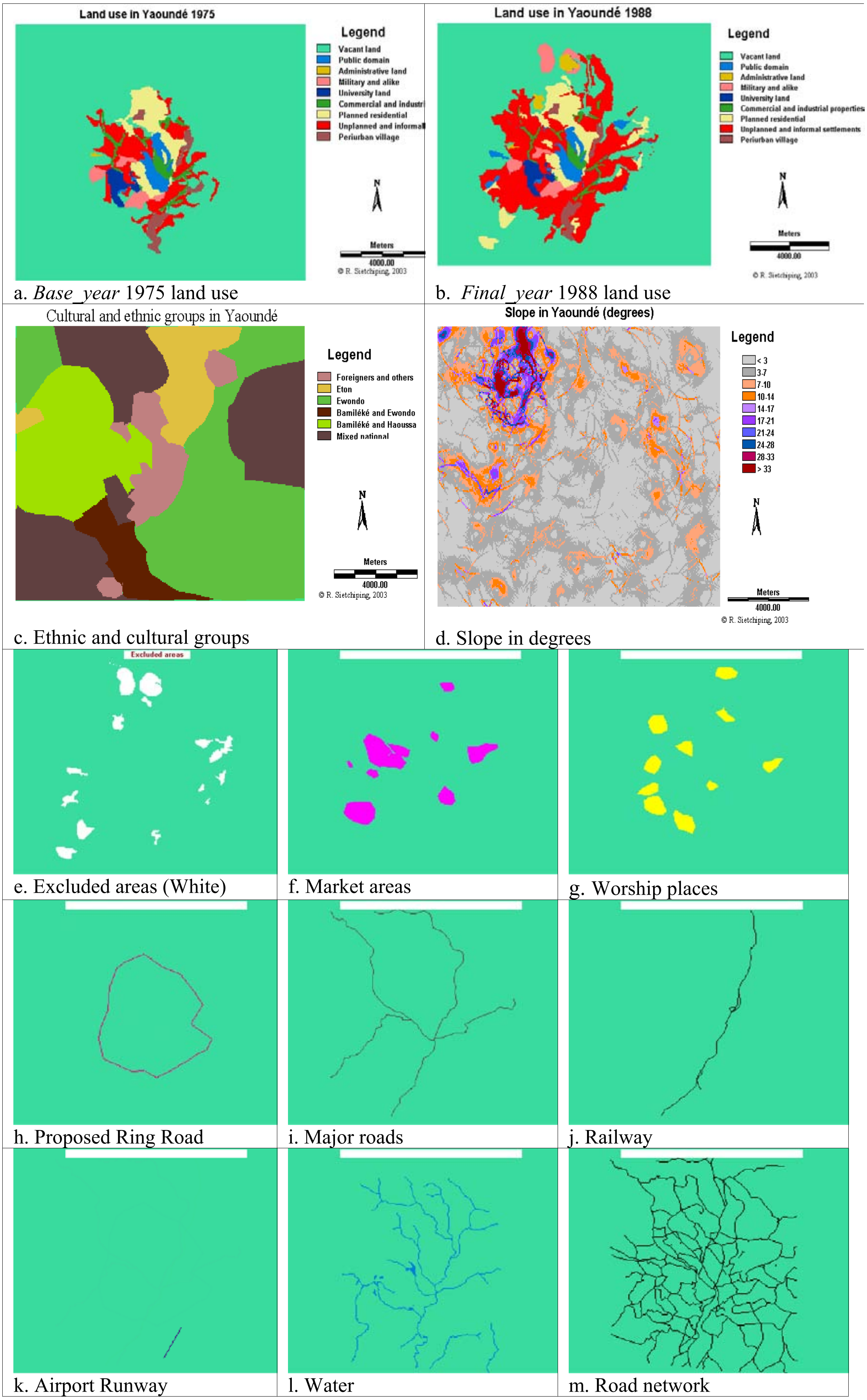
Source: MINUH, 1990

6.4.2 Data requirements: selection of variables and the data merging process

This section first presents the individual variables (as layers) used to test the ISGM in Yaoundé. A short explanation of the choice of each variable is also provided. In the second part, the process of merging files for data input (as a dataset) is explained.

6.4.2.1 Map layers used for the ISGM of Yaoundé

The selection of input maps to be incorporated into the model is based upon their respective influence on the emergence and growth of IS. Factors considered by the ISGM include: transportation networks (railway, major roads, other roads and a proposed ring road), land use categories (base and final years), river systems, places of worship and markets, topography, and cultural and ethnic places. All these layers have the same configuration and structure (e.g., 313 columns and 250 rows, i.e. 78250 square cells) with a cell resolution of 43 meters to reflect the scale of the original maps. Figure 6.8 presents the individual files (variables) used in the model. Note that for clarity and space, the legend-scale bar, north arrow and map key are purposely omitted for repeated and simple maps. (Appendix 9 explains the legend applied for each variable, and appendix 12 provides more detailed maps).



a. *Base_year* 1975 land use
b. *Final_year* 1988 land use
c. Ethnic and cultural groups
d. Slope in degrees
e. Excluded areas (White)
f. Market areas
g. Worship places
h. Proposed Ring Road
i. Major roads
j. Railway
k. Airport Runway
l. Water
m. Road network

Figure 6.8 Individual layers considered in the ISGM of Yaoundé

The following section discusses the choice of the 13 different variables and the content of the input for those variables.

The *base_year* map represents the status of land use in Yaoundé in 1975. It is used in the ISGM as the 'seed' for the simulation of IS patterns. The *final_year* map presents the status of land use in Yaoundé in 1988. It is used in the ISGM to calibrate and validate the simulation outputs. The base_year and final_year maps have nine main land use categories: vacant land, public domain, administrative land, military and related property, university or education land, commercial and industrial, planned residential, unplanned and IS, and peri-urban villages. The *excluded* map represents areas where IS cannot occur, especially known planning schemes. The *cultural and ethnic group* file encapsulates the distribution of ethnic groups in the Yaoundé urban area. Appendix 10 provides more detail on the interaction between cultural groups in Yaoundé. The *slope* map is used to test the influence of the topography on the emergence and expansion of IS. The *market* map represents the main markets in Yaoundé.

An attempt was made to identify markets as points. This approach caused the macro to run too slowly because the points were too remotely scattered. Similarly, increasing the neighbourhood search radii caused the macro to slow down significantly. To resolve this dilemma, each market place was represented as an area using its importance and its impact within the urban area of Yaoundé as discussed by Santoir (1995) and Bopda (2003). These authors highlight the importance of each market place, using criteria such as the size (spatial coverage), the volume of goods and services, the variety of goods, the number of retailers and the customer range. Based on these criteria, a map of the main market areas in Yaoundé was devised for this study, taking also into account the presence of the IS in the neighbourhood. Further discussion on market conditions in Yaoundé is available in appendix 11.

The *places of worship* map is used to encapsulate the key role religion plays in the emergence and the socio-cultural structure of IS. The *proposed ring road*[2] is

[2] The Yaoundé *ring road* was proposed in the 1982 Master Plan, but was never constructed. The Ring Road was meant to divert the traffic from the city centre to pass through what was, back then, the periphery of Yaoundé. From the early 1980s, the population rapidly gravitated to the proposed ring road site in anticipation of the construction infrastructure. However, the project has never been implemented.

incorporated into the model to show the influence of the proposed urban planning delimitation on the general distribution of IS. The transportation networks, especially *major roads*; *roads* and *rail lines* are some of the main driving forces behind the expansion of IS. These files are used to capture the intrinsic relationship between IS patterns and the transportation network. The *airport runway* map exemplifies the type of 'buffer-zone' or physical barrier, that urban infrastructure can pose to the spread of IS patterns. The *river* map portrays the central role of valleys and fragile environments in the expansion of IS. Unlike other linear features such as road networks, which define IS outwards; rivers pull IS inwards, that is from highland to the valleys or riverbed.

These map layers are used as variables in the ISGM. However, some of these layers are merged into single files, in order to speed up the simulation procedure, and cut down the macro running time.

6.4.2.2 Merging layers for the ISGM of Yaoundé

The merging of layers aims to create a single file that contains as much information as possible, while preserving the individual properties of each variable. The *map algebra* and *logic modeler* modules in Idrisi™ are used to perform the consolidation and the merging of these files. It is worth remarking that the idea of merging the files emerged at a later stage of the modelling procedure, as a measure to improve the performance of the proposed model.

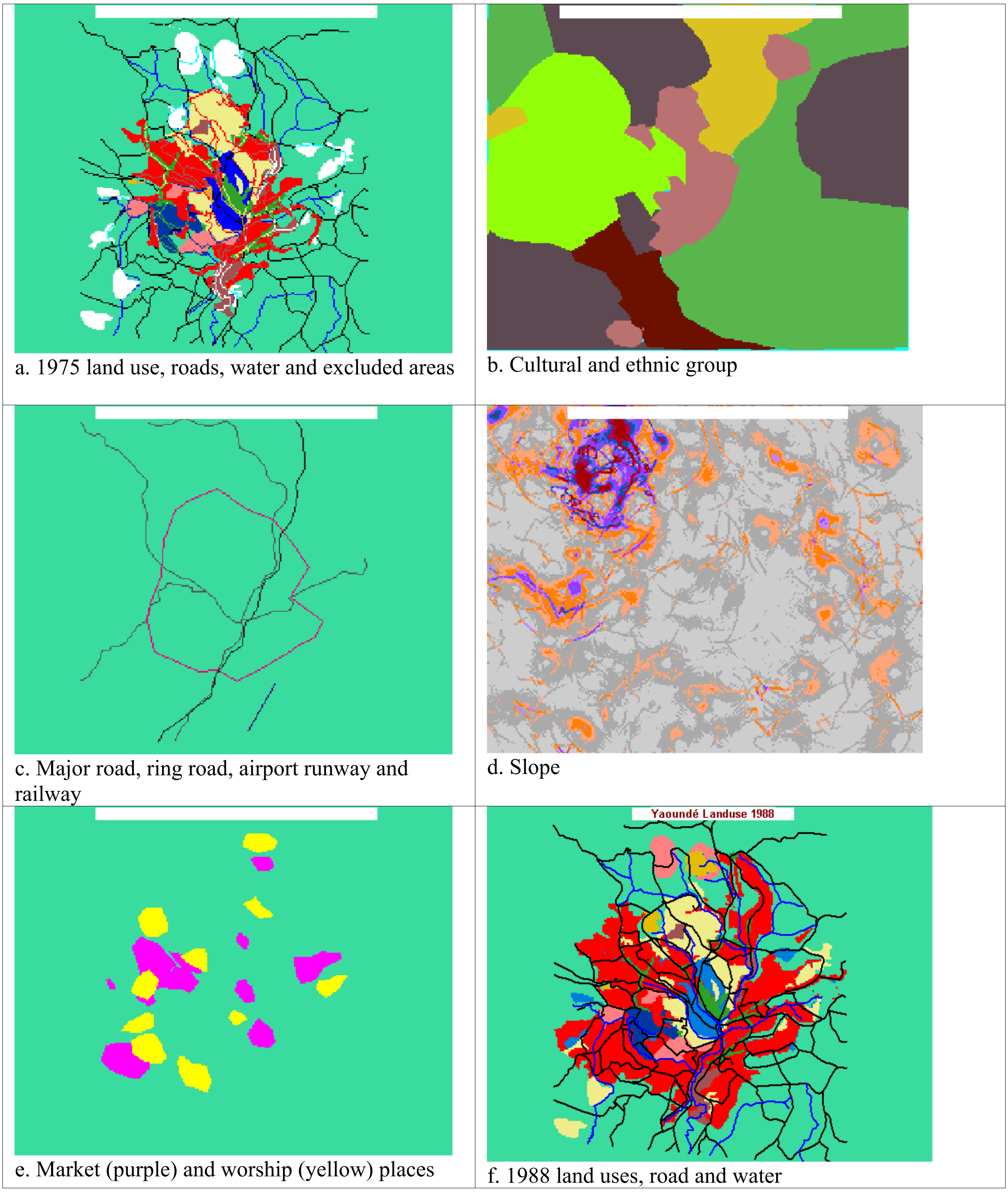
The advantage of the operation is threefold: first, to make a variety of raster information available and legible on a single file; second, to reduce the length of the macro and to cut down the repetitive sequence of the macro commands; and third, to shorten the running time of the macro. For example, instead of the macro searching each file to implement the rules; it carries out the same operation just once within the merged-layer file.

There are, however, a number of disadvantages associated with this type of operation. One is possible misclassification. For instance, when a road in raster format is merged with other raster data (e.g., water and land use), the transformation algorithm in Idrisi™ can allocate some pixels to the wrong class. Hence, the merged maps need to be reclassified and the error corrected to reattribute the classes. Despite these corrections, there can still be some residual pixels that the class cannot reconstitute and associate with the original class or identification number (ID). Yet, in the case of the images used for this application, after reclassification and rectification, the transformation error was less than 0.2. These errors mostly occurred in already built-up areas where many variables were superimposed. They had limited influence on the simulation process, because they were almost non-existent on vacant land where the simulation of IS would occur. Another disadvantage of overlaying many files is the negative effect it can have on the visual quality of the information. Cartographically, a merged map can have too much information and can, therefore, divert attention away from the main message the map is aiming to portray. To improve the visual contrast for this application, a colour palette is created where IS is shown in *red*.

The overlaying operation concerns only some files that can be merged with limited loss of information. Features merged maintain their respective properties and ID. For this application, *major roads, the ring road, airport runway and railway* are merged to form a new file. Similarly, *markets* and *places of worship* are merged to form a new single file. Additionally, *roads, water* and *excluded areas* are combined with the base_year map (1975). The final_map (1988) is merged with *roads* and *water* files. Other files, such as *slope* and *cultural and ethnic groups* cannot be overlaid because the overlay operation wipes off the values of one file and replaces it with another.

Merging the files will also cause the overall statistical validation (calculation) non reliable because the number of categories of the simulate image (1988) will not exactly match that of the reference image. I considered and experimented with the possibility of comparing the results of different simulations (for example using *Validate* or *Relative Operating Characteristics* in *IDRISI*™) because they had the same number of categories. However, it should be noted that the model results will not be fully investigated using statistical analysis. As strongly argued and implemented in section 5.4.2 (and to preserve consistency), the simplicity and practicability of the visual comparison and validation will be largely used to assess the best-fit patterns for the simulated maps in ISGM. Nonetheless, the statistical validation will also be presented.

Figure 6.9 shows the final maps used for the simulation of IS in Yaoundé. Note that for clarity and space, legend-scale bar, north arrow and key- are purposely omitted for maps, but a sample of these maps with complete legends is available in appendix 12.



a. 1975 land use, roads, water and excluded areas

b. Cultural and ethnic group

c. Major road, ring road, airport runway and railway

d. Slope

e. Market (purple) and worship (yellow) places

f. 1988 land uses, road and water

Figure 6.9 Final maps used for the calibration of ISGM: merging files

After following all these data preparation steps, the ISGM macro can now be tested on a 'real world' situation.

6.5 Running the ISGM on Yaoundé

The ISGM underwent a series of modifications to optimize the output. To statistically validate the model, the VALIDATE module in *Idrisi*^{TM} (Release 2) was used to assess the level of accuracy of the model's output. To achieve such statistical validation, the *reality map* (1988) and the *simulated map* (1988) of each version were converted into two classes: informal settlement and non-informal settlement. The VALIDATE run then returned a series of *kappa* and other statistics about the quantity and location accuracy of the simulation outputs (Pontius, 2000). Overall, the quantity scores of the simulated maps perfectly agreed (1) with the reality map, because in the ISGM, the user predefines the quantity of simulated IS cell before the calibration. In contrast, the locational scores largely vary between simulations. This section discusses how changes in relation to data input, and the rules, have progressively improved the model and also shows how well the simulated IS cells of each version best fit with the reality map. Only versions of the macro where significant changes have been introduced will be presented. The presentation of the selected versions of the model is as follows: first the main features, the aim and hypothesis to be tested by the simulation of each sub-model are presented. Secondly, the rules applied to achieve a verification of the hypothesis are presented. Thirdly, the result of the simulation is displayed[3] with its kappa location score (*V* as the percentage of location accuracy, that is the number of times the location of IS cells on the simulated map exactly matches the location of the cells on the reality map), along with the base_year and the final_year maps for visual comparison. Finally, the results of the simulation are discussed.

6.5.1 Version 1: Exponential expansion of informal settlement

Version 1 of the macro simulates the exponential growth of IS on vacant land, using *threshold* as the only constraint. The threshold concept adopted in the proposed model only states the variables subjected to change. In this case, probability of change occurs only at the neighbourhood level of existing IS and along river and road cells. Table 6.1 presents the rules that apply for this early version of the model and figure 6.10 shows the output maps.

[3] Note that for clarity and space, legend-scale bar, north arrow and key are purposely omitted for maps. However, samples are available in appendix 12.

Table 6.1 Probability rules for exponential growth of IS

Add values to probability as follows:	
(Five neighbourhood search)	**All stages**
Informal settlements	0.4
River	0.2
Road	0.3
Road and water	0.1

1975: *Base_year* | 1988: Simulated ***V: 43.1%*** | 1988: Reality

Figure 6.10 Version 1: Simulation of the exponential growth of IS based on the proximity of the existing IS and of road and river cells

The result was not satisfactory because the road and river files were stored and read separately to the base year map. The road and river files had limited effects on the direction of the IS, despite their relatively high probability (60%). The limited effect of the roads was partly due to the spatial importance of their pixel, and the fact that they were read separately from the base_year map. The simulated map showed an exponential expansion of IS in areas (South, West and East) where vacant land prevailed, and more importantly, at the edge of existing IS. The number of variables used in this application, as well as the loosely defined constraints, also contributed to the poor simulation shown by this version of the macro. Another problem was that the model placed IS on known planned developments, which will be later designated as *excluded* areas. The next versions of the macro gradually address these weaknesses.

6.5.2 Version 2: Excluded area based ISGM

One of the lessons learned from the previous version of the application was that the model was too permissive (no constraints), which led to an exponential IS expansion in the proximity of existing IS. To correct this discrepancy, a constraint value was added to the base_year map. This value takes the form of the 'excluded' areas, and therefore, keeps the expansion of IS away from areas that should not be converted into IS, especially planned developments that will occur between 1975 and 1988. It would later been shown that the final calibration could be used to simulate beyond the final_year of the calibration (1988).

This version (2) of the macro aimed at testing two hypotheses. First, to verify the effect of excluded areas on the distribution patterns of IS between 1975 and 1988. Secondly, to gauge the contribution of existing IS to the overall expansion of the future of IS. The hypotheses were tested according to the probability that change is 1 if the cell is in proximity to an IS cell, and 0 if it is in proximity to any other land use category. To test these hypotheses, a new base_year map of 1975 was created with 'excluded areas' (in white) as a new category. The concept of *probability_boost* was also introduced, which basically served to increase the likelihood of IS occurring when the potential IS was in proximity to features (s) that could trigger the conversion from vacant cell to IS. Figure 6.11 shows the simulation of new IS cells in proximity to existing IS.

