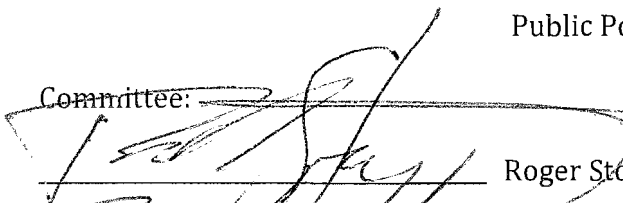


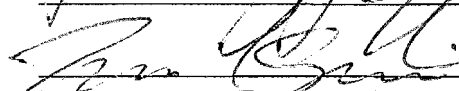
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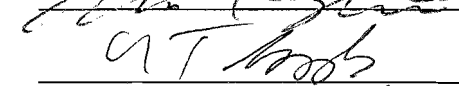
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A Dissertation  
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in Partial Fulfillment of  
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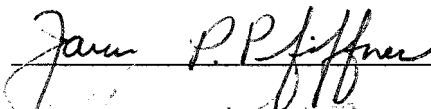
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## **DEDICATION**

To my loving wife Phoram Shah.

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## LIST OF ABBREVIATIONS AND SYMBOLS

Ahmedabad Municipal Corporation .....	AMC
Ahmedabad Urban Development Authority .....	AUDA
City Development Plan .....	CDP
City Development Strategy .....	CDS
Community Based Organization.....	CBO
Development Plan .....	DP
Discrete Event Simulation.....	DES
Economically Weaker Sections .....	EWS
Geographic Information Systems.....	GIS
Government of Gujarat.....	GoG
Government of India.....	GoI
High Income Group .....	HIG
Indian Rupee .....	₹
Low Income Group .....	LIG
Middle Income Group.....	MIG
Ministry of Housing and Urban Poverty Alleviation.....	MHUPA
Non-Governmental Organization.....	NGO
Rajiv Awas Yojana .....	RAY
Remote Sensing .....	RS
Slum Networking Project .....	SNP
Slum/Shack Development International .....	SDI
Town Planning Scheme .....	TPS
United Nations Human Settlements Programme.....	UN-Habitat
United Nations .....	UN
Agent-based Modeling .....	ABM

## **ABSTRACT**

SLUMULATION: AN INTEGRATED SIMULATION FRAMEWORK TO EXPLORE  
SPATIO-TEMPORAL DYNAMICS OF SLUM FORMATION IN AHMEDABAD, INDIA

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George Mason University, 2012

Dissertation Director: Dr. Roger Stough

More than 900 million people or one third of world's urban population live in either slum or squatter settlements. In the past decades, international, national and local development agencies have taken several policy actions to address this challenge. Despite these policy efforts, slum-free cities remain a distant goal for many developing countries. It is thus important to investigate the empirical questions related to slum formation for informed policymaking: (i) *how* do slums form and expand? (ii) *where* and *when* are they formed? and (iii) *what* types of structural changes and/or policy interventions could improve housing conditions for urban poor? This dissertation integrates Discrete Event Simulation (DES), Agent-Based Modeling (ABM) and Geographic Information Systems (GIS) into a single simulation framework, named *Slumulation*, to explore slum formation dynamics. *Slumulation* is designed to serve as a decision support tool that could be useful for urban planners

and policymakers to experiment with new policy ideas *ex-ante* in a simulated environment with minimal data requirement. The core of this framework is a linked dynamic model operating at both micro and macro geographical and demographic scales. *Slumulation* explores the collective effect of many interacting inhabitants of slums as well as non-slums and how their interactions with the spatial environment of the city generate emergent structure of slums at the macro scale. *Slumulation* is tested with a case study of Ahmedabad, a sixth largest city of India with 41% of its population living in slums.

## CHAPTER 1. INTRODUCTION

Slums provide shelter for nearly one third of the world's urban population, most of them in developing world cities (UN-Habitat 2003). Despite such a large scale presence of deteriorated living conditions, research on the formation and expansion of slums is generally lacking. Therefore, it is important to enhance our knowledge on the unprecedented expansion of slums. Previous studies have used descriptive speculation about underlying forces of slum formation and expansion, but they have not generated sufficient understanding to develop useful and effective slum policies (Amis 1995; Sietchiping 2008). As a result, there has been a piecemeal application of planning procedures and slum policies that are often designed for developed countries (Pugh 2001).

This dissertation presents an integrated simulation framework named *Slumulation* that could be used to design slum policies in the unplanned context of cities in the developing world. *Slumulation* is designed to explore the spatio-temporal dynamics of slum formation in cities of the developing world. The model is calibrated and validated for the city of Ahmedabad in India.

Primarily, *Slumulation* is designed to serve as a policy support tool for urban planners and policymakers to test and evaluate new policy ideas in a simulated environment. Additionally, researchers and spatial scientists could also use

*Slumulation* as an urban laboratory to conduct experiments and generate new hypotheses related to slum dynamics in cities. *Slumulation* also demonstrates the importance of modeling geographical space and human behavior explicitly when analyzing slums and designing slum policies.

## **1.1 Research Context**

Scholars often consider urbanization a positive factor for the economic growth of developing countries (Beall and Fox 2009). Unfortunately, economic growth and urban poverty may coexist in a society when high levels of socio-economic inequalities are present. These qualities are manifested in extremely poor housing conditions within city slums. Developing countries have more and more people living in cities. The population living in slums in these cities is simultaneously rising (Davis 2006).

This rapid and continuing urbanization combined with rising intra-urban social inequality is expected to aggravate the slum situation in developing countries more so than in any other time in history (UN-Habitat 2010). The issue of poor housing conditions in slums has received a renewed focus from policymakers worldwide. Both the global scale of the issue and an increased concern worldwide makes research on policy support tools such as *Slumulation* timely and relevant. The following sub-sections on the magnitude and salience of this issue will highlight this point.

### **1.1.1 Nature and Magnitude of Slums**

For the first time in the world history, humanity has more people living in urban areas than in rural areas. The proportion of urban population is predicted to be over 75 percent by the year 2100 (United Nations 2007). Researchers estimate that most of this population growth will take place in cities of the developing world by 2020 (Davis 2006).

Unfortunately, as the number of people living in cities has grown, so has the amount living in slums (Davis 2006). According to the most recent and the only global estimate available to date, approximately 924 million people, or one third of the world's urban population, lives in slums. This number is projected to increase to 2 billion people by 2030 if adequate actions are not taken (UN-Habitat 2003).

Slum dwellers in Asian cities account for 60 percent of the world's total slum dwellers, or 554 million people (UN-Habitat 2003). 158 million of these Asian slum dwellers, or 17% of the world's total, reside in Indian cities. In terms of the slum incidence rate<sup>1</sup>, this equates to 55% of India's urban population, which means one in two urban residents of India live in slums. The slum incidence rate is higher in India than the average incidence rate in many developing countries, which stands at 43% and much higher than that of developed countries, which stands at only 6% (UN-Habitat 2003).

The data above estimating the slum population are based on the definition suggested by UN-Habitat (2006), one of the most widely used definitions of slums.

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<sup>1</sup> The proportion of urban population living in slums. Rural populations are not considered for the calculation of the slum incidence rate.

According to this definition, a household is a slum household if it lacks any one or more of the following five elements: i) access to water, ii) access to sanitation, iii) secured tenure, iv) durable housing and v) sufficient living area. An advantage of this definition is that it defines a slum at the household level. Most other definitions define a slum at the neighborhood level (e.g. Census of India 2001; Neuwirth 2005; Roy and Alsayyad 2004), thereby making it difficult to differentiate between living conditions of the households within a slum<sup>2</sup>.

### **1.1.2 Salience of the Issue**

Many recognize that the proliferation of slums is one of the most complex and pressing challenges that developing countries face today (Anzorena et al. 1998; UN-Habitat 2003). An inappropriate housing condition for the urban poor is becoming an important concern for policymakers in developing countries. Furthermore, it is recognized that slums adversely affect the well being of the entire city, raising wide concerns such as public health and safety (Pugh 2001).

The international development community has recognized the growth of slums as an important societal issue, especially for rapidly urbanizing developing countries. As a response, Target 11 of the Millennium Development Goals (MDG) aims to significantly improve the lives of 100 million slum dwellers by 2020 (United Nations 2000). Several donor countries are also acting on the issue of slums. For example, the United States has introduced a bill which proposes to increase aid for

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<sup>2</sup> Chapter 2 discusses various slum definitions and their implications on research and policy in detail.

“Shelter, Land and Urban Management” (SLUM) in developing countries (Library of Congress 2011).

National and local governments in many developing countries have also called for slum up-gradation and slum improvement programs. The expansion of urban renewal programs and a greater focus on making cities slum-free has taken a front seat among policymakers in most developing countries around the world. For example, in Kenya, their commitment to address the challenge of slums now appears in the national development agenda (UN-Habitat 2003).

In India, the issue of slums has recently received significant political salience. For instance, the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) highlights slum issues as a key task (Government of India 2005). The current president of India announced a policy targeted to make India slum-free within the next five years (Times of India 2009), which has resulted in a massive housing program for slum dwellers called Rajiv Awas Yojana (RAY)<sup>3</sup> (MHUPA 2011).

### **1.1.3 Why Slumulation?**

Slums are recognized as an important global challenge. The policymakers have renewed their focus to address this challenge. However, slums are not a new phenomenon and several policy actions in the past have attempted resolve this issue. Unfortunately, none of them proved to be a panacea to making cities slum-free. It is evident that improved responses are required to address this challenge. Such a task is difficult, especially when there is a gap between slum policies and the

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<sup>3</sup> RAY and other slum policies are discussed in detail in Chapter 3.

understanding of slum formation and expansion processes in literature. In particular, the tools to predict the spatial aspects of slums that could assist with planning responses are limited (Abbott 2002). Even less understood is how the adaptive behavior of several actors, like households, developers and politicians in a city, influences slum policy outcomes.

*Slumulation* is an attempt to develop a tool that could be useful to urban planners for preventing slum formation and expansion in cities. For example, programs such as RAY in India require each city government to develop a plan to make their city slum-free. While many other factors affect slum formation and expansion, urban planning is a vital component. *Slumulation* could be a useful tool for policymakers to develop such plans, ultimately helping to create slum-free cities.

## **1.2 Research Goals**

The goal of this dissertation is twofold. First, it aspires to examine the spatio-temporal dynamics of slum formation and the expansion process using a simulation approach. Second, it aims to build a framework that could serve as a decision support tool for urban planners and policymakers. The framework will serve as an urban laboratory to conduct policy experiments in a simulated environment. It aims to provide a tool to conduct policy experiments which are not always feasible to conduct in the real world.

### 1.3 Research Questions

This dissertation attempts to answer the following research questions: i) how do slums form and expand in a city? ii) where and when are they formed? and finally iii) what kind of structural changes and/or policy interventions improve housing conditions for urban poor?

In addition, as a policy support tool, *Slumulation* is an interactive, multi-scalar spatio-temporal system that can help policy makers analyze and evaluate various policy scenarios related to urban land and housing management programs by measuring the impacts on housing for the urban poor. The following theoretical and policy scenarios were analyzed using *Slumulation*.

#### 1.3.1 Theoretical Scenario Analysis

There are several theoretical propositions made in the slum literature that identify factors influencing slum formations. *Slumulation* is used to study the influence of these factors on slum formation patterns in a simulated environment. An advantage of a simulation approach is to be able to test the impacts of policy scenarios that may not be feasible to implement in the real world due to their irreversible nature (e.g. awarding legal titles to slum dwellers). In addition, simulation is useful in developing scenarios for urban planning especially the scenarios that predicts the future state of the city system. It is particularly useful when '*natural experiments*' are not available. The following theoretical '*what-if*' scenarios were explored using *Slumulation*:

1. *What-if* the migration to the city doubles in next decade?

2. *What-if* the households' preference to live with neighbors with similar ethnicity or with similar income becomes milder over time?
3. *What-if* income inequality reduces from X to Y in next five years in the city?

### **1.3.2 Policy Scenario Analysis**

Several '*what-if*' type of questions were asked to see the impact of the relevant policy changes on slum formation and expansion patterns. Specifically, the policy ideas analyzed were as follows:

1. *What-if* the minimum standard for land parcel size is reduced to half of the current minimum?
2. *What-if* lower income group households are provided with easy access to incremental housing finance?
3. *What-if* rent control policies are introduced for X % of housing in the core city?
4. *What-if* commute to satellite towns is reduced to an hour from Central Business District (CBD) by building new rapid transit systems (e.g. proposed metro-rail system between Ahmedabad and Gandhinagar)?

## **1.4 Research Approach and Dissertation Structure**

The development of *Slumulation* involved three distinct activities in tandem: i) literature review, ii) designing the model structure and iii) empirical analysis of the city of Ahmedabad. The research questions described in the previous section

served as the compass and the filter for narrowing the focus and limiting the scope for each of these activities.

The literature review is further divided into three major categories and presented as three separate chapters in this dissertation: a) literature pertaining to slums b) literature pertaining to slum policies and c) classical theories and models pertaining to the spatial organization of cities.

The first category of the literature is presented in Chapter 2. The review in this category focused on general characteristics of slums and factors that influenced slum formation in cities. The findings from this review provided a general understanding of slums that helped in initial development of the model structure.

The second category of the literature is presented in Chapter 3. The review focused on the literature pertaining to evaluation of slum policies and programs. The goal was to identify the shortcomings of these policies in resolving slum issues. The focus was on identifying underlying gaps between research and practice. The literature also helped in identifying the behavioral factors of various actors that influenced the outcomes of the past policies. Inclusion of these factors helped the model to become relevant for policymaking.

The third category of literature is presented in Chapter 4. The review focused on identifying theoretical basis for the simulation model. Assumptions for the model were based on the established urban theories delineated in the literature. The literature was also explored to assess whether individual urban modeling methods were appropriate to explore emergence and expansion of slums in cities in

developing countries. In addition, an attempt was made to understand the potential benefits of the individual methods and how the integration of different methods could be achieved in a single simulation framework in order to gain a greater understanding by visualizing and analyzing the spatio-temporal dynamics of formation and expansion of slums.

The second major activity, development of the model, is presented in Chapter 5. A prototype simulation model was developed and verified for internal consistency in stages. Various elements of the model were added incrementally and this stage-wise approach made verification simpler and easier. After each significant stage, model was verified before developing the next version. Chapter 5 highlights the stage-wise evolution of the model in detail.

The third major activity, empirical analysis of the city of Ahmedabad, is presented in Chapter 6. An extensive analysis was conducted for the city of Ahmedabad which provided the empirical inputs for the simulation model and allowed outputs to be compared to empirical data. These empirical findings were also useful for the validation of the simulation model presented in Chapter 7. Finally, several policy scenarios were explored specifically for Ahmedabad using the validated model. Chapter 8 presents policy conclusions and concludes with the way forward.

## 1.5 Modeling Approach

Based on the findings from the literature review, *Slumulation* appropriately integrates Discrete Event Simulation (DES), Agent-Based Modeling (ABM) and Geographic Information System (GIS) within a single framework. Each of these modeling techniques serves a distinct purpose. DES provides a framework to model the population growth in the city, ABM provides a framework to model the housing location behavior, and GIS provides the ability to create a multi-scale spatial environment. Statistical and spatial analysis techniques are used to validate the model outputs.

DES simulates population growth for the modeled city within *Slumulation*. Slums develop as a result of the gap between the demand created by this population growth and the existing supply of housing in a city. *Slumulation* is capable of exploring the links between regional population dynamics and slum formation in a city. For example, it could be used to show how different population growth rates can lead to different slum patterns within a city.

ABM simulates individuals' adaptive behavior within *Slumulation*. Slums develop from the bottom-up as a result of such behavior in *this model*, rather than from the more traditional top-down normative constraints of classical models (Clifford 2008). *Slumulation* is designed to explore links between individual behaviors and aggregate outcomes (Casti 1999). For example, it could be used to show how different household behavior can lead to the emergence of different patterns, or explore how different urban policies may potentially lead to similar

outcomes or discover outcomes that were not anticipated originally (Parker et al. 2003).

*Slumulation* uses GIS to represent the spatial environment of a city. Slums develop as a result of the human interaction with this spatial environment.

*Slumulation* is designed to explore links between spatial configuration of a city and the emergence of slum patterns. For example, it could be used to show how different land parcel sizes in a city could lead to different slum patterns.

In terms of outputs, *Slumulation* shows the evolution of key indicators, such as housing density, housing price to income ratio, number and the size of slums over space and time in the form of maps and graphs.

## **1.6 Validation Strategy**

The model is calibrated and validated empirically for the city of Ahmedabad as a test case. Ahmedabad is the sixth largest city of India with a population of 4.5 million (Census of India 2001), out of which approximately 43% lived in slums. A second-tier city in Western India, Ahmedabad has more than 900 slum communities located in various parts of the city (AMC 2001). This research attempts to identify the spatio-temporal patterns of slum formation in Ahmedabad, which is then used to validate the model outcomes<sup>4</sup>.

Ahmedabad was chosen as a case study for two main reasons. First, a large proportion of the global slum population lives in Indian cities. India's second-tier cities are facing similar challenges that the large metropolitan areas faced in 1970s.

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<sup>4</sup> Empirical analysis of slums in Ahmedabad is presented in Chapter 6.

Secondly, as discussed in Chapter 3, the prevailing salience of the issue is very high. According to policymakers, academicians and NGOs working in the field, it will be very timely if effective policies are designed to avert the similar trends in cities of the size of Ahmedabad (Author's personal interviews with experts and policymakers 2011). The author's prior experience working with slum communities in Ahmedabad facilitated a first-hand understanding of the city and its slums.

### **1.7 Scope and Limitations**

This model uses an approach that is exploratory in nature; hence the focus is on the development and testing of a framework. The validation is preliminary and is limited only to the city of Ahmedabad, India. Nonetheless, the process is completely transparent and user-friendly so that *Slumulation* could be used not only for other cities in India, but for cities in other developing countries as well, albeit with local adaptation and customization.

### **1.8 Research Contributions and Expected Policy Outcomes**

Integrating multiple analytical frameworks is a relatively new topic and most applications have been developed for the developed world context. To the best of the author's knowledge, no research has been published that integrates these three different methods, ABM, DES and GIS in a single framework. This dissertation may be the first attempt to integrate these methods and to apply it to alleviate the slum situation in the developing world. The research contribution is thus twofold: the

potential policy implications of *Slumulation* and an innovative methodological approach.

From a policy standpoint, *Slumulation* provides an urban laboratory to conduct thought experiments in a simulated environment. Often, innovative policy ideas are not tested in the real world, either due to the lack of political feasibility of conducting an experiment or simply because the potential impacts of such policies are unknown. Given the long history of slum policies that lead to unforeseen and adverse impacts on urban poor, this functionality of *Slumulation* could be useful to envisage intended and unintended outcomes of the policies *ex ante*. The possibility of testing completely new ideas in a simulated environment might equip policymakers to devise innovative policies. The scenario analysis conducted for the test case of Ahmedabad provides a clear demonstration of how the framework could potentially be used for policymaking in the real world.

*Slumulation* is methodologically innovative because it integrates DES, ABM and GIS within a single framework to understand slum formations. Methods used to answer different questions on slum formation and expansion (how, where and when) are integrated to achieve a holistic understanding of the slum phenomenon. Specifically, *Slumulation* provides an integrated framework that is both dynamic through space and time, with the various modules interacting with each other.

## CHAPTER 2. UNDERSTANDING SLUMS

What is a slum? What are the general characteristics of slums and the people who reside in slums? What are the factors that influence the formation and expansion of slums? Slum literature was reviewed to answer these questions. In particular, the review was conducted to identify relevant characteristics and factors in order to conceptualize *Slumulation*. For example, factors that influence the emergence of slums provide important processes for the model. The literature review is presented in four sections in this chapter: section 2.1 provides several slum definitions; section 2.2 describes general characteristics of slums and slum dwellers; section 2.3 identifies factors that influence formation and expansion of slums; section 2.4 identifies the relevant points for the development of *Slumulation*.

### 2.1 Defining Slums

The definition of slums varies widely from one country to another, even differing between cities and agencies within a country. For example, the definition of slums across governmental agencies within India is differs and often depends on different parameters, as discussed in section 2.1.2.

There are several terms associated with poor housing conditions. Most prevalent are the terms slum, informal settlement or squatter settlement. The

differences between these terms arise mainly from the nature of settlements to which they refer. For example, *informal settlement* emphasizes the unplanned nature of these settlements, whereas *squatter settlement* emphasizes illegal occupation of lands or structures. However, both these terms are increasingly synonymous for *slums* (e.g. UN-Habitat 2003). In addition, they are not mutually exclusive categories, i.e. an informal settlement could also be a squatter settlement. This dissertation uses the term slum and does not differentiate between these three terms.

Slums are also known by different names, often referring to different aspects or characteristics of slums. For example, in Pakistan, slums are known as *katchi abadis* (a term associated with huts made with building materials of non-permanent nature). Whereas, in Indonesia, slums are known as *kampung* (a term associated with a village-type settlement in an urban or rural area). There are several terms referring to slums, for instance, *Bidonvilles* in former French colonies (e.g. Cameroon), ghettos (e.g. United States), shantytowns, slums or squatter settlements in formerly British colonies (e.g. India), *favelas* (e.g. Brazil), etc. There are several other local terms only limited to one or two cities. For example, *chawl* refers to a specific housing type in Ahmedabad and Mumbai.

Nonetheless, there have been attempts to develop a definition that could be used to enumerate slums within monitoring instruments, such as national population census or demographic and health surveys. While there is a broad consensus on what is considered a slum, several definitions prevail both in theory

and practice. This section discusses some of the widely accepted definitions given by international developmental agencies and national governments in developing countries. Section 2.1.4 compares and contrasts definitions of slum to identify underlying elements used in these definitions. They are also evaluated for their usefulness to identify slums within *Slumulation*.

### **2.1.1 The Cities Alliance Definition**

One relevant definition is offered by the organization - Cities Alliance, which is comprised of a global coalition of cities, national governments, non-governmental and multilateral organizations such as the World Bank and UN-Habitat. The Cities Alliance definition primarily focuses on the issue of slums as reflected in their mantra "Cities Without Slums." In the "Cities Without Slums Action Plan," Cities Alliance (1999) provided the following definition of a slum:

*Slums are neglected parts of cities where housing and living conditions are appallingly poor. Slums range from high-density, squalid central city tenements to spontaneous squatter settlements without legal recognition or rights, sprawling at the edge of cities. Some are more than fifty years old, some are land invasions just underway. Slums have various names, Favelas, Kampung, Bidonvilles, Tugurios, yet share the same miserable living conditions.*

This definition provides a general description of a slum. The definition's main parameters identifying slums are negligence and legal recognition, presumably, by city governments as legitimate and recognized parts of the city. Secondly, there are two parameters that the definition explicitly considers unimportant for defining slums: the location in a city (e.g. "squalid central city tenements and sprawling at the edge of cities"), and the age of a slum (e.g. "some are fifty years old, some are land invasions just underway").