1975: Base_ year | 1988: Simulated ***V: 45.7%*** | 1988: Reality

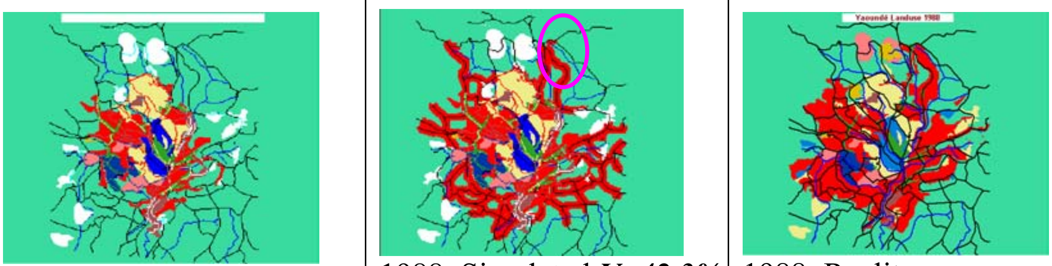
Figure 6.11 Version 2: Excluded areas-based simulation of IS in proximity to existing IS

The simulated map of 1988 on Figure 6.11 clearly showed IS patterns emerging only in proximity to existing IS cells. The IS 'patches' were more homogeneous and compacted than in the previous version of the model. The results also showed that IS did not occur on *excluded* areas. While these outcomes conformed to the stated hypotheses, they were not, however, satisfactory. For instance, the shape was too coarse to portray the required details of IS patterns and associated nuances as demonstrated in the reality map. The next version will improve the IS cell allocation by adding the roads feature into the model.

6.5.3 Version 3: Road-based informal settlement

The previous version simulated the growth of IS based on the proximity of existing IS cells. This version of the application portrayed IS patterns as more compact than they are in reality, showing that it was important to allow for the contribution of other variables. In order to address these deficiencies, the third version of the model incorporated line features (roads and rivers) into the macro.

Before combining the variables, it was worth testing the sensitivity of the macro to line features. This version (3) of the macro also tested how the programme performed when many variables are merged under a single file. The macro is then modified to simulate the expansion of IS only if it is close and accessible to road networks (road probability = 1, else = 0). It is noteworthy that in Yaoundé as in most LDC cities, the quality of the road is considered marginal (in comparison to accessibility) for the emergence and growth of IS. Figure 6.12 shows how the model simulates the IS growth along road networks.



1975: *Base_year*	1988: Simulated ***V: 42.3%***	1988: Reality

Figure 6.12 Version 3: Road-based simulation of IS

The results of this simulation demonstrate how the model is sensitive to the road network as an input parameter. One of the clear improvements to the model was that this version of the model was able to simulate the expansion along roads, especially in the Northern part of the map. Such changes showing the influence of road networks were not able to emerge from the previous versions." This is important because in Yaoundé, the urbanisation pattern largely follows the road networks (see base-year and Reality maps on Fig 6.12). Such changes showing the influence of road networks were not able to emerge from the previous versions. The merging of different files into a single file (base_year), made this version of the model also run twice as fast as the earlier one (from 30seconds per iteration to 14s for the road-based). The results of this version show that the macro is sensitive to a single input variable, and the next version of the macro will test the sensitivity on two variables.

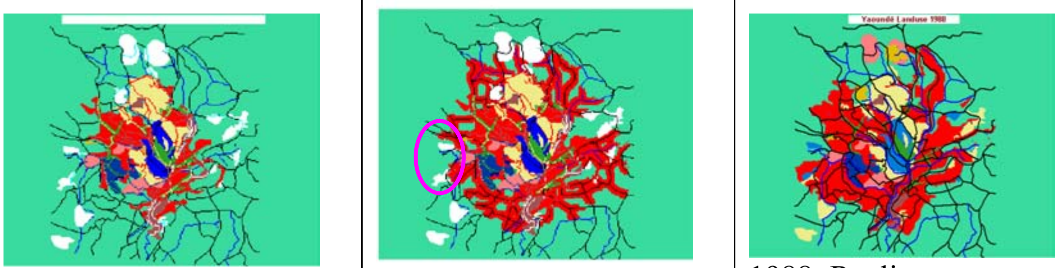
6.5.4 Version 4: River and road-based simulation of informal settlement

The previous version revealed that the model is sensitive to the input of a single variable. The range of factors that underpin the expansion of IS required that more than one variable needed to be accounted for in the ISGM. This version of the model therefore tested the macro's capacity to handle multiple variables. It also sought to validate the effectiveness of merging the files into the overall output of the model. This version 4 of the model also tested the theory that roads and rivers are some of the main drivers of IS expansion in LDC. Table 6.2 presents the variables used and the respective probabilities applied.

Table 6.2: Probabilities used to derive road and river driven IS

Add values to probability as follows:	
(5 neighbourhood search)	**All stages**
River	0.5
Road	0.5

Figure 6.13 shows how the model performed in the simulation of IS cells in relation to road networks and river systems with equal probability (50% each).



1975: Base_year | 1988: Simulated ***V: 46.5%*** | 1988: Reality

Figure 6.13 Version 4: Road and river based simulation of IS

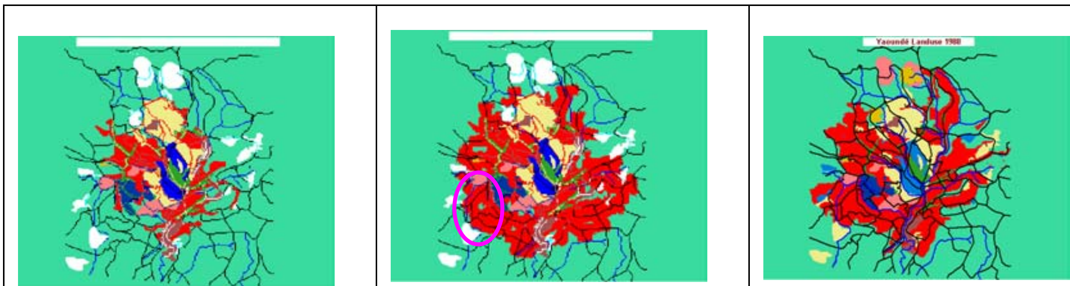
The results of this application indicated that the macro was sensitive to multiple input variables. In particular, version 4 of the macro highlighted and validated the influence of road and river networks in the expansion of IS. This was evident by the changes the model showed in the western part of the simulated map where a pocket of IS (figure 6.13) has emerged that was not depicted in the previous application. While this version showed how the model reacted to road and river system input variables, the model could not yet discriminate between the importance of these road networks and river systems. For instance, there are some gaps between the lines. In addition not all roads or river have the same level of influence on the expansion of IS. The capacity of the model to differentiate between these varying levels of influence is important. The later versions attempted to iron out these weaknesses by adding more variables into the model.

6.5.5 Version 5: Roads, rivers and the existing IS based simulation

Once the previous versions had demonstrated the sensitivity of the model to the two input variables, the next version planned to test the sensitivity of IS to three variables. The previous version had revealed that the existence of IS, road networks and rivers constitute an important factor for the emergence of new IS cells. The next version of the macro tested whether the results of the simulation could be improved by adding probabilities to the calculation in the proximity to roads, rivers and existing IS. The aim of version 5 was to fill the gaps along and between the line features (version 3 and 4), and avoid compacting patterns (version 2). Table 6.3 presents the variables used and the respective probabilities applied.

Table 6.3: Probabilities used to derive IS, road and river driven IS

Add values to probability as follows:	
(5 neighbourhood search)	**All stages**
Informal settlements	0.4
River	0.3
Road	0.3



1975: *Base_year* | 1988: Simulated ***V: 51.0%*** | 1988: Reality

Figure 6.14 Version 5: Roads, rivers and existing IS-based simulations of IS

Figure 6.14 shows a significant improvement in the model's predictive capacity. Many parts of the simulation map show better predictions than those in the previous versions of the model. This is the case in the northeast, southeast and west of the map of Yaoundé. The results of this simulation validated the hypothesis which postulates that *roads*, existing IS and *rivers* play an important role in the distribution of IS. There were, however, some gaps between line features still visible on the map. These would be addressed by adding a topography variable into the model. There was also an exaggeration of IS expansion on the eastern part of the map, which was inappropriate. This could be rectified by adding more variables or constraints to the model.

6.5.6 Version 6: Topography-based simulation

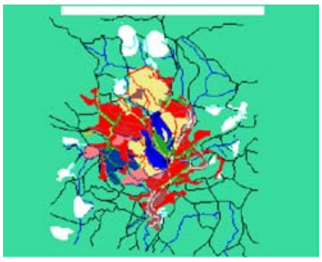
The previous versions had clearly shown that the model was sensitive to line and polygon types of feature input, which were all available on a single layer. Version 6 of the macro would fulfil two main objectives: first, to improve the IS pattern distribution and fill the gaps between the lines; secondly, to assess the effectiveness of the model to handle point features and different data layers.

To achieve these aims, the following variables were introduced into the model with their respective probability: slope, main roads, markets and places of worship (as points). Market and places of worship represent significant community meeting points and associated housing development. Places of worship and markets were identified as points and merged on the base_year map. Similarly, a new road data set was prepared containing only 'major roads', but stored as a separate file. As shown in versions 4 and 5, not all road networks have the same potential to trigger the cluster of IS along their trajectory. A *major road* network map was therefore created and introduced into the model with the residual network being ignored in this application. This version of the model also used the slope map to test the likelihood of IS expansion on lowlands (0-3% slope), along with other variables.

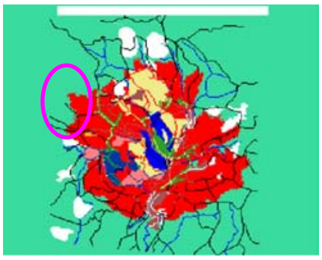
In terms of rule formulations, version 6 of the model now distinguished between *general probability* and *local probability* given that there were other variables that could now be incorporated. The general probability was equally applied to all the input variables. Each local probability was multiplied by the general probability so that the relative importance of each input parameter could adjust if the local probabilities did not reach or exceed the *annual_pixel_gain threshold*. Table 6.4 presents the variables and probabilities used for this version of the model.

Table 6.4 Probability and rules applied for topography-based IS growth

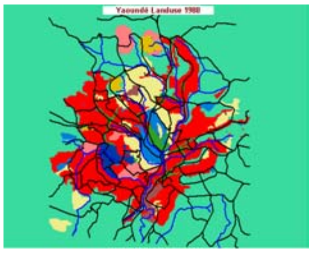
Add values to slope probability (0.3) as follows:	
(Five neighbourhood search)	All stages
Proximity of Informal settlements	0.1
Markets	0.2
Place of worship	0.1
Main Roads	0.3
River	0.1
Slope	0.2



1975: *Base_year*



1988: Simulated ***V: 57.6%***



1988: Reality

Figure 6.15 Version 6: Topography-based simulation of IS

The simulated map of Yaoundé in 1988 (figure 6.15) shows how the slope can consolidate the patterns of IS. There were still few gaps remaining between the line features. After testing different slope gradients in the case study of Yaoundé, it was concluded that a slope of less than 3% was more likely to depict the closest form and shape that were associated with IS.

The slope factor underlined the importance of accounting for this factor. In particular, this version demonstrated how the expansion of IS could be constrained by a slope gradient of more than 3%. The hills in the western part of Yaoundé, for example, almost stopped the IS from rapidly expanding outwards, despite having a larger concentration of IS patterns in 1975. If the slope factor had been ignored, the expansion of the IS would have been forecast to be more important in the western part of the map than it actually was. Another contribution of the slope variable was its prediction of the 'stretch' of IS patterns which occurred in the south-western part of Yaoundé (which in 1975 had insignificant patches of IS). However, the slope factor predicted a significant expansion of IS in the eastern part of Yaoundé, which was not correlated with the reality map.

This version of the model showed that there are some limitations attached to relying on roads, rivers and existing IS without considering slope. In this version, the road factor did not capture the expansion of the IS in the north and south of Yaoundé, especially because some further variables which were influencing the expansion of IS were yet to be accounted for. Such discrepancies in some parts of the simulated map of 1988 (figure 6.15) suggested that there were other factors that control the distribution of IS and which needed to be incorporated. It is also worthy to note that the attempt to use markets and places of worship as points to determine the expansion of IS was not satisfactory. In this version, the spatial insignificance of these point features rendered them inadequate to trigger change, even if their probabilities were significantly greater than those for the other factors. This problem could be corrected by representing market and places of worship as polygons (areas). Overall, this version of the model successfully performed the simulation of line and area type features, and showed that it can accommodate up to six different variables from different layers.

6.5.7 Version 7: Influence of cultural and ethnic groups on IS growth

The previous version showed that the model performed poorly on points as input variables, yet could accommodate a wide variety and number of layers. Version 7 was designed to test the following questions: Would the distribution of cultural and ethnic groups (as areas) influence the growth of IS? Would the markets and places of worship (defined as areas) improve the prediction of IS patterns? Could this version accommodate additional variables?

To correct the poor performance of the model in depicting points, version 7 uses markets and places of worship as areas. A new map of places of worship was created and represented each market and place of worship based upon its importance (see appendix 11). A map of cultural groups in Yaoundé was prepared to test the influence of ethnic composition on the expansion of IS. The ethnic and cultural groups map of Yaoundé used in this application was an extrapolation of the real spatial distribution of cultural groups in Yaoundé.

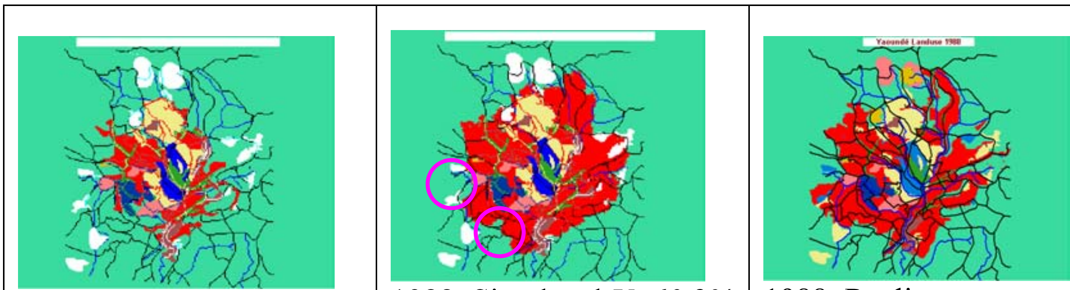
It is worth mentioning that extrapolation was necessary because the existing cultural map was limited to the urbanised area of 1982 and was not useful for the simulation of future expansion of IS. More than two hundred ethnic groups live in Cameroon, and Yaoundé, the political capital, constitutes a microcosm of this variety (Bopda, 2003). For the purpose of this research, only the dominant ethnic groups who influence the structure of urban land uses in Yaoundé are selected (Franqueville, 1984; Santoir & Bopda, 1995). Cultural entities are grouped into the following six main categories: foreigners and others, Eton, Ewondo, Bamiléké, Haoussa and mixed national. In relation to their respective influence on the expansion and structure of IS, these six categories are further reorganized into 3 main groups. The first group is composed of foreigners and wealthy nationals who live in the 'up-market' and planned suburbs of Yaoundé such as Bastos. The Bamiléké, Ewondo, Haoussa and Eton dominate the second group. Respecting IS structure in Yaoundé, there is a correlation between ethnic groups and IS patterns. This is the case in Nkomkana and Mokolo (Bamiléké), Mvog Mbi (Ewondo), Briqueterie (Haoussa), Nkol Eton (Eton). In the third group, mixed nationals occupy mostly planned development areas.

The likelihood of generating new IS was unevenly distributed amongst the cultural groups. The probability weight for each cultural group was determined by the ratio of IS in the area and the ethnic composition. It is important to note here that this version of the model (and henceforth) automatically readjusts the total and relative probability when the simulation reaches its quota. It was also noticed that when the probabilities were proportionally adjusted, there was no significant difference on the simulation outputs. This is so because the cultural groups and the slope values, for instance, are self-exclusive. The final probability for each ethnic group category was adopted through a process of trial and error, until the best solution was found. To improve the shape of the simulated map, three line features were added to the model: the railway, the proposed ring road and the airport runway. First, this version of the macro attempted to encapsulate the filling of space by Yaoundé dwellers who are increasingly settling in along the railway yards. The aim would be to improve the prediction in the northern and southern parts of the simulated map. Secondly, the contribution of this version of the model would be to capture the behaviour[4] of urban dwellers along the route of a proposed road. Finally, version 7 of the model will assess the deterrent impact of the physical presence of the airport (fenced environment, in the southeast of the image) on the expansion of IS. Table 6.5 presents the variables and their respective probabilities used to simulate cultural influence on IS patterns.

[4] The literature on Yaoundé suggests that the future ring road proposed for Yaoundé in an 1982 urban planning document accelerated the expansion of IS in proximity to the proposed road corridor (Franqueville, 1984; Pettang, 1998; MINUH, 1990), because many urban dwellers settled along the proposed corridor in anticipation of the accessibility and connectivity to other parts of the city.

Table 6.5 Probabilities and rules used to simulate cultural based IS

Add values to slope probability (0.3) as follows:	
(Four neighbourhood search)	**All stages (boost factor)**
Proximity of Informal settlements	0.1
Markets	0.2
Place of worship	0.1
Main Roads	0.3
River	0.1
Railway	0.1
Proposed Ring road	0.1
Airport runway	0.0
Cultural group1	0.1
group2	0.6
group3	0.2



1975: *Base_year* | 1988: Simulated ***V: 60.9%*** | 1988: Reality

Figure 6.16 Version 7: Cultural and ethnic influence on IS simulation

Figure 6.16 clearly shows how the changes in input parameters and the formulation of the model improved the general output. The cultural group factor played an important role in refining the shape of the simulated map, especially in the east, south and west of Yaoundé. The expansion of IS at the edge of Yaoundé was also better contained and distributed than in the previous versions of the model. Clearly, without the cultural group parameters, the shape and direction of the IS expansion would have been difficult to predict. This version of the model successfully applied the *market* and *place of worship* rules when they were represented as areas. The most significant example of this was the improvement to the southwest of the image. The *proposed ring road* factor also consolidated the patterns around the city of Yaoundé. The *roads* and *railway* variables improved the prediction of IS expansion along the major roads to the south and north of Yaoundé as the reality map demonstrates.

Despite the improvements to the detail of the model, it still appeared to over stress the expansion of IS in the northeast of Yaoundé. There are two possible explanations for this. First, the neighbourhood properties of the model (introduced after version 6) that 'fills the gaps' between simulated IS patterns partly explain why the visible gaps between the two line features (north of Yaoundé) are now filled. In general, however, the extent of IS reflected the pattern of the reality map of 1988. The second reason could be the composition of ethnic and cultural groups themselves. It is likely that there are more differences and complexities to defining and accounting for these groups than can be captured in this model. The extrapolation of the spatial distribution of ethnic growth in Yaoundé could have been too coarse to adequately depict all the nuances. The results suggested that a more disaggregated spatial composition of cultural and ethnic groups might improve the model's prediction and nuances.

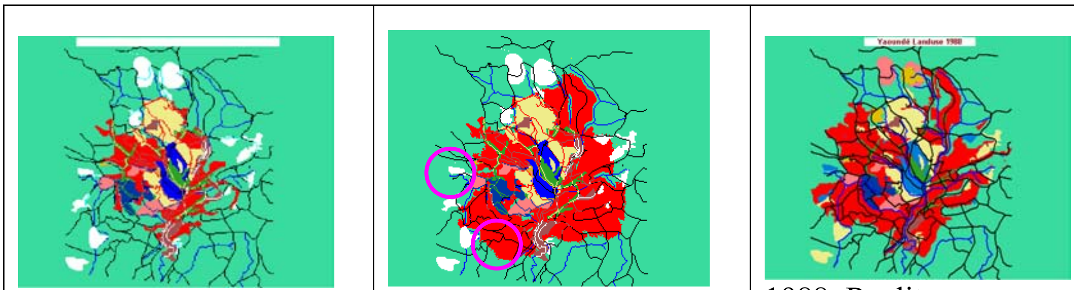
Another issue with this version was the way it represented the expansion of IS according to the influence of rivers. Currently, expansion along the river course is shown as being outwards, whereas it should be inwards, and possibly at different stages. Moreover, all the previous models simulate the IS in one time block. It is possible that some events occur at certain stages of the simulation periods, or that the IS growth rate is not the same for the all calibration periods. The next version would seek to address some of these conceptual and practical aspects of the model.

6.5.8 Version 8: Informal Settlement Growth Model

The previous versions of the model generated IS expansion during a single stage. This version of the model tested the model's performance when the rules are defined at different steps of their developments. This version also attempted to apply the multiplication factor to the different components of the variables, so that the importance of each variable's contribution could be established. Version 8 also sought to improve the 'distance from the water cell' function. In the previous versions, the proximity to the water cell was defined the same way as the road conditions. That is, the vacant cell at the neighbourhood of a *road* or *water* cell had a certain probability of becoming an IS cell. As a result, new IS emerged along the river course and spread outwards. A close examination of water-based expansion, however, revealed that the informalisation process along the river was significantly different from the method implemented so far. To correct this misrepresentation, the water-influenced IS expansion was defined as expanding onwards following the three stages of this ISGM. For the application of ISGM in Yaoundé, the three stages were obtained by dividing the number of iterations into three equal periods. Table 6.6 details the variables used to simulate IS, and their respective probabilities at each of the three stages.

Table 6.6 Input variables, probabilities and stages of ISGM

Add probabilities during the simulation stages as follows:			
Variables/Stages	**Stage 1**	**Stage 2**	**Stage 3**
Slope (Slope ≤ 10^0)	0.1	0.3	0.3
Market places	0.01	0.03	0.04
Worship places	0.01	0.01	0.01
River (> 0.66 neigh) and road	0.3	0.3	0.7 (road); 0.2 (not road)
River (> 0.33 neigh) and road	0.1	0.2	0.3 (road); -0.8 (not road)
River (< 0.33 neigh) and road	-0.5	-0.2	0.3 (road); -0.3 (not road)
All roads	0.01	0.02	0.03
Major roads	0.5	0.4	0.4
Proposed ring road	0.2	0.3	0.3
Rail lines	0.2	0.3	0.2
Airport Runway	0.3	-0.3	-0.4
Cultural group 1	-0.1	-0.2	-0.3
Cultural group 2	0.2	0.4	0.3
Cultural group 3	0	0.1	-0.1
Cultural group 4	0.1	0.3	0.3
Cultural group 5	0	0.03	0.01
Cultural group 6	0	-0.2	-0.1



1975: *Base_year* | 1988: Simulated ***V: 72.7%*** | 1988: Reality

Figure 6.17: Informal settlements based on all variables

The results of this simulation indicated that the function of river cells to attract IS cell inwards (not outwards) was successfully tested. The simulated map on figure 6.17 showed that the new IS cells did not emerge from the river course; instead, they gradually expanded towards the riverbed. Another improvement concerned the way in which the three stages of IS growth distributed the patterns over time. When the model output was dynamically visualised, the three stages of the expansion of IS were better depicted (see section 6.7). The results of this simulation also indicated that the incorporation of multiple variables/factors influencing the growth of IS improved the overall results. There were, however, two exceptions: one overshoot in the South and one undershoot in the west of Yaoundé.

The overshoot in the south of Yaoundé is associated with two major enclosed landmarks close to each other: the military zone (Military Headquarters) and religious properties (Mvolyé Catholic Church). The military headquarters and the Mvolyé Catholic Church cover a total area of about 100 ha and were established prior to the 1950s. These two entities slowed down the 'normal flow' of the expansion of IS. Unlike other properties or urban structures in town, Military and Religious Authorities have established physical constraints (barriers) that keep squatters and other potential IS dwellers outside their 'territories'. One of the effects of such physical barriers was to slow down the expansion of IS at the edge or alongside the 'fences'. Due to the time constraint, such information was not encapsulated into a layer and then incorporated into the ISGM. However, it is anticipated that during the future fine tuning phase of the model, the role of such physical constraints will be accounted for.

The undershoot at the west of the simulated map had other explanations. Unlike the preceding case of Mvolyé and the military headquarters, two possible reasons can explain the fast expansion towards Etoug Ebe suburbs. One explanation relates to the existence of IS in the neighbourhood and the relatively small size of the constraints governing IS expansion. During the 1970s, the western part of Yaoundé had a larger concentration of slums, but the landscape (steep slopes on the west) slowed the spread outwards. The Etoug Ebe corridor was created in the early 1980s, and then the extra population from the overcrowded neighbouring slums such as Mélen and Mokolo rapidly filled out the area (Pettang, 1998). An improved version of the model would take into account such developments as had occurred between the base_year and the final_year of the calibration.

The overshoot at the west of the simulated map can also be explained by the expansion of IS around markets and places of worship in the Mélen area. In other parts of the map, the presence of markets helped in the prediction of the expansion of IS, except in the south of Yaoundé, where there was an overshoot around Biyemassi

Market. The Presidential Guard compound in Mélen and the Cité Verte Housing Scheme, which were not included in this model, also impinged on the 'normal flow' of IS. Another explanation for the overshoot in the west can be traced back to the general rules, which state that changes operate only on vacant land, not considering the land cover. In the eastern part of Yaoundé, the dense vegetation could have well slowed down the advance of the IS. Such vegetation cover, however, was not considered as a general rule in IS expansion, but might be a key influence in this part of the city.

This last version of the model had many other add-on properties and features. For instance, it automatically displayed the colour palette and gave the option for the user to select other output formats than the default proposed by the software in use. In particular, the output of ISGM using Idrisi™ displayed Idrisi™ format, as well as Bitmap (*.BMP)* maps readily available to create an animation. This operation saves the cumbersome task of manually converting the software-specific format to a user-defined desktop publishing format, and thus adds extra flexibility to the model. The proposed ISGM is a work in progress and can be improved in many ways.

The next section discusses how ISGM could be used to explore future expansion of IS.

6.6 Predicting future expansion of informal settlements in Yaoundé

The previous section described the various stages undertaken to develop the predictive ISGM. It also discussed the range of issues that arose at each development stage and how successive versions of the model attempted to deal with each scenario. Importantly, the model was developed to incorporate a range of variables, to respond to their degree of influence on the expansion of IS, and to capture changes over time.

This section describes the final adjustments made to the ISGM model in order to refine and improve its capacities. In particular, this section tests the model's predictive ability. The simulation of probable expansion based upon the variables under consideration provides another capacity to the ISGM, especially as a tool to generate different scenarios of probable expansion of unplanned developments. One of the key issues to be grappled with is the model's prediction beyond the final_year used for the calibration. This was achieved by modifying two main parameters of the model: *number of iterations* and *nett_pixel_gain*. The new number of iterations is the result of the difference between the base_year and the final_year (which is the *predictive year)*. The nett-pixel_gain for the simulation period can be estimated in different ways such as exponential growth, linear and non-linear models, regression equations, extrapolation, least square and line of best fit. The choice of the predictive methods, however, will depend on the user, who can alter the probability of the input variables and include different stages and constraints (excluded areas) into the prediction.

Using the same procedure, ISGM was used to simulate and then predict the future expansion of IS growth in Yaoundé between 1976 and 2001. The number of iterations is changed from 13 to 26 (to fit the calibration year), and the nett_pixel_gain is obtained by applying the IS growth rate of 10.5% obtained from a 'trial and error' calibration procedure. The rules and probabilities used to simulate IS growth in section 6.5.8 was applied to test the predictive capacity of the ISGM. Figure 6.18 shows the results of the simulation of future distribution of IS in Yaoundé. The full set of predictive maps along with the animation is available on the CD-ROM attached at the back of this thesis.

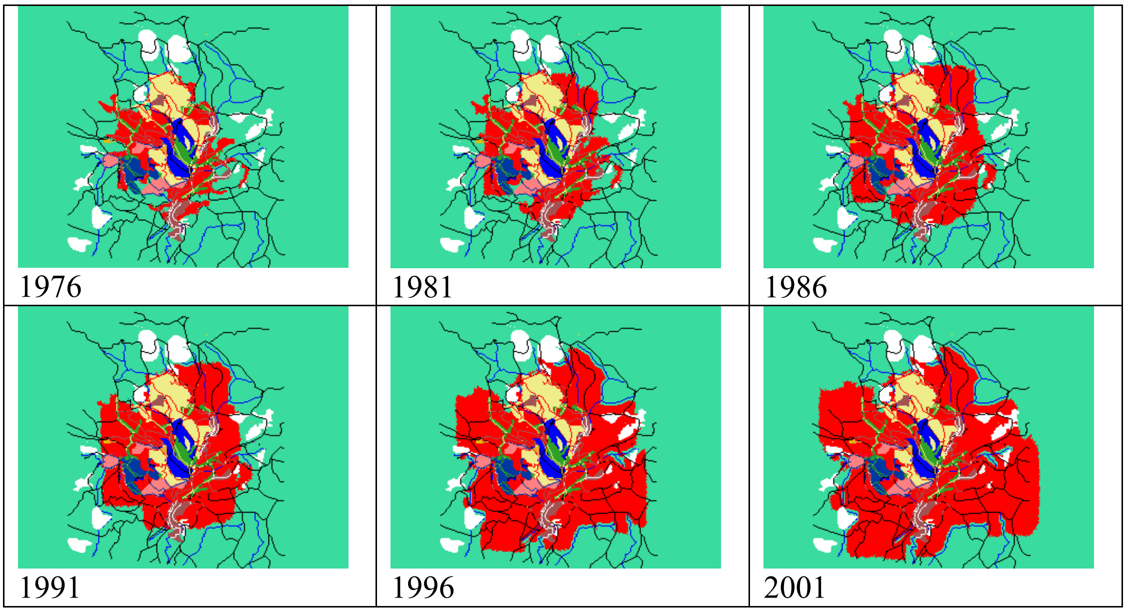


Figure 6.18 Selected samples of prediction of informal settlements expansion in Yaoundé between 1975 and 2001

Figure 6.18 indicates that is it relatively easy to predict the future expansion of IS, once the model has been successfully calibrated. The sensitivity of the ISGM to further input variables suggests that different scenarios can be generated from the datasets and the rules. The prediction of IS growth in Yaoundé conforms to the growth rate applied, as well as to the probabilities and rules implemented. However, it is important to note that the spatial coverage of road networks and other variables used in this model could not be sufficient to extrapolate beyond the current boundary of this map. The predictions of future spatial expansion of IS might have been improved if additional rules were added to simulate the generation of future market and places of worship based, for instance, on central place theory. As a result, a prediction beyond 2001 could have been largely misrepresentative of the IS reality in Yaoundé. It is therefore recommended that long-term prediction would require up-to-date datasets, which were not available for the case study. Such long-term prediction was not the focus of this research. It is worth mentioning that although the issue of data quality and availability is commonly debated in developing cities, one of the premises of this research was to indicate that there is still sufficient information to show how an ISGM can be developed.

The predictive capacity of the ISGM remains vital for planners and urban stakeholders in LDC, who can begin to more effectively obtain information to gauge the future growth of unplanned areas. The visualisation of possible future expansion of IS could inform strategic planning, especially in the area of services, infrastructure, land management and urban policymaking. Such information can be even further improved if dynamic visualisation and animation of IS growth is incorporated into the planning process. Accordingly, the next section discusses how this dynamic visualisation (animation) can be created from the ISGM simulation outputs.

6.7 Dynamic visualisation of ISGM

One of the critical components of urban dynamic modelling in geography is to simplify the understanding of processes by facilitating their visual interpretation. An important part of such a dynamic visualisation and representation is to ensure that the processes are not represented in a static manner. The ISGM implements the dynamic visualization through the time-series animation of the simulation output. The practical aim of developing the dynamic visualization of the ISGM output is to allow a quick and easy appraisal of the expansion of IS patterns over time. Time-series functionalities such as animation are not readily available in most GIS environments.

By allowing the option of generating a simulation output according to a user-defined format, the ISGM provides the flexibility to export the data to the available animation medium to create either a movie or a simple map animation.

For this model, the IS macro generated the output in two different formats: Idrisi^{TM} format and *Bitmap* (*.BMP*). The time-series algorithm in Idrisi^{TM} failed to support the creation of the visual animation of the output layers from Idrisi^{TM} format files (.RST). It is worth noticing that before the automatic format conversion was developed and incorporated into the model, each Idrisi^{TM} output format was manually converted into a desktop publishing format such as .BMP. The automation of data conversion saved this tedious task of manual conversion, hence facilitating the creation of dynamic visualisation.

To produce dynamic visualisation of the output file, a desktop format, namely .BMP, was used. Two different approaches are used: visual animation in *MS PowerPoint*^{TM}, and the creation of movie files using a trial version of a video editing freeware, *VideoMatch*^{TM}. When creating the animation in PowerPoint, files are individually imported into the program, and then the time and order of each simulation are set in the *custom animation* window. There are options to add text and comment to the images as they appear on the screen. This method is an effective way to display in detail the growth of IS over time, and monitor trends in their expansion. Animation in MS PowerPoint^{TM} also has the advantage of showing the features clearly, and at the same level of detail as the simulated map. It is also easy to modify the timing and order to suit a specific audience. One of the disadvantages of this method is that the user requires a PowerPoint application to run the dynamic visualisation.

When creating a video using VideoMatch^{TM} (software freely available on the internet), individual files are imported into the program. The sequence of appearance and the duration of each appearance are then set by the user. The number of input files and the duration of each appearance determine the size of the video. One of the drawbacks of this method is that the file can be big and take time to be converted into a movie format. Unlike PowerPoint, the spatial resolution, and therefore the visual contrasts are lost during the conversion from .*BMP* to a movie format. Nevertheless, the user has a range of options to visualise and transfer the data.

The actual animation of the model output was important to expose the emergence of IS patterns at different parts of the map. Without the animation of simulated maps of Yaoundé for instance, the model would not have identified the need to suggest the three-phase development of IS to capture the change in IS growth at different periods. From the dynamic visualisation of IS emergence and growth in Yaoundé, it was possible to identify sections of the city (southern and western) experiencing rapid expansion of slums. It was also useful in rapidly correlating and recognising the central role of cultural and ethnic groups, road networks and topography in the IS growth mechanisms. This suggests that urban planners and policy makers could incorporate the dynamic visualisation of IS expansion in their quest to understand the *informalisation* process. Samples of animations are available on a CD ROM in the back pocket of this thesis.

6.8 Conclusions

This Chapter has presented the proposed IS Growth Model (ISGM) and tested the model in a real-world scenario using information on IS in Yaoundé, the capital city of Cameroon. The proposed model enriches the discourse on IS dynamics, which has long been dominated by descriptive approaches. The ISGM is primarily an attempt to test theories, hypotheses and factors of IS growth. In doing so, the ISGM has shown the potential to suggest answers to *What If* questions. For instance, what would happen if there was an introduction of a *boost* factor (such as main roads or market places) in an area dominated by a certain ethnic group? Various versions of the model have proven to be effective in investigating such hypotheses. The proposed model implemented various rules based upon constraint factors, probabilities, different stages, and various variables.

The various developmental phases of the model show its capacity to accommodate a significant range of variables and time-scales, and to generate relevant outcomes. Importantly, the model has been able to incorporate both physical dimensions as well as socio-cultural (such as places of worship, markets and ethnic groups). Whilst it was observed that there were some limitations associated with the socio-cultural factors, they could nevertheless be incorporated. This is an important outcome given that many models to date have been unable to sufficiently account for the role of such factors.

The proposed model has been gradually refined through the testing of various IS growth sub-models. In particular, expansion of IS was simulated under dominant factors such as the transportation network, topography, market and cultural groups. Further implementation on the dataset of Yaoundé has shown that the proposed ISGM is sensitive to data input and to the respective probabilities of different variables within the dataset. The results therefore suggest that the model can be beneficial for a better understanding of the intrinsic dynamic of IS over time, and its key contributors. The application of the ISGM in the study area has successfully simulated IS growth over time. The dynamic visualization of the output has the potential to significantly improve the understanding of the IS growth process. This indicates that the model is an appropriate way for investigating the geographic dynamics of IS, and the possibilities of using a framework that integrates GIS and cellular automata modelling into IS management approaches. The ISGM thus provides a good starting point for more sophisticated dynamic IS growth models.

Based on the theories and concepts elaborated in this Chapter, developers can now take the model to another level and expand it into software ready to be implemented in any computer environment that supports Visual Basic and raster GIS software. Moreover, urban planners in LDC now have a tool to test some of their assumptions about the probable growth of IS. Practically, planners in LDC can use the ISGM to weigh up their options and decisions. Similarly, governments and decision-makers can use the method to test and weigh up development hypotheses and strategies in order to improve strategic planning, particularly for service and infrastructure planning. This can potentially lead to a better use of resources, instead on spending on *post ante* strategies that cause more bottlenecks and perpetuate the burden of IS problems.

The ISGM has shown some relic ties due to local conditions. These relics from the model constitute exceptions to the general rules of IS expansion. It is therefore important to have local knowledge that helps explain and accommodate these exceptions. The flexibility of the proposed model does however provide a framework to take into account residual allocations appropriate to local conditions. Some of these residual allocations are the result of policies and economic conditions, model uncertainties which were not incorporated into the model. The next Chapter discusses the results of the testing of the model and uses these results to evaluate its usefulness.