### **2.1.2 Census of India Definition**

The definitions suggested by international development agencies are not always universally accepted by their member countries. Many developing countries have their own slum definitions. Usually, they are developed for the purpose of conducting a census. For example, the Census of India (Census of India – Metadata 2010) provided the following definition of a slum for the 2001 census:

*For the purpose of Census of India, 2001, the slum areas broadly constitute of: (i) All specified areas in a town or city notified as 'Slum' by State/Local Government and UT Administration under any Act including a 'Slum Act' (ii) All areas recognized as 'Slum' by State/Local Government and UT Administration, Housing and Slum Boards, which may have not been formally notified as slum under any act (iii) A compact area of at least 300 population or about 60-70 households of*

*poorly built congested tenements, in unhygienic environment usually with inadequate infrastructure and lacking in proper sanitary and drinking water facilities.*

This definition relies on the legal recognition of various public authorities to determine the slum status of a specific place (e.g. criteria (i) and (ii) in the definition). In addition, it emphasizes density and overcrowding as important criteria qualifying a place as a slum (e.g. "compact area", "congested tenements"). It also placed an emphasis on poor housing conditions and a lack of basic services (e.g. "poorly built", "inadequate infrastructure").

### **2.1.3 UN-Habitat Definitions**

The United Nations Human Settlements Programme (UNHCP), now referred as UN-Habitat, is the United Nations' (UN) agency for human settlements. The UN General Assembly mandated it to promote socially and environmentally sustainable cities with the goal of providing adequate shelter for all. Thus, it may be worthwhile to discuss how the UN-Habitat defines a slum. One of the first UN-Habitat definitions (2002) of a slum is as follows:

*A slum is a contiguous settlement where the inhabitants are characterized as having inadequate housing and basic services. A slum*

*is often not recognized and addressed by the public authorities as an integral or equal part of the city.*

This definition emphasizes poor physical conditions of housing stock and a lack of basic services as important elements to identify slum areas. The definition is also explicit about spatial dimension of slums (e.g. "contiguous settlement"). The third element making this definition distinctive is the lack of recognition of these areas as legitimate constituencies (e.g. "not recognized and addressed by the public authority as an integral or equal part of the city").

Over time, this definition has undergone several revisions. The most current definition adapted by the UN-Habitat (2006) is as follows:

*UN-HABITAT defines a slum household as a group of individuals living under the same roof in an urban area who lack one or more of the following: i) Durable housing of a permanent nature that protects against extreme climate conditions. ii) Sufficient living space which means not more than three people sharing the same room. iii) Easy access to safe water in sufficient amounts at an affordable price. iv) Access to adequate sanitation in the form of a private or public toilet shared by a reasonable number of people. v) Security of tenure that prevents forced evictions.*

This definition is different from other definitions discussed above in two important ways. First, it takes a depravity based approach in identifying slums. It recognizes that not all slums are homogeneous and not all slum dwellers suffer from the same degree of deprivation. The degree of deprivation depends on how many of the five elements are lacking within a slum household, which is a significant improvement over a dichotomous slum/non-slum approach of other definitions. For example, this definition can differentiate between the slums that lack only water and the slums that lack both water and sanitation. In contrast, a simple dichotomous approach will treat both these areas as slums without making any distinction based on the degree of deprivation.

Secondly, this revised definition relies on a single household's living condition as opposed to that of a neighborhood. This is an important distinction from the previous definitions because it does not rely on a minimum contiguous area or population size to recognize a place as a slum. In contrast, Census of India's definition (discussed in section 2.1.2) will not recognize a place with 60 or less households as a slum.

This definition also has a practicability in determining whether or not a particular area is a slum. For example, it is possible to objectively measure the overcrowding in a house or to determine whether the house has access to basic services or not. Because of its strengths and versatility, *Slumulation* applies this definition for the purpose of identifying slums within the model.

#### **2.1.4 Implications of Multiple Definitions of Slum**

The multiplicity of definitions poses a challenge to researchers and policymakers when trying to measure slums. In particular, the choice of a specific definition has a direct implication on the estimation of slum population. Using one definition to calculate a city's slum population can lead to an estimate that is quite different when using another definition. For example, there are at least three extremely different estimates describing the slum population in India for the year 2001. Following the definition presented in section 2.1.2, the Census of India (2001) reported 52.4 million people living in slums. In contrast, a recent report from the Committee on Slum Statistics/Census revised the definition and back-estimated the number of slum dwellers to 75.26 million in 2001 (MHUPA 2010). Neither of these come close to the UN-Habitat's estimate of 157 million slum dwellers, which is based on the later definition presented in 2.1.3 (UN-HABITAT: India 2010).

The choice of definition is of particular interest for policymakers since the enumeration of slum dwellers has economic and political implications. For example, a greater number of slum dwellers may mean that a national government needs to allocate more resources for welfare programs. From the research point of view, the multiplicity of definitions across agencies makes it difficult to compare slum situations across places. Similarly, when the definitions are frequently changing within an agency, it complicates the process of analyzing a slum situation over time. Not only is this an issue at the national level, but also at the city level. For example, data on slums in Ahmedabad also suffers from variations in definitions over time

and across agencies, which in turn results in different estimates of slum population, limiting the validation of *Slumulation*.

## **2.2 Characteristics of Slums**

Once a slum is defined, it is useful to explore the characteristics of slums to enhance our understanding of them. This section, therefore, reviews literature from various disciplines to identify common characteristics of slums and slum dwellers. Such characteristics of slums pertain to the location of slums (section 2.2.1), densities and overcrowding (section 2.2.2), the status of basic infrastructure (section 2.2.3), the affordability of housing in slums for urban poor (section 2.2.4), ownership structure (section 2.2.5), residential mobility and migration patterns of slum dwellers (section 2.2.6) and community building and leadership (section 2.2.7). The characteristics of slum dwellers pertain to the economic conditions of the households, their migration behavior and the demographic composition. These characteristics of both slums and slum dwellers are useful in designing and conceptualizing the simulation model. For example, understanding general characteristics of slum locations guided the choice of spatial elements included in the environment of the model.

### **2.2.1 Location of Slums**

Literature suggests that slum locations have several common characteristics across cities. For instance, slums are normally found in locations that are unsuitable for housing and urban development (UN-Habitat 2003). These locations include

hazardous sites such as river banks, steep slopes, solid waste disposal sites, vacant land along the railway tracks and wetlands. Areas with safety hazards, like landslides, pollution, health hazards, fire, flooding and areas unsuitable for human habitation are also correlated with slum locations (Jenkins 2001). Slums are also found in unattractive areas such as cemeteries and graveyards e.g. city of the dead in Cairo, Egypt (Garr 1996). They are located both in the central areas of cities as well as in the peripheries (Barros 2005).

Although locational characteristics of slums in relation to land characteristics are well known, a complete understanding of slum locations in relation to each other and to other features of the city, such as places of employment, markets etc., does not exist. However, these characteristics of slum locations suggest that unattractiveness and/or a hazardous locations are important features for the model.

### **2.2.2 Density and Overcrowding**

Overcrowding is one of the key parameters that characterizes slums in developing countries. In particular, slums have very high population densities compared to the rest of the city in which they are located. For example, Dharavi, a slum in Mumbai, has a density of 336,000 persons per sq km, which is 11 times denser than the rest of the city, 29,500 persons per sq km for Mumbai as a whole (Dharavi.org 2010). In Nairobi, Kenya, the average slum density is 75,000 persons per sq km, which is 25 times higher than in the planned parts of the city, 3000 persons per sq km)(Alder 1999). Therefore, density is an important parameter for

*Slumulation* that can aid in identifying slum areas. The ratio of densities between slums and non-slums in a city is also used as a basis for validation.

### **2.2.3 Depravity Continuum**

It is important to recognize that there is not a dichotomy that divides a geographical space into a slum and a non-slum. Rather, slums are a continuum along dimensions of depravity to plenty. For example, Weeks et al. (2007) used a ten percent sample of Census data from Accra, Ghana to identify varying degrees of "slumness" rather than following a simple slum/non-slum dichotomy. Using characteristics of individual housing units, the authors created a slum index at the Census Block level. The authors applied geospatial aggregation methods to identify contiguous areas that had a similar slum depravity index score. The neighborhood structure identified through this analysis showed significant spatial discontinuity in the slum index scores and negated the view that slums are spatially concentrated in a particular part of the city. Also, the work showed that intra-slum heterogeneity is only visible when a continuous scale is applied. This is an important finding from the perspective of validating spatial patterns of slum locations. *Slumulation* uses The UN-Habitat's multi-criteria definition, which is particularly useful in operationalizing this continuum as discussed in section 2.1.3.

### **2.2.4 Affordability of Slums for Urban Poor**

Conventional wisdom suggests that slums play a critical role by providing low-quality and low-cost housing to the urban poor. However, Gulyani and Talukdar

(2008) found the opposite situation in Nairobi. That is, the poor slum dwellers paid only 20% lower rents than the non-poor residents. They reported that, in 2004, a poor household paid \$126 on average to rent a house, which amounts to a cumulative \$31million per year, indicating a huge informal housing market in slums. This study suggested that occupying a dwelling in a slum is not always free or affordable to urban poor, but it might have an exorbitant price due to the supply constraints within these slums.

#### **2.2.5 Ownership and Renting**

A common misunderstanding regarding slums is that the structures within them are built and owned by the respective residents. However, a study of slums in Nairobi (Gulyani and Talukdar 2008) found that a rental market for properties exists in slums. The people living in the structures did not always build or own them. The distinction between renters and owners has important implications for policies striving to improve housing conditions in slums. Ignoring these realities has led to policies that bring unintended consequences. For example, as the authors report, improving the infrastructures of slum structures increased the rents and made them unaffordable for the poor. Furthermore, the government provided secured tenure to these slum properties. However, granting tenure did not benefit actual slum dwellers but only provided security to owners who were not necessarily occupiers. Despite receiving tenure and higher rents, slum owners were not interested in improving the quality of housing. The authors argued that innovative

interventions are required in the slums, bringing renters and owners to a table to devise an effective policy to protect renters' interests.

The important implications of this research for *Slumulation* are twofold: first, houses in slums are not always built by their occupiers. In some cases, they are also informally owned by those who do not live there but rent it to others. Hence, any intervention that improves houses in a slum may not necessarily benefit renter slum dwellers. Secondly, a parallel market for properties exists in slums so properties could be easily sold and rented informally. While the distinction between owners and renters is important, *Slumulation* did not model them separately for simplicity's sake.

#### **2.2.6 Residential Mobility and Circular Migration**

It is worthwhile to explore who lives in these slums, where they come from and how long they stay at the same location. Is residential mobility relatively low in these slums or do people change their homes more frequently compared to people living in formal housing? Do they tend to be new migrants or have they lived there for generations? These are interesting aspects that need to be incorporated in the simulation framework explicitly.

A longitudinal study by Beguy et al. (2010) revealed several interesting dimensions of mobility in the slums of Nairobi. The authors monitored the population in two slums in Nairobi for five years, from 2003 to 2007. The study revealed that there is a high intensity of circular migration among slum dwellers. Circular migration means that there is a greater propensity to move freely between

origin and destination. In-migration from origins to these slums was high for adolescents, while out-migration from these slums to their origins was high among migrants over 25 years of age. This finding suggests that migration to the city is a transient phase in the rural population's life cycle. In-migration attracted migrants not only from rural areas but also from other slums and non-slum areas of Nairobi, suggesting intra-urban residential mobility. Their regression analysis of in-migration and out-migration revealed that population turnover is positively correlated with the lack of livelihoods, tenure, and poor basic amenities and social services in slum settlements. The authors argued that policies that actually aimed to improve basic amenities and introduced secured tenure forced the poorest migrants to either relocate to other slums with lower rents or return to their rural origin.

In a similar study, Tutu (2010) explained the propensity of return migration in slums in Accra, Ghana. The author found that both proximate (i.e. conditions in the destination) and remote factors (i.e. conditions in the origin) influence the duration of stay for migrants in Accra's slums. A multivariate analysis of primary survey data of migrants in slums indicated that a shorter stay was associated with marital intentions, learning a trade (i.e. migrants expected to go back to origin after learning a trade in the city) and whether they had strong local ties to access information in the city. Higher income was also associated with higher propensity to return to rural areas, probably because they had enough savings to venture back to their origin. These results were counterintuitive and suggested that migrants spend time in a slum as a transient phase of their lives. They chose to return to their

original homes once favorable conditions were achieved instead of living in the slums for the rest of their lives.

Neekhara (2008) found a similar propensity for return migration among slum dwellers in Bhopal, India. A multivariate regression using survey data indicated that people migrated to cities for employment opportunities, but if they later found employment in their origin, they would like to return rather than living in a slum. Nonetheless, the survey found that the propensity of return migration was lower in slums with better amenities. These are important insights and suggest that population does not always flow in one direction. There is a fraction of slum dwellers who return to their origin and are thus willing to reverse-migrate.

These studies provided insight about intra-urban and inter-slum residential mobility. This is an important element to model and it is operationalized as the duration of stay in the simulation model. Thus, slum dynamics are affected by both in-migration and out-migration in the model.

### **2.2.7 Community Building and Leadership in Slums**

Slums are also commonly characterized by the presence of spiritual and religious sites. A mapping project in Kibera, a slum in Nairobi, Kenya, shows the presence of such buildings (Map Kibera 2012). Choguill (1987) reported that in most slum communities, religious and other places of worship are present. There are two reasons for the presence of such buildings: first, it provides security against the demolition of slums brought by the religious sentiments attached with a place of worship. Secondly, membership in the same religious group is the second most

important factor (after similar income group) that defines newly formed slums in many developing countries. Furthermore, such buildings foster a sense of community commonly found in slums (Berg-Schlosser and Kersting 2003).

Jha et al. (2005) studied civic engagement in the slums of New Delhi, India. They used a mix of quantitative and qualitative methods that they called "participatory econometrics" to identify democratic responsiveness and leadership. The authors found that comparatively "wealthier" slums had better access to formal governance of the city, whereas poor slum communities accessed formal governance through an informal leader who helps eliminate the constant threat of demolition, theft and uncertain property rights. Ethnically homogenous communities often recreate their existing leadership structure at the rural origin. In contrast, newer or ethnically diverse slums identify informal leaders who achieve their authorities through political connections, education and networking skills. Most importantly, this study provided a generalized understanding of the internal governance of slums, providing an input for *Slumulation*. For example, the role of local leaders in mobilizing communities to resist eviction pressures, as well as obtaining community facilities such as a basic infrastructure, is modeled explicitly in *Slumulation*.

### **2.3 Factors Influencing Emergence of Slums**

This final section reviews the literature that identifies key factors for the slum emergence in the developing world. Such factors include rural-urban

migration (section 2.3.1), location choice factors (section 2.3.2), household preferences and location choices (2.3.3), planning and policies (2.3.4), and political and historical context (section 2.3.5). Understanding of these factors will provide important insights for conceptualizing *Slumulation*.

### **2.3.1 Rural-Urban Migration**

Rural-urban migration is considered to be an important factor that influences slum formation in cities. Ullah (2004) concluded that most migrants to Dhaka from rural Bangladesh ended up in slums. Mitra and Tsujita (2006) explored whether migrants improved their living conditions over time. The authors conducted a survey of individuals in the slums of New Delhi in 2006 to pursue whether migrants were likely to experience upward income mobility in their place of destination. Their findings contradicted the view that migrants merely transfer poverty from rural areas to large cities. They found that, in the long term, migration improved the living standard for migrants. Thus, how long a household stays at a destination is an important variable for several reasons; How long a household has stayed in the city determines its income level, which may change the household's propensity to return. Hence a dynamic view of individual households, their post-migration income levels and duration of stay are explicitly modeled in *Slumulation*.

### **2.3.2 Location Choice Factors**

Lall et al. (2008) explored the factors impacting location choices for slum dwellers in the city of Pune, India. They used a multivariate analysis of survey data.

The authors explored three major location choice factors suggested in the classical housing location choice literature from developed countries: commuting costs (Alonso 1964; Mills 1972), local public goods (Tiebout 1956) and individual preferences for neighborhood composition (Schelling 1971). The study found that location choices were based on housing quality, neighborhood amenities and community structure in addition to the three classical factors. This finding has a major implication for policies that involve the relocation of slums (e.g. sites and services as discussed in Chapter 3), since slum dwellers assign a value to the location of slums, configuration of the community and amenities in the neighborhood. The study quantified the welfare loss for slum dwellers for resettlement policy alternatives. The authors suggested that, while cities could achieve land use efficiency through the resettlement of slums, the concomitant welfare losses for slum dwellers would be high, particularly for those incurred by difficulty in maintaining the same configuration of community structure at a new site. The negative preference towards forced relocation among slum dwellers is thus incorporated into *Slumulation*.

### **2.3.3 Planning and Policies influencing Emergence of Slums**

It is not well understood how planning process and policies may influence the formation and expansion of slums (Pugh 2001). As discussed in section 2.2, policies designed to improve the lives of slum dwellers could work against them. The mechanisms of such adverse relationships are often not understood. In a noteworthy study, Mata et al. (2007) showed one such mechanism. The authors

examined the impacts of local zoning and land use policies on slum formation in Brazilian cities between 1980 and 2000. The authors provided a counterintuitive explanation that slum formation was higher in the cities that enacted pro-poor housing policies, such as smaller lot sizes. A smaller minimum lot size tends to provide a favorable framework for poor migrants in the city by increasing formal housing supply and potentially creating affordable housing. However, the author showed that migrants often took pro-poor housing policy as a positive signal in their migration decisions, and hence, the cities with pro-poor housing policies tended to attract more migrants compared to other cities lacking such policies. This, in turn, created a new demand in the city which offsets the net effect of increased supply originally created by pro-poor housing policy.

Where formal housing markets were perfectly elastic, this would not pose a problem because the housing supply would increase with higher demand. However, in developing and emerging countries like Brazil, formal housing markets are far from elastic both for housing prices and income shifts. Thus, whether slum formation would increase or decrease depends on the net effect of increased migration and market responses to the increased demand. Thus slum formation may increase despite pro-poor zoning policies, or even because of such policies.

This study provided important insight into the way policies that are intended to operate at one scale (i.e. city) might induce changes at a different scale (i.e. regional level migration), ultimately working against the intended outcomes. Models such as *Slumulation* could provide a tool to study such unintended outcomes of a

policy change. Therefore, it is important to build a multi-scale linked system that models both city level dynamics (e.g. housing market dynamics) and regional level dynamics (i.e. migration dynamics). Secondly, it is important to explicitly model the elasticity of a housing market.

In another country-level study of 162 countries, Martinez and King (2010) illustrated how a policy change may work against its intended goal in the short run. The authors used cross-national data of property rights protection scores and growth indicators from 1995 to 2005. Authors found a positive relationship between property rights protection and a reduction in poverty. However, when they studied improvements in property rights protection, this association disappeared. In other words, the authors did not find a positive relationship between change and improvement in property rights protection and a reduction in poverty. Thus, when a policy that induces change in a regime, that *change* itself might not lead to the outcomes expected in the short term. This finding provides the basis for the usefulness of building dynamic models such as *Slumulation* to study the immediate impacts of policy changes.

#### **2.3.4 The role of Path Dependence**

Path dependence simply means that history matters (Batty 2005). The outcomes of interest may have been shaped by historical context even if the history is no longer relevant. Historical factors are important elements in explaining the pattern of slum formation and expansion. For example, Fox (2008) found significant influence of colonial legacies of urban governance and planning practices on slum

incidence in those countries. The author explained variation in slum incidence in developing countries using cross-national data that includes colonization, political fractionalization etc. The other major factors that influenced the level of slum incidence were initial income level (GDP) and political fractionalization. Exploration of path dependence of colonial rule, initial income levels and the effect of political fractionalization are suggestive of the issues related to urban governance and its consequences on slum incidence. The initial conditions of a city have important implications for the future course of slum formation and expansion process. Hence, it is important to consider the role of path dependence in the model building.

### **2.3.5 The Role of Institutions**

It is important to understand how institutions, such as local governments, may influence slums. For example, Mukhija (2003) provided a detailed account of the institutional failure of slum redevelopment projects in Mumbai, India. The slum redevelopment projects envisaged the redevelopment of slums at existing locations. In addition, private developers were allowed to build extra units sold in the open market to recoup the cost of the projects. The key idea was to exploit the financial potential of the land and convert it into an opportunity to improve the housing conditions for slum dwellers, as well as to create new housing stock for the city. The policymakers assumed that the private sector would come forward to exploit the opportunity created by this policy. The success of this slum redevelopment strategy required the cooperation of the slum community in taking a role as a partner in development projects. However, these projects were capital intensive and private

developers controlled the project. Although originally intended, the slum community never realized its role as an equal partner. There was a need for a tight regulation in order to protect the slum dwellers' rights. But at the same time, it was required to provide flexibility to the private sector to develop each project uniquely depending on potential property prices of that particular site and the number of slum dwellers. The government's role as a facilitator of the right balance of regulation and deregulation was necessary for avoiding disputes between developers and slum communities. This especially applied over financial benefits generated from such projects (see Mukhija 2003 for a detailed case study of a slum redevelopment project in Mumbai).

The role of institutions is often not incorporated in urban modeling efforts. For example, in an attempt to simplify slums as a mathematical optimization problem, Sai et al. (1978) developed a nonlinear programming model to maximize the living conditions of slum dwellers while minimizing investment costs for the developers for the slum redevelopment projects discussed above. Mathematical approaches, such as nonlinear programming, assume that policymakers could pull all the projects and implement an optimal solution by maximizing the overall welfare of the system without worrying about maximizing the benefits or minimizing the costs for the individual projects. However, such approaches fail to understand that individual slum dwellers or developers of these projects will be interested only in maximizing benefits and minimizing costs from their own project. They may not be interested in the welfare of the entire system. Such approaches fail

to understand the roles of institutions that could settle the conflicting interests of slum dwellers and private developers (Mukhija 2003). From this discussion, it is evident that households, developers and government should be modeled separately in the simulation, with each of them acting for their own self-interest, rather than working towards maximizing the overall system level benefits.

## **2.4 Discussion**

It is evident from the above discussion that significant information exists on the nature of slums in the developing world. Empirical findings about household characteristics and behavior of households in housing markets are also well documented. In addition, characteristics of slums in terms of their location, densities, socio-economic and political conditions are known. The literature delivers a foundation for developing a model that could provide a comprehensive understanding of slum dynamics.

It is possible to discern important actors, processes (such as housing location choice) and spatial variables (such as slum locations) from the literature and case studies. Also, inputs for several variables could be derived from the stylized facts available from the empirical studies discussed above, such as proportion of renters and owners in slums. The literature based on household surveys could be also helpful in determining rules for simulating household behavior.

## **CHAPTER 3. EVOLUTION OF SLUM POLICIES**

There is a long history of policies implemented to tackle slum issues in the developing world. The policies have ranged from slum demolitions and forced evictions (Mahadevia and Narayanan 1999) to participatory slum redevelopment (Pugh 1989; 2001). Despite these efforts, slum-free cities remain a distant goal for most developing countries. Slum issues became more prevalent after 1950s due to an increased rate of urbanization, and induced large-scale policy responses (Pugh 1997). This chapter discusses the evolution of major policy debates around slum issues after the 1950s, with a specific focus on developing countries.