Chapter 7

Informal Settlement Growth Model — Appraisal

7.1 Introduction

This thesis has developed an Informal Settlement Growth Model (ISGM) to assist the scientific community, as well as planning practitioners in Less Developed Countries (LDC), to better understand processes of informal settlement (IS) emergence and growth, and hence, to positively intervene through relevant policy and planning actions.

The previous Chapter presented the framework of the proposed ISGM and its application to a real world situation. Variables incorporated in the execution of the ISGM were tested, along with their respective rules and probabilities.

This Chapter evaluates the performance of the proposed ISGM. The aim of the evaluation is to ensure that the suggested model possesses a satisfactory range of accuracy consistent with the intended objectives and application of the research. The discussion of the ISGM performance is based upon the criteria suggested by Daniel and Vining (1983) and Giudici (2002), which includes ascertaining its reliability, sensitivity, validity and utility. The appraisal of the proposed model also considers elements such as the range of input variables, the accuracy of the output; the sensitivity of the variables used, the format of the output; the ability to incorporate a range of time lines and the predictiveness of the model, and finally, the usability of the model including its 'user-friendly' nature. Some of these criteria were discussed in Chapter Three where the literature made it clear that they are key benchmarks for assessing a model at this developmental stage (Agarwal *et al.,* 2000; EPA, 2000).

7.2 Reliability

Reliability refers to the quality and accuracy of the results provided by the model. Specifically, reliability checks the agreement and consistency of the results with the intended application of the proposed model. According to the literature, a computerised model such as the ISGM should illustrate the conceptual framework within reasonable accuracy limits (Bossel, 1994).

In the case of the ISGM developed in this thesis, reliability mostly depends on the quantity and quality of the data used and the accuracy of the projection of values into the future. In regard to these factors, the proposed ISGM has performed well. In a number of ways, it generated the expected outputs based on the data input, the rules and the probabilities.

First, the ISGM generated IS patterns according to the proximity to variables such as existing IS cell, topography, and road networks. It used existing urban land use as a constraint on the emergence of IS cells as suggested by the *Regional Urban Model* (Xia & Yeh, 1998; 2001). In terms of including variables that represent the emergence and growth of IS, the model was able to progress previous research (such as the Urban Growth Model presented in Chapter Five) by incorporating important socio-cultural factors such as ethnic and cultural groups, markets and places of worship. The inclusion of these factors into such a model in a LDC context has not been achieved before and therefore represents an important contribution and innovation in this area.

The second positive result in terms of reliability was the proposed model's ability to cope with the data requirements. The review of good urban dynamics models in Chapter Three made clear that the data must meet certain requirements to ensure the execution of the model. These requirements include the capacity of the data to be available, assessable, relevant, and flexible, and have the ability to be produced and re-produced. Chapter Three highlighted the fact that these factors have significant implications for the ease of collection, preparation, level of disaggregation, type of data and the ability for the data to have a time-series component, as well as for the number of files required. Compared to other existing urban dynamics models (e.g., UGM, TRANUS and CUF), the proposed ISGM developed in this thesis offers a flexible approach in several aspects of these core data requirements. Data used in the model is generally available in many LDC cities and include physical features (topography, delimitation of IS patterns, river course and transportation networks and other urban land uses) as well as socio-cultural aspects (cultural and ethnic composition, markets and places of worship).

Third, within the *Visual Basic* macro of the proposed ISGM, the time-series and the level of disaggregation can be easily customised to user-defined variables. This represents an innovation in the sense that it is flexible enough to be adjusted and therefore have the potential to be implemented in other contexts with flexible modifications. While the preparation of this data can be tedious and time consuming for an individual or a small urban planning team with little experience in GIS technologies, the ability of the proposed model to accommodate unlimited numbers and types of data constitutes an important advantage in comparison to other urban dynamics models such as UPLAN and UGM.

A fourth factor to be considered in terms of reliability is the model's capacity to provide dependable predictions of informal settlement growth and expansion. EPA (2000) considers the ability of a model to predict emergent patterns (as is the case for the proposed ISGM) as the prime objective of urban dynamic modelling. One of the objectives of this research was, therefore, to apply the simulation methods to informal settlements (as a system) in order to assess how they change over time, so that we may understand their spatial and temporal behaviour as well as their dynamic characteristics. In this regard, the proposed neighbourhood scale model was able to show, in relative detail and consistent with the input data, how unforseen patterns (in this case IS cells) would emerge and expand over time. The model's ability to show this emergence was assisted by its capacity to dynamically present or visualise IS. The model's capabilities were also successfully reflected in the case study. The application of the proposed model to Yaoundé indicates that it is possible to predict the future expansion of IS once the model has been successfully calibrated. To do so, the user modifies two main parameters of the model: *number of iterations* and *nett_pixel_gain*. The multiple outputs can then be compiled together to produce an animation of future expansion of IS.

There were, however, some limitations in the capacity of the Yaoundé data in terms of predictiveness, that should be noted. While the variation of input variables used in the ISGM has suggested that different scenarios can be generated from the datasets, rules and probabilities, this was not always the case in this example. In Yaoundé, the spatial coverage of road networks did not continue beyond a certain point, which means that it might not be possible to extrapolate beyond their current boundaries and make a reliable prediction. If this is the case, the prediction for 2001 might not exactly represent the IS reality in Yaoundé. That is, the long term prediction of future IS patterns would require up-to-date datasets, which were not available at the time this case study was implemented.

Despite this limitation, the predictive capacity of the ISGM is a useful resource for planners in LDC seeking to gauge the future growth of unplanned areas. In particular, visualisation of the possible future expansion of IS may better inform strategic planning, especially in the area of services, infrastructure provision, land management and urban policymaking. Dynamic visualisation of the ISGM outputs is a useful method for assessment and monitoring of IS growth. The information available to the planners and decision-makers can be further improved if the dynamic visualisation and animation of IS growth is incorporated into the planning process.

The fifth factor in terms of reliability is the model's ability to collect significant quantities of strategic planning data, such as the future spatial distribution of IS patterns, which are hardly ever obtainable in cities within LDC, particularly as IS are not incorporated into urban planning schemes. In that sense, the simulation of IS by the ISGM could allow planners and policy-makers to do a reliable preliminary *What if?* analysis with the purpose of assessing the system's behaviour under different conditions (especially those pertaining to the emergence and growth of IS), and evaluating which alternative policies should be adopted. This is an important development in terms of providing a more dependable system on which to base important urban planning decisions in response to IS dynamics than the piecemeal post-hoc responses governing current practices as discussed in Chapter Two.

Two final issues must be discussed in terms of the reliability of the model's capacity to incorporate and predict certain forms of human behaviour and simulate other IS contexts in LDC. In regard to human behaviour, the application of the proposed ISGM to Yaoundé has shown that the choice of key IS growth factors including socio-cultural factors, the definition of rules and the application of sound probability estimates, significantly improved the calibration of the predicted output. However, the model does not take into consideration other important factors, such as changes in urban policies, or the behaviour and motivation of urban dwellers, government bureaucrats and politicians. These factors could have improved its performance if it was possible to develop an appropriate way of incorporating such parameters into an IS modelling context.

In regard to the model's dependable applicability to other urban contexts, if time had allowed, it would have been appropriate to test the proposed model on another LDC city where IS prevails. This would have enabled a further check on the model's capacity and suitability for predicting such growth in LDC.

7.3 Sensitivity

Sensitivity assesses the behaviour of the model whenever changes are made to its properties, structure, configuration and inputs. In the case of Yaoundé, the ISGM has clearly demonstrated that modification of the configuration of the model is reflected in its output. For instance, the output of a road-based ISGM was different from the combination of river and road calibration output. The ISGM tested various hypotheses about IS, especially when different key factors were progressively added to the model. In that respect, factors such as main roads, vacant land, cultural and ethnic groups, topography and market places appear to be the most sensitive variables correlating with the emergence and expansion of IS. By contrast, enclosed and protected areas, such as military camps and airports were shown to inhibit and deter the exponential growth of IS, proving these variables to be accurate examples of predictors of areas from which future IS would be excluded.

Different levels of sensitivity were partly embedded into the ISGM configuration, formulation and assumptions. For instance, a new IS cell would only occur on vacant or available land. Also, new IS would only emerge at a certain proximity to existing IS. Similarly, the proposed model reacted accordingly when the proximity factor was refined to capture the essence of IS growth towards the river course, in contrast to other variables, such as roads, where growth occurs along the road and spreads outwards, possibly at different stages.

To improve the simulation outputs, the ISGM also implemented three levels of probability: general, local and timeframe-dependent (which assigned different probabilities for each of the three periods within the simulation timeframe). The application of the ISGM to Yaoundé showed that the modification of any of these probabilities reflected on the overall calibration outputs.

The proposed ISGM was developed with the assumption that all types of features (points, lines and polygons or areas) would have a similar simulation response. The application indicated that although the calibration process properly captured line and area features, point features, however, performed poorly. To correct the misrepresentation of point features, they were represented as an area. However, there may be ways to improve the representation of point features in future versions of the model.

The application of ISGM to Yaoundé indicated that the model could be a useful tool for generating different scenarios of IS expansion that could ultimately serve as a decision support in urban planning. The sensitivity of the model to adjustments to its rules, and to the selection and weighting of variables allows it to predict the possible direction and extent of IS growth under a variety of future conditions. Thus, by testing and comparing the results of different scenarios, urban stakeholders can make informed decisions about the management of probable emergence and growth of IS and, more importantly, can take proactive measures to curb the negative ramifications of informal settlements.

The next section discusses the validation of the proposed model.

7.4 Validity

Validity assesses how the output agrees with the conceptual framework of the model. Two main methods are commonly used to validate urban dynamic models: quantitative (measures of match) and qualitative (pattern recognition) (Torrens & O'Sullivan, 2001). The quantitative approach uses statistics tests such as *chi-squared*, *confidence intervals*, *kappa-statistics* and *fuzzy logic* to assess the goodness-of-fit. On the other hand, the pattern recognition approach uses techniques such as graphical validation to assess the simulation output. Both were used to assess the validity of the model.

Qualitative method was used because when GIS and CA are used as a modelling and simulation tool for the decision-support or decision-making process, government officials and urban planners, for example, are more likely to use the qualitative judgement and perception, rather than the quantitative representation (Couclelis, 1997). Moreover, Willmott and Gaile (1995) demonstrate that graphic comparison is one of the best ways to evaluate model fit. In a qualitative scenario a better qualitative distribution of IS patterns was therefore produced, partly because the quantitative calibration of the new IS cells was dealt with in the ISGM configuration.

Quantitative validation of the model involved using the VALIDATE module in *Idrisi* to measure the level of precision of each simulation. It was shown in Chapter 6 that the precision of the outputs increased with the sophistication of the model. For instance, the implementation of the ISGM on Yaoundé clearly demonstrated how accuracy of prediction improved from 43% (version 1) to 72.7% (version 8). Nevertheless, future development of the ISGM could well benefit from the incorporation and strengthening of the statistical analysis and evaluation built within the program itself.

The qualitative validation used the visual or graphic comparison between the simulated map (1988) and the final or target year (1988) to assess the *best fit* IS patterns on the simulated map. This method consists of displaying the simulated final year map and the current target year. If the distribution of IS patterns is very different on the two maps (simulated and real), then the variables are modified to generate another scenario. In that way, different versions of the model were developed to reach a point where the simulated map was as close as possible to the reality map. This method was refined using a 'trial and error' approach.

The ISGM uses a heuristic calibration approach, which consists of altering one parameter, variable or value at a time, and then running the simulation to observe the results. While this 'trial and error' approach is sometimes tedious and time consuming, the necessity for such work could be reduced as the model is developed. Although the graphical validation and animation enable researchers to represent the transient dynamics of the model and thus prove useful in terms of pedagogy, in terms of model adjustment and the visual appreciation of IS behaviour, they do not, however, provide a full validation of the model. To achieve a better validation, it is necessary to be able to calibrate the proposed ISGM on the basis of several other real situations, for example on different cities in LDC.

It is worth mentioning that the calibration procedure (module 2) of the ISGM controls the number of pixels to be transformed between the base year and the final year. Unlike other urban dynamics models, the ISGM has the advantage of ready-built-in calibration modules named *Nett_pixel_gain* and *threshold*. These two modules regulate the parameters of the model and verify their accordance with the starting and ending years. It was useful to implement an internal pixel calibration, because it was then possible to control the number of pixels created between the base year and the final year (see 6.2.3). A similar approach could be used to automate the location accuracy of the simulated map.

At the fundamental level, the calibration results showed that it is possible to combine the GIS and CA approaches to simulate and predict IS dynamics. One of the advantages of the implemented loose coupling between the flexibility of CA (*Visual Basic macro language*) and the graphical facilities of a GIS environment is that it makes it easy to build models from scratch, maintain models, modify probabilities and explore what happens if the model mutates its structure due to new information, or due to spatial and temporal changes. This ability constitutes one of the most important characteristics of operational urban dynamic models as discussed by Agarwal *et al.* (2000).

In particular, the proposed model has demonstrated the main driving forces behind the expansion of IS, as well as showing their respective weights at different stages of urban development (Sietchiping *et al.*, 2004). Significantly, the model was able to successfully incorporate a number of socio-cultural characteristics. This is an important development given that most models have tended not to grapple with these important aspects that define human settlement. The capacity to combine physical changes with socio-cultural aspects is also important in terms of increasing our understanding of IS behaviour in order to improve urban planning responses. This knowledge is especially vital for urban planners and governments so they can better anticipate the emergence of future IS. It means that on a practical level, urban policies can be tailored to monitor the expansion of IS in a particular direction, by acting upon the attractiveness of the prevalent criteria such as road, cultural neighbourhood and economic centres. However, the results of the ISGM could not be compared with other models' results, only because such similar IS models do not exist.

7.5 Utility

The utility of the proposed model will be assessed considering its useability, efficiency and generality. Useability refers to the efficiency and generality of the model. Efficiency refers to the model's precision given time, equipment and expertise limitations. Generality will assess the extent to which a proposed model can be successfully applied, with minor modifications, to a wide range of contexts and cities. The proposed ISGM model developed in this thesis displays a number of important utility improvements in comparison to other models, which increase its capacity to be relevant to planning in LDC.

Compared to other urban dynamics models, the ISGM is a *low cost* model (Wyatt *et al.*, 2002). The source can be obtained free of charge from the author. That is, the source code of the proposed model can be made accessible, adapted and modified by the potential user or developer. Other mechanisms will be investigated to make the program widely available to any person who might be interested, within the academic regulations. The expensiveness of the urban dynamics model in general, first discussed by Lee (1973), remains one of the most recurrent criticisms of existing operational urban dynamic models (Klosterman, 1994; Wegener, 2000). In Chapter Three, the affordability of the urban dynamics model was one of the selection criteria considered. Additionally, the assessment of existing urban dynamics models in Chapter Four clearly indicated that fees attached to some modelling packages such as *TRANUS*, *SmartPlaces* and *What If?*, constitute a serious limitation to the implementation of a similar approach in other contexts. In addition, some urban dynamic modelling packages still operate as a 'black box', with restricted access to their sources code which again limits their accessibility to a wide range of users. The proposed ISGM developed in this thesis alleviates these restrictions and can serve as a stepping-stone for further improvement and adaptation. For planning institutions in LDC, which often cannot afford expensive program and add-on fees (for instance training, hardware and software), the ISGM presents a cost effective tool for the informed management and planning of fast growing cities. Additionally, the portability of the proposed model between GIS packages (that is, its capacity to be independent from the software package) brings another flexible dimension to the model.

Another significant criticism of existing urban dynamics models is their data hungriness (Lee, 1994). The proposed ISGM model provides a flexible environment where the user can incorporate the desired and available number of data. Also, there is no set minimum or maximum number of rules or parameters to run the ISGM and yet maintain the essential IS growth variables such as proximity to existing IS, cultural and ethnic groups, transportation network and topography. These arrangements provide another flexibility to the proposed model, in comparison to other urban dynamic models such as Urban Growth Model (Clarke & Gaydos, 1998), which accepts up to five categories, and Urban and Regional Development Model (Xia & Yeh, 2001), which accepts two classes (urban and non urban).

A further flexibility factor the model displays is its capacity to run fast, be quite flexible in regards to data input and be monitored in a range of ways. In other models, UGM for instance, the results are only available at the end of a lengthy operation, whereas in ISGM, a toggle point can be added to the Visual Basic macro command line to monitor the behaviour of the program. The program can be suspended at any time to make changes or view the available output. Additionally, the output of the calibration is immediately available and displayed on the GIS environment thus making monitoring and change substantially easier.

Another advantage of the ISGM in regard to utility is that the conversion of data format (for instance from *Idrisi*^TM^ format to *ascii* and then to a range of graphics formats is embedded into the program, and so avoids the tedious and time-consuming task of manual conversion that other urban models require. Other urban dynamics models do not provide the same level of flexibility in this regard. For instance, UGM requires that the input data be converted into a unique program coding name, and the output is limited to *.GIF* format. Moreover, compared to other urban dynamics models, the ISGM provides the option to create and apply user-defined colour palettes. The user can, therefore, employ a specific colour to stress or offset some facts or events that the default colour palette in much software does not necessarily provide. Similarly, the output format of the calibration can be displayed with the user-defined format (e.g., *.BMP*, *.GIF*, *.RST*), whereas other urban dynamic models, such as *What if?* and UGM, do not provide this level of flexibility in regard to the output format.

In terms of *equipment*, the ISGM is versatile and can be implemented on a standard computing platform with a *Visual Basic* application, and user-nominated raster GIS software. To successfully implement the program, it is desirable that the user has access to a computer with sufficient Central Processing Unit (CPU) capacity. The speed of the computer in use will definitely improve the performance and the running time of the ISGM macro. It is also recommended that the user have an understanding of desktop publishing software, especially when it comes to creating a dynamic visualisation from the output data. The proposed model was developed taking into consideration the fact that commercial GIS software tends to be expensive and not always available for planners in LDC. The versatility of the proposed model to use raster data (during data preparation, for data analysis and for visualisation) imported from and exported to other applications constitutes an improvement in the operational urban dynamic modelling.

A further advantage of the ISGM in relation to utility is that it has the potential to be implemented in other settings at the present stage with minor modifications. The testing of the ISGM on Yaoundé clearly showed that the model has the potential to be successfully used to explore the expansion of IS in other cities of LDC. Nevertheless, the viability of the proposed model would be even greater if the program were converted into menu driven software, to make it user-friendlier and thus increase its applicability and flexibility in different contexts.

In terms of personnel and expertise utility requirements, a successful implementation of the proposed ISGM requires knowledge of GIS technology and its applications, Visual Basic programming language, informal settlement dynamics, and cellular automata concepts. At its current level of development, the lack of prior knowledge in these areas could limit the successful implementation of the proposed model by the potential users. However, the conversion of the proposed model from a command-line to window-driven software would make it more accessible and available to a larger audience, and prior knowledge of Visual Basic programming, for instance, would become unnecessary or optional. Such a conversion could be undertaken while ensuring that the potential developer still has the option to access the source code to make any necessary modifications that could enhance the application.

Another usefulness of the ISGM is its ability to generate multiple outputs for dynamic visualisation. This makes it a very useful tool for sketching the overall framework of IS patterns in a given city. The multiple outputs provided by the model facilitate the creation of visual animations or 'movies' of IS dynamics, thus allowing better insights into the behaviour of IS patterns. For example, with the visual animation component of the proposed ISGM could be particularly useful for pinpointing the directions of IS spread, such as its expansion along highways, for instance. The ISGM also outlines the overall framework of a more sophisticated IS dynamics model. Similarly, the proposed model can allow the rapid simulation of different development scenarios, which could greatly improve interaction between urban stakeholders when assessing IS developments. In particular, the proposed ISGM can serve as a reliable tool for participatory planning, whereby IS stakeholders could use their expertise to evaluate and discuss alternative measures and plan ahead. In the case study of Yaoundé, the ISGM allowed the rapid simulation of different types of growth. Access to such information could greatly improve communication and interaction amongst government officials, planners, private sector and IS communities. This is of paramount importance for proactive strategic planning that can anticipate the future location of IS and then act before they become widespread.

The review of IS policies and strategies in LDC in Chapter Two has demonstrated that the lack of proactive measures to provide basic services and infrastructure before the expansion of IS leads to expensive and inefficient strategies that in turn, do not mitigate the expansion of new IS. It is not, therefore, surprising that IS remains predominant in most LDC cities and is associated with rapid, unstructured and unplanned expansion, conflicting land tenure and property rights, poor-quality dwellings, decay of the physical environment, severe social problems, and low socio-economic status for IS occupants. The proposed ISGM would help foresee and prevent such problems. For instance, such a model could anticipate the location of IS, thereby indicating what type of services and infrastructure will be needed prior to the settlement of urban dwellers in the identified future IS areas. In addition, the simulation of future expansion of IS could support businesses in expanding their activities. Providers of services, such as telecommunication, transportation, property development, education and health, will gain an advantage by developing their business plans based on the probable location of IS.

7.6 Limitations of the proposed model

The proposed model was developed primarily to test its capacity to reflect and capture the emergence and growth of IS according to the theories, hypotheses and practical examples of such developments. The previous section outlined the capacities and benefits of the ISGM model across a range of key assessment criteria. This section discusses some of the limitations of the model.

One of the limitations of the model relates to using a cell-based (bottom-up) approach in an IS dynamic model in order to predict development. Cell based methods make it difficult to accommodate 'top-down' interventions and other uncertainties that also influence the expansion of IS. Some of these top-down interventions include (but are not limited to) general conditions (economic, political and financial issues), local and regional urban policies (for example the decision to build a regional or national highway could change the direction of growth of IS). Additionally, the implementation of the cell-based simulation showed that applying probabilities and rules as a whole made it difficult to design an IS model where important behaviour of model components would not be lost in the overall evolution. In the future, a comprehensive IS simulation model could incorporate other techniques, such as multi-agents, with cellular automata and GIS. The multi-agent approach would allow for the behaviour of individuals within the predictive modelling by the next generation ISGM, whereas CA would address general behaviour and GIS would be used to prepare and organise the data and display the outputs.

The second limitation of the proposed model is in relation to the lack of statistical outputs. It was noticed that a module similar to VALIDATE (in Idrisi) could have been built into the ISGM and would automatically generate the statistics on location accuracy. Such a module would have saved precious time in reclassifying the outputs before assessing the location precision. In the case study of Yaoundé, the constraints incorporated into the framework guided the simulated emergence and expansion of IS so that the mapped simulation output accorded with the path and shape of the target year. Despite these precautions and the heuristic calibration of the model, it was observed that the exact location of the IS was not always replicated. It was noted, however, that graphic calibration could actually be supplemented by statistical calibration. Internal statistical evaluation would have helped to easily identify where particular changes were needed. If time had allowed it, a statistical module would have been incorporated into the model. A rigorous statistical calibration of the ISGM constitutes another area that needs to be explored and incorporated into the IS model evaluation.

The third limitation of the proposed model is the lack of testing, as yet, on other cities. This was constrained by time and resources. A full validation of the model will largely depend on the application of the proposed model to other cities experiencing rapid expansion of IS. In the future, it is the intention of the author to improve the current version of the model and to make the program generally available to other researchers interested in the investigation of IS. It becomes also clear that, considering the potential of the proposed model, a research and development team with additional expertise would be a good way to take the ISGM to a much more operational level.

Finally, to improve the user-friendlessness of the proposed model, the current command-line version can be developed into menu-driven software. The macro could also be made more sophisticated with the assistance of well-skilled programmers, preferably in a multidisciplinary research setting to maximise its design, availability and application in different cities.

7.7 Conclusions

In conclusion, this Chapter has highlighted the important contribution the ISGM model developed in this thesis has made to understanding and predicting IS in LDC. The Chapter has also examined the model's limitations and proposed a number of ways these limitations can be addressed.

In summary, the Chapter has made it clear that GIS technology can be loosely coupled with the CA approach to simulate the behaviour of IS dynamics. The *Visual Basic* language used for the simulation allows considerable versatility and flexibility to the ISGM, and provides the user with full control (customisation) over the modelling and simulation processes. The ISGM embodies the logic of IS growth, sheds light on human settlement behaviour in LDC and in doing so, helps urban researchers to better understand the processes of unplanned expansion in order to inform planning.

The proposed ISGM represents an important contribution to the 'state-of-art' of informal settlement dynamics and urban planning in cities within developing countries. The evaluation of the proposed model based upon its sensitivity, reliability, validity and useability has indicated that the ISGM can potentially improve the urban planning and decision-making processes that would lead to the improvement of the quality of life in developing cities.

Importantly, the model adds to the capacity of key stakeholders to plan for IS because it enables the incorporation of a larger range of variables than can be handled by existing modelling software used in urban planning. In particular, it allows the inclusion of socio-cultural characteristics that are vital to understanding human settlement behaviour. In doing so, it could be argued that the model begins to challenge the assumption that models cannot be used to predict human behaviour because they cannot negotiate such action. The presented model shows that, within certain boundaries and recognising its limitations, important human dimensions and characteristics can be incorporated into a simulation environment. In particular, some of the major contributions of the proposed model include flexibility and versatility in data handling (input and output), portability, and the inclusion of ethnic and cultural dimensions in the urban dynamic modeling framework.

This Chapter has also shown the application of dynamic simulation to IS growth to be extremely promising, yielding a variety of valuable information concerning the way IS emerge, grow and change, and more importantly, the way they might be 'planned' and managed.

The proposed model possesses some limitations that can be overcome, especially in the setting of a research team with the resources to carryout further software development and multiple testings on a range of real-world scenarios. The proposed model is at an early stage and so has room for further improvement, especially in the area of fine-tuning the model, improving its user-friendliness capacity, increasing the rigorousness of the design and the execution of the calibration algorithms, and finally, developing a menu-driven interface.

Based on the evaluation and limitations of the ISGM discussed in this Chapter, the next Chapter concludes the thesis. It first outlines the main findings of the research and then suggests possible directions for future work.

Chapter 8

Conclusions

The aim of this research has been to develop a model for exploring the emergence and expansion of informal settlements (IS) in less developed countries (LDC). To achieve this aim, five main areas were covered: IS discourses and policies, the review of the state-of-the art in urban dynamics model, the attempt to use Clarke's Urban Growth Model to explore urban dynamics and assess its ability to simulate IS in LDC, and the development of a dynamic expansion of IS. The previous Chapter evaluated the performance of the proposed Informal Settlement Growth Model (ISGM). This Chapter first provides a summary of the thesis, then presents the main contribution of the work, and finally indicates directions for further research.

8.1 Summary of the thesis

This thesis has demonstrated that it is possible to predict the emergence and growth of informal settlements (IS) patterns within the boundaries of known contextual variables such social, cultural, economical, physical and infrastructural factors; and with the assistance of computing techniques. Simulation and modelling approaches of this type are of great importance for at least two reasons: first, because rapid expansion of IS is a growing problem in most cities in LDC for various and complex reasons; and second, because it has been demonstrated that the poor performance of past and current attempts to curb rapid expansion of IS has caused new problems while failing to adequately resolve existing ones. This suggests a need for new strategies that can be inspired by complex urban systems and computing technologies. This research has proven that such new approaches could be based upon simulation and modelling techniques, as tools that could ultimately help decision makers and IS stakeholders in cities in LDC to improve their understanding and management of IS growth.

This thesis has reviewed existing urban dynamics models and concluded that it was possible to build on existing conceptual and theoretical frameworks by loosely coupling Geographic Information Systems (GIS) and cellular automata (CA) techniques.

In doing so, the ultimate aim was to propose an informal settlement growth model, which would inform and enrich the discourse on the problematic and rapid expansion of IS in LDC. After discussing issues and criteria to consider for the development of a dynamic urban model in the context of developing countries, it was concluded that such models would utilise factors pertaining to the emergence, existence and expansion of IS, and would then highlight the importance of dynamic visualisation techniques in advancing the knowledge of emergence and growth of IS patterns. An attempt was made to adapt Clarke's Urban Growth Model to the context of LDC' cities, which was unsatisfactory. This research finally developed a loosely-coupled GIS and CA Informal Settlement Growth Model framework as the basis for a predictive modelling programme, which was written in *Visual Basic macro*. The application of the ISGM to Yaoundé (Cameroon) was then presented and discussed and the overall assessment of the model performance was analysed. The next section presents the main contribution of the thesis.

8.2 Research contributions

The Informal Settlement Growth Model proposed in this research constitutes an innovative contribution to the theoretical knowledge and practical capacity of urban dynamics modelling, especially in the following areas:

- Developing a useful and relevant model framework for the simulation and prediction of IS in fast growing cities of LDC as a tool for strategic urban planning;
- Integrating GIS and cellular automata technologies to develop an understanding of the factors underpinning the IS dynamics, particularly their growth and spatial expansion;
- Increasing the flexibility and versatility of the data input and output, automatic file conversion, transferability of and accessibility to data in a loose coupling between GIS and cellular automata environments;

- Incorporating ethnic and cultural variables in urban dynamics modelling to show that within certain boundaries, human dimensions and characteristics can be incorporated into computerised urban dynamic models;
- Demonstrating the importance of incorporating dynamic visualisation (or animation) into the model to improve the visual expression of IS emergence and growth;
- Providing a tool to enable a deeper understanding of IS dynamics in the cities of LDC, particularly in terms of the practical responses to their growth and expansion.

These capacities of the proposed ISGM indicate that it has the potential to identify and predict the likely location of IS, based upon the criteria of their emergence and growth. This predictive capacity has been achieved because the ISGM embodies the logic of IS growth, shedding light upon human settlement behaviour in LDC. Furthermore, the simulation and dynamic visualisation capacity of the proposed model provides a new possibility for planners and policy-makers to undertake a preliminary *What if?* analysis with the purpose of assessing probable IS behaviour under different conditions and evaluating which alternative policies should be adopted. In so doing, the model can help urban researchers to better understand unplanned expansion in order to inform the urban planning processes.

The proposed ISGM also provides an indication of how modelling and simulation approaches can help urban planning in areas such as urban growth management and monitoring, and urban policy appraisal. Importantly, the proposed model has the potential to improve strategic and participatory urban planning in LDC cities, involving various urban stakeholders (e.g., planners, policy-makers, IS dwellers, private sector stakeholders, non-government organizations and international institutions).

Considering the original objectives of the research and the specifications of the proposed model, the aim of this research has therefore been achieved, especially in using new spatial technologies to model and simulate how IS emerge and grow.

8.3 Recommendations for future research

The model developed in this thesis has also inspired ideas and new opportunities for further research and improvements. The recommendations for further research stems from the application of the proposed model, its evaluation and limitations. Three major areas yield special attention: hybrid modelling, uncertainty and complexity assessment, and the operationalisation of the ISGM.

- The first potential area for investigation concerns the incorporation of *agent-based models* into the IS simulation process. The cell-based simulation and modelling approach implemented within the proposed ISGM draws from a bottom-up approach. However, it has become clear from this research that informal settlers, policy-makers and NGOs are all involved in the emergence and growth of unplanned developments. For instance, planning restrictions, together with urban infrastructure such as highways, are implemented from a top-down perspective, and do not necessarily emerge from a local perspective. It would therefore conceptually enrich future versions of the ISGM to be able to incorporate or account for such decisions and changes that affect IS expansion via a hybrid approach (for instance, GIS, cellular automata and agent-based models), whereby the two approaches (bottom-up and top-down) are encompassed within a single simulation and modelling package. While the incorporation of these top-down decisions into a modelling scenario could be somewhat problematic given the eclectic nature of individuals and politics, the hybrid approach has some potentialities to develop in the sense that one will gain better insights into IS dynamics by incorporating *multi-agent* behaviour into the socio-economic and physical conditions of IS.

- The second area of potential research is in relation to the measurement of the level of uncertainties and complexities. This research has shown that there are limits to predictions and simulations. Testing a predictive model against known real-world outcomes yields some unknown factors that were not taken into account, but which could be measured to assess their level of contribution to the process. Future research could look at how to assess, specifically evaluate, quantify and visualize the degree of uncertainties in IS modelling. Such research could investigate how the 'non-predictable' factors (uncertainty), such as future political decisions and social instabilities, could be considered in future models; and how they influence the overall output of the model.

- Finally, at the operational level, the current ISGM could be developed from this foundation and refined into a more sophisticated, popular and user-friendly version. It would then become a very useful resource for urban planners in cities in LDC with limited knowledge of programming and cellular automata techniques, who could implement the model without being frustrated by the technicality of the programme. Although this research did not aim to develop readily useable software, the development of a menu-driven version of the proposed model has emerged as a useful avenue to explore in the future, preferably in multidisciplinary research and development team settings. This move would yield several benefits such as a greater accessibility to audience and practitioners in LDC, improved ease of use when testing the model on other cities, knowledge sharing, and increased commercial potential, as well as providing a more useable and comprehensive tool for urban planners and decision-makers.

These recommendations are only preliminary sketches, but they serve to show that there is significant scope for discussion and further research on the topic of informal settlements, urban stakeholders and the integration of urban dynamics modelling into the planning process.

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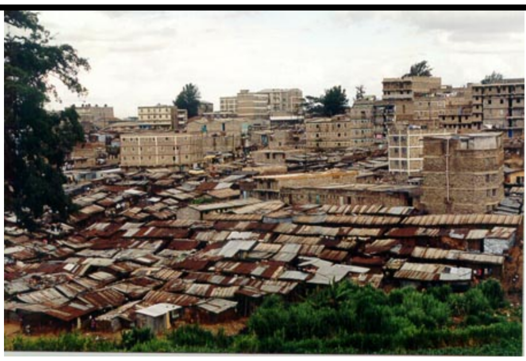
Appendix 1

Photos plate: multiple facets of informal settlements



Some slums are centrally located (Matthare valley, Nairobi)

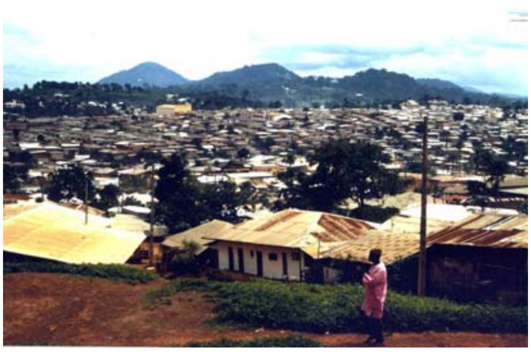
Informal settlement on a dumping site (Payatas, Manila)

Informal settlements are subject to demolition (Bombay)

Slum dwellers live in poor environment (Nairobi)

No access to clean water or sewage system (Bogota)

Environmental threat (Elobi, Yaoundé)

 Extent of informal settlements (Mélen, Yaoundé)	 Informal settlements (MvogMbi, Yaoundé)
 Demolition of informal settlements in a student residential area (Bonamoussadi, Yaoundé 06/10/02)	 'Exodus' of the victims of the demolition (Bonamoussadi-Yaoundé 6/10/2002)
 Commercial activities in slums—before the demolition (Bonamoussadi, Yaoundé)	 Demolition can be very brutal and mean heavy loss for informal settlement investors (Mumbai)

Appendix 2

Estimates of Informal dwellers as a Percentage of Total Population in Selected Cities

City	Year	%	Year	%
Algiers	1954	33	-	-
Amman	1974	12	-	-
Ankara	1968	65	1970	65
Baghdad	1965	29	1970	25
Bangkok	1970	20	-	-
Blantyre	1970	56	-	-
Brasilia	1962	41	1970	41
Buenaventura	1964	80	1969	80
Cairo	-	-	1998*	92
Calcutta	1970	33	-	-
Caracas	1961	21	1969	40
Casablanca	1970	70	-	-
Colombo	1973	57	-	-
Dakar	1970	60	-	-
Dar-es-Salaam	1967	34	1970	50
Delhi	1968	14	-	-
Hong Kong	1970	10	1979	10
Istanbul	1970	45	-	-
Izmir	1965	35	1970	65
Jakarta	1961	25	1971	25
Kabul	1968	21	-	-
Karashi	1961	33	1970	23
Kinshasa	1970	60	-	-
Kuala Lumpur	1961	25	1971	37
Lima	1970	40	1998*	53
Lusaka	1967	27	-	-
Manila	1977	35	1998*	57
Mexico	1966	41	1970	46
Oran	1954	33	-	-
Port-au-Prince	-	-	1998*	68
Rio de Janeiro	1961	21	1973	20
Saigon	1970	35	1973	26
Santiago	1964	24	1973	17
Seoul	1970	30	-	-
Singapore	1966	15	1970	30
Tunis	1960	16	-	-

Sources:
Drakakis-Smith D., 1981, *Urbanisation, Housing and the Development Process*, P.58
* de Soto, H., 2000, *The Mystery of capitalism*, pp251-4
-: Data non available

Appendix 3

Percentage of active population employed in the informal sector in 20 different countries between 1975 and 1998

Country/Year	1975	1980	1985	1990	1998
Benin	37	42	60	67	75
Burkina-Faso	40	45	62	65	74
Cameroon	33	37	55	63	72
Colombia	31	39	57	62	68
Ivory Coast	27	31	51	59	68
Ghana	38	42	63	68	73
Haiti	41	47	66	71	80
India	37	42	55	62	69
Kenya	33	39	61	65	70
Madagascar	38	43	63	68	72
Mali	40	45	61	66	74
Mexico	28	34	50	53	60
Nigeria	38	43	59	63	70
Niger	42	46	64	69	75
Philippines	38	43	64	70	71
D.R. Congo	35	42	65	73	82
Senegal	29	35	53	64	71
Thailand	21	32	41	47	54
Togo	43	48	64	69	74
Vietnam	37	40	53	61	69