Slum policies implemented within the last six decades fall into six main categories and their evolution roughly follows a chronological order: business-as-usual in the 1950s (section 3.1), public housing in the 1960s (section 3.2), sites-and-services programs in the 1970s (section 3.3), slum upgrading in the 1980s (section 3.4), security of tenure in the 1990s (section 3.5), and cities without slums in the 2000s (section 3.6) (Pugh 1997; UN-Habitat 2003). While these policies originated and became popular among policymakers in those decades, most of them are still found in practice even today. This chapter reviews the literature to identify the basic concepts of each policy and their respective strengths and weaknesses. Most of these policy innovations were prescribed by international development agencies,

primarily the World Bank and the UN-Habitat (formerly UNCHS). In addition, the chapter also discusses several indigenous policy ideas that were implemented in India, including in Ahmedabad (sector 3.7).

Policymakers implemented many of these policies at a large scale in several cities throughout the developing world without fully understanding the extent of their impacts, sometimes unintended, beforehand. For example, literature predicting the outcomes of the Slum Upgradation Policy (section 3.4) was almost non-existent when it was under consideration in 1980s. However, there is no dearth of literature that evaluated the policy after the projects were implemented (e.g. Laquian 1977; Materu 1986). There is an abundance of *ex-post* analyses reviewing these policies (e.g. Bamberger et al. 1984; Viratkapan et al. 2006; Takeuchi et al. 2006) but scholars have rarely attempted to understand the implications and qualify these policies *ex-ante*. With a brief overview of the evolution of slum policies, this chapter will illustrate how policymakers failed to fully anticipate the unintended consequences of policies in advance. An attempt is also made throughout the remainder of this chapter to identify relevant points that are useful for making the design and structure of *Slumulation*.

### **3.1 Business as Usual: Slums are Temporary**

While in the 1950s slums were not new in developing countries, slum population increased substantially as the economy shifted from a rural agrarian base to an urban manufacturing and service base. Local governments in urban areas

initially considered slum formation as a temporary phenomenon caused by newly migrated rural populations, and thereby failed to take any immediate policy action.

In the 1950s, cities attracted a large flow of rural migrants but governments usually turned a blind eye to housing that was built outside the official regulations (Farvacque-Vitković et al. 1992). In fact, policy makers and urban planners regarded slums as a traditional form of temporary housing, and thus a minor problem. Slums were considered to be remains of traditional villages that were in the process of being absorbed by the new urban development (Dwyer 1974). New slums established by recently arrived migrants were considered a temporary solution to the lack of affordable housing. Although they were viewed with suspicion and hostility, they were generally tolerated (Smart 2001). Most of these settlements remain even today in cities in developing countries.

The evidence of the last 60 years shows that in the face of unavailability of affordable housing in the formal market, new households will build their own housing. Hence, for *Slumulation*, it will be useful to conceive households in a dual role where they are both the producers and the consumers of the housing stock.

### **3.2 Public Housing: Government would Build**

In the 1960s, governments began to realize that slums were becoming permanent. At that time, they considered subsidized public housing as an appropriate policy response for those who could not afford housing otherwise. Nonetheless, public housing was allocated in a discretionary fashion, largely

because new political leaders who replaced colonial rulers perpetuated similar social and class divisions as the previous colonial rulers (Fanon 1963). The main beneficiaries of public housing schemes were civil servants and middle and upper-income earners, but not the poor who were most in need (Fekade 2000). As the Grimes' (1976) study concluded, one reason for this was that 60 percent of the population of developing countries was simply too poor to afford the cheapest unit of subsidized public housing.

Furthermore, public housing was in limited supply due to public sector's budget constraints. Therefore, efforts to meet housing demands of a large number of urban poor fell short. For example, public housing schemes provided less than 5% of housing needs among the poor in Africa (Hope 1996). The failure of public housing was also attributed to factors such as cost, socio-economic discrimination, inappropriate design and ignorance of cultural context in housing planning schemes.

### **3.3 Sites and Services: Let them Build Elsewhere**

International institutions became concerned with the increase in the number of slums in the 1970s. Issues concerning slums, such as security, environmental health and limited access to basic infrastructure became visible as more and more people were being affected (Pugh 1989). Recognizing the immediate need to intervene, the World Bank and UN-Habitat developed a policy called "site and services" which was implemented in the 1970s in many developing countries such, as El Salvador, Kenya and India (Kaufman and Quigley 1987; Mayo and Gross 1987).

This program demolished slums and developed new sites with basic infrastructure services (e.g. water and sanitation) for relocating slum dwellers. Policymakers hoped that "sites and services" would make cities slum-free (Bamberger et al. 1982). Slum dwellers were expected to pay for serviced land so that local governments could recover the cost of these projects. They were also expected to build houses at a new site and pay for those services. Most slum dwellers could not afford these additional costs that they could not afford. Also, there were high building standards expected for dwelling units on newly developed sites, which drove up costs and made housing unaffordable for the urban poor. The scheme failed to help the poor who lost their houses after the demolition of slums but could not afford to build a new house at a new site.

Often, the relocation of slum dwellers also meant loss of employment for them due to poor access to their original jobs from their new locations. Many activities were also banned on these sites (e.g. agricultural activities and animal husbandry) which were essential for the livelihood for many slum dwellers (Peattie 1982). In fact, serviced land was eventually occupied by middle-class and higher income groups who could afford these sites such as in Pakistan (Jacobsen et al. 2002). The original slum dwellers were forced to find unplanned areas elsewhere which resulted into the mere relocation of slums. For example, in Zambia, Zimbabwe and Kenya, only 6 percent of the intended beneficiaries actually benefited from "site and services" due to the precise reason of affordability (Hope 1996).

Ironically, this scheme created a housing shortage by demolishing existing housing units in slums. Many evicted slum dwellers had difficulties being qualified for newly serviced parcels due to a lack of land titles and rights, illiteracy, corruption and bureaucratic hurdles (Malpezzi and Sa-Aadu 1996). Moreover, the sites and services programs did not respond to the magnitude of the slum problem because projects were expensive and barely provided affordable housing to the poor if at all (Apiyo 1998). The “sites and services” program failed to understand the core requirements of housing for urban poor, mainly the proximity to livelihood opportunities and affordability (Gattony 2009). Thus, the program could not deliver the promise of a slum-free city.

There are several points that emerge from the review of the “sites and services” program that are relevant for the development of *Slumulation*. First, it is clear that individual households have their preferences for the location based on their place of employment. Furthermore, urban poor may have limited mobility due to a lack of resources available for transportation, in addition to the lack of public transit in cities of the developing world. Therefore, it is important for *Slumulation* to model households' location preferences and access to jobs explicitly. Secondly, households have varying levels of affordability. It is important to model household affordability criteria, which determine each household's location preference within its budget constraints. Lastly, it is evident that formal and informal housing markets interact because they essentially operate within the same city space. The serviced sites may fulfill the demand of the formal housing market if it is undersupplied.

Thus, it is important to model both slums and non-slums (i.e. the entire city) in *Slumulation* even if our primary interest is to understand slums.

### **3.4 Slum Upgrading: Upgrade the Environment, Wherever They Are**

Learning from these failures, the World Bank proposed an improved policy known as "Slum Redevelopment", which was implemented in many developing countries, including India, in the 1980s (Pugh 1989; 2001). The policy recognized the importance of housing locations for the urban poor. Slum upgrading projects improved basic infrastructures at the original slum location. The policy differed significantly from earlier policies, as the focus shifted from individual dwelling units to the community infrastructure. The community environment was improved by investing in the provision of basic services such as water, electricity, street pavements and social infrastructure, including health centers and schools. Policymakers hoped that improvements at the community level infrastructure would encourage slum dwellers to improve their own housing units.

Policymakers also understood the importance of existing housing stock and did not advocate for demolition. Slum upgrading projects were an improvement upon the "site and services" program because it accepted the lower standard of housing, which in turn made it affordable to poor households (Fekade 2000).

However, the major drawback of this approach was the lack of secured tenure (right to occupy the informal properties without fear of eviction). The perceived threat of demolition amongst slum dwellers resulted in a lack of

investments for improving individual housing units (Gulyani and Bassett 2007; 2008). As a result, deterioration of housing stock continued, despite improvements in community level facilities. While investments in community infrastructure implicitly indicated a secured tenure *de facto*, tenure was not awarded *de jure* (Gulyani and Bassett 2007).

Furthermore, slum upgrading policies were thought to generate economic growth, and subsequently achieve social and spatial sustainability (Banes et al. 2000). However, the empirical evidence suggested otherwise. Amis (1995) conducted a study in Indian cities and found that slum upgrading projects were not correlated with poverty reduction, employment and land security, as the program had originally aimed.

Ironically, improvement in community level infrastructure led to an increase in real estate prices and made housing unaffordable to original slum dwellers. As a result, the areas were eventually occupied by middle class and higher income groups, forcing the urban poor to construct new slum-like conditions elsewhere in the city. For example, Petrella (1999) conducted a study after ten years of implementation of the slum upgrading program in Nairobi, Kenya and found that over half of the occupiers were middle and high income dwellers, and they were not the occupants at the initiation of the project.

In addition, these programs were financially unsustainable. They were undertaken with the financial support from international agencies which eventually depleted (Brennan 1993). As a result, slum upgrading could not reach a large

majority of slums due to financial dependency on foreign assistance. Even in a limited number of slums where the policy was implemented, the situation did not improve in the long term.

Once again, the formal and informal housing markets interact with each other. Land which is improved for the informal housing sector could potentially serve the demands from the formal sector. It is important to model both these markets within the same framework of *Slumulation*. Secondly, households and other actors are adaptive. They react to changes in the policy environment. For example, when slum land is serviced, it becomes a desirable location for middle-income households. This suggests how household preferences for the same location could change with a policy.

### **3.5 Security of Tenure: Let us Legalize Them**

Realizing the importance of security of tenure from the experience of past policies, international agencies, such as UN-Habitat, proposed and supported security of tenure in the 1990s as a contingent measure to limit the eviction and demolition threat within slums (Jenkins 2001). As it was done in many other developing countries, several local governments in India also awarded legal titles to slum owners, hoping that it would encourage slum dwellers to invest in their property and improve living conditions (Pimple and John 2002).

Under this policy paradigm, slum dwellers do not necessarily have legal titles over land but security of tenure means they can undertake improvement on their

properties without fear of eviction. The security of tenure approach also postulates that availability of and accessibility to urban land provides a sense of "belonging" and brings stability to an urban area (Kombe and Kreibich 2000). The security of tenure approach is based on the premise that when the residents have the sense of appropriation, they also have confidence, motivation and willingness to upgrade or improve their environment (Kombe and Kreibich 2000). The legal recognition of slums helps address the problem of tenure insecurity and the consequent cycle of construction, destruction, eviction and reconstruction.

Another argument for security of tenure is from the property rights perspective, originally suggested by Turner (1972) and more recently made popular among policymakers by De Soto (2003). De Soto argues that a huge amount of capital is held informally with urban poor *de facto*. Security of tenure can uplift millions of urban poor by giving *de jure* rights to the properties they are occupying. De Soto argues that it would unlock access to financial markets for urban poor who can use their property as collateral given that they have secured tenure. However, critics of this idea, mainly Gilbert (2002), suggest that there is no market for the assets in slums and hence it cannot generate wealth for the urban poor. There is a vast amount of literature providing evidence for (e.g. Durand-Lasserve 1996; Durand-Lasserve and Royston 2002; Masland 2002) and against (e.g. Burgess 1978; 1985; Fernandes 1999) "security of tenure" policy. It is uncertain if it is an effective solution to resolve the informal housing problem in developing countries.

The “security of tenure” policy has two major limitations. First, this policy is in favor of slumlords, rather than slum dwellers. Legal titles were awarded to slumlords, who did not necessarily live in slums. This only resulted in increased rent prices for the slum dwellers. Furthermore, legal titles allowed the owners to enter the formal housing markets and sell those properties for formal housing development, thus decreasing the affordable housing stock. Slumlords tended to re-sell or rent their properties in the formal market, eventually at a higher price because the land value increases with the tenure security (Fernandes 1999). Thus, slum dwellers who failed to claim their rights, or who were renting, went on to create slum-like conditions elsewhere. Second, the implementation of security of tenure did not guarantee any long-term solution to stop the emergence of new slums. In fact, it created a moral hazard problem because there was an incentive to build new slums as one could now hope to get legal rights over land informally occupied.

The above discussion shows again that there is an inherent risk of eviction in informally occupied land. There are two implications of this for *Slumulation*. First, when faced with a risk, households will not invest in their housing. Second, there exists a parallel market for slums with lower prices because of the risk of eviction (as evident from section 3.4). As a corollary, when a slum is legalized, it could potentially serve demands in a formal market and hence induce a price rise. Hence, it is important to explicitly model the “legality” of occupying a housing unit in *Slumulation*.

### **3.6 Cities Without Slums: Let us have a Vision**

In 1999, the World Bank and UN-Habitat initiated the "Cities Without Slums Action Plan", which now constitutes a part of the Millennium Development Goals. Specifically, the action plan aimed 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 was to move away from the physical eradication or upgrading of slums goal, to dealing with poverty, which is one of the fundamental reasons why slums exist in the first place. The recognition of slums largely as a physical manifestation of underlying urban poverty, and focusing on poverty reduction or eradication was a noteworthy element of the action plan. This approach to tackle poverty in order to improve the slum situation was encouraging, but it raised two important concerns. First, the number of targeted slum dwellers was far too modest, compared to the 924 million people currently living in slums and nowhere near the projected 2 billion by 2030 (UN-Habitat 2003). Second, the plan did not propose new measures or policies to curb the emergence of slums.

### **3.7 Slum Redevelopment and Slum Networking: Indigenous Policies**

Not only there have been efforts by international actors to reduce slums, but also national and sub-national governments are actively seeking local solutions to tackle the issue of slums. There have been examples of such indigenous policy ideas implemented in Indian cities and possibly elsewhere. For instance, Mumbai implemented a unique "Slum Redevelopment Scheme", with a tripartite partnership

between slum dwellers, developers and local government (Burra 2005). Slum dwellers were provided with formal housing on the same location in lieu of allowing developers to sell the extra units in the formal market. Local government also provided transferable development rights to developers (for building extra units elsewhere) to accommodate the existing slum population where densities were already high. However, this policy has largely failed due to conflicting interests of slum communities and developers (Mukhija 2001; 2003).

The city of Ahmedabad experimented with a policy called the "Slum Networking Project" that envisioned linking slums with existing networks of the city infrastructure and providing services such as water and sewerage (Tripathi 1998). The pilot project implemented in Sanjaynagar, a slum in Ahmedabad, was once considered a success story but the policy could not be replicated in any of the other slums in Ahmedabad due to institutional failures, such as a lack of resources required for scaling the initiative (Chauhan and Lal 1999; Dutta 2000; Acharya and Parikh 2000). While innovative, these approaches have also failed to alleviate slum issues both in Ahmedabad and Mumbai.

It is clear from the above discussion that households, developers and local governments have their own self-interests, which often lead to conflicts of interest among these stakeholders. It is thus important for *Slumulation* to model these actors as separate forces with their own behavioral rules that satisfy their own interests.

### **3.8 Rajiv Awas Yojana: Slum-Free India in Five Years**

"Cities without Slums" was a clear goal that soon became the mantra for policymakers in many countries, including India. In 2009, Ms. Pratibha Patil, then the President of India, endorsed this rhetoric and appealed to make India slum-free within five years (Times of India 2009). Following this, the Ministry of Housing and Urban Poverty Alleviation launched a massive housing program called Rajiv Awas Yojana (RAY) in 2011 (MHUPA 2011).

In essence, RAY is a mixture of the different policies discussed above. While RAY emphasizes security of tenure, it also includes elements of public housing, "sites and services" and "slum upgrading". This program is built upon the experience of the predecessor programs, namely, Jawaharlal Nehru Urban Renewal Mission (JNNURM) and Integrated Housing and Slum Development Programme (IHSDP). Several existing slum programs, such as Affordable Housing in Partnership and Interest Subsidy Scheme for Housing the Urban Poor, have been dovetailed RAY. In other words, it is not a new policy but a renewed focus on slums in Indian cities.

Despite knowing the shortcomings of policies of the past, the Indian government is keen to implement these same policies under a new name (i.e. RAY) in 250 Indian cities. The policy evaluation studies have already shown that these policies in isolation have not worked in the past (Harms 1982; Abelson 1996; Harris 1998; Laquian 1977; Materu 1986; Gulyani and Basset 2008). What remains to be seen is whether the implementation of all of them simultaneously and selectively will make India slum-free. Each city is expected to prepare a slum-free city plan that

identifies appropriate projects for various slums in the city (e.g. slum upgrading for some while sites and services for some others). It is for these cities that *Slumulation* could provide a tool to explore a variety of policy options for their slum-free city planning.

### **3.9 Discussion**

From the discussion above, it is evident that slum policies have been either incremental or experimental (e.g. "Slum Networking" in Ahmedabad or "Slum Redevelopment" in Mumbai). Both types of policies have been implemented by policy makers without identifying all of their adverse implications *a priori* for either individual urban poor at the micro-scale or slum formation in cities at the macro-scale. Ex-post analysis is in abundance (e.g. Bamberger et al. 1982; Viratkapan and Perera 2006; Takeuchi et al. 2006), but people have rarely attempted to understand the implications of these policies *ex-ante*. In this sense, slum policies have thus far been heuristic rather than evidence-based. Part of the problem is a lack of analytical tools available to urban planners and policy-makers for slum research. Specifically, research tools that analyze 'what-if' questions to evaluate proposed policy interventions are almost non-existent, with a notable exception of the Informal Settlement Growth Model (Sietchiping 2004; 2008) discussed in more detail in Chapter 4. *Slumulation* is one such tool to test and evaluate new policy ideas in a simulated environment before they are implemented in the real world.

There are several points that have emerged from the review of slum policies that help guide the design and the development of *Slumulation*: i) households, developers and local government have their own self-interests and often they conflict; ii) formal and informal housing markets interact with each other and compete within the same city space; iii) actors in the housing market are adaptive and react to changes in the policy environment, which could in turn affect policy outcomes; iv) households have a location preference within their affordability limits. *Slumulation* attempts to incorporate these points in its design, which could therefore make it a reliable tool to evaluate policy ideas.

## **CHAPTER 4. THEORIES AND MODELS OF SLUM FORMATION**

Slums are common features of the urban landscape in the cities of developing countries. In fact, unplanned and informal developments found in slums are the norm in those cities, while formal and planned developments are the exception (De Soto 2003). Urban theories attempt to explain how the informalisation of cities in the developing countries has emerged, and postulate why slums have grown exponentially. It is therefore useful to understand theories that explain emergence and the growth of slums in order to identify the factors that a dynamic spatial model must include to predict the location of slums. The purpose of this chapter is threefold: i) to assess the theories behind the spatial organization of urban areas ii) to identify the basis for the assumptions required to design and develop a simulation model and iii) to identify the methodological gaps in slum research to establish the need for an integrated simulation approach.

The literature review is presented in four sections in this chapter: section 4.1 briefly reviews theories that explain spatial organization of cities and sheds light on why and how people choose to live at a specific location (location choice behavior); section 4.2 presents empirical studies that describe slums and its characteristics; section 4.3 reviews the past attempts to develop statistical and simulation models;

section 4.4 concludes the chapter with the relevant points for the conceptualization of *Slumulation*.

## **4.1 Theories of Spatial Organization of Cities**

This section reviews the theories of spatial organization of cities to understand urban residents' location choice behavior, and in particular, why the urban poor congregate in particular locations (section 4.1.1). It also examines the studies largely known as factorial ecology<sup>5</sup> or social area analysis<sup>6</sup> that empirically measures spatial inequality<sup>7</sup> and residential segregation among various groups within a city (section 4.1.2).

### **4.1.1 Ecological School and Neo-Classical Models**

An essential characteristic of a city is its dynamic nature: there is constant building and rebuilding, succession and occupation of various groups, and location and relocation of various activities in a city. In a city with a free market for urban land, this process is largely driven by the search for optimal land use at the city level and higher returns from the investment in land at the individual investor level. This process has often led to the physical expression of inequality. For example, income-based segregated patterns found in the cities where slums emerge is a result of the inability of poor to compete in the housing market.

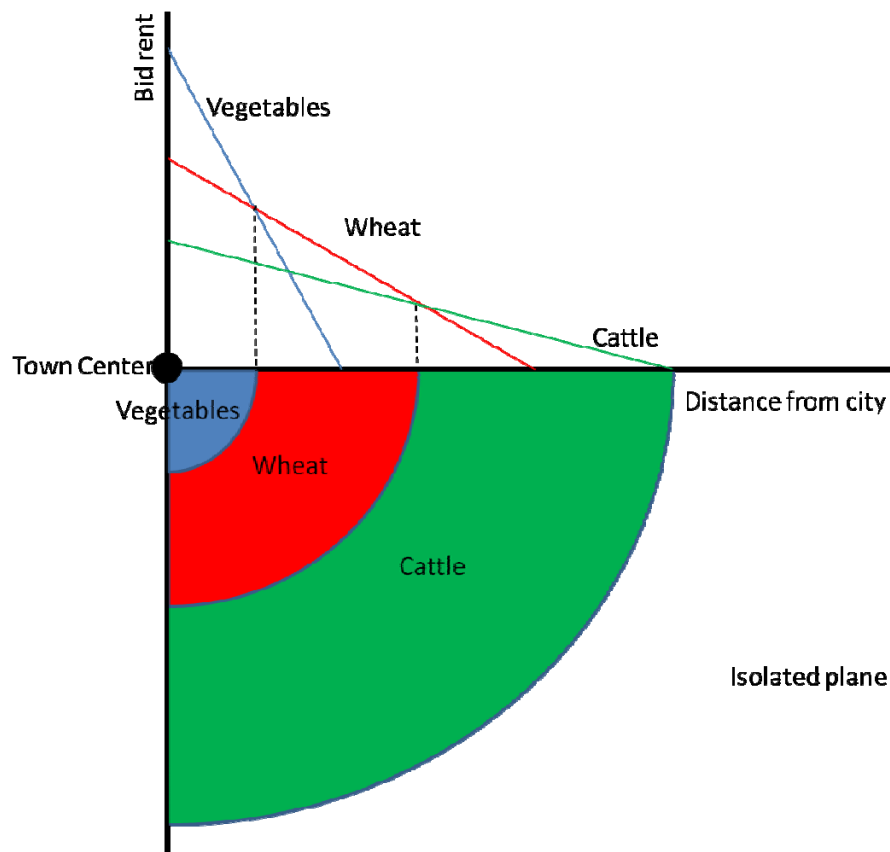
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<sup>5</sup> The term, factorial ecology, emerged in mid-60s and refers to the use of factor analysis to differentiate areal (ecological) units using the characteristics of residents (Janson 1980).

<sup>6</sup> Social area analysis essentially involves a statistical procedure to identify from a sometimes quite large database of socio-economic data the most salient underlying variables. Very often most of the variance in a group of dozens of variables can be accounted for by three or four dimensions (Janson 1980).

<sup>7</sup> Spatial inequality refers to unevenness of distribution of sub-population over space. It is a condition in which different spatial or geographical units are at different levels on some variable of interest, usually income, race, etc. (Lall and Chakravorty, 2005).

How does an economy allocate use of space through market interactions? In the regional context, Von Thünen (1826) in the early nineteenth century pioneered a class of models that are still relevant in answering this question. The Von Thünen model assumes an isolated plane with a town center surrounded by farmers. In this model, transportation costs of various agricultural products to a town center play a critical role in determining the type of products produced and the rent that farmers would be willing to pay for the land at a given distance from the town center.



**Figure 1: Von Thünen Model of Land Use**

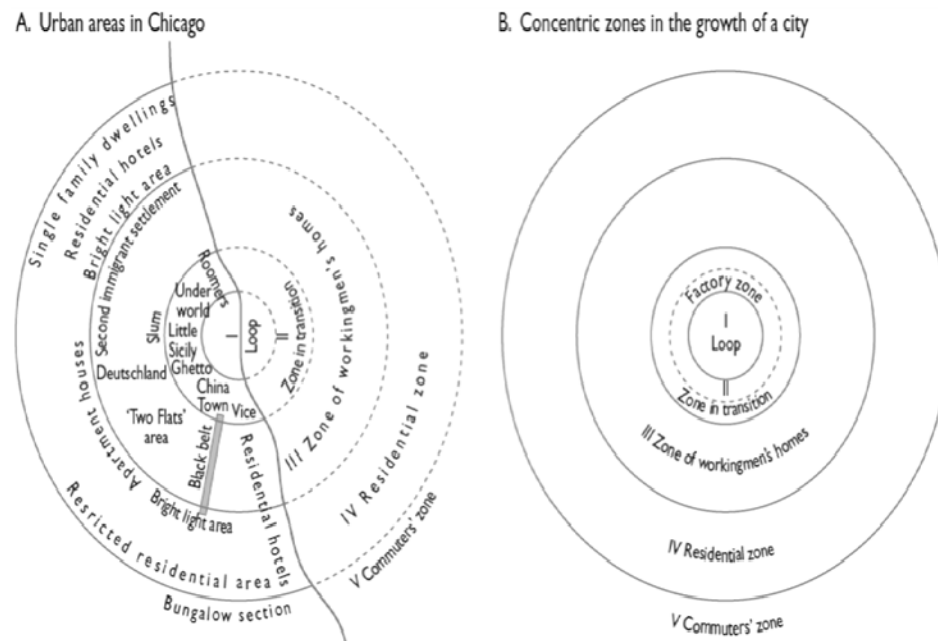
(adapted from: Fujita, Krugman and Venables 1999)

In this model, a bid-rent curve depicts the maximum rent that farmers are willing to pay for a given crop at each location as shown in Figure 1. When the one-dimensional distance from the town center is transformed over two-dimensional space, these bid-rent curves result in a concentric ring pattern of land use. This model is extremely simple in nature, but provided significant economic insight of land use. It is a classic example of efficient allocation of land that emerges purely as a market outcome in a non-centrally planned economy.

In 1920, this approach was applied in the context of space allocation within a city, mainly by Burgess, Hoyt and others, collectively known as the "Chicago School". According to the Chicago School, the organization of a city is an outcome of "ecological competition" for niches between different types of land occupiers who compete with each other to use the land for their respective purposes. The economically strongest groups occupy the most desirable location and the weaker groups occupy the residual spaces in a city. The Burgess (1925) Model is the first model in urban geography to empirically test this concept to identify where "working men's housing" and "zones in transition" are located in the form of ghettos and slums in inner city locations, as shown in Figure 2.

The biggest limitation of this model and other models based on Alonso's work is their heavy dependence on a single center resulting into the concentric ring pattern of land use that is often not found in cities today. Further, the Von Thünen and the Alonso models assume the presence of a center and then explain the spread of activities from that center. The question of the emergence of that center in the

first place is untouched by this approach. Moreover both the Von Thünen and the Alonso models are static models and do not allow for change in land use over time. Nonetheless, it is a very useful approach to explain market-driven allocation of land in a city in relation to its CBD.



**Figure 2: Ecological Schema for Chicago**

(Source: Burgess 1925 cited in UN-Habitat 2003)

Over time the theories developed by “Chicago School” became more rigorous with the advances in neo-classical economics. In particular, the works of Alonso (1964), Muth (1969) and Mills (1972) show how a declining "rent gradient" could explain allocation of space in a city. Alonso (1964) interprets the Von Thünen Model by substituting commuters for farmers and a town center for a Central Business

District (CBD). This is an important extension of the Von Thünen model that yielded concentric rings of industrial and residential land use in a city with one CBD.

Alonso's model remains today as the basis for modeling land use patterns of a city (e.g. Ahlfeldt 2011; Van Vliet et al 2012; Barros 2012). According to this model, rents for urban land decline in proportion to the distance from the center of a city. This model demonstrates how a “rent-gradient” could be used to predict the locations of various groups of people within a city.

However, the biggest limitation of this model and other models based on Alonso's work is their heavy dependence on a single center resulting in the concentric ring pattern of land use that often is not found in cities today. Further, the Von Thünen and Alonso models assume the presence of a center and then explain the spread of activities from that center. The question of the emergence of that center in the first place is untouched by this approach. Moreover both the Von Thünen and Alonso's models are static models and do not allow for change in land use over time. Nonetheless, it is a very useful approach to explain market-driven allocation of land in a city in relation to its CBD.

It should also be noted that these theories and methods were originally developed and empirically tested to explain market-driven cities of the developed world, where land use is determined by economic competition. Therefore, these theories and methods are not directly applicable to the cities of the developing world. The land use in those cities is often dictated partially by traditional use (e.g. farming in peri-urban areas) or controlled by the governments (e.g. through zoning

policies). For example, a peri-urban village that becomes a part of the city, as a result of expansion of city limits, may retain its traditional land use, i.e. agriculture. There are also instances where the Government controls and dictates land use in the cities of developing country. For example, the slums may have emerged as a result of artificial shortage of formal housing arising from government's decision to limit the supply of serviced land.

A pure market based approach to land use is not sufficient to explain slum formation in the cities of developing countries. However, many cities in developing countries are gradually adopting market based approach through various urban land reforms (e.g. repeal of the Urban Land Ceiling and Rent Control Act (ULCRA) in many Indian states) (NIUA 2002). Therefore, the theories and the methods of urban spatial analysis are now becoming more relevant for urban research in the developing world context.

Nonetheless, this central concept of "ecological competition" behind all these theories of spatial organization of cities provides a powerful foundation as the starting point to build *Slumulation*.

#### **4.1.2 Factorial Ecology and Social Area Analysis**

The advent of computers and the availability of large scale data, primarily from detailed urban census, provided new insights into the spatial organization of cities in the 1970s. Since then, there have been several attempts to explain residential locations of various groups using urban census data with models largely known as factorial ecology or social area analysis (see Janson 1980 for a review).

The factorial ecology studies also provide empirical evidence for Chicago School theories (e.g. Shevky and Bell 1955; Berry and Kasarda 1977; Wyly 1999; Flood 1997). These models have shown that cities are divided into different spatial clusters of people identified by common factors, such as socio-economic advantage, family type, ethnicity and, according to more recent literature, preference for urban life style. One of the first studies from the 1950s by Shevky and Bell's (1955) model showed that households in the city were spatially separated from each other based on three key factors: i) socio-economic status; ii) family status; and iii) ethnicity. In different cities and cultures, the impact of these factors on the spatial organization varies but the social factors still play a key role in determining the spatial organization of the cities. The underlying principle of factorial ecology is that populations sort themselves geographically to form socio-economically differentiated areal units or neighborhoods (Burgess 1925; Robson 1969).

While such work allows for understanding spatial segregation in a city, the approach has often been criticized for lacking a link between theories of social change and realities of areal differentiation within cities (Johnston 1971). For example, these works tell us little about why people make certain location choices that lead to segregation.

Nonetheless, these studies developed advanced methods to analyze suburban census data and to identify spatial clusters of various groups. A number of measures are now available to indicate spatial clustering such as an index of dissimilarity showing segregation based on income and race (Duncan and Duncan

1955). Some of these measures provide the basis for the empirical analyses of Ahmedabad and validation of *Slumulation*, as presented in chapter 7. The methodological advancements developed by factorial ecology studies provide the appropriate tools to form a quantitative base for the model construction, and to analyze simulation outputs for empirical validation of *Slumulation*.

## **4.2 Empirical Studies on Slums**

While theories and models from the developed world provide an underpinning to the model, empirical studies conducted in the context of the developing world provide stylized facts about slums. It is important to understand various aspects of slums that are useful for the modeling purpose. There are mainly three types of studies that fall under this category: i) anthropological and literary studies; ii) studies with statistical analysis and iii) spatial analysis with Remote-Sensing (RS) and GIS.

### **4.2.1 Anthropological and Literary Studies**

Anthropological and literary works surrounding slums are a rich source of the descriptive account of urban poverty and slum growth. These studies usually provide a detailed account of a specific slum in a specific time period but lack generality (e.g. Liebow 2003; Roberts 2005; Lapierre 1992). In rare instances, they also provide a long-term account of transitions of slum dwellers. For example, in a noteworthy study, Pearlman (2010) provides a detailed account of lives of people in three *favelas* of Rio de Janeiro. She compares the socio-economic situation of the

households in 1969 with that of their children and grand-children after four decades. The author provides details on various aspects of changes in the lives of people living in a *favela*, ranging from the changes in home-ownership over three generations to the changes in their perceptions about city governance. These studies provide the basis for making assumptions for several aspects of the lives of slum dwellers for the model (e.g. the next generation prefers parent's home when they cannot afford to buy or rent on their own). However, these stylized facts should be interpreted with caution since they are based on the accounts of specific slums for specific time periods and cannot be generalized. Nonetheless, these are often the only available details in under-researched areas such as slums and hence immensely valuable for the conceptualization and construction of a model such as *Slumulation*.

#### **4.2.2 Statistical Analysis**

Statistical approaches adopted to study slums largely falls into two categories: a) large scale statistical analysis using secondary data, such as cross-national comparisons and b) statistical analysis using survey data usually conducted at a city or a slum scale.

As presented in chapter 2, in a study using cross-national data from 162 countries examined property rights and growth indicators from 1995 to 2005 (Martinez and King 2010). The study challenges the widely accepted policy notion of protecting property rights. Fox (2008) uses cross-national data to explain variation in slum incidence in developing countries using multivariate statistical approach.

A common response to the limitation of data at a fine scale is to conduct a primary survey at the individual and household level in slum communities. Among survey-based studies, Mitra and Tsujita (2006) explore if migrants are likely to experience upward social mobility in their place of destination based on primary survey of individuals in slums of New Delhi, India. Another study presented in chapter 2 uses multivariate analysis of primary survey data showing factors affecting location choice of slum dwellers in Pune, India (Lall et al. 2008). The primary survey revealed that the location choice of the slum dwellers in Pune were governed by three major factors suggested in literature, namely, commuting cost, local public goods and individual preferences for neighborhood composition. Gulyani and Talukdar (2008) report monthly rents in slums of Nairobi, Kenya from the primary survey data as discussed in chapter 2. The findings of this study challenged the conventional wisdom by showing that securing tenure did not benefit the actual slum dwellers, but only provided security to owners who are not the occupiers of the slums.

Typical questions explored in these statistical studies include, among others, the reasons for migration (e.g. Beguy et al. 2010), implications of living in slums, land management (e.g. Kombe and Kreibich 2000), the factors affecting the choice to live in slums (Lall et al. 2008), housing affordability and improvements in living conditions over time (e.g. Sheuya 2004). While the studies involving large scale secondary data provide a unique opportunity to understand the relationships between slum formations and other measurable indicators, these studies are often

limited to aggregated statistics at the city or country levels. The studies based on a primary survey, on the other hand, are usually too focused on localized conditions and thus lack the ability to draw generalized conclusions. Nonetheless, the statistical studies are a rich source of information and often help guide decisions on what quantitative input parameters are required or adopted for simulation models (Robinson et al. 2007).

#### **4.2.3 Geographic Information Systems (GIS) and Remote-Sensing (RS) studies**

The recent developments in RS and GIS provide additional tools to urban researchers. These advancements have been particularly useful for slum researchers since detailed spatial data on slums has been limited due to informal nature of slums and lack of recognition of slums by the government. Several studies have attempted to tackle the challenge of enumeration of slums using these technological developments (Weeks et. al., 2007; Sen et. al., 2003; Thomson and Hardin 2000). However, attempts have rarely been made to discover the underlying spatial patterns of slums using advanced spatial analysis techniques (with rare exception of Sliuzas et. al., 2004; Baud et. al., 2009). Nonetheless, the need to incorporate a stronger spatial element in slum research has been emphasized several times (e.g. Fiori and Brandao 2010). There is an increased focus on collecting geographical data on slums (e.g. RAY in India emphasize on building a GIS based Management Information System for slums in cities). This new data and well-developed methods of spatial analysis could provide new insights into the spatial

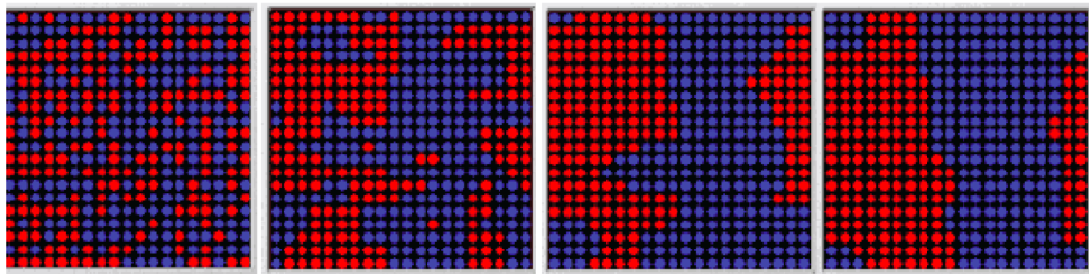
organization of slums that could improve planning and policy responses and serve as an additional means to empirically validate predictive models like *Slumulation*.

### **4.3 Decentralized Models**

The majority of previous models that explored slum formation and city growth approached the problem as a static phenomenon (e.g. Alonso 1964), which has been challenged with the growing realization that urbanization and slum formation are largely dynamic processes (Batty 2005; Barros 2012). Dynamic models that accommodate this flux and complexity are thus called for (Batty 2005). Cellular Automata (CA) models provide a dynamic approach but lack behavioral elements seen within cities (Crooks and Heppenstall 2012). ABM provides an ideal framework to study such dynamic processes while taking behavioral aspects into account (Batty 2005).

ABM focuses on the localized behavior of individual agents whose interactions with other agents as well as the environment give rise to the global phenomenon of our interest. For example, Schelling's (1971) model explains segregation by modeling agents (city residents) who behave in a certain fashion while interacting with other agents (neighbors) and the environment (the city). The agents choose a particular site as their residence, only if one-third of their neighbors are of similar race. In a simulated environment, the agents behaving according to this rule generate a highly segregated spatial pattern in the city as shown in Figure 3.

Secondly, cities are complex systems, which are more than the simple sum of their parts (Batty 2005). A simulation approach provides an opportunity to explore the sub-systems (e.g. slums) that are complex themselves but are also a part of an overall complex system (e.g. the city).



**Figure 3: Emergence of residential segregation from initial random conditions in Schelling model**

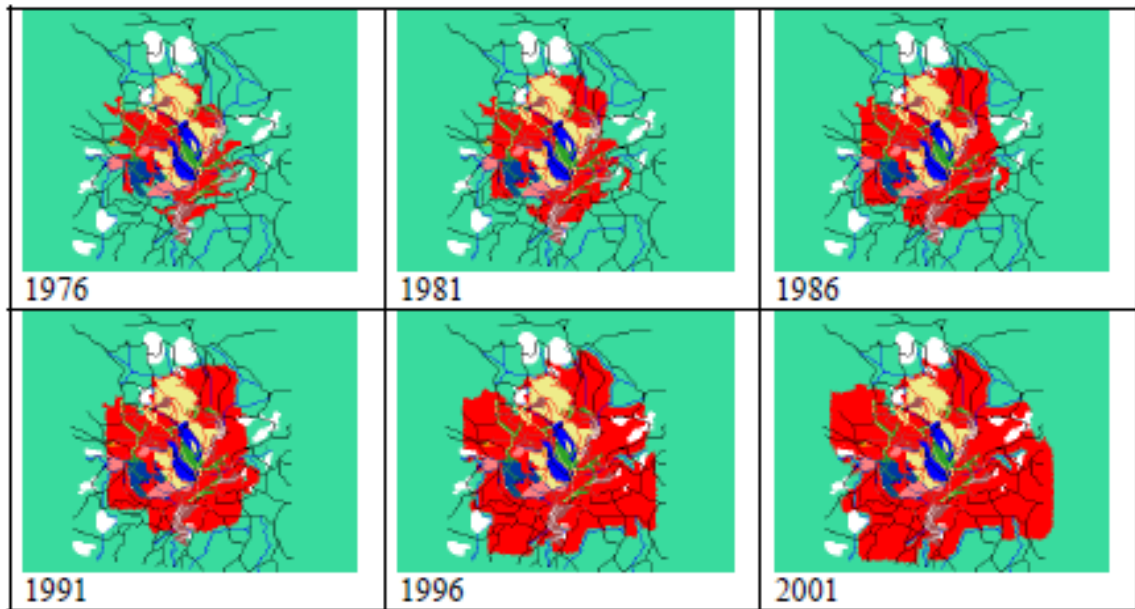
(Source: Crooks 2010)

While there is a growing amount of work focusing on ABM and urbanization (see Benenson and Torrens 2004; Batty 2005; Heppenstall et al. 2012, for instance), the use of agent-based and other simulation models for exploring slum formation is still in its infancy. Only a few attempts have been made to explain slum formations using ABM and CA. These include the models developed by Sietchiping (2004) presented in section 4.3.1; Barros (2005); Vincent (2009) and Augustijn-Beckers et al. (2011) presented in section 4.3.2.

#### **4.3.1 Cellular Automata-based Model**

Sietchiping's (2004; 2008) CA model, called the Informal Settlements Growth Model (ISGM), is one of the earliest simulation-based attempts to predict informal settlements. ISGM predicts slums as a type of land-use at a particular location by adapting the CA-based urban growth model called SLEUTH (originally developed by Clarke et al. 1998). As in the SLEUTH model, each 43 m x 43 m cell in a spatial environment has particular geographical attributes such as slope, transport, land use, hillshade etc., which determines the probability of that cell to convert into an informal settlement. Each iteration changes some cells into informal settlement which in turn also increases the probability of neighboring cells to convert into informal settlements.

In this approach, the model is initiated with a particular state of the system in a given year and then simulated over time to generate a spatial pattern of informal settlements. The model uses empirical inputs for the initial conditions in Yaoundé, Cameroon in 1976 and then simulates the city for several subsequent years as shown in Figure 4). Once calibrated for the years for which empirical data is available (i.e. 1981, 1986, 1991, 1996 and 2001 shown in the figure 4), the model is then used to predict informal settlement patterns for the future years. This is probably the first and the only available model that can simulate an entire city and predict locations of informal settlements in the context of cities of developing countries.



**Figure 4: Simulation Results from ISGM Model**

(Source: Sietchiping 2004)

However, such a model does not capture individual level human behavior and focuses more on probabilistic cell transitions. Secondly, this model relies on a "brute force" calibration method, which requires historical data from multiple years, which is often not available for slums in developing countries. Thirdly, However, it only models whether land use at a given location is informal or not. The model has several types of land uses such as commercial, industrial, etc, in the initial condition as shown in Figure 4. However, the CA cell-state is binary<sup>8</sup> (i.e. informal settlement or not), ignoring the possibilities of a cell converting into other non-residential land uses. As a result, this model tends to predict informal settlements (IS) on the locations where other land uses might prevail in reality.

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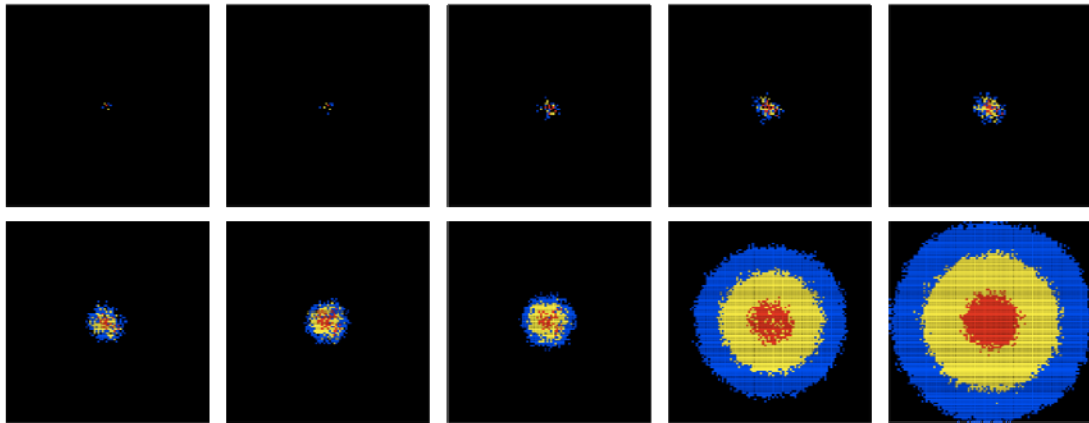
<sup>8</sup> Some CA models allow for multiple cell types e.g. DUEM (Batty et al. 1999) but a "true" CA only has a binary switch (Batty 2005).

#### **4.3.2 Agent-based Models**

Agent-based models can partially overcome the limitation of CA models. One such advancement is that the human behavior can be incorporated in agent-based models (Bonabeau 2002). It is also possible to introduce several types of agent within a single framework. This provides the flexibility to incorporate distinctly different and often competing behavior at a particular location. ABM also allows the movements of agents between cells, which could be useful when modeling residential mobility (Crooks and Heppenstall 2012).

Barros (2005; 2012) developed one of the first ABM that explains slum formation through households' behavior. The model explores how decentralized decision-making can be incorporated into slum modeling. There are two versions of her model, known as the "Peripherization" and the "City of Slums" models. The later is a variant of the Peripherization model.

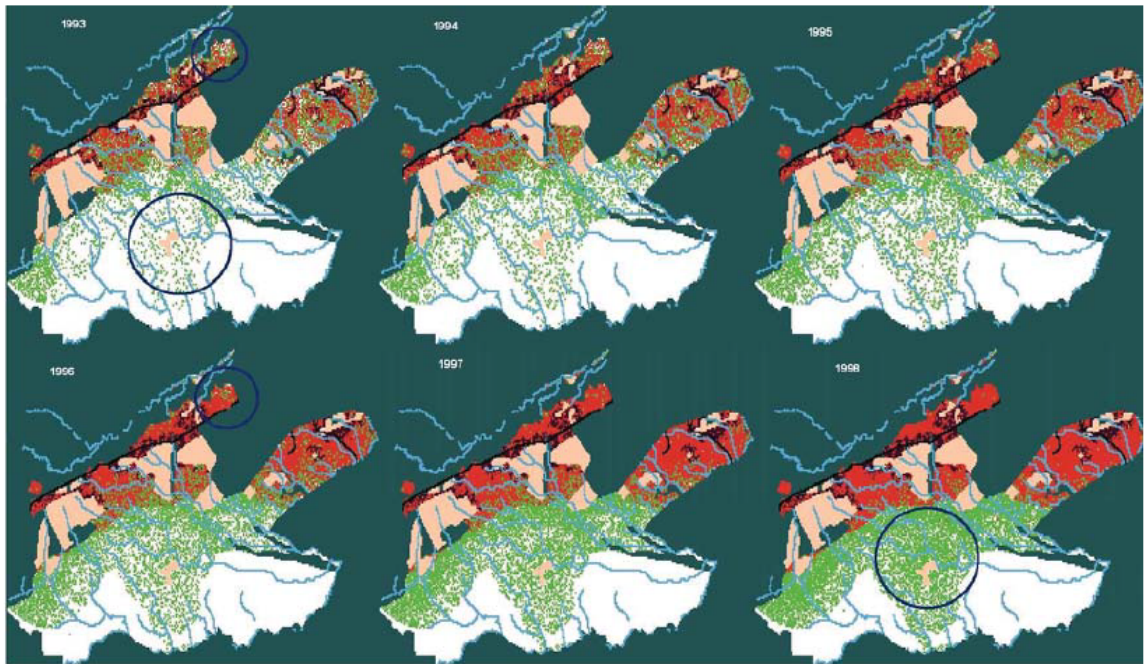
In the model, the household agents with three different levels of income (low, medium and high) compete for a location through succession and occupation. As a result, a spatial pattern of various income group is generated. As evident from Figure 5, low income households, shown in blue, are always pushed to the peripheries whereas the high income households, shown in red, occupy the center of the city as shown in Figure 3. This is the first model that generates a spatial pattern both dynamically and from bottom-up. The author analyzed relative locations of various income groups in Latin American cities and found concentric rings similar to that simulated in the model.