Source: Kengne, 2000, pp. 25-26

Appendix 4

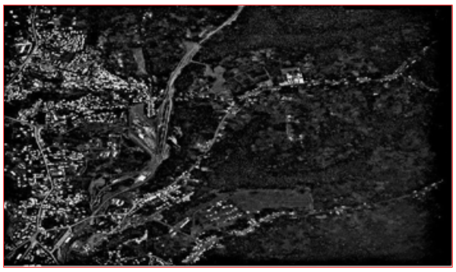
Duration for the acquisition of a land title in selected cities in LDCs

Country/City	Steps	Years	Bureaucratic procedures	Sources
Lima	728	> 6		de Soto, 2000, pp.18-28
Manila	168	13-25	98	Opcit.
Cairo	77	5-14	31	Opcit
Port-au-Prince	111	>11	65	Opcit
Accra	24	>10	-	Farvacque & McAuslan, 1992, pp.V
Yaoundé	-	>5	-	Opcit.
Malaysia	55	>5	-	World Bank, 1993, p.85

-: Data not available

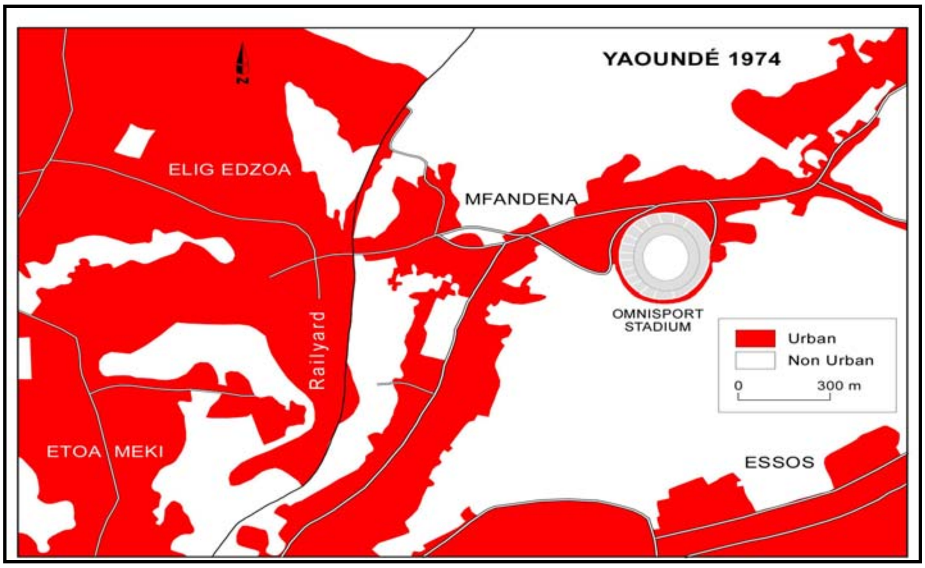
Appendix 5

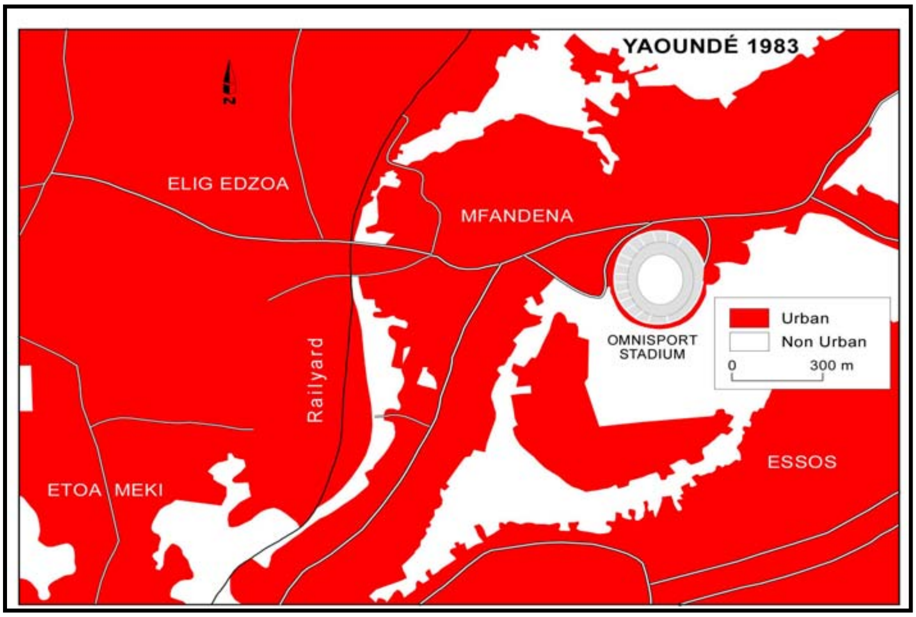
Using aerial photographs for mapping urban IS expansion



1974

1983





Appendix 6

Definition of terms in UGM 2.1

Definition of Control Statistics Scores

For all scores, 1 represents the exact match of modelled to control data. The closest the value to 1, the best the model reflects the changes. In UGM 2.1, the log file *control.stats* produces the following scores that can be sorted.

Definitions below are provided by the program.

1. composite score : All other scores multiplied together.
2. compare : comparison of modelled final population* to real data final population count.

   ```
   if (target > actual){
   compare = actual/target;
   } else {
   compare = target /actual;
   }
   ```

   where: target = real data value and actual = modelled data value
3. r2 population* : least squares regression score for modelled urbanization compared to actual urbanization for the control years
4. edge_r2 : least squares regression score for modelled urban edge count compared to actual urban edge count for the control years.
5. r2 clusters : least squares regression score for modelled urban clustering compared to known urban clustering for the control years
6. mean_cluster_size_r2 : least squares regression score for modelled average urban cluster size compared to known mean urban cluster size for the control years
7. leesalee : a shape index, a measurement of spatial fit between the model's growth and the known urban extent for the control years
8. average_slope_r2 : least squares regression of average slope for modeled urbanized cells compared to average slope of known urban cells for the control years.
9. pct_urban_r2 : least squares regression of percent of available pixels urbanized compared to the urbanized pixels for the control years.
10. xmu_r2: (center of gravity (x)) least squares regression of average x_values for modeled urbanized cells compared to average x_values of known urban cells for the control years.
11. ymu_r2: (center of gravity (y)) least squares regression of average y_values for modeled urbanized cells compared to average y_values of known urban cells for the control years.
12. sdist_r2 : standard deviation averaged over (XY)
13. lu_value** : a proportion of goodness of fit across landuse classes

    match_count / (match_count + trans_count)

    where: match_count = number of per pixel land use matches between modeled and real data and trans_count = number of per pixel land use non-matches between modeled and real data

    if land use is not being modelled lu_value = 1.0

* *Population indicates # of urban pixels*

*** Land use category was not used in the application of Yaoundé; therefore the output was constant (1) at all iterations.*

Definition of five control parameters

Diffusion coefficient sets the probability of the distribution of cells from the starting point.

Breed parameter introduces the likelihood of the state of the cell at the next generation.

Spreed coefficient estimates the amount and tendency of new development from the existing development.

Slope resistance factor calculates the constraint for new urban cells to develop on stepper slopes.

Road gravity coefficient estimates the attractiveness of new urban cells along the communications networks (road or rail). The values of these factors are input in the model before processing the calibration.

Appendix 7

A draft of a version of the Informal Settlement Growth Model (ISGM) written in Visual Basic

```
*************************************************************************
Sub Macro1()
'Macro was initially written by Dr. Ray Wyatt, but extensively modified by Remy Sietchiping. Dr.
Hemayet Hossain developed the loose coupling and display commands of the macro.

' This macro runs a cellular automata model, on Idrisi, using "if" statements below
' It works off a 1975 map and a 1988 map, so that the pixels in the informal settlement land use
classification
' change by a controlled number each year to eventually attain their true numbers by 1988

'Land use 1 = Vacant; 2 = Public Domain; 3 = Administrative; 4 = Military; 5 = University;
' 6 = Commercial/Industrial; 7 = Planned residential 8 = Informal; 9 = Periurban Village;
' 11 = Markets; 22 = Rivers and Lakes; 23 = Road; 24-33 = Slope Values; 34 = Chapel;
' 44 = Major Road;  45-50 = Cultural and ethnic groups; 51 = Airport runway;  52 = Proposed ring
road; 53 = Railway

Dim prefix As String, tempstr1 As String, tempstr2 As String, tempstr3, tempfile1 As String,
tempfile2 As String
Dim tempstr4 As String
Dim temppalette As String, success As Integer, cols As Integer, rows As Integer, co As Double
Dim j As Integer, k As Integer, l As Integer, m As Integer, n As Integer, jj As Integer, kk As
Integer, jk As Integer, jl As Integer, jn As Integer
Dim closest(53) As Integer, Annual_target As Integer, Annual_change As Integer, cmdstr As
String
Dim former_change As Integer, Iterations As Integer, ending As Integer, tempdouble As Double
Dim neighbourhood As Integer, Nett_pixel_gain As Integer, Probability As Double, tempprob As
Double

'***   Set calibration parameters
'columns and rows refer to the map image; Iterations = number of chunks of time into which the
'period, between base year (1975) and final year (1988), will be divided;
'pixel_gain is no of extra informal settlement pixels

5   rows = 250: cols = 313: Base_year = 1975: Iterations = 13: Nett_pixel_gain = 7493

'   --> -->   Set neighbourhood search radius here
neighbourhood = 3
    tempno1 = neighbourhood * 0.66: tempno2 = neighbourhood * 0.33

'   Set up arrays with dimensions = rows, columns: ValPre3 is the land use value/category of a
pixel/cell
Dim ValPre3(250, 313) As Integer, ValSlope(250, 313), ValMajorRoad(250, 313) As Integer,
ValCult(250, 313) As Integer, ValWorsecof(250, 313) As Integer

'   Get working directory used by the IDRISI GIS
prefix = idrisi32.GetWorkingDir

'   Display initial and final files
tempfile1 = "yde_1975f": temppalette = "remy1": tempfile2 = prefix & tempfile1
success = idrisi32.DisplayFile(tempfile2, temppalette, 0, 0, 1, 1, 0, True, tempfile2)
```

```
tempfile1 = "yde_1988": tempfile2 = prefix & tempfile1
success = idrisi32.DisplayFile(tempfile2, temppalette, 0, 0, 1, 1, 0, True, tempfile2)


'   Convert initial image's "*.rst" file to a new ASCII format file so that it can be read from
tempfile1 = "yde_1975f": tempstr1 = prefix & tempfile1 & ".rst": tempstr2 = prefix & tempfile1 &
"_ascq" & ".rst"
cmdstr = "1*" + tempstr1 + "*" + tempstr2 + "*1*1*2"
success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
'   Read in pixel values from the ASCII file (other sorts of files cannot be read from in Excel)
Close #2
Open tempstr2 For Input As #2
   For jj = 1 To rows
      For k = 1 To cols
         Input #2, ValPre3(jj, k)
      Next k
   Next jj
Close #2

'      Convert Slope image's "*.rst" file to a new ASCII format file
tempfile1 = "yde_sloped": tempstr1 = prefix & tempfile1 & ".rst": tempstr2 = prefix & tempfile1
& "_ascq" & ".rst"
cmdstr = "1*" + tempstr1 + "*" + tempstr2 + "*1*1*2"
success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
'      Read in pixel values for slope
Close #2
Open tempstr2 For Input As #2
   For jj = 1 To rows
      For kk = 1 To cols
         Input #2, ValSlope(jj, kk)
      Next kk
   Next jj
Close #2

'      Convert Cultural and Ethnic groups image's "*.rst" file to a new ASCII format file
tempfile1 = "yde_cult1": tempstr1 = prefix & tempfile1 & ".rst": tempstr2 = prefix & tempfile1 &
"_ascq" & ".rst"
cmdstr = "1*" + tempstr1 + "*" + tempstr2 + "*1*1*2"
success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
'      Read in pixel values for Cultural and Ethnic
Close #2
Open tempstr2 For Input As #2
   For jj = 1 To rows
      For kk = 1 To cols
         Input #2, ValCult(jj, kk)
      Next kk
   Next jj
Close #2

'      Convert Worship and Market image's "*.rst" file to a new ASCII format file
tempfile1 = "yde_worsecof": tempstr1 = prefix & tempfile1 & ".rst": tempstr2 = prefix &
tempfile1 & "_ascq" & ".rst"
cmdstr = "1*" + tempstr1 + "*" + tempstr2 + "*1*1*2"
success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
'      Read in pixel values for Worships and Markets places
Close #2
Open tempstr2 For Input As #2
```

```
   For jj = 1 To rows
      For kk = 1 To cols
         Input #2, ValWorsecof(jj, kk)
      Next kk
   Next jj
Close #2

'     Convert Major Roads, Ring Road and Airport Ring Road image's "*.rst" file to a new ASCII
format file
tempfile1 = "yde_mrd_rr_arw_rw": tempstr1 = prefix & tempfile1 & ".rst": tempstr2 = prefix &
tempfile1 & "_ascq" & ".rst"
cmdstr = "1*" + tempstr1 + "*" + tempstr2 + "*1*1*2"
success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
'     Read in pixel values for main roads (=44), ring road (=52) and airport (=51)
Close #2
Open tempstr2 For Input As #2
   For jj = 1 To rows
      For kk = 1 To cols
         Input #2, ValMajorRoad(jj, kk)
      Next kk
   Next jj
Close #2

'  Start iterations loop to run the simulation for designated number of iterations
70  For j = 1 To Iterations
         ave = Nett_pixel_gain / Iterations
         If Iterations Mod 2 = 0 Then Annual_target = ave - (((Int(Iterations / 2)) - j) * (ave /
Iterations)) Else Annual_target = ave - (((Int((Iterations + 1) / 2)) - j) * (ave / Iterations))
         If j < Int(Iterations * 0.35) Then Stage = 1 Else If j < Int(Iterations * 60) Then Stage = 2
Else Stage = 3
         ending = 0
         co = 1

'  Set this year's annual change to zero
      Annual_change = 0

'  Choose a random cell
777 k = Int(Rnd(1) * rows)
   l = Int(Rnd(1) * cols)

'  Generate another cell if this one is not informal settlement
If ValPre3(k, l) <> 8 Then GoTo 777

'  Search out to the jn-level neighbourhood to find nearest vacant land cell

   For jn = 1 To 50
      If jn Mod 2 = 1 Then GoTo 410
         For jk = k + jn To k - jn Step -1
            If jk > rows Or jk < 1 Then GoTo 550
            If jk Mod 2 = 1 Then GoTo 510
               If jk <> k + jn Or jk <> k - jn Then GoTo 506
                  For jl = l + jn - 1 To l - jn + 1 Step -1
                     If jl > cols Or jl < 1 Then GoTo 505
                     If ValPre3(jk, jl) = 1 Then GoTo 600
505                 Next jl
506               jl = l + jn: If ValPre3(jk, jl) = 1 Then GoTo 600
               jl = l - jn: If ValPre3(jk, jl) = 1 Then GoTo 600
```

```
                GoTo 550
510               If jk <> k + jn Or jk <> k - jn Then GoTo 546
                   For jl = l - jn + 1 To l + jn - 1
                       If jl > cols Or jl < 1 Then GoTo 545
                       If ValPre3(jk, jl) = 1 Then GoTo 600
545                   Next jl
546               jl = l + jn: If ValPre3(jk, jl) = 1 Then GoTo 600
                jl = l - jn: If ValPre3(jk, jl) = 1 Then GoTo 600
550        Next jk
        GoTo 585
410        For jk = k - jn To k + jn
            If jk > rows Or jk < 1 Then GoTo 570
            If jk Mod 2 = 1 Then GoTo 515
                If jk <> k + jn Or jk <> k - jn Then GoTo 556
                   For jl = l + jn - 1 To l - jn + 1 Step -1
                       If jl > cols Or jl < 1 Then GoTo 555
                       If ValPre3(jk, jl) = 1 Then GoTo 600
555                   Next jl
556               jl = l + jn: If ValPre3(jk, jl) = 1 Then GoTo 600
                jl = l - jn: If ValPre3(jk, jl) = 1 Then GoTo 600
            GoTo 570
515               If jk <> k + jn Or jk <> k - jn Then GoTo 561
                   For jl = l - jn + 1 To l + jn - 1
                       If jl > cols Or jl < 1 Then GoTo 560
                       If ValPre3(jk, jl) = 1 Then GoTo 600
560                   Next jl
561               jl = l + jn: If ValPre3(jk, jl) = 1 Then GoTo 600
                jl = l - jn: If ValPre3(jk, jl) = 1 Then GoTo 600
570        Next jk
585  Next jn

'   If no edge cell found, generate another cell
GoTo 777

'   If an edge, vacant land cell found, adopt it
600 k = jk
    l = jl

'   Skip this bit --- (maybe later)
GoTo 779

'   Find number of informal settlement cells in the neighbourhood
Neighbours = 0
    For jj = k - 2 To k + 2
        If jj < 1 Or jj > cols Then GoTo 24
            For kk = l - 2 To l + 2
                If kk < 1 Or kk > cols Then GoTo 23
                If ValPre3(jj, kk) = 8 Then Neighbours = Neighbours + 1
23          Next kk
24  Next jj

779 Probability = 0
sloped = 0: marketed = 0: chapeled = 0: watered = 0: roaded = 0: arterialed = 0
ringroaded = 0: airported = 0: grouponeed = 0: grouptwoed = 0: groupthreeed = 0
groupfoured = 0: groupfiveed = 0

'   Search an ever-growing neighbourhood to find closest cell of a type of land use
```

```
For m = 11 To 53
    closest(m) = 0
Next m
    For m = 11 To 53
'   Skip over superfluous land use categories
        If m > 11 And m < 22 Then GoTo 887
        If m > 34 And m < 44 Then GoTo 887
'   Make neighbourhood get larger as iterations progress
'   If j < (Iterations * 0.33) Then neigh = neighbourhood / 3 Else If j < Iterations * 0.5 Then neigh
= neighbourhood Else If j < Iterations * 0.88 Then neigh = neighbourhood * 2 Else neigh =
neighbourhood * 3
    neigh = neighbourhood
        For jn = 1 To neigh
            If jn Mod 2 = m Then GoTo 1410
                For jk = k + jn To k - jn Step -1
                    If jk > rows Or jk < 1 Then GoTo 1550
                    If jk Mod 2 = m Then GoTo 1510
                        For jl = l + jn - 1 To l - jn + 1 Step -1
                            If jl > cols Or jl < 1 Then GoTo 1505
                            If ValPre3(jk, jl) = m Then GoTo 1600
                            If ValMajorRoad(jk, ll) = m Then GoTo 1600
                            If ValWorsecof(jk, jl) = m Then GoTo 1600
                            If ValCult(jk, jl) = m Then GoTo 1600
1505                        Next jl
                    GoTo 1550
1510                        For jl = l - jn + 1 To l + jn - 1
                            If jl > cols Or jl < 1 Then GoTo 1545
                            If ValPre3(jk, jl) = m Then GoTo 1600
                            If ValMajorRoad(jk, ll) = m Then GoTo 1600
                            If ValWorsecof(jk, jl) = m Then GoTo 1600
                            If ValCult(jk, jl) = m Then GoTo 1600
1545                        Next jl
1550                Next jk
            GoTo 1585
1410                For jk = k - jn To k + jn
                    If jk > rows Or jk < 1 Then GoTo 1570
                    If jk Mod 2 = m Then GoTo 1515
                        For jl = l + jn - 1 To l - jn + 1 Step -1
                            If jl > cols Or jl < 1 Then GoTo 1555
                            If ValPre3(jk, jl) = m Then GoTo 1600
                            If ValMajorRoad(jk, ll) = m Then GoTo 1600
                            If ValWorsecof(jk, jl) = m Then GoTo 1600
                            If ValCult(jk, jl) = m Then GoTo 1600
1555                        Next jl
                    GoTo 1570
1515                       For jl = l - jn + 1 To l + jn - 1
                            If jl > cols Or jl < 1 Then GoTo 1560
                            If ValPre3(jk, jl) = m Then GoTo 1600
                            If ValMajorRoad(jk, ll) = m Then GoTo 1600
                            If ValWorsecof(jk, jl) = m Then GoTo 1600
                            If ValCult(jk, jl) = m Then GoTo 1600
1560                        Next jl
1570                Next jk
1585 Next jn

GoTo 887
```

```
1600    closest(m) = (((neigh + 1) - jn) / neigh)

887 Next m
'Sloped values: 24 = 0-3%; 25 = 3-5%; 26 = 5-9%; 27 = 9-13%; 28 = 13-18%; 29 = 18-23%; 30= 23-27%; 31 = 27-32%; 32 = 32-37% 33 = +37%
'Cultural groups description: 45 = Foreigners and others; 46 = Eton; 47 = Ewondo; 48: Bamileke and Ewondo; 49 = Bamileke and Haoussa; 50 = Mixed national
If ValSlope(k, l) > 22 And ValSlope(k, l) < 26 Then sloped = 1
If closest(11) > 0 Then marketed = 1
If closest(22) > 0 Then watered = 1
If closest(23) > 0 Then roaded = 1
If closest(34) > 0 Then chapeled = 1
If closest(44) > 0 Then airported = 1
If closest(51) > 0 Then ringroaded = 1
If closest(52) > 0 Then arterialed = 1
If closest(53) > 0 Then railed = 1
If closest(45) > 0 Then grouponeed = 1
If closest(46) > 0 Then grouptwoed = 1
If closest(47) > 0 Then groupthreeed = 1
If closest(48) > 0 Then groupfoured = 1
If closest(49) > 0 Then groupfiveed = 1
If closest(50) > 0 Then groupsixed = 1
'----------------------------------------------------------------------------------------------
'  *** APPLY THE RULES ...
'   Remember, stage 1 = early years; stage 2 = middle years and stage 3 = later years
GoTo 1003
'   Boost probability according to number of informal settlement cells in the neighbourhood = 1 to 25)
1002    If Neighbours < 4 Then Probability = Probability * 3 Else Probability = Probability * 0

'   Boost probability if slope is moderate
1003    If sloped <> 1 Then GoTo 1004
      If Stage = 1 Then Add = 0.1 Else If Stage = 2 Then Add = 0.3 Else Add = 0.3
        Probability = Probability + Add
'   Boost probability of change according to closeness of nearest markets
1004    If marketed <> 1 Then GoTo 1005
      If Stage = 1 Then Add = 0.01 Else If Stage = 2 Then Add = 0.03 Else Add = 0.04
        Probability = Probability + Add
'   Boost probability of change according to closeness of nearest chapel areas
1005    If chapeled <> 1 Then GoTo 1006
      If Stage = 1 Then Add = 0.01 Else If Stage = 2 Then Add = 0.01 Else Add = 0.01
        Probability = Probability + Add
'   Reduce probability of change according to closeness of nearest water cell
'   remember - tempno1 = neighbourhood * 0.66: tempno2 = neighbourhood * 0.33
1006    If watered <> 1 Then GoTo 1007
        If closest(22) > tempno1 Then If Stage = 1 Then Add = 0.3 Else If Stage = 2 Then Add = 0.3 Else If roaded = 1 Then Add = 0.7 Else Add = 0.2
        Probability = Probability + Add
        If closest(22) > tempno2 And closest(22) < tempno1 Then If Stage = 1 Then Add = 0.1 Else If Stage = 0 Then Add = 0.2 Else If roaded = 1 Then Add = 0.3 Else Add = -0.8
        Probability = Probability + Add
        If closest(22) < tempno2 Then If Stage = 1 Then Add = -0.5 Else If Stage = 2 Then Add = -0.2 Else If roaded = 1 Then Add = 0.3 Else Add = -0.3
        Probability = Probability + Add
'   Boost probability of change according to closeness of nearest road cell
1007    If roaded <> 1 Then GoTo 1008
        If Stage = 1 Then Add = 0.01 Else If Stage = 2 Then Add = 0.02 Else Add = 0.03
```

```
          Probability = Probability + Add
'   Boost probability of change according to closeness of nearest arterial road cell
1008    If arterialed <> 1 Then GoTo 1009
          If Stage = 1 Then Add = 0.5 Else If Stage = 2 Then Add = 0.4 Else Add = 0.4
          Probability = Probability + Add
'   Boost probability of change according to closeness of nearest ring road cell
1009    If ringroaded <> 1 Then GoTo 1010
          If Stage = 1 Then Add = 0.2 Else If Stage = 2 Then Add = 0.3 Else Add = 0.3
          Probability = Probability + Add
          '   Boost probability of change according to closeness of nearest railway cell
1010    If railed <> 1 Then GoTo 1011
          If Stage = 1 Then Add = 0.2 Else If Stage = 2 Then Add = 0.3 Else Add = 0.2
          Probability = Probability + Add
'   Decrease probability of change according to closeness of airport runway cell
1011    If airported <> 1 Then GoTo 1012
          If Stage = 1 Then Add = 0.3 Else If Stage = 2 Then Add = -0.3 Else Add = -0.4
          Probability = Probability + Add
'   Boost probability according to being in cultural group one's area
1012    If grouponeed <> 1 Then GoTo 1013
          If Stage = 1 Then Add = -0.1 Else If Stage = 2 Then Add = -0.2 Else Add = -0.3
          Probability = Probability + Add
'   Boost probability according to being in cultural group two's area
1013    If grouptwoed <> 1 Then GoTo 1014
          If Stage = 1 Then Add = 0.2 Else If Stage = 2 Then Add = 0.4 Else Add = 0.3
          Probability = Probability + Add
'   Boost probability according to being in cultural group three's area
1014    If groupthreeed <> 1 Then GoTo 1015
          If Stage = 1 Then Add = 0 Else If Stage = 2 Then Add = 0.1 Else Add = -0.1
          Probability = Probability + Add
'   Boost probability according to being in cultural group four's area
1015    If groupfoured <> 1 Then GoTo 1016
          If Stage = 1 Then Add = 0.1 Else If Stage = 2 Then Add = 0.3 Else Add = 0.3
          Probability = Probability + Add
'   Boost probability according to being in cultural group five's area
1016    If groupfiveed <> 1 Then GoTo 1017
          If Stage = 1 Then Add = 0 Else If Stage = 2 Then Add = 0.03 Else Add = 0.01
          Probability = Probability + Add
'   Boost probability according to being in cultural group six's area
1017    If groupsixed <> 1 Then GoTo 1018
          If Stage = 1 Then Add = 0 Else If Stage = 2 Then Add = -0.2 Else Add = -0.1
          Probability = Probability + Add
1018
'-----------------------------------------------------------------------------------------

' Determine whether cell should change and, if not, generate another random cell by returning to
line 777

1700    tempprob = Rnd(1)
        If tempprob >= Probability Then GoTo 777
        ValPre3(k, l) = 8
        Annual_change = Annual_change + 1

'----------------------------------------------------------------------------------------------
' If total annual change has been achieved then display output file, else generate another random
cell
766 If Annual_change < Annual_target Then GoTo 777
```

```
' Check whether it is time to output a map, if not, iterate one more year (loop at line 997)
'601    If j = 13 Then GoTo 824 Else GoTo 997
'       If j Mod 3 <> 0 Then GoTo 997

'Set up output file
824 tempstr2 = prefix & "Simulation_" & Base_year + j & ".csv"
   Close #4: Open tempstr2 For Output As #4
' write header information to it
      For m = 1 To 2
         For n = 1 To cols
            Write #4, 1
         Next n
      Next m

'Write to, and close output file
      For k = 1 To rows
         For l = 1 To cols
            Write #4, ValPre3(k, l)
         Next l
      Next k
   Close #4

'Import progress map's output into idrisi for display
   tempstr1 = prefix & "Simulation_" & Base_year + j
   cmdstr = "Simulation_" & Base_year + j & ".csv*" + tempstr1 +
"*1*250*313*plane*meters*1.0*106301.524328*120045.0581682*422720.802413*433698.0658
636"
   success = idrisi32.RunModule("sstidris", cmdstr, True, "", "", "", "", True)
'   success = idrisi32.DisplayFile(tempstr1, "remy1", 0, 1, 1, 1, 0, True, tempstr1)
   success = idrisi32.DisplayFile(tempstr1, "remy1", 0, 0, 1, 1, 0, True, tempstr1)

   tempstr1 = prefix & "Simulation_" & Base_year + j & ".rst"
   tempstr2 = prefix & "Simulation_" & Base_year + j & "_ascq" & ".rst"
   cmdstr = "1*" + tempstr1 + "*" + tempstr2 + "*1*1*2"
   success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
   tempstr3 = prefix & "Simulation_" & Base_year + j & "bb" & ".rst"
   cmdstr = "1*" + tempstr1 + "*" + tempstr3 + "*3*2*2"
   success = idrisi32.RunModule("convert", cmdstr, True, "", "", "", "", True)
   tempstr4 = prefix & "Simulation_" & Base_year + j & "bb" & ".bmp"
   cmdstr = "1*" + tempstr3 + "*" + tempstr4 + "*" + "remy1"
   success = idrisi32.RunModule("bmpidris", cmdstr, True, "", "", "", "", True)


' begin to next iteration
997 Next j

100 End Sub
*****************************************************************************
```