**Figure 5: Emergence of Peripherization of Slums**

(Source: Barros 2012)

However, the end result is a mere replication of the Von Thünen (1826), or the Alonso, Model (1964), in which a similar concentric ring pattern is observed, except that the process is dynamically occurring as the simulation progresses. The underlying logic also follows Alonso's bid-rent concept, in which three different groups of people have varying degrees of willingness to pay for a particular location. Secondly, this model is a purely human to human interaction model, and the spatial environment does not play any role in the emergence of this concentric ring pattern, nor does the author conduct any sensitivity analysis for various search strategies for agents. For example, it is quite possible that the resultant pattern is an artifact created by the search process that always starts from the center for a new agent arriving in the system. If the agents were created from the periphery, there is no explicit process that could drive higher income group towards the center or the poor towards periphery.



**Figure 6: Simulated Outputs from ISGPM**

(Source: Vincent 2009)

In another but similar effort, Vincent (2009) developed an ABM called the Informal Settlement Growth Pattern Model (ISGPM), which advanced the work of Barros. The author applies his model for a ward in the city of Dar es Salaam, Tanzania. The type of agents and rules of behavior are similar to the peripherization model (Barros 2004) with a notable exception that the agents consider multiple locations and choose a location that maximize their utility derived from that location. search process is based on a utility maximization approach as opposed to a random-walk approach. In other words, each agent who is searching for a house, samples and evaluates the utility received from multiple locations and chooses a

location that maximizes the utility. The spatial environment for this model is an actual representation of the ward as shown in Figure 6.

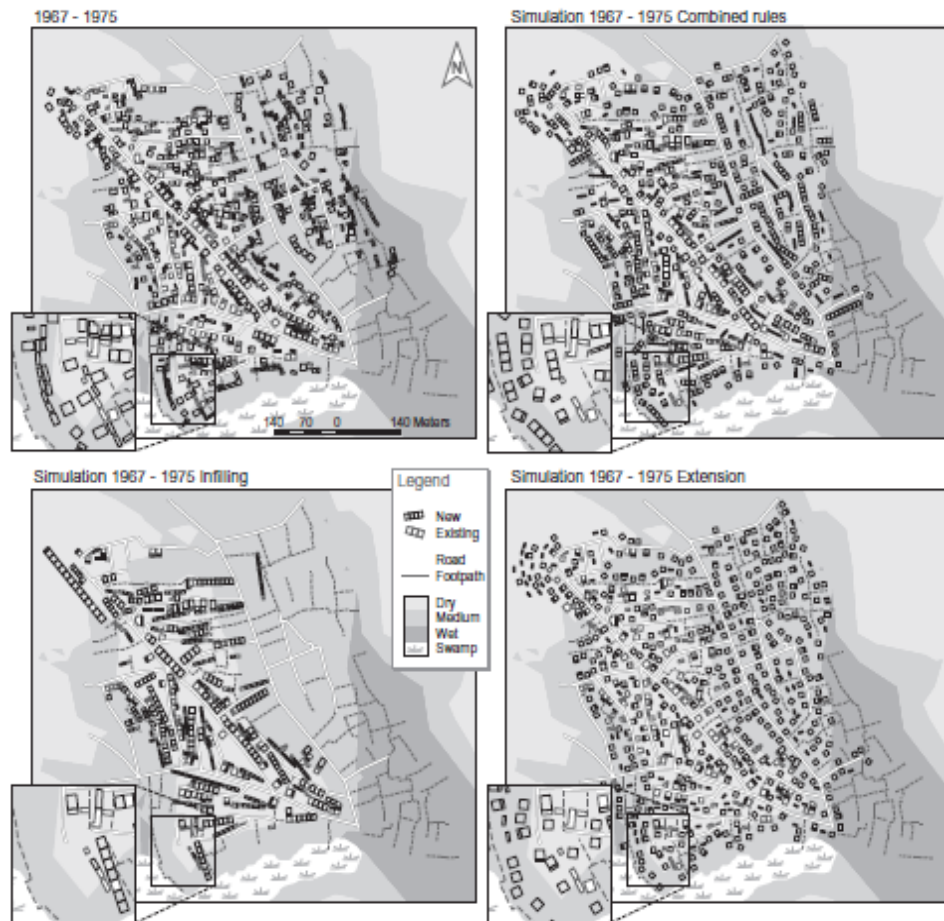
This model is a significant improvement over the Peripherization model of Barros (2004). This approach allows the author to validate the results by comparing it with empirically observed patterns. Vincent's approach is useful to empirically validate simulated outputs. This serves as a starting point for empirical validation of spatial patterns of slums in a city. For example, comparison of various measures, such as number of patches occupied by slums, mean nearest neighbor distance etc, is useful for validation.

However, this model does not allow more than one agent in a 50 m x 50 m single cell which is a large patch especially in a slum context<sup>9</sup>. Since the larger patch size meant fewer cells per unit area, the entire population could not be accommodated in the model. To overcome this limitation, the author uses a 7 percent sample of the actual population as agents in the model to match with the number of patches in the spatial environment. However, that partially defeats the purpose of an ABM in which each individual can be represented. Secondly, the model simulates only a small part of the city. However, as it is clear from the literature presented in Chapter 2, households move from one slum to another within a city. A ward simulated in isolation ignores the rest of the city where there may be other suitable locations for many of the agents simulated. In other words, the model is too locally focused and cannot capture the city-wide view of slums.

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<sup>9</sup> The average density of Dar es Salaam is 4 households per cell as reported by the author but densities in slums often is several times higher than the city average.

Finally, both the Peripherization (Barros 2005) and the IGSP (Vincent 2009) models suffer from the lack of definition of a slum. Both of these models predicted where poor people live which is not necessarily the same as slums. In fact, not all housing where the poor people live is a slum and not all people who live in slums are poor.



**Figure 7: Spatial Patterns of Houses in a Slum of Dar es Salaam**

(Source: Augustine et al. 2011)

In another effort to model slums in Dar es Salaam, Tanzania, Augustijn-Beckers et al. (2011) advanced ABM in the slum literature by relying on primary surveys. They use prior empirical studies to identify behavioral rules used in the model. The model generates a spatial pattern of organization of individual houses within a slum using ABM approach. Three simple rules, namely, extension of the street by building next to an existing house, in-filling between houses and enlargement of existing houses generates a spatial pattern of internal organization of a slum that matches with the empirically observed pattern as shown in See Figure 7.

The main advancements of this approach are: the use of a vector-based spatial environment; behavioral rules based on empirical studies; and use of quantitative measures for validation (similar to that of Vincent (2009)). However, this model provides the street pattern as an exogenous input which was the guiding factor in the simulation. This is a limitation since, in most slums, street formation itself is an emergent phenomena as slums organically grow. Secondly, the model does not use any of the agent characteristics to drive the behavior unlike in the peripherization model (Barros 2004) or ISGPM model (Vincent 2009). The model simulated the geometric arrangements of rectangular shaped houses following simple rules, as opposed to human agents driving the simulation (similar to, for example, that of Vincent (2009) or Barros (2004)). Thirdly, the agents do not adapt and change their behavior in response to changing environment. For example, the

agents do not consider infilling, when extension becomes difficult due to space constraints.

While all these efforts took different approaches to model informal settlements, four main points emerge. First, explicit modeling of the spatial environment is important, as slums emerge in distinct areas. Second, slums are partly a result of human-environment interactions. Third, individual households make location choices. Fourth, local government plays an important role as it takes city-wide actions such as slum eviction or slum up-gradation to alter the slum conditions or to eradicate them. The models discussed above incorporate one or some of these aspects but none of them incorporates all of them into a single modeling framework.

This dissertation attempts to model a city system where several slums form, grow and disappear as a result of human-environment interactions at multiple spatial scales. For example, the household level behavior is confronted with the city level political forces in a multi-scale environment. This point of view calls for creating a human-environment interaction model where the human behavior is modeled in a multi-scalar spatial environment. Hence, *Slumulation* attempts to incorporate the complexity of urban morphology combined with the social complexity of human behavior in a stylized manner. Although, multi-scale modeling of urban systems is not a completely new idea (e.g. O' Sullivan 2009), this is the first attempt to build a multi-scale model of slum formation to the best of the author's knowledge.

#### 4.4 Discussion

Urban planning and policy-making for slums in developing countries often exclusively relies on theories and models from the developed world (Pugh 2001). Empirical studies of slums have either focused on policy evaluation or descriptive characteristics of slums and slum dwellers. While the spatial organization of cities in the developed world has been a well-studied field in urban geography, a parallel explanation of cities in developing countries is generally lacking. This may be partly due to a lack of detailed sub-urban level data required to conduct similar empirical analysis (UN-Habitat 2003). This is rather a serious concern since the housing sector in developing countries has taken a different course compared to that of developed countries in earlier, similar stages of development (Pugh 2001). *Slumulation* attempts to bridge this gap by developing a simulation tool that could be used for urban planning and policy-making specifically in a developing country context.

The research concerning slums is at an interesting juncture. The underlying concepts, such as "ecological competition" from the theories based on the developed world, are relevant for developing countries as they embrace market-based approaches for land use. Similarly, the data required for spatial analysis such as factorial ecology are now slowly becoming available (as discussed in section 4.1). An adequate understanding of descriptive characteristics of slums as well as slum dwellers is also emerging through empirical studies (as discussed in Chapter 2 and briefly considered in section 4.2). The intended and unintended implications of past

policy experiments and lessons from them are also well documented (as discussed in Chapter 3).

The time is ripe to seize the opportunity to construct a comprehensive model of slum formation using advancements in theory, empirical findings and use of computing in social sciences. The simulation approach is considered the most appropriate approach to model slum formation in such a context when comprehensive data is still limited but studies and theories with stylized findings and generalized behaviors are in abundance. Some of the examples of such studies include: spatial separation of rich and poor based on land and housing cost (Alonso 1964), differing employment opportunities (Sanchez-Jankowski 1999), similarity of preference for amenities amongst similar income or ethnic groups (Benenson et al. 2003; Florida 2002), preference to live with similar neighbors (Schelling 1971), exclusionary zoning and cultural resilience and continuity through generations (Soja 2000). The findings emerging from these studies could be easily used for formulating behavioral rules for the households in *Slumulation*. A simulation approach can conduct experiments based on these various theoretical notions, which in turn could be compared to empirically observed slum patterns.

## **CHAPTER 5. SLUMULATION**

In the past, understanding slum behavior and characteristics has been limited by descriptive approaches. One way to gain a greater insight into slum formation is to introduce computational and simulation methods that could explore past and current slum patterns, physical and socio-economic factors that generate such patterns, and scenarios of future distribution (Torrens and O’Sullivan 2001). As discussed in the first part of this dissertation, recent progress of research on complex urban systems in developed countries (e.g. Batty 2005) combined with current research on slums in the developing world (e.g. Gulyani and Talukdar 2008; Jha et al. 2007; Sanyal and Mukhija 2001) should provide new insights into the spatio-temporal dynamics of slums.

The slum formation process is modeled by integrating three components into a single framework, namely, ABM to incorporate human behavior, GIS to incorporate spatial environment, and discrete event simulation (DES) to micro-simulate regional population dynamics. This chapter develops this framework for a hypothetical urban system before adapting and customizing it for a case study in Chapter 7.

Section 5.1 presents the rationale for such an integration, section 5.2 discusses all three modules of the framework and how they are connected with each

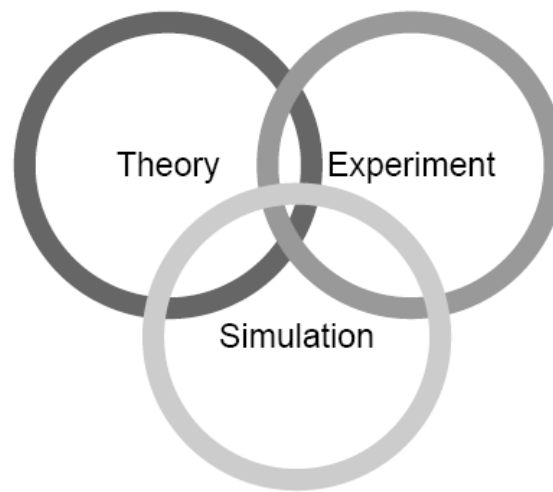
other, sections 5.3 and sections 5.4 presents phase-wise evolution of two of the modules of the framework. Section 5.5 concludes with the model that integrates DES and ABM. This model is subsequently integrated with GIS, taking a real-world city as a case study. The integration of all three methods is presented in Chapter 7.

## **5.1 Why Integrated Simulation Framework?**

In the evolution of any social science field, there is an interplay between three approaches, namely theory, experiment and simulation as shown in Figure 8. Adequate efforts have been made to formalize theoretical foundations for slum formation and expansion process as presented in chapter 2 (e.g. Malpezzi and Mayo 1987; Hamnett 1994; Mayer 2001; Glaeser et al. 2000; Glaeser and Gyourko 2002). Similarly, there is a long history of policy experiments to solve slum issues, albeit with limited success as presented in chapter 3 (e.g. Turner 1972; Pugh 1989; de Soto 2003; Viratkapan and Perera 2006; Gulyani and Bassett 2007; Cities Alliance 2008; Handzic 2010).

Historically, the modeling and simulation approach has been lagging in slum research. In particular, the simulation approach is rarely used for designing and evaluating slum policies. Simulation can play an important role to bridge the gap between theory and practice (Axelrod 2007). Not only does it allow one to test many existing theories and ideas pertaining to slums (such as those discussed in Chapter 2 and 3) but also to develop new theory by providing a framework for thought experiments. Simulation also allows to ask "*what-if*" type of questions for scenario

analysis and to study impact of various policy options in a simulated environment (Axtell 2000).



**Figure 8: Interplay of Simulation, Theory and Experiment**

As the review of literature presented in Chapter 2 and Chapter 3 illustrates, a long-term perspective and an anticipatory approach is required to predict where new slums will be formed, and more importantly, how adaptive behavior of various actor could affect outcomes of new slum policies. The simulation approach can demonstrate past trends and assist in projecting the possible locations and the characteristics of future slums (Abbott 2002). *Slumulation* exemplifies one such predictive approach that builds upon the existing knowledge of factors contributing to the emergence and growth of slums as well as a sound understanding of location

and investment choices of households. Its purpose is to provide a tool to predict future slum locations and to evaluate new policy ideas in a simulated environment.

From urban planning perspective, there are five aspects that justifies an integrated simulation approach. First, urban systems are inherently intertwined. Hence, policy interventions in a sub component of the urban system could also transmit through linkages in other parts of the system (Engelen et. al., 2003). For example, when some cities in Brazil implemented favorable housing policies for urban poor, those cities attracted more migrants than other cities, thereby increasing slum population rather than decreasing it (Lall et. al., 2007). This seems counter-intuitive and surprising if a planner looks at a city in isolation, but plausible when a city is considered merely a part of the nationwide urban system. Therefore, *Slumulation* is built as an integrated framework where the integral parts of a city are modeled along with the regional system of which a city is merely a part.

Second, urban systems are dynamic, evolving constantly and are never in equilibrium (Batty 2005). Policy intervention in a changing system could cause unanticipated outcomes (Allen 1997). Therefore, the simulation methods capable of modeling dynamic systems are deployed, namely, ABM and DES.

Third, urban systems are inherently spatial (Crooks et al. 2008). Unfortunately, slum policies have frequently neglected spatial elements, such as locations and internal organization of houses within slums. Urban development authorities have also overlooked the representation of slums in formal spatial planning documents or "Master Plans" (Abbott 2002). As a result, ideas such as

connecting slum areas with rest of the city infrastructure were rarely considered as a policy option (Fiori and Brandão 2010). Besides, slums have always been seen as a "temporal problem" to be dealt with in "near future" (Abrams 1966) but spatial elements have largely been ignored (Beaton et al. 1996; Mason et al. 1997). In order to tackle this problem, GIS is integrated as a part of *Slumulation*.

Fourth, urban systems are inherently affected by uncertainty (Batty and Torrens 2001). Policy makers should to be aware of uncertainty rather than expecting deterministic outcomes. The stochastic nature of ABM and DES allows for incorporating such uncertainty in the model.

Fifth, policymakers usually assume the "average" behavioral response from people when implementing a new policy. However, individuals behave heterogeneously for their own interest (Meen and Meen 2002). Consequently, a better model would be to incorporate individual behavior that keeps adjusting dynamically in response to changing policies and environment. Integration of ABM, DES and GIS in a single framework would provide adequate foundation for incorporating all five aspects of urban planning discussed above. By integrating these methods the limitations of each method could be overcome (Briassoulis 2000; Parker et al. 2003).

Integrated simulation is not a completely new idea in the context of developed world. Such approaches are seen in a number of planning support systems (Brail 2008; Brail and Klosterman 2001; Maguire et al. 2005; Clarke and Gaydos 1998; Clarke et al 2006; Engelen et al 2003). However, as highlighted in

Chapter 4, only a handful of attempts have been made in this direction in the developing world context.

## 5.2 Conceptual Framework

*Slumulation* intends to answer three types of research questions related to slum formation and expansion, *where*, *when* and *how*, by integrating several cutting-edge techniques, which include stochastic simulation - DES, ABM, and statistical and geospatial models. At the core of *Slumulation*, dynamic models operating at both micro and macro geographical and demographic scales are linked as outlined in Figure 9. The model has three distinct modules - Population Dynamics Module (PDM, section 5.3), Housing Dynamics Module (HDM, section 5.4) and Empirical Module (EM, section 5.6).

DES is used to simulate regional level population dynamics, mainly because DES is capable of micro-simulating the arrival process of new households using empirical estimates. ABM is used to simulate the city level housing dynamics since it allows to incorporate human behavior. Statistical and geospatial modeling is used to provide input parameters to both PDM and HDM. The EM is also used to provide spatial environment which is important for housing dynamics as households consider spatial factors such as access to jobs, transportation network, social amenities etc. in making residential location choices. This module also provides the empirical foundation to the model which is important to calibrate and validate the model.

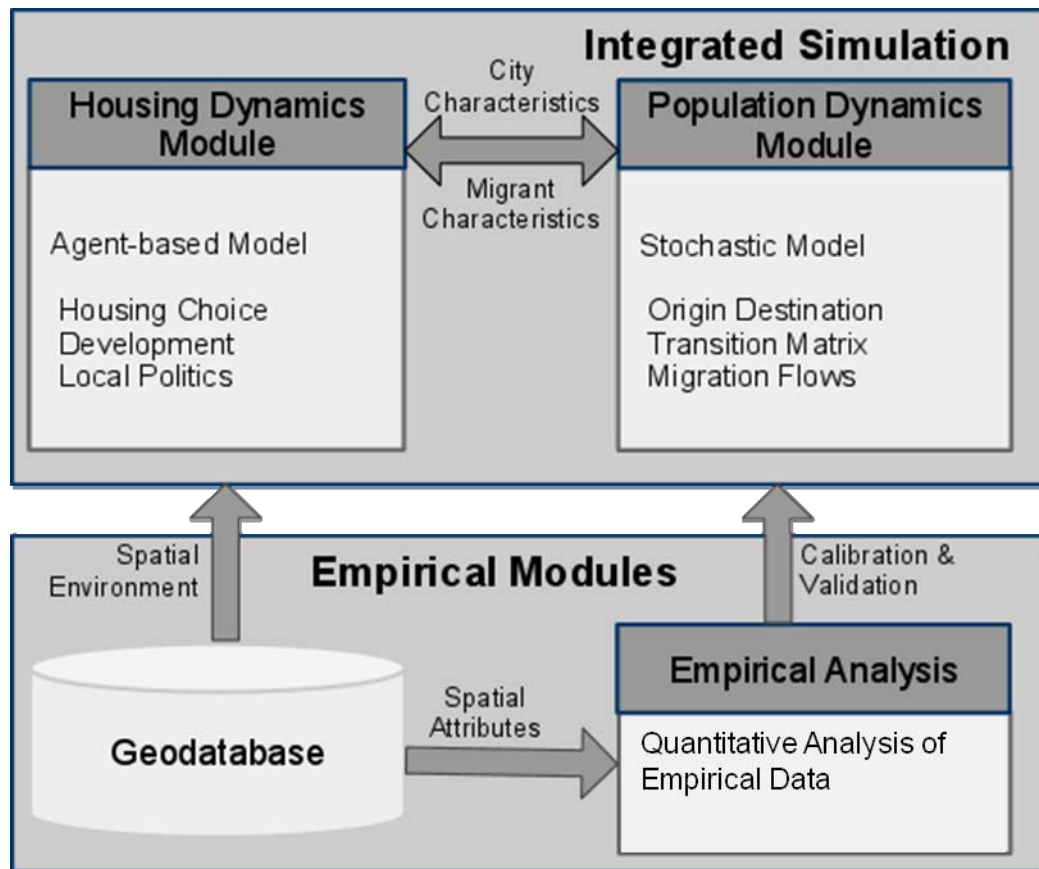


Figure 9: Schematic of the Integrated Simulation Framework

The organization of individual modules at different geographic and demographic scales allows for incorporating varying levels of details appropriate for each module. For example, migration flow is modeled at regional level whereas housing market is modeled at city level. Each module is coupled to exchange information but developed separately in order to verify and validate results from individual modules. As a policy support tool, individual modules are designed to generate scenario to evaluate various policy interventions at regional and city levels. *Slumulation* is tested for Ahmedabad for empirical validation.

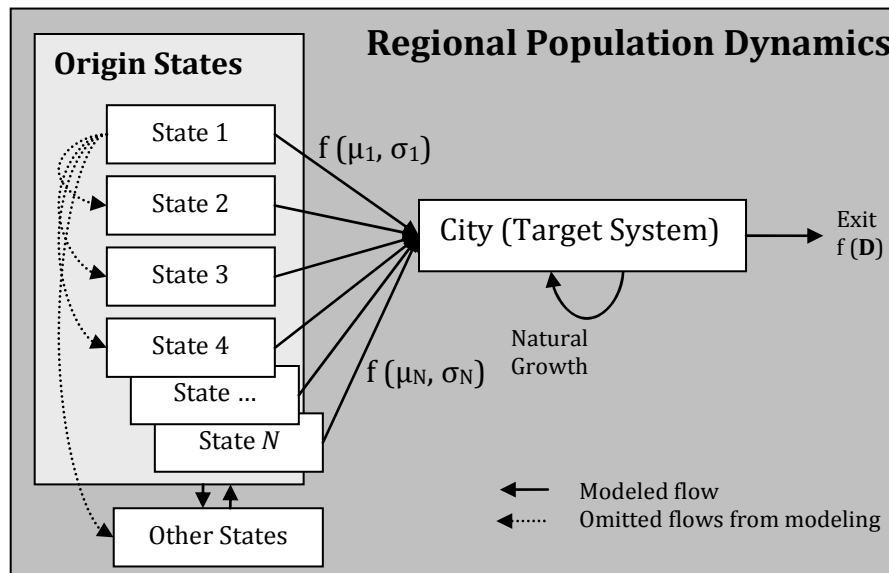
### 5.3 Population Dynamics Module

The *Population Dynamics Module* (PDM) estimates migration flows to the modeled city using DES. The estimates of this module are used as an input to the HDM that simulates the behavior of individual migrants and land use pattern via ABM (see section 4.2).

DES is a type of simulation used to model "events", such as migration, that causes changes in the state of a system, such as population distribution across states. DES is useful for estimating future demand that events create, such as demand for housing. In policy planning, DES has been used for resource allocations to develop prisons, public housing, health-care facilities, etc. (Korporaal et al., 2000; Koizumi et al., 2005; Kuno, et al., 2005). In DES, events are generated as if they happen in the real world: a migrant arrives to a city, stays in a city for several years, and returns to the state of origin or departs to another region. After each event, simulation time is incremented to the time of the next event. Classic references for DES include Hiller and Lieberman (1967); and Nelson (2003).

The migration to the city of Ahmedabad is generated as an event from a probability function. The frequency of migration is determined by the mean of the probability function. For instance, a large volume of population flow to Ahmedabad would be characterized with a large mean. A typical probability distribution used to describe arrival per year is a Poisson distribution while those used to represent length of stay include Exponential, Weibull, Gamma, Erlang, Cox, Phase-type, etc. A conventional approach in a DES analysis is to run simulations based on several

different distributions that are commonly used and see whether the results are sensitive to the functional form assumed to describe the event. The states of origin in India in this module comprise the states from which people have migrated to Ahmedabad since 1991 (Census of India 2001). All other states are aggregated and dealt outside the system as "other states".



**Figure 10: Population Growth in DES Framework**

The data to estimate necessary parameters, such as arrival rate to a city, is calculated from the Indian census for example in the case of Ahmedabad. The migration tables from census (Migration Tables - D Series, Census of India 2001b) provide the data to estimate the mean arrival rate to Ahmedabad from respective states. In addition, it provides information pertaining to the reasons for migration,

gender and age-group. The simulation uses a year as the time unit, due to the limited details available in migration tables in the census data.

In the DES model, each migrant is characterized with attributes used in the HDM. These could include language, caste, household size, occupation in the destination city, migrated as single or as a family etc. A household formed from an existing household (e.g. offspring forming their own household when they reach adulthood) within destination city inherits most characteristics from the parental household while some characteristics are of their own such as family size, expected income and occupation.

The outputs of this module are the newly formed households along with their characteristics. This household information feeds into the HDM, as shown in Figure 14, as exogenous inputs. Household formation from natural growth and migration is consciously kept exogenous to housing model assuming that choice of destination city itself is independent of subsequent choice of housing in a destination city for a particular household. This assumption is in line with a widely accepted migration theory developed by Harris and Todaro (1970) that explains rural to urban migration in developing countries as a result of differences in expected wages in urban area and real wage in rural origin, attributes of labor market conditions. Furthermore, empirical findings from the literature suggest that cities with favorable housing scenario compared to other possible destination cities in the system attract more migrants (Lall et. al., 2007).

### 5.3.1 Phase-wise Evolution of the PDM

The PDM has two components: natural growth component and mechanical growth component. After initial verification of both of these components, this section combines both of them to create the PDM. The demographic scale of the PDM is an individual whereas HDM operates at household scale. Therefore, this module is developed further to add an algorithm that creates family links between individuals to create households (section 5.5). This approach allows the module to operate at the individual scale but enables it to generate outputs at the household scale. This becomes important when this module is integrated with HDM.

#### 5.3.1.1 Modeling Natural Growth Component

There are two main drivers of population dynamics in a city: i) natural growth and ii) growth due to migration (sometimes, referred as mechanical growth). There are four events that determine population growth: births (***B***) and deaths (***D***) that determine the net natural growth of native citizens (***B - D***) whereas in-migration (***I***) and out-migration (***O***) determine the net migration component (***O - I***) population growth. Therefore, the population growth for a period can be expressed as:

$$\Delta P = (B - D) + (I - O) \quad (1)$$

The objective is to simulate these events over a period that results into an overall estimate of population growth; described in Equation 1. As described in section 5.2, DES is an appropriate framework for simulating these events. The arrival rate parameter governs the arrival events in the DES framework and the Length of Stay (LOS) parameter determines when the exit events would occur.

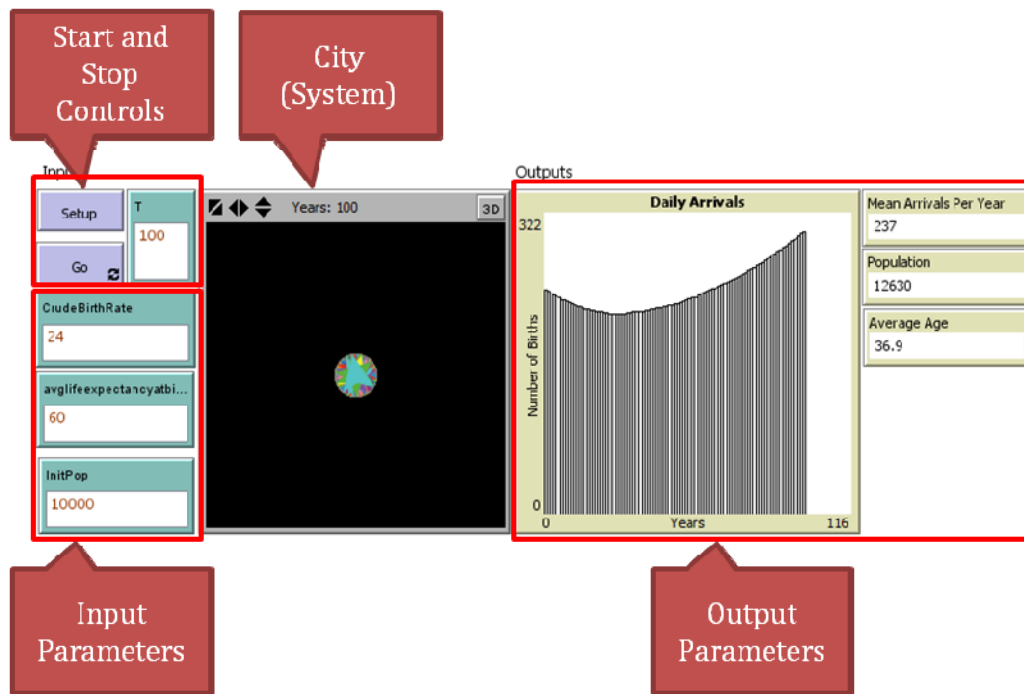
For the natural growth component, the Crude Birth Rate (CBR) provides the arrival rate parameter whereas the average life expectancy at birth is the equivalent of average LOS. For the net migration component, the in-migration rate provides the arrival rate parameter estimate whereas average stay in the destination (city) is equivalent to the average LOS. In addition, death could also determine a migrant's exit from the system. Similarly, a native could also out-migrate from the modeled city.

The PDM was built in phases so that each component can be verified before moving to the next level. First, the natural growth with CBR and life expectancy at birth is modeled to generate natural growth. The key output parameter to observe in this model is the total population. For the conceptual verification purpose, average age of the population was also observed.

While there are several software packages that could be used to develop a DES model (e.g. Simulink®, Arena®), NetLogo 5.0 (Wilensky 1999) was chosen. There are two main reasons for such a choice. First, it allows us to micro-simulate the agent populations as a result of events occurring in the system e.g. a birth event creates an agent in the city. Second, it is inherently suitable for ABM and hence

integration does not require any additional algorithm to link the two. In addition, NetLogo's GIS extension provides the ability to explicitly model the spatial environment.

The model interface of this intermediate version of the PDM is shown in Figure 11. To aid replication and experimentation, the model code is given in Appendix 1A.



**Figure 11: Natural Growth Model Interface (Intermediate)**

As is common with the models developed in NetLogo, experiments can be easily carried out by changing input parameter values using the sliders on the top-left of the graphical user interface (GUI) as shown in Figure 11. The visual

representation of the city over time (center of Figure 11) is not important at this stage of the model since outputs of this model do not exhibit any spatial behavior of our interest<sup>10</sup>. Nonetheless, the GUI allows us to visualize the trends of key output parameters such as total population and average age of the population (right section of Figure 11). Some indicators are also displayed in the form of graphs such as arrival rates over time and monitors such as total population, in order to summarize the dynamic behavior of the system as the simulation progresses. Such an interface is helpful in understanding and debugging the model, especially in the development stage (Grimm 2002).

In India, life expectancy is estimated 65 years and CBR is estimated 24 births per thousand population per year (World Bank 2012). The model was run for 100 years with these data as input parameters. The model was initiated with null population and hence, initial simulation outputs required to ignore the burn period. The output parameters of the simulated system showed a 1.27% annualized population growth. This output is within a plausible range, since the annual population growth in India in the last decade was recorded at 1.3% (CIA Fact book 2012). It should be noted that real world systems are usually open systems and hence it is difficult to separate pure natural growth from the mechanical growth (since migrants also reproduce and add to natural growth).

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<sup>10</sup> NetLogo does not have a feature to eliminate this element but it allows us to uncheck "updates" if we are not interested in the visualization. However, this feature becomes useful since we will eventually combine DES with ABM to visualize behavior of agents in spatial environment of a city. See Section 5.5

However, at this stage, the input parameters could be changed and the impact on the output parameters could be studied to see if it makes intuitive and conceptual sense. For example, testing the model for several values for CBR indicated that increase in the CBR results in an increasing population growth rate as well as reducing the average age of the population<sup>11</sup>. After gaining initial confidence in the model outcomes of the natural growth component, the migration component is developed.

#### ***5.3.1.2 Modeling Migration Component***

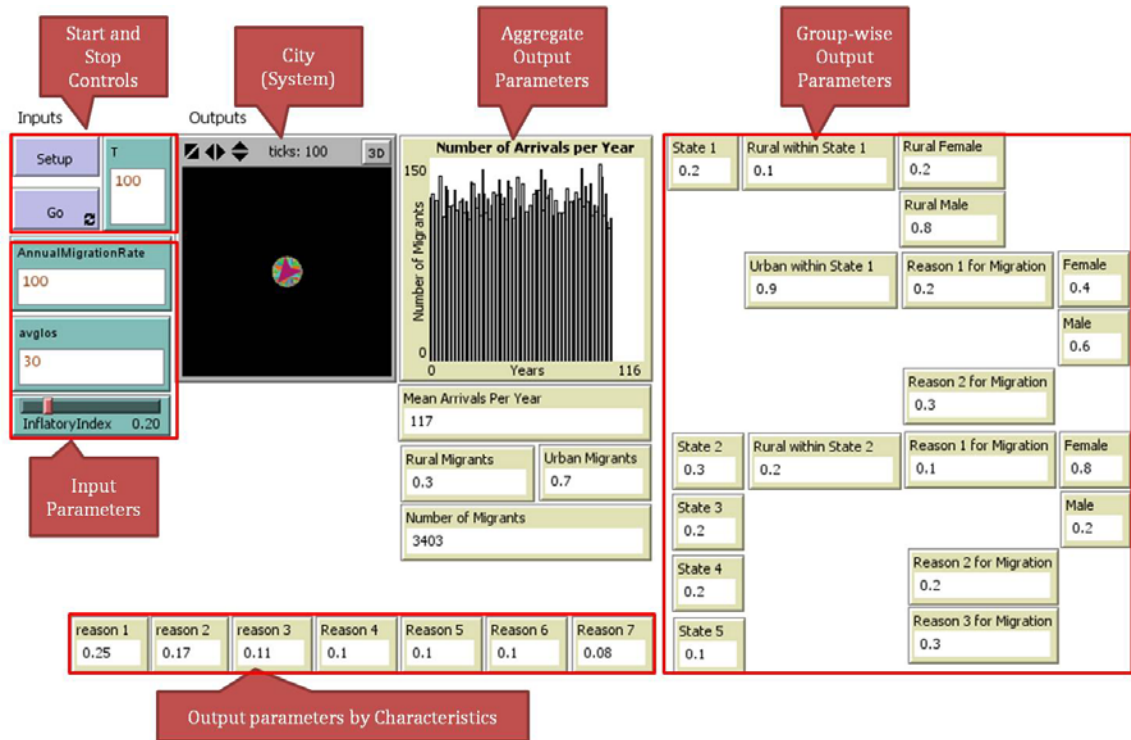
The second component of the population growth is due to migration. It is a net effect of in-migration and out-migration of individuals from a city. Similar to the approach taken in the previous section, migration is modeled using the annual migration rate  $M$  and the average Length of Stay (LOS) in a city. At each time period, the number of migrants is randomly generated from a Poisson distribution with a mean annual migration rate  $M$ . The length of stay for each individual is randomly generated from an Exponential distribution with a mean of average LOS. Each individual's total stay in the system is recorded from the time they arrive in the city to the time they leave the city. As the simulation progresses, when a migrant's actual stay in the city equals her LOS, she exits the system.

In addition, this module assigns several characteristics (e.g. gender, reason for migration and rural/urban origin) based on specified proportions which were

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<sup>11</sup> Results of these experiments are useful during the model development stage but they are rather obvious and hence not reported here for brevity.

calculated from Census data. The proportions for such an assignment are provided as inputs to the model. The model interface of this intermediate version is shown in Figure 12. The key output parameter for this component is the total number of migrants at any given time  $t$ . To aid replication and experimentation, the model code is given in Appendix 1B.



**Figure 12: Migration Component Interface (Intermediate)**

As is the case with the natural growth component, experiments can be easily carried out by changing input parameter values using the sliders on the top-left of the GUI as shown in Figure 12. The visual representation of the city (center of Figure

12) is not important at this stage of the model as discussed earlier. The GUI allows to visualize the trends of key output parameters e.g. number of total migrants. In addition, the following characteristics of migrant population are monitored: proportion of males and females, proportion by reason of migration (right section of Figure 12), reasons for migration include work/employment, marriage, joining the existing household, etc. (see chapter 6). These output parameters are observed only for the verification purposes since these proportions are already provided as input parameters in the model. Some indicators are also displayed in the form of graphs and monitors in order to summarize the dynamic behavior of the system as the simulation progresses. Once again, such an interface is helpful in understanding and debugging the model in the intermediate stages of the model development (Grimm 2002).

Although, the actual arrival rates for migration are desirable, individual incoming migrants' arrivals and departures are not registered at the city level in the real world. Instead, decennial census provide the number of migrants enumerated in the city in that year. Thus, it does not include migrants who were not present in the year of enumeration. For example, people who came to a city after the 1991 census but left before the 2001 census would not be captured in either of the censuses in that city. Similarly, those who were born in a city after 1991 but out-migrated from that city before the 2001 census would also not be enumerated at the place of our interest. In order to compensate for this underestimation, an Inflationary Index ( $I$ ) is introduced to adjust the migration rate. The value of  $I$  is

calibrated in such a way that the simulated number of migrants are well within the observed number of migrants at the confidence interval (CI) of 95%.

In a hypothetical example of a 10 year simulation of a city, suppose there were 1100 migrants in the observed year  $t = 10$ . In a previous census, let us assume that this number was 100 migrants. Then, it can be inferred that total 1000 new migrants were added in the system in the last 10 years. This implies that the migrant arrival rate  $M$  will be 100 migrants per year. However, such a number will be an underestimate since it does not include those who were not observed (either because they left before  $t = 10$ , or both, entered and left the system between  $t = 0$  and  $t = 10$ ). By simulating the system with 100 migrants at  $t = 0$  and an average migration arrival rate of 100, the number of migrants will be less than the observed number of migrants i.e. 1100. The simulation experiment was run for 1000 times to calculate the simulated number of migrants at time  $t = 10$ . The mean of these 1000 simulation runs was 936 (934 to 938 at 95 % CI), which is lower than the observed number of migrants at time  $t = 10$  in our example. The value of the Inflation Index is iteratively changed in order to achieve the observed number of migrants and found that  $I = 0.180$  produces the mean number of migrants 1100 (1099 to 1103 at 95% CI) as observed in the real world.

Furthermore, several experiments were conducted by changing input parameters: time  $t$ , migration rate  $M$  and  $LOS$ , and concluded that each combination of these three parameters requires  $I$ , that is unique to that combination. The direction of change in the Inflation Index made conceptual and intuitive sense. For

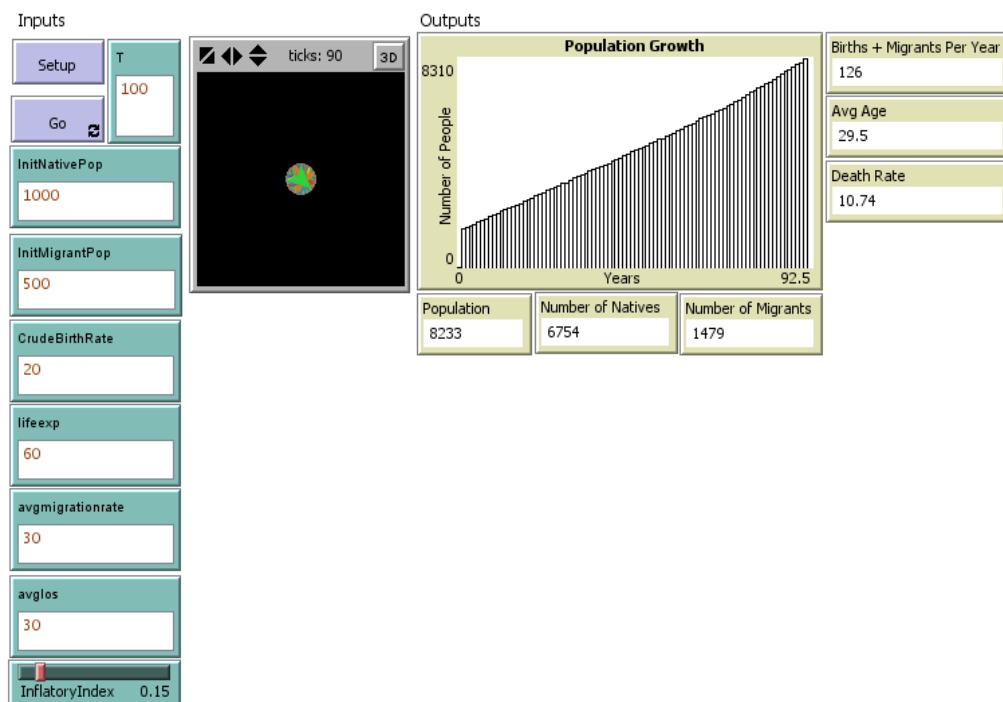
example, when the simulations were run for longer periods (e.g.  $t = 20$ ), it was found that a higher  $I$  is needed because there will be more people who would have left the system and remained unobserved in those 20 years. Thus, a particular value of  $I$  is sensitive to a particular combination of input parameters. After gaining initial confidence in the outcomes of the migration component, both the components are integrated to develop the comprehensive population growth model in the next section.

#### ***5.3.1.3 Combining Natural Growth and Migration Components***

The natural growth and migration component are developed in isolation to understand and debug the model. However, real world systems have both these components adding to the overall population growth. Therefore, both these models are integrated to simulate population dynamics in a city.

Total population growth of a city is not a simple summation of population growth generated separately from both these individual components. The process becomes complex since migrants could also reproduce (adding to the natural growth); natives could out-migrate before they die (reducing the natural growth) or migrants could die at the destination (reducing the migration growth). The integrated module models these processes accordingly. Similar to migration component, for each combination of input parameters, Inflation Index  $I$  is used for calibration purpose which now compensates for unaccounted growth or decline resulting from all of the above mentioned processes.

The model interface of this integrated version is shown in Figure 13. The key output parameters for this integrated version are the total population, number of natives and number of migrants at any given time  $t$ . To aid replication and experimentation, the model code is given in Appendix 1C.



**Figure 13: PDM Model Interface**

The model requires input parameters described in section 5.3.1 and 5.3.2 to generate the overall population growth. Those include CBR, migration rate, life expectancy at birth, average LOS and initial native and migrant population. The

input parameters used in a hypothetical example of a 10 year simulation of a city are shown in Table 1.

**Table 1: Input Parameters for Population Dynamics**

<b>Parameter</b>	<b>Value</b>
Initial Native Population	1000
Initial Migrant Population	500
Crude Birth Rate (CBR)	20
Life Expectancy	60
Migrants per Year (M)	30
Length of Stay (LOS)	60

The simulation experiment was run for 1000 times to generate total population at time  $t = 10$ . The mean of the simulated total population was 2197 (Standard Deviation (SD): 31), which suggests 4% annual average growth rate. The population consisted of 1340 natives (SD: 21) and 857 (SD: 20) migrants (40% of total population). These output parameters (i.e. population growth rate and proportion of migrants) are within plausible ranges for the input parameters used. For example, the cities in India grew annually at 4% between 1991 and 2001 (Chatterjee 2002). The population growth of several of these cities is due to migration which is reflected as large proportions of migrants. For instance, 33% of Ahmedabad's population was migrants in 2001. Calibration and validation of the PDM for the case is discussed of Ahmedabad in Chapter 7.

The migration data is usually available at the individual level which required us to model events at a demographic scale of the individual. However, the HDM

operates at the household scale. Hence, an algorithm is developed that could create households from the individuals generated in this module.

## 5.4 Housing Dynamics Module

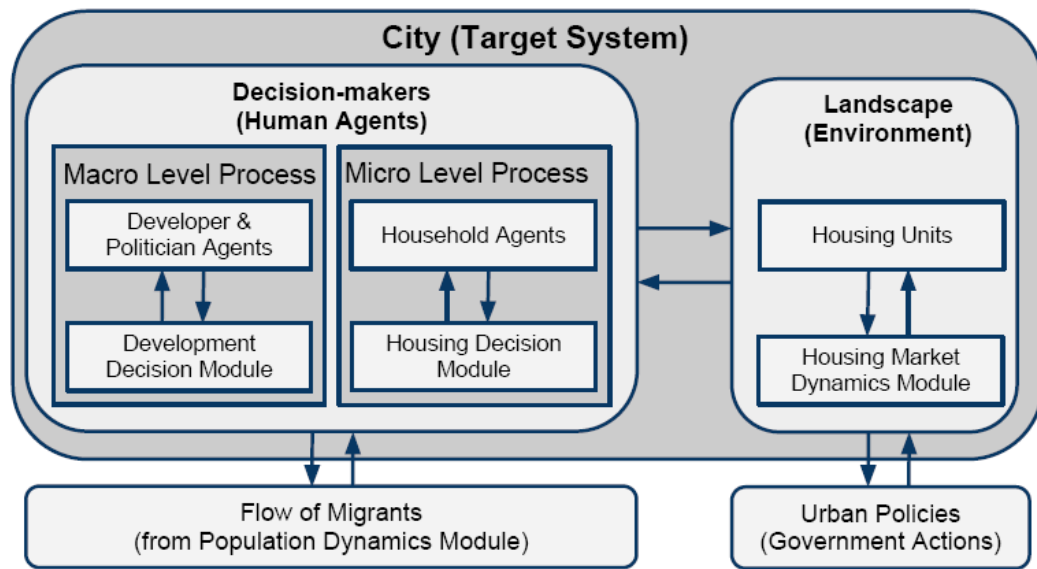
The *Housing Dynamics Module*<sup>12</sup> (HDM) simulates household residential choice behavior in a spatially explicit housing market. The HDM models the micro-processes of housing choice behavior at household level and captures the emergent macro-phenomenon of formation and expansion of slums at city level. ABM is a type of simulation used to model human behavior (Kennedy 2012) from bottom-up (Epstein and Axtell 1996), such as residential and other types of choice, that has implications for the environment, such as changes in neighborhood ethnic composition, which in turn influences behavior of other humans (or agents, Benenson et al. 2002).