Appendix 8 Complete legend for maps used

ID	Color	Representation	Category
1		Vacant land or Background	
2		Public domain	
3		Administrative land	**Land use 1975**
4		Military and alike	**&**
5		University land	**Land use 1988**
6		Commercial and industrial	
7		Planned residential	
8		Unplanned and informal settlements	
9		Peri and urban villages	
10		Excluded from informal settlements developments	**This file is used only on yde_1975f to prevent the expansion on some planned developments**
11		Etoudi also Markets	
12		Essos	
13		Nkol Eton	
14		Mfoundi	
15		Mokolo	
16		Mélen	
17		Biyemassi	
18		Madagascar	
19		Briqueterie	
20		Mvog Mbi	
21		Nkolbisson	
22		River course and lakes	
23		Road networks	**Roads**
24		0-3º or 0-3%	
25		3-7º or 3-5%	
26		7-10º or 5-9%	
27		10-14º or 9-13%	
28		14-17º or 13-18%	
29		17-21º or 18-23%	
30		21-24º or 23-27%	**Topography: Slope in degrees and percents**
31		24-28º or 27-32%	
32		28-33º or 32-37%	
33		33-57º or 37-75%	
34		Obili chapel also Worships	
35		Mvolyé chapel	
36		Cathedral	
37		Mélen chapel	
38		Mokolo chapel	
39		General Mosque	**Worship places**
40		Tsinga Mosque	
41		Nlongkak Protestant Church	
42		Etoudi chapel	
43		Essos chapel	
Cultural and ethnic groups			
45		Foreigners and others	
46		Eton	
47		Ewondo	
48		Bamiléké and Ewondo	
49		Bamiléké and Haoussa	
50		Mixed national	
Other Transportation networks			
44		Major Road	
51		Airport runway	
52		Proposed Ring Road	
53		Railway	**Major Road and rail networks**

Appendix 9

Cultural and ethnic groups in Yaoundé

Four main ethnic groups share the Yaoundé urban space: Ewondo, Eton, Bamiléké, Haoussa and others. The Ewondo and Bané accommodate the indigenous inhabitants of Yaoundé (figure 6.7 or 6.5.1). There is a strong link between cultural and ethnic background and prevalence of IS and an even stronger relationship with land use.

The **Ewondo**, indigenous of Yaoundé, are mostly found in urban villages in the East and South of Yaoundé, especially Mvolyé, Mvog Mbi, Mvog Ada, Awaé and Nkondongo. Some of these villages, such as Mvog Mbi and Mvog Ada, have been 'swollen' by the city of Yaoundé, and now form pockets of informal settlement in urban areas to which new informal settlements gravitate. They have thus 'evolved' from rural villages to informal settlements.

Originally from the area north of Yaoundé, **Eton** is the one of the biggest ethnic groups whose area of origin is geographically close to those of the Ewondo and Bané groups. The attraction of Yaoundé as an emerging urban centre, and the high population density in the Eton country in the 1950s, caused the Eton to be amongst the earliest migrants to Yaoundé in the 1950s. The Eton settled along the main road north of Yaoundé in the suburbs now known as Nkol Eton, Nkoldongo and Djoungolo.

Land pressure in the **Bamiléké** country, similar to that experienced by the Eton, coupled with the Yaoundé urban attractions and functions (especially administrative and educational) explains the migration of Bamiléké to Yaoundé from the late 1950s. They came from as far as 400 km away to take advantage of the opportunities Yaoundé had to offer. Compared to the Ewondo whose land is always available to them under traditional tenure, the Bamiléké and the Eton have a voracious *appetite* for land and use various strategies to acquire land, mostly illegal. They prefer to deal directly with the traditional owners rather than employ the 'formal' channels. These strategies range from bargaining to ruse.

The **Haoussa**, mostly from the Islamic North of Cameroon, travel as far as 1500km to settle in Yaoundé, partly because of the favourable political and economic conditions they benefited from under government policy in the 1960s. They settled in the western outskirts of Yaoundé, especially in Briquetterie and Tsinga.

The mixed cultural and ethnic suburbs (e.g., Bastos, Centre Commercial) are generally planned developments occupied by foreigners and wealthy citizens, or suburbs with strong mixed cultural groups due to their multicultural functions such as educational centres (e.g., Ngoa Ekele). In relation to urban land use, informal settlements a feature of migrant communities (Bamiléké, Haoussa and Eton) are less prevalent in mixed communities.

Appendix 10

Markets places in Yaoundé

Yaoundé has more than fifteen markets places and the most important popular markets are respectively Mokolo, Mfoundi, Mvog Mbi, Essos Biyemassi, Mélen, Nkol Eton and Nkolbisson. This section presents the main characteristics of two types of market places, Mokolo and Mfoundi, in respect to their role in structuring the informal settlements.

The Mokolo market was established in the 1960s by migrants from the Northern (Haoussa and Fulbé) and Western the Bamiléké parts of Cameroon, on what was back then the fringe of the urban area of Yaoundé. Santoir (1995) estimates that Mokolo provides more than 55% of goods flux (distribution) in Yaoundé, and therefore one of the main sources of the informal sector economy in Yaoundé. The importance of the Mokolo market can also be assesses by it spatial importance, which now agglomerates adjacent markets, especially Madagascar and Briqueterie. Through out the years, the importance of the Mokolo market has been correlated with and reinforced by the increasing densely populated informal settlements that in its close neighbourhood. In fact, notorious informal settlements in the neighbourhood of the Mokolo market have their names[1] associated with particular markets, namely Mokolo, Briqueterie and Madagascar. As far as the influence physical proximity of IS with the market places in, a similar pattern is observed for other markets in Yaoundé such as Mvog Mbi, Biyemassi, Mélen, Essos, Mvog Ada, Elig Edzoa and Nkol Eton.

The Mfoundi central market is the oldest and the second most important shopping place in Yaoundé. The Mfoundi central market regroups three market places which are spatially connected but different in their specific functions: Modern stores, businesses and supermarkets are located at Central market, whereas the small retailers are found at the Marché des Femmes, and finally food products are sold at the Mfoundi. Unlike other markets places in Yaoundé, the Mfoundi central market is located in the CBD and is the only market place in Yaoundé which is not associated with informal settlements neighbourhood expansion, and yet, the role of IS in the strengthening of informal economic sector, one of the main employment suppliers of informal settlers, is very important (Bopda, 2003).

[1] It is common in Yaoundé that main market places are located in informal settlements areas and therefore adopt the same name such as Mokolo, Madagascar, Briqueterie, Mélen, Mvog Ada, Mvog Mbi, Etoa Meki and Elig Edzoa.