In ABM, human behavior is governed by behavioral rules that are common for all agents but behavior still varies for each agent because of variation in characteristics of individual agents used in decision-making (Crooks and Heppenstall 2012). For example, a generic behavioral rule in a housing model may stipulate that agents must find another house if they no longer can afford their current house. However, for each agent affordability depends on their own characteristics such as income level, preference for proportion of income spent on housing etc. These characteristics vary across agents but the behavioral rule to

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<sup>12</sup> This section is accepted for publication in Journal of Artificial Societies and Social Simulation. Patel, A., Crooks, A., Koizumi, N., (*Forthcoming*). "Slumulation: an Agent-based Modelling Approach to Slum Formations". *Journal of Artificial Societies and Social Simulation*. Vol. X No. X.

check for affordability is consistently applied to all agents in the model. At the core of this module are agents and their behavior and interaction with the spatial environment as shown in Figure 14.



**Figure 14: Architecture of HDM at the City Level**

The main agents that influence the slum formation process as identified from the literature are households, developers and local politicians (Parthasarathy and Pothana 1981; Singh 1986; Chege 1981; Bharucha 2011). In the HDM, the household agents make housing location decisions; the developer agents create housing units on vacated housing sites thus adding to the existing housing stock; while the politician agents provide a subsidy to slum dwellers. This subsidy discounts the

"economic rent" in varying degrees, which in turn facilitates the retention or eviction of existing slums within an area.

In this module, households are on the demand side while developers and politicians control the supply in the housing market, however, households, developers and politicians operate at different spatial scales. For example, household agents would consider spatial environment at housing unit level whereas politicians would consider a large scale of electoral ward that consists several hundred housing units. Consequently, the environment is built on two spatial scales.<sup>13</sup> The first layer models housing sites that contain housing units in which households make locational decisions on where to live and developers make development decisions. The second layer consists of electoral wards that contain several housing sites and other geospatial elements such as road network, public infrastructure etc., in which politician agents play their role.

As a first step to initiate this module, the baseline conditions such as initial population of households, their locations and household characteristics for a base year are generated using data from *Geodatabase* (section 5.6.1). As the simulation progresses, newly formed household and migrants for subsequent time periods are micro-simulated in the PDM as described in previous section. The HDM receives a set of newly formed households in each time period. Given that outputs from PDM are generated using year as the time unit, each time period in ABM is also a year.

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<sup>13</sup>*Housing Dynamics Module* currently only tackles the spatial scale. However, we note that different temporal scales play a role. For example, residential movement occurs at a different temporal scale than that of political elections and the development of land.

The households are the main agents, who drive the housing demand in the model. Two other types of agents, local politicians and developers influences the supply of housing stock within the module.

The agents and their behavior and spatial environment are simulated based on several behavioral and transition rules that are at the core of this module (section 5.4.1.6). The behavioral aspects (e.g. where does a household locate when facing a choice) are informed from survey-based studies as advocated by Robinson et. al., (2007) and based on extensive reviews of other modeling efforts (e.g. Barros 2005 2012; Vincent 2009; Augustijn-Beckers et al. 2011). The assumptions underlying behavioral rules, such as preference to live closer to CBD or live within budget constraint are also supported by the theories developed in residential choice literature (e.g. Burgess 1925; Alonso 1964; Schelling 1971; Sanchez-Jankowski 1999; Benenson et al. 2003; Florida 2002; Soja 2000). Moreover, behavioral rules are supplemented by calibrating micro-process parameters based on their fit to macro outcomes. This is because geospatial empirical data alone only provides a mechanism to build landscape, it does not provide a mechanism to discover new decision-making frameworks or behaviors (Robinson et al. 2007). This also supports what certain practitioners of ABM argue, that rules are easier to determine at the level of the individual, while the rules for the macro-scale are often unknown or difficult to deduce (Clifford 2008).

In a typical run, this module receives new households with several characteristics (e.g. caste, household income) generated from PDM. These

characteristics are then used in simulating housing location choice. A modeled behavior of such a process is governed by multiple rules: a newly formed household *searches* for a housing location, *determines utility* derived from each potential location using individual preferences such as desired size, ethnic composition of neighborhood, and distance to jobs etc. Finally, in order to make the housing choice, the agent checks if it is within the constraints such as income, etc. After each "active" household (searching for housing in that time period) finds its preferred housing, simulation time is incremented to the next time period (as is common in many applications of ABM, see Heppenstall et. al., 2012). The households "read" data related to housing units and their spatial environment from *Geodatabase* to inform their choice (section 4.3).

Local politician and developers' actions create the supply of serviced land and housing stock in the model. Local politician govern the supply of public infrastructure in the city as well as determine the fate of illegal slums (whether to evict or protect from eviction). These agents operate at the electoral ward level. Behavioral rules governing their actions involve trade-offs between utility derived from slum votes by protecting slums and accepting kick-backs from developers by evicting slum dwellers. Developers' actions determine the supply of formal housing as well as influence local politicians to get slum dwellers evicted to obtain the land underneath for formal development. Unlike household agents, developer agents operate at a land parcel (or lot) level, which allows them to "sense" the collective demand for housing from household behavior. The behavioral rule involves

maximizing profits by taking up housing development projects within their financial capacity constraint. ABM is particularly useful here since it provides a flexible way of combining multi-agent processes at multiple spatial and temporal scales (Parker et al. 2003; Crooks and Castle 2012).

Land parcels (i.e. individual housing sites) along with several attributes (e.g. housing price, size etc) form the spatial environment within the model, which is stored in the *Geodatabase* component of the EM (section 5.6). Electoral ward boundaries are also superimposed to form an appropriate spatial environment for politicians. GIS is used to consolidate ward level attributes such as percent slum population in each ward, required for micro-processes for political agent's to determine their behavior. The spatial environment evolves as the simulation progresses (e.g. percentage of slum population in a particular ward will change as a result of household agents' location decisions). Aspatial parameters such as economic growth of the city, level of informality of economy etc. are also important parts of this module that is supplied exogenously and affects change in household characteristics during the simulation such as income levels.

The simulation outputs of this module will be compared with analytical results from the EM for calibrating and validating this module (Ngo and See 2012) and to help identify uncertainty and errors in terms of input data, parameterization, model outputs (Evans 2012) along with sensitivity testing.

A conventional approach in ABM is to run simulations based on several different behavioral rules for each type of agent and see whether the aggregate

emergent phenomenon is comparable to the real world. The outputs of interest from this module are in the form of maps, charts showing aggregate measures of both final and intermediate values (thereby showing historical progression). These include maps of slum locations and densities, charts of size distribution of slums, percentage slum population over time etc. The outputs also include city level aggregate measures of segregation such as dissimilarity index (Duncan and Duncan 1955).

#### **5.4.1 Phase-wise Evolution of the HDM**

The HDM was developed in two stages. In the first stage, only household agents and housing market were modeled. In the second stage, the developers and the politician agents were added and a second layer of political wards in the spatial environment was introduced, as discussed in section 5.2. Although, several versions were built during the development phase (Patel 2010a; Patel 2010b; Patel et al, *in press*), only the fully developed module is discussed in this section for brevity. To aid replication and experimentation, the model code is given in Appendix 2.

In terms of Axtell and Epstein (1994) schema of classification, agent-based models that portray a caricature of the agents behavior are called "Level 0" models and those attaining qualitative agreement with the patterns of emerging "macro-structures" are "Level 1" models. While a "Level 2" model attains quantitative agreements of emerging macro-structures, a "Level 3" model attains quantitative agreements with both emergent macro-structures as well as the individual agent's micro-behavior. As shown below, it is in qualitative agreement with the empirical

macro-structure of slum patterns in cities, and hence represents a "Level 1" type of model.

HDM is conceptualized as a spatial agent-based model of a city that consists of agents, their attributes, behavioral and transition rules tied to spatial entities (e.g. places to live), which all interact through space and time. Each of these elements are described in detail below, first describing the main agents before discussing their behavioral and transition rules.

#### ***5.4.1.1 Household Agents***

Households are the key agents in this module. One of the most important attributes for households is their income level. Based on the income level, each household finds an affordable place to live. If rent goes beyond what a household can afford, they consider relocating to an affordable place in the next time period. As with many exploratory agent-based models (e.g. Schelling 1971), the time frame for the model is purely arbitrary but it is considered as yearly intervals. Households also belong to one of the three income-groups, low, middle or high. For simplicity it is assumed that households can only share a housing site with the same income-group when they choose to live in a multi-family housing unit within a single housing site. Nonetheless, there is no restriction on living within a neighborhood of a higher income group. It is assumed that there is an implicit preference for living close to higher income groups as long as households can afford it. Poor households who cannot afford a housing unit could consider sharing it with other households. If they do not find another household to share within a specific time-frame, they are

forced to move to an affordable place elsewhere. How long a household can sustain residing at a given location despite an unaffordable rent depends on the household's financial "staying power" i.e. households in the low-income group cannot pay unaffordable rents for a long period compared to those in the high-income group. Financial staying power is discussed further below.

#### ***5.4.1.2 Developer Agents***

Developers construct housing units in order to gain profits. They buy vacant properties that were once occupied. The acquired properties are then developed, usually with a larger number of units (e.g. an apartment building at a site of a previous single family house). Developers hold a property until all the newly developed units are occupied by households. A developer agent is activated only on a housing site that is completely vacated and remains active only until all units are occupied. The developers are not explicitly shown as visual objects in the model interface but their actions are incorporated within the model processes.

#### ***5.4.1.3 Politician Agents***

In the model politicians monitor the demographics of their electoral wards. Each ward consists of multiple households. Politicians reduce the "effective rent" for slum dwellers in proportion to the percent of slum population in each ward in a hope to win votes from the slum dwellers. This relates to the notion of an implicit subsidy provided in the form of favorable policies such as protection against eviction and thus excluding a slum site from entering a formal market primarily to create an electorate (Glaeser and Shleifer 2003; Murray 2010). Slum dwellers living

in wards with a higher proportion of slum households pay lower rents than those living in the wards with a lower proportion of slum households. This relates to the notion that votes of slum dwellers are more important in the wards having a higher concentration of slums. It is well known from the literature that politics play an important role in determining the eviction of slum dwellers or persistence of a slum (e.g. Chege 1981; Mahadevia and Narayanan 1999). Politicians are active agents in all time periods and operate at the electoral ward scale. Politicians are not shown explicitly in the visualization, but their behavior is reflected in the calculation of effective rents.

#### ***5.4.1.4 Environment***

The environment in this model is both spatial and aspatial. The spatial environment consists of two types of entities as mentioned earlier: i) housing sites and ii) electoral wards. The households occupy the smallest spatial entity, a housing site, which may house multiple households in case of multi-family housing such as apartments or slums. The second spatial entity, electoral ward, is larger in scale and divides the city into several political electorates. Each electoral ward consists of multiple housing sites in a spatially contiguous manner. The demographics of an electoral ward are incorporated into the determination of a subsidy by politicians for slum dwellers.

To capture the dynamics relating to city growth and the changes in income and population composition, the model also has an aspatial environment. The city economy grows at a user-specified rate, which in turn determines the change in

income levels of individual households. Population growth results from both natural growth and migration into the city, which is specified as the population growth rate for simplification in this module<sup>14</sup>. Newly formed or newly arrived households search for a home that they can afford. The city economy is also divided into formal and informal sectors, which is common in many developing countries (Sethuraman 1976; Field 2011). Poor households working in the informal sector do not see as much upward income mobility compared to those working in the formal sector (Urban Age 2007).

#### ***5.4.1.5 Modeling Interface***

The model interface of HDM is shown in Figure 15. As is common with models developed in NetLogo, experiments can be easily carried out by changing input parameter values using the sliders on the top-left of the GUI as shown in Figure 15. One can view an updated visual representation of the city over time (center of Figure 15), together with the trends of key output parameters (right section of Figure 15). The GUI also allows one to keep track of economic and demographic variables (bottom-left section of Figure 15).

The physical space in which housing units and political wards are placed is a square grid in a two-dimensional space. The larger squares are political wards that consist of many housing sites represented by the smaller squares. The housing market consists of housing sites in the spatial environment represented by a 51 x 51 square grid resulting into 2601 housing sites. Each square on the grid represents

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<sup>14</sup> The integration with PDM will replace this parameter in the version presented in section 5.5.

one housing site but it can accommodate a single family or multiple families depending on the number of housing units built on it (e.g. a townhouse, an apartment or a slum). Each housing unit at a given location has a rent associated with it that a household pays in order to occupy it. For simplicity, ownership is not distinguished here and rents are assumed to be equivalent to the mortgage payments for owner-occupiers, often referred as imputed rents.

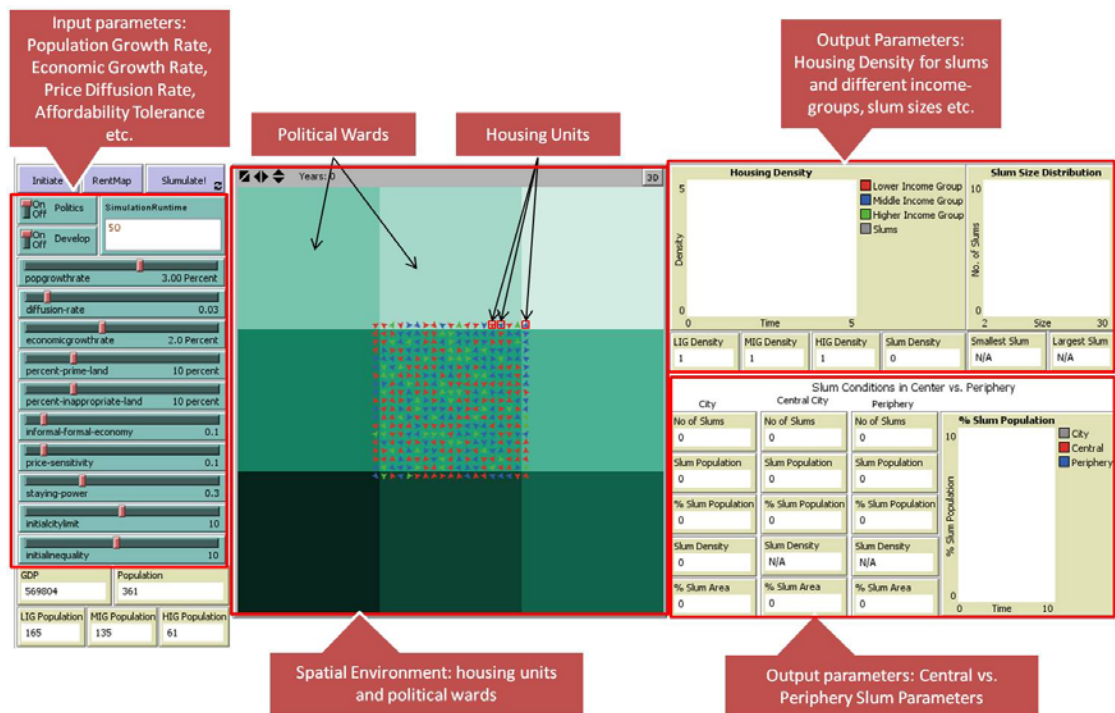
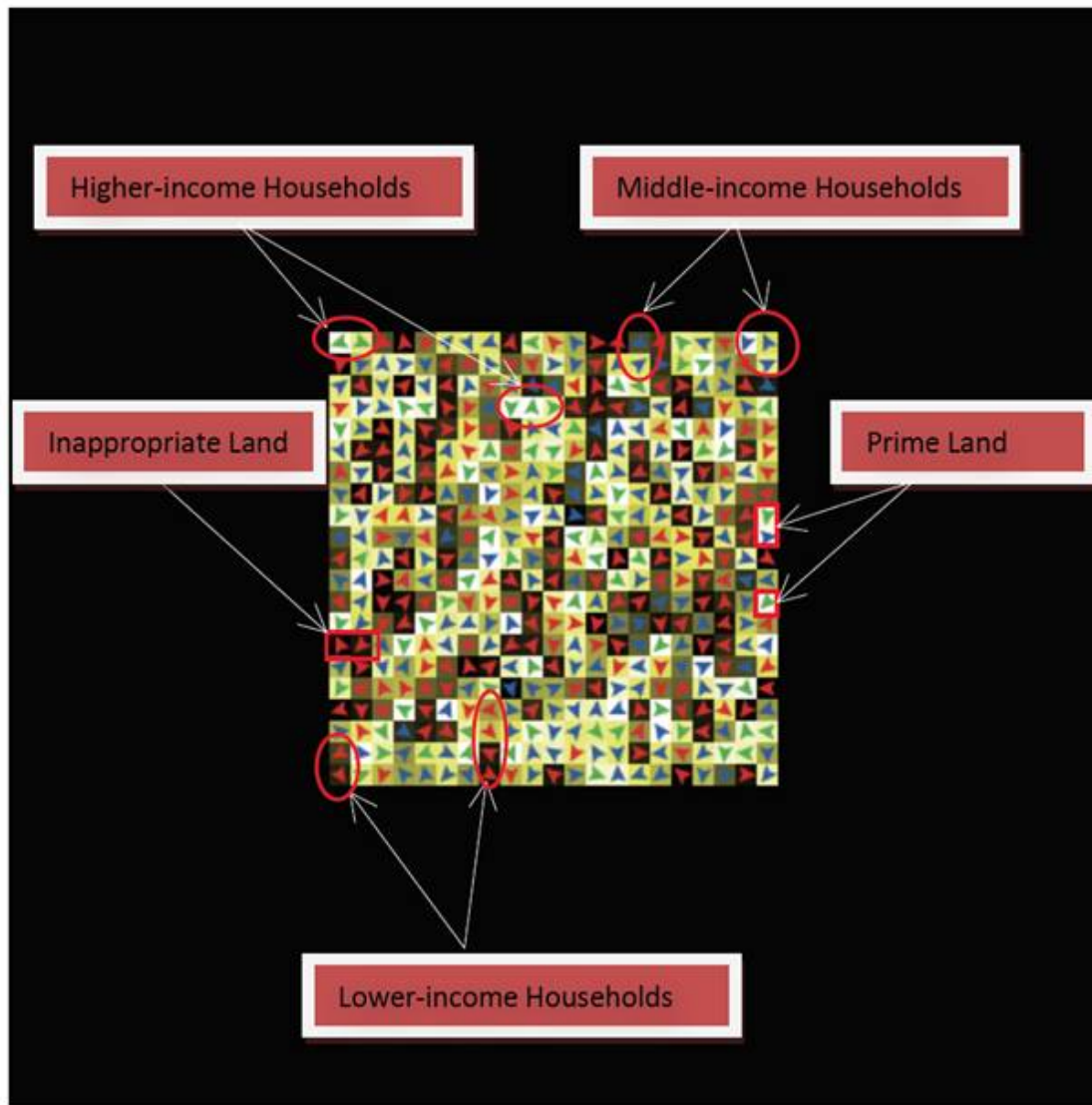


Figure 15: GUI for HDM.

The city is divided into nine equal political wards, each ward consisting 289 housing sites. The demographics of the wards keep changing as new households

appear in the landscape and old households relocate in the simulation process. The effective rent for a given site in a ward is set by politician agents as a function of the dynamically changing proportion of slum dwellers in the ward.



**Figure 16: Rent Choropleth Map of the Housing Units Occupied by the Different Income-Groups.**

Figure 16 shows a choropleth of the property rents. The color intensity of the smaller squares represent the rents for that property; the prime properties have the highest rents in the city and are shown in brighter shades of yellow, whereas the properties unsuitable for development (e.g. hazardous sites, riverbed, landfills etc.) have the lowest rents and are shown in darker shades of yellow. The triangular-shaped objects in Figure 16 represent household agents. The color of each triangle represents the income-class that each agent belongs to; red, blue and green are respectively associated with the agents in low, middle and high-income groups.

#### ***5.4.1.6 Transition and Behavioral Rules***

This section describes transition rules for the various attributes of both the agents and the various spatial entities within the HDM. The transition rules define how each entity will evolve over time as the simulation progresses. It also describes the behavioral rules for the household agents and its mathematical formulation in the model. The behavioral rules define how agents will respond to the changes in the environment. As in many agent-based models, the transition and behavioral rules are fixed but parameterization of these rules is flexible and user-specified. For example, how the economic growth affects housing prices is specified in the model, but the users can easily alter the value of the economic growth rate to study its impact on the slum formation process.

#### ***5.4.1.7 Housing Prices***

Although the user specifies the initial city size, the percentages of prime and inappropriate sites within the city limits, the actual location and rents for the rest of

the housing sites are set randomly by the model. Within the initial city limits, rents are randomly drawn from a normal distribution ranging from the lowest rents for an inappropriate site to the highest rent for a prime site. Outside the initial city limit, the rent is initially set to zero at the beginning of the simulation. This assumption is supported by the notion that cities grow and expand into virtually zero priced rural land in the periphery (e.g. Alonso 1964). However, as the simulation progresses, the immediate peripheral land starts gaining value as a response to the anticipated future demand, an effect also seen in the real world.

During a simulation run, rent may change as a result of the neighborhood effect (captured in diffusion rate below) and economic growth of the city. Rent for each property is calculated at the end of each time period, with the new monthly rent  $R_{it}$  of a property  $i$  at time  $t$  defined as:

$$R_{it} = (1 + \beta G)R_{i(t-1)} + \sum_{\substack{j=1 \\ j \neq i}}^8 dR_{j(t-1)} \quad (2)$$

where  $d$  is the diffusion rate defined by a user and  $j$  indicates eight properties in the Moore neighborhood of the property  $i$ .  $G$  is the economic growth rate and  $\beta$  is the fraction of economic growth attributable to housing market. With this specification in place, rents ( $R$ ) tend to move towards the neighborhood average through price diffusion over time. This process also ensures that periphery is

increasingly added into the initial city and thus pushes its boundaries outward into previously rural land.

The effective monthly rent  $ER$  is calculated for each housing unit that a household takes into consideration in their location choice decisions. This rent  $ER_{it}$  could be lower than the monthly rent  $R_{it}$  of an entire property. The effective rent takes into account the decisions from politicians, developers and slum dwellers. Politicians can lower the effective rent of a slum property in the form of subsidy. Developers can add more housing units on an existing site by for example converting a townhouse into apartments. Finally, slum dwellers can increase the number of households living on the same site through illegal squatting. Thus, the effective rent per household,  $ER_{it}$  at site  $i$  at time  $t$  is given by:

$$ER_{it} = \frac{R_{it}}{N_{it}} (1 - \alpha_{jt} S_{it}) \quad (3)$$

where  $N_{it}$  is either the number of households in a slum site, or the number of units if the site is held by a developer. In the latter case, the units do not have to be occupied.  $\alpha_{jt}$  indicates the proportion of slum population in the ward  $j$  at time  $t$  (ranging between 0 and 1) which determines the level of subsidy provided to all the slum sites in that ward.  $S_{it}$  is a binary slum-status for the site  $i$  at time  $t$  (1 if the property is a slum, 0 otherwise).

#### **5.4.1.8 Household Incomes**

The initial population of households are created within the city limit which is an input specified by the user. At the start of the simulation, each housing site is occupied by a single household whose income level is set to match the rent of the property that it is occupying which in turn is set as specified in section 5.4.1.7. Thus, high income households are located on prime properties and vice versa. Each household is also classified as a low, medium or high income household based on the percentile of their income compared to the average income in the city. Household income level changes as the simulation progresses and the income-group may also change as a result, as explained below.

The newly formed or migrant households are randomly assigned an income drawn from the distribution of the income in the city at that time. They are also stochastically assigned to either the formal or informal labor market in such a way that maintains the predefined proportion of workers in informal sector as reflected by the Informality Index.

At the start of each time period  $t$ , income  $y_{kt}$ , for household  $k$  changes based on various factors, namely, its income in previous time period,  $y_{k(t-1)}$ , its labor status  $f_k$ , and the economic growth rate  $G$ . Formally this can be written as:

$$y_{kt} = y_{k(t-1)} + G\delta y_{kt} + Gf_k(1 - \delta)y_{k(t-1)} \quad (4)$$

where  $f_k$  is a binary variable indicating whether the household's labor status is formal or informal. If households are in the formal sector, they can experience full upward income mobility compared to households working in an informal sector who can only experience a fraction ( $\delta$ ) in their upward income mobility.

#### **5.4.1.9 Residential Mobility**

Newly formed or recently arrived households search for an affordable housing unit. They locate at a housing unit that has the rent-payable  $RP_{it}$  that is less than their capacity to pay  $C_{kt}$  (the latter is defined as a pre-determined fraction of their income level). The households already residing on a particular site keep checking that they can continue residing at their present locations by comparing their  $C_{kt}$  with the prevailing  $RP_{it}$ . When the rent-payable exceeds their capacity within a certain fraction of their income, defined by the price-sensitivity  $RS_{kt}$ , the households are willing to share the unit with another household of a similar income-group and effectively divide the cost of the rent.  $RS_{kt}$  ranges between 0 and 1. The lower price sensitivity results into low tolerance for volatility in rent-payable. The households compare their ability to pay rent with the price-sensitivity adjusted rent-payable when considering the willingness to share. Their transition rule is, *remain open to share the unit* if:

$$RP_{it} > C_{kt}(1 + RS_{kt}) \quad (5)$$

Furthermore, there is a limit to persistence of looking for another household to share the housing unit. The financial staying power,  $FS_{kt}$ , determines how long the household can stay at an unaffordable housing unit in a hope to find a household to share with them.  $FS_{kt}$  ranges between 0 and 1. When the rents cross the limit beyond their financial staying power, they are forced to leave the current place and start searching for an affordable housing unit elsewhere. Their transition rule is, *start searching for a house* if:

$$RP_{it} < C_{kt}(1 + FS_{kt}) \quad (6)$$

#### **5.4.1.10 Population Growth**

Before we integrate the PDM, a simple population growth mechanism is introduced. The model is initiated with one household per housing site within the initial city limit specified by the user. The population  $P$  changes at the user-specified population growth rate  $\lambda$  during the simulation. The population growth rate is assumed to incorporate both natural growth and the migration. Thus, the population  $P_t$  at time  $t$  increases to:

$$P_t = (1 + \lambda)P_{(t-1)} \quad (7)$$

#### **5.4.1.11 Economic Growth**

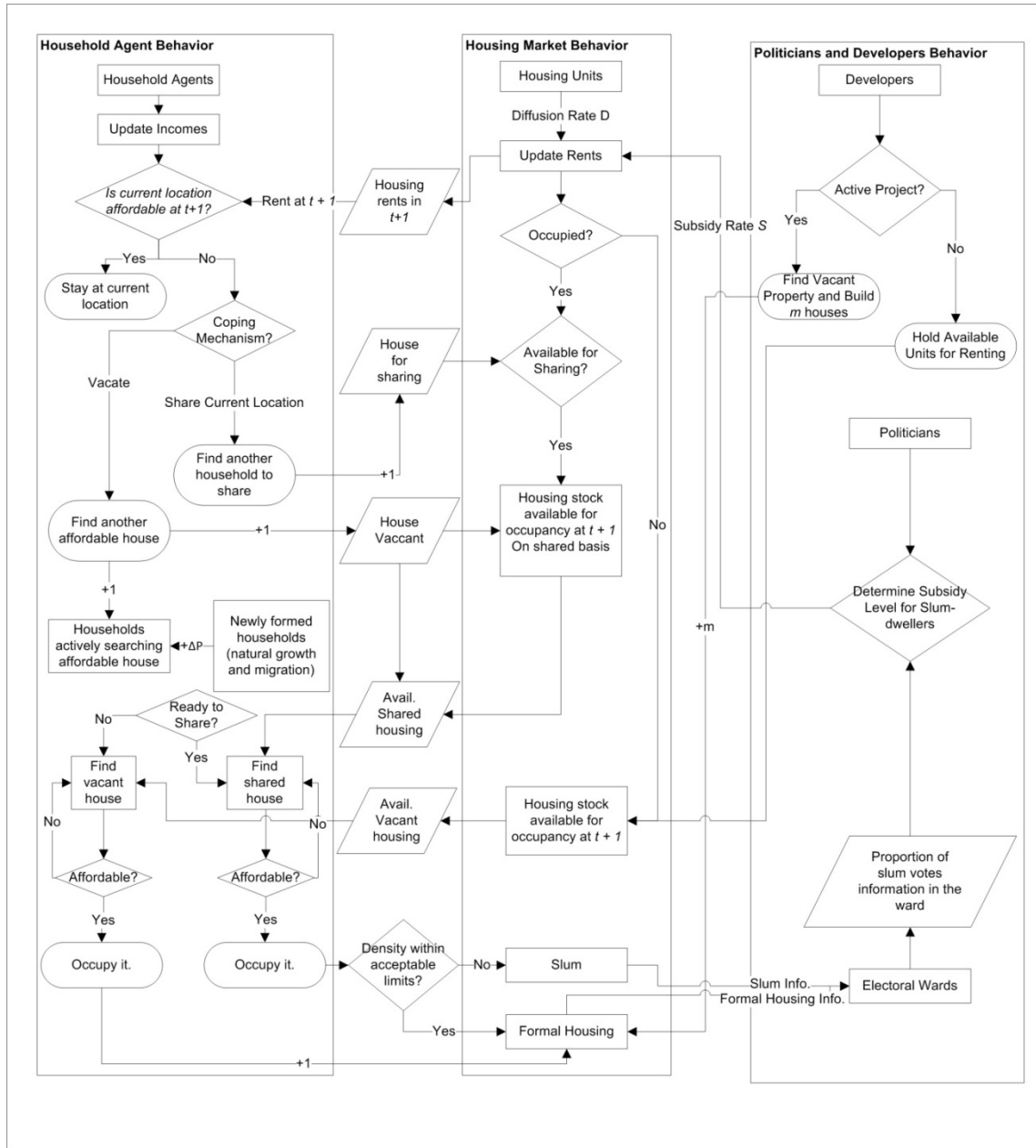
The initial total output of the city  $Y$  is the sum of individual incomes of the initial population. Total output changes at user specified economic growth rate  $G$  as the simulation progresses. The total output  $Y_t$  at time  $t$  is thus defined as:

$$Y_t = (1 + G) Y_{(t-1)} \quad (8)$$

#### **5.4.2 A Typical Simulation Time-step in HDM**

The model is initiated with an initial population of household agents and housing units occupied by them. A user also specifies various parameters such as initial city size, proportion of prime and inappropriate land in the city, population growth rate, economic growth rate, initial income distribution, price diffusion rate for housing and the level of informality of the economy. Each time-step is notionally considered to be one year in the model and the simulation is run for user-specified number of years. Outputs are recorded for each time period. The map of the city at the end of the simulation is also recorded as an output. Figure 17 shows how different entities interact in each time period during the course of a simulation.

While model-wide temporal changes such as agents' income levels and housing prices are updated synchronously at the end of each time-step, household relocation and the resulting change in newly occupied housing sites (i.e. occupancy status, number of occupants etc.) are updated asynchronously.



**Figure 17: Model Logic and Interactions Between Different Entities During the Course of a Simulation.**

All active households that are searching for a new location are relocated within the time-step but they are initiated one by one in a randomized order. During the simulation, an empty housing site is occupied by a newly created developer

whose principal role is to create new housing units on that site and hold the vacant units for future occupancy by households. Once all newly created units are occupied, the developer agent on that site becomes inactive.

#### **5.4.3 Outcome Measures**

In the model, the fifth criterion of the UN-Habitat (2006) definition of a slum household, i.e. insufficient living area, is used to declare a housing site as a slum. This criterion was chosen primarily because it is the only criterion that reflects household's choice. For example, households may influence the decisions pertaining to the first two criteria at a particular location (i.e. lack of water and sanitation), but these are primarily the outcomes of large-scale infrastructure investment decisions by public authorities and are usually taken at neighborhood or even larger area scale. The third and fourth criteria of the slum definition, namely, secured tenure and durable structure, can be assumed to be directly reflected in prevailing housing prices and rents (e.g. a housing unit with a durable structure will be priced higher than that of one with a temporary structure). Housing density is the only parameter that collectively "emerges" from individual household's location choices and interaction with other households such as sharing behavior. The housing density parameter provides an outcome measure resulting purely from household behavior and hence it is important from the perspective of building an agent-based model. It is intended to incorporate the other four criteria as part of spatial environment in future versions of *Slumulation*.

In the real world, the insufficient living space criterion is considered to define slums. As three or more persons occupy a single room, the household is declared as a slum household (UN-Habitat 2006). In order to implement this criteria in the model, a simple density approach was taken; a housing site was declared as a slum if it is occupied by more households than the number of units available on that site, since neither the housing units are modeled at the room level and nor are the households modeled at the individual level. However, this simplification captures the essence of the UN-Habitat definition. Once a housing site is classified as slum or non-slum, a series of indicators are calculated to study the overall outcome of the model. Particularly, average slum density, the number of slums, percentage of slum population, percentage of area under slums, both for the center and the peripheral areas as well as the average for the entire city are reported. Graphs are also created that show density for slums as well as for all three income groups over time. Similarly, slum size distribution for the entire city is also reported as shown in Figure 15.

#### **5.4.4 Model Verification**

Each input parameter of *Slumulation* is varied to understand its effect on the simulation outcome, in particular the final patterns of housing density (for slums as well as for other income-groups) and the percentage of slum population in the city. Verification is referred as a means of ensuring that the implemented model matches its design (North and Macal 2007), a process that involves checking that the model behaves as expected. Such verification is sometimes referred to as testing the "inner

validity" of the model (Brown 2006). First, the model is run with the input parameter values shown in Table 2. Some of the values chosen as default were those typically found in the cities in developing world. For example, the population in Indian cities grew at 3% annually on average between 1991 and 2001 (Census of India 2001). However, generalizable empirical data on certain parameters are often not collected or publicly available. In such cases, an informed judgment is made in choosing the values.

**Table 2: Input Parameters for a Typical Simulation Run**

<b>Input Parameters</b>	<b>Values</b>
Population Growth Rate ( $\lambda$ )	3.0%
Economic Growth Rate (G)	2.0%
Housing Price Growth Rate Fraction ( $\beta$ )	0.5
Initial Prime-land	10.0%
Initial Inappropriate-land	10.0%
Neighborhood Price Diffusion Rate	3.0%
Price-Sensitivity (RS)	0.1
Financial Staying Power (FS)	0.3
Informality Index	0.7
Income Growth Rate Fraction for Informal Sector ( $\delta$ )	0.1
Fraction of Income available for Housing Rent (C)	0.3
Initial City Population	361
Politics	On
Development	On
Initial Inequality	10
Simulation Run Time (T)	50

The simulation experiment was run for 50 time periods (years) and was repeated 100 times. 50 time-steps were chosen as it represented a long enough

simulation time but it could be run for longer time period. However, the simulation stops if physical space runs out while households are searching for new locations which limits, to an extent, this model's capacity to test population growth scenario. Choosing a smaller city-size as the initial condition can help to partially overcome this limitation. The model was run with smaller initial city-size for 150 time periods and it was found that some of the outcome parameters such as overall slum percentage stabilizes after approximately 40 time periods and roughly remains at that level for the remainder of the run. It should also be noted that the approach here, by design, is to make this model dynamic and hence all parts of the system never reaches an equilibrium state *per se*.

Figure 18 illustrates a typical simulation run, where the maps show the spatial distribution of the rents, and the charts show the evolution of housing density for each income-group and the percentage slum population. As is visible from Figure 18d, housing density increases for both slums and the lower-income group (LIG) from the beginning of the simulation suggesting inability of the poor to keep up with the rising housing rents. Whereas, housing density for the higher-income group (HIG) virtually remains the same throughout the simulation period, suggesting no economic hardship on the housing front for the high-income group. However, the middle-income group (MIG) also experiences hardship when faced with rising housing rents, suggesting that the middle-income group opts for high-density housing types (e.g. apartments) over single family-homes.

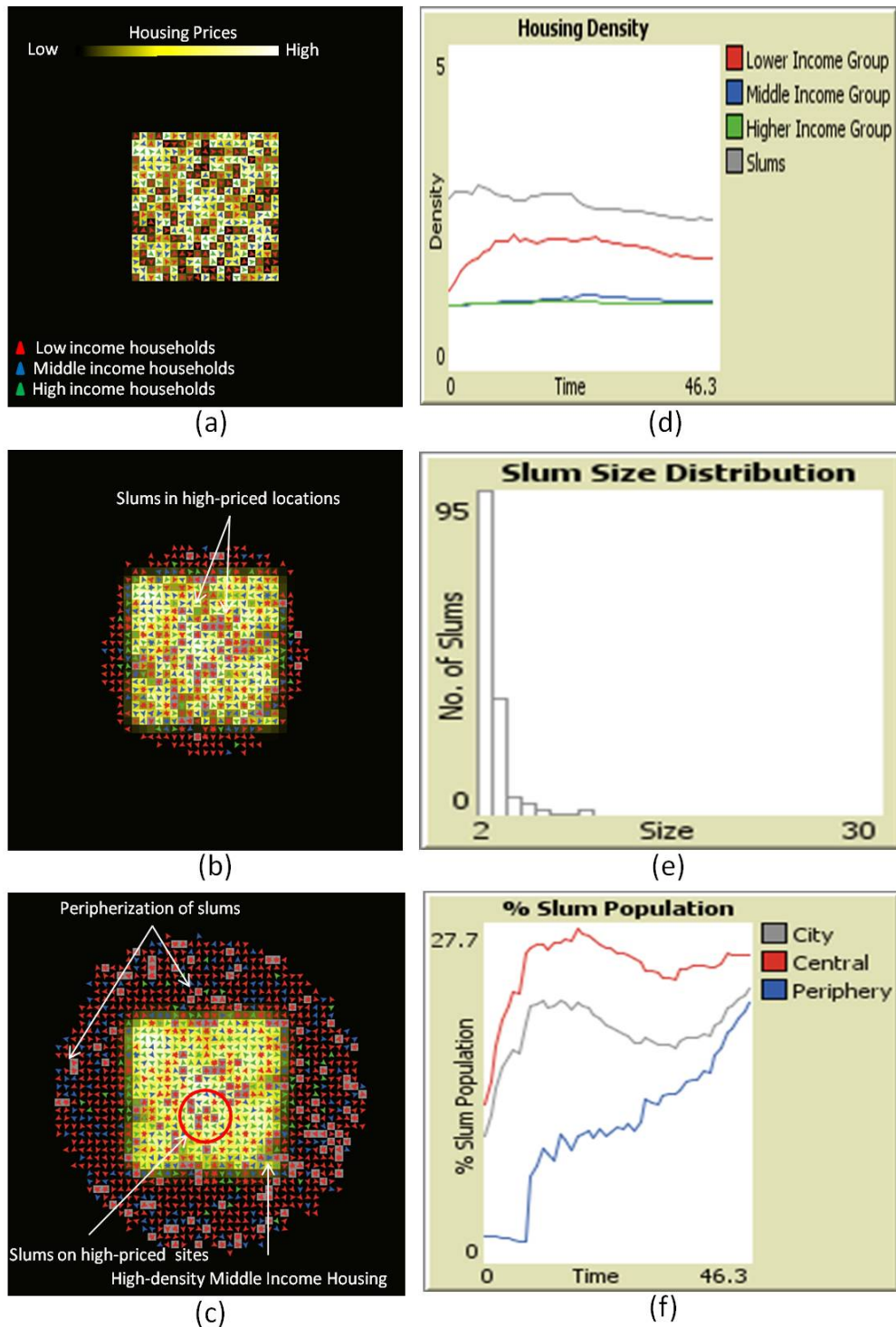


Figure 18: Typical simulation outputs: initial conditions (a), housing rent gradient and occupancies at time  $t = 25$  (b), and  $t = 50$  (c). Housing density for slums and other income-groups (d) slum size distribution at  $t = 50$  (e), and, % slum population over time (f)

The maps of the rent gradients and locations of the various income-group households in Figure 18 suggest another story. The lower-income group tends to occupy the peripheral housing sites because rents are comparatively low in the periphery. This pattern is similar to the patterns observed in the developing world cities, where such peripherization of urban slums is documented, for example, in several Latin American cities (Barros 2005). However, lower-income households also occupy some of the most expensive housing sites in the later part of the simulation. These properties are made affordable by extensive sharing which results in high densities. Densification is dominant in the central ward because the already high proportion of slum households benefit from the subsidy provided by politicians. This result is also consistent with the politics of slums. For example, Dharavi in the city of Mumbai occupies a site that would be highly priced in formal market but residents have not been evicted despite several proposals in the past (Mahadevia and Narayan 1999).

Table 3 highlights average slum population, number of slums and slum density in different regions of the city from multiple simulation runs using the input parameters from Table 2. This exploratory model produces housing conditions that are observed in some cities in developing countries. For instance, in the city of Mumbai, the densest slum, Dharavi, is 11 times as dense as the city's average density (Mukhija 2001; Rao 2007). The densest slum in this simulation is 7.3 times denser than the city's average density, while the proportion of slum population in the simulation is 19.7% which are plausible results. However, individual cities vary

dramatically in slum prevalence (UN-Habitat 2008) and hence the goal of this model is not to produce the actual percentage of slums for a particular simulated city. Rather its aim is to produce outcomes for a wider range of instances and therefore it should be sensitive to input parameters as discussed in subsequent model experiments section. In the simulation above, slums have a higher density in the central electoral ward (2.69) compared to peripheral wards (2.21 on average for 8 peripheral wards) as shown in Table 3. This trend is indicative of higher prices prevailing in central part of the city combined with households' higher preferences to live closer to the center. Furthermore, the high-density housing of middle-income households is also visible in the central part of the city suggesting the concentration of high-rise/high-density apartments. Developers within the model play a key role in this densification process by financing and replacing single-family housing with multi-family apartments, thereby reducing effective rent *per household*.

**Table 3: Mean of Key Output Parameters at t = 50 for 100 simulation runs**

<b>Output Parameters</b>	<b>City</b>	<b>Center</b>	<b>Periphery</b>
Percent Slum Population	19.0 (0.3)	16.8 (0.4)	19.7 (0.4)
Percent Area under Slums	10.1 (0.2)	8.5 (0.2)	10.6 (0.2)
Slum Density	2.30 (0.01)	2.69 (0.04)	2.21 (0.01)
Number of Slums	125 (2)	24 (1)	101(2)

In the next phase of the model verification, various model components were configured in many different ways to study the impact of selected model

specifications. For example, the model was run with and without politician and developer agents. All other parameters were kept the same as the control case, reported in Table 2. It was also verified that the presence or absence of each component impacts the results in a plausible manner.

**Table 4: Impact of Politics and Development Component on Model Outcomes**

Output Parameters		Politics ON Development ON (Base)	Politics OFF Development ON	Politics ON Development OFF	Politics OFF Development OFF
Percent Slum Population	City	19.2 (0.3)	18.7 (0.2)	24.4 (0.4)	25.3 (0.2)
	Center	16.0 (0.4)	13.9 (0.3)	24.8 (0.5)	22.0 (0.4)
	Periphery	20.3 (0.3)	20.2 (0.3)	24.2 (0.4)	26.1 (0.3)
Percent Area under Slums	City	10.3 (0.2)	10.1 (0.1)	12.1 (0.2)	12.5 (0.1)
	Center	8.3 (0.2)	7.3 (0.1)	11.2 (0.2)	9.6 (0.2)
	Periphery	11.0 (0.2)	11.0 (0.2)	12.3 (0.2)	13.3 (0.1)
Slum Density	City	2.26 (0.01)	2.28 (0.01)	2.35 (0.01)	2.37 (0.01)
	Center	2.54 (0.04)	2.62 (0.04)	2.62 (0.03)	2.66 (0.03)
	Periphery	2.20 (0.01)	2.20 (0.01)	2.28 (0.01)	2.31 (0.01)
Number of Slums	City	128 (2)	126 (2)	158 (2)	163 (1)
	Center	24 (1)	21 (1)	32 (1)	28 (1)
	Periphery	105 (1)	105 (2)	125 (2)	135 (1)

As seen in Table 4, when politician agents are deactivated, the slum population in the central ward decreases from 16.0% to 13.9%. This trend is indicative of slum dwellers' inability to resist economic forces (reflected in increasing housing rents) in absence of subsidy by the politicians. Similarly, when developers are turned inactive, slums increase all over the city. This outcome is indicative of developers' central role in creating dense housing types in highly

priced sites and thus making housing affordable at desirable locations. In absence of such formal densification, one would expect the rise in slum population i.e. informal divisions of properties to make them more affordable.

The model was also verified by changing several other components to study their impacts on model outcomes. For example, the model was tested for two different types of search processes when a household considers relocation: i) prefer locations near the current location, or ii) prefer locations close to the center. While the search process might have an impact on individual households' residential mobility patterns, it was found that the aggregate result for various slum measures such as the percentage of slum population, slum density and percent slum area, were not very sensitive to the choice of search process.

Similarly, the model was also tested for sensitivities of several different specifications of the model whose outputs are not reported for brevity. For example, it was tested how the rule to determine availability of housing units in a slum changed the model outcomes. In one scenario a slum site is made available to potential households even if the slum site is within the affordability range of the current residents. Alternatively, as it is implemented in the model presented here, it can be restricted from potential residents when all the original residents can afford it. This choice of specification on availability affects some of the outcome measures.

#### **5.4.5 Simulation Scenario and Analysis**

Once the model is calibrated and validated, the parameter space was explored by varying input parameters, one at a time. The configuration, showed in

the previous section (Table 2), acts as the base scenario for these parameters.

Several mechanisms were tested: population growth