Appendix 11

Maps with legends

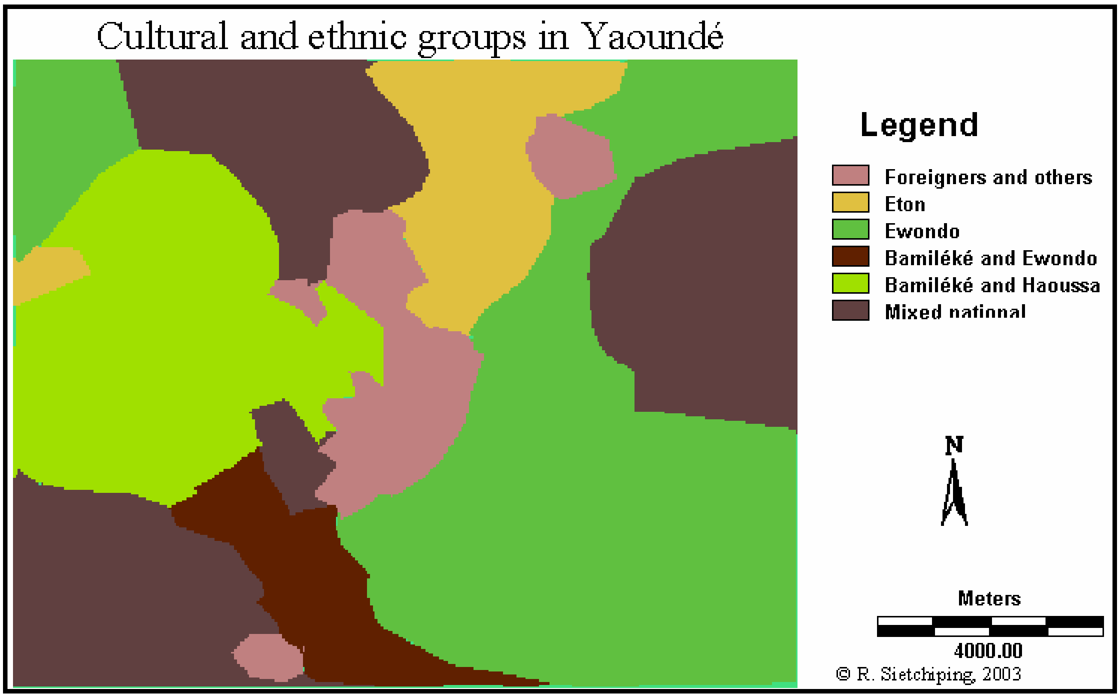


Figure 11.1 Cultural and ethnic groups in Yaoundé

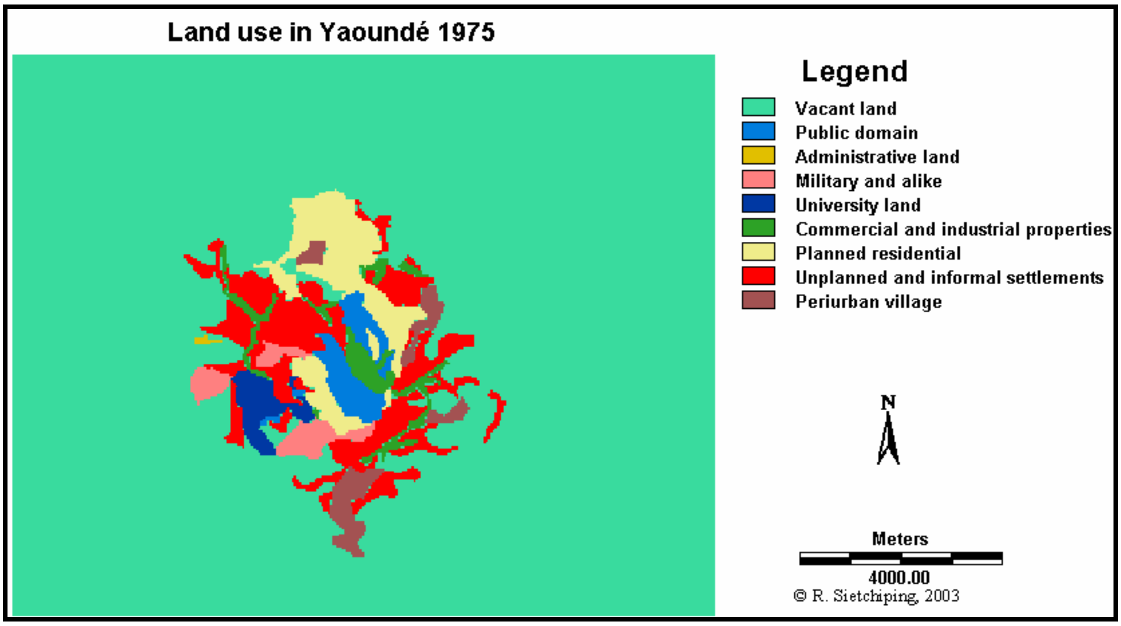


Figure 11.2 Land use in Yaoundé, 1975

Appendix 11 continued

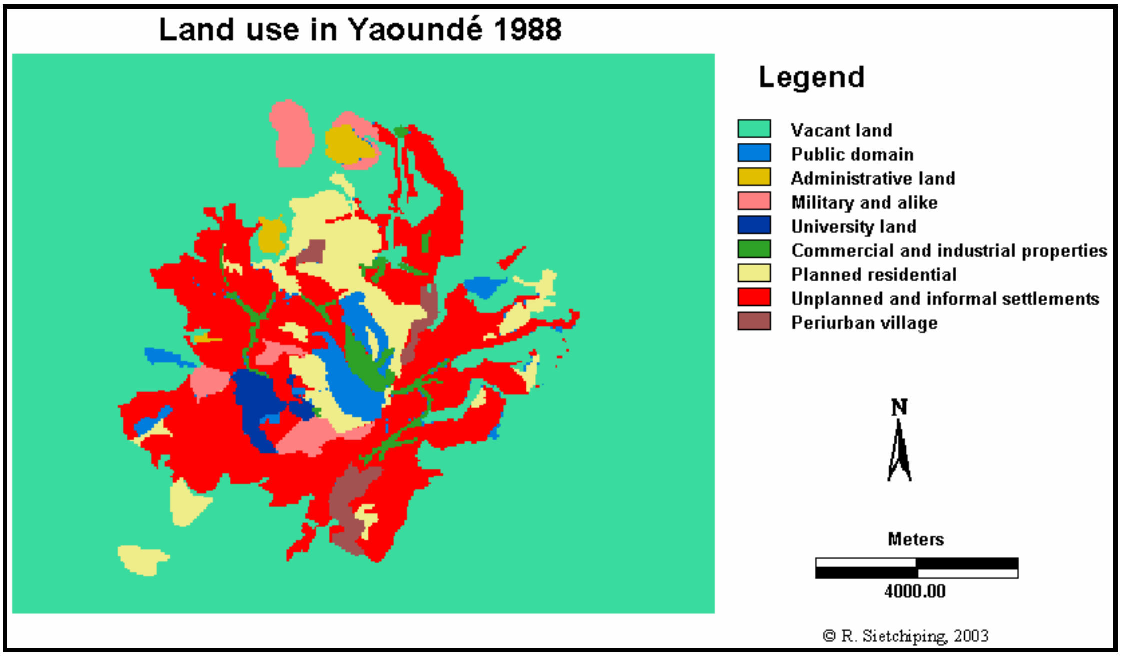


Figure 11.3 Land use in Yaoundé, 1988

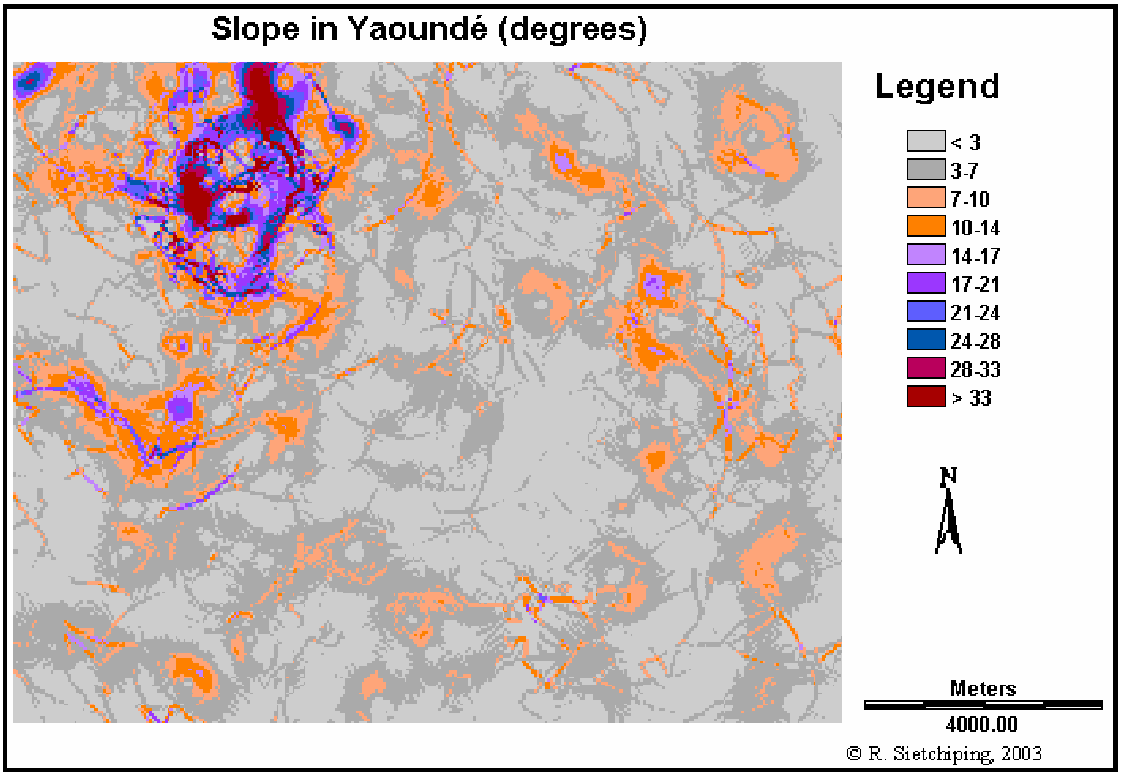


Figure 11.4 Slope in Yaoundé (degrees)

Appendix 11 continued

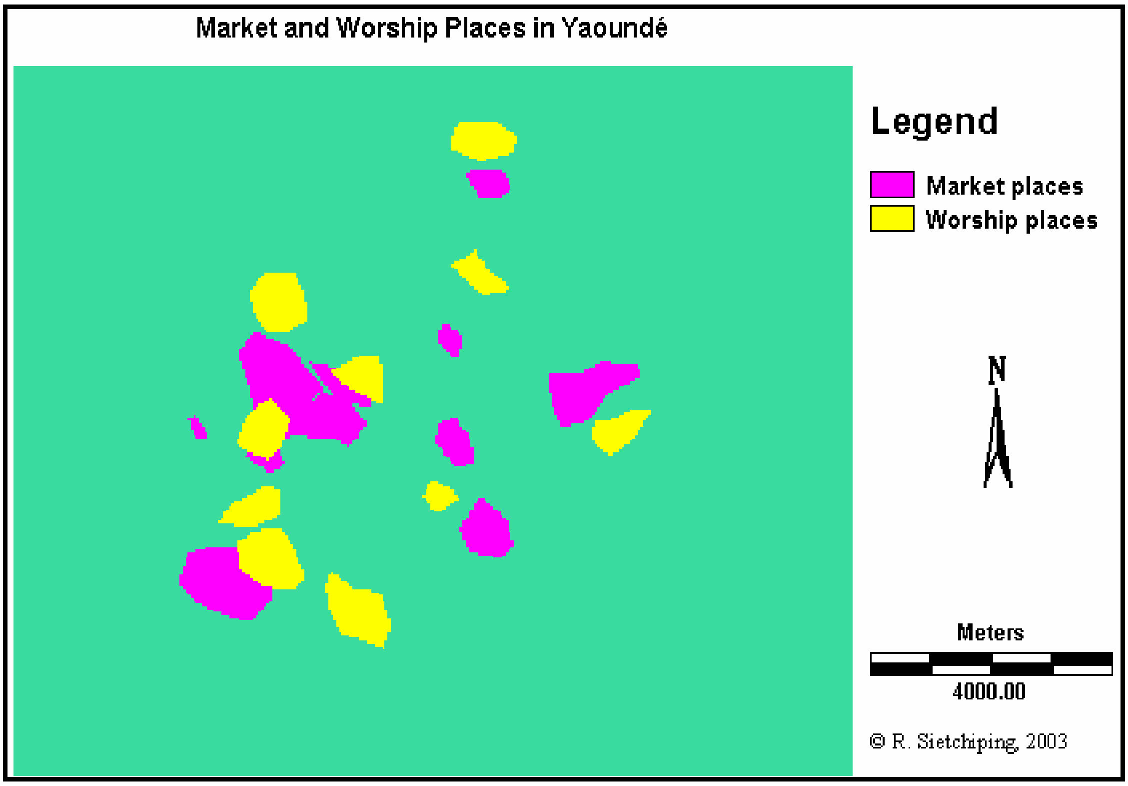


Figure 11.5 Markets and worship places in Yaoundé

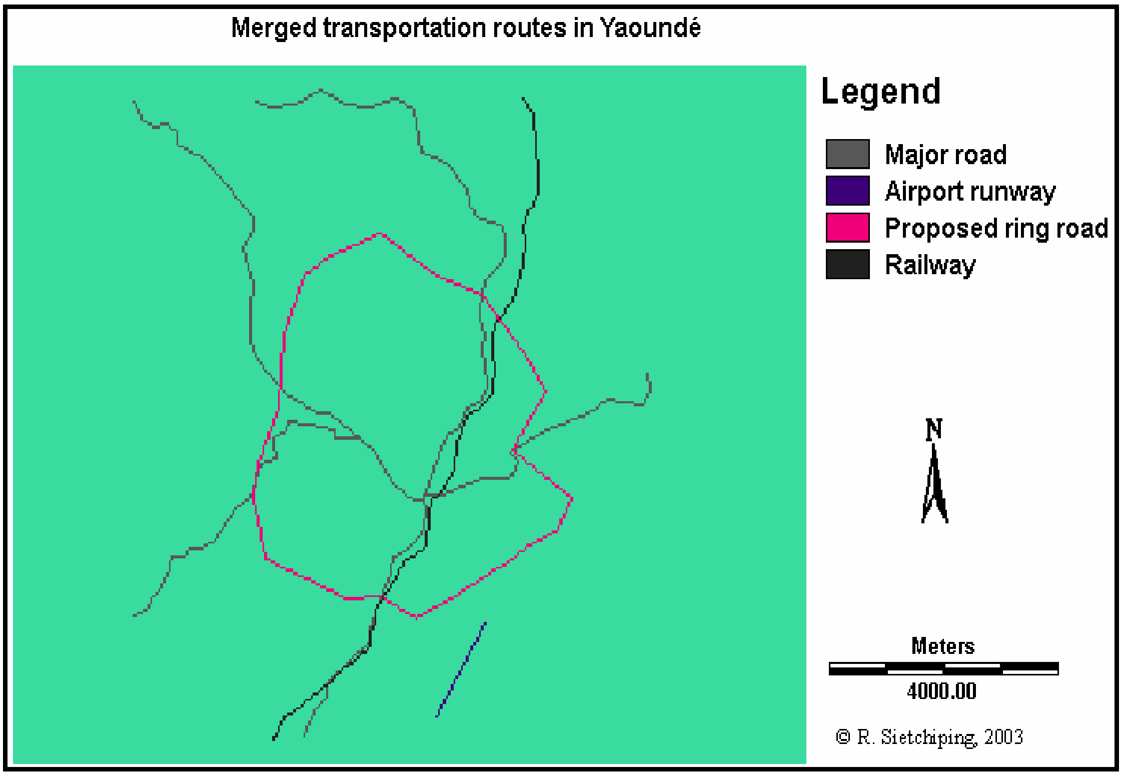


Figure 11.6 Transportation map in Yaoundé, showing merged major road, airport ring road, proposed ring road and railway

Appendix 11 continued

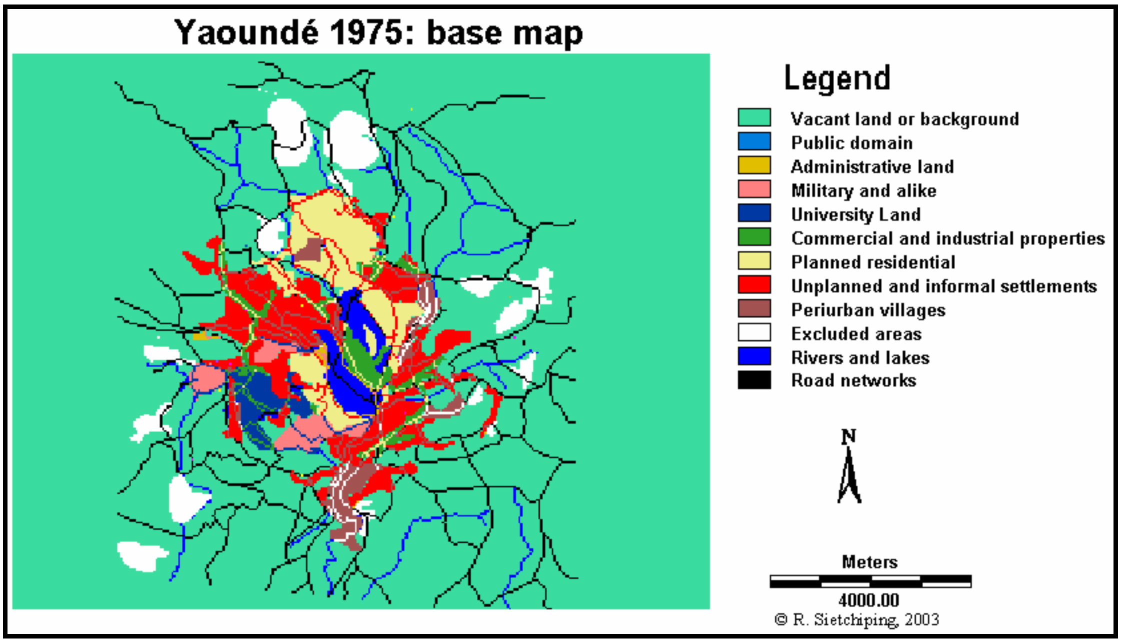


Figure 11.7 Base map used for the simulation where four layers are merged: land use (1975), roads, water and excluded area

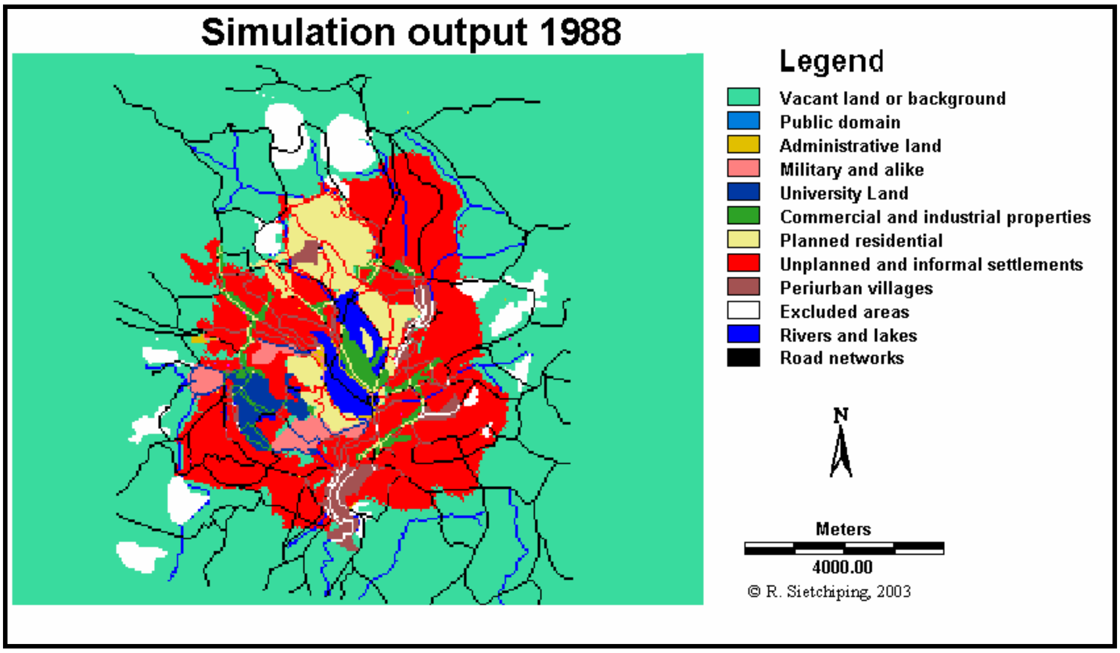


Figure 11.8 Sample of simulated map showing the growth of informal settlement patterns on the base map

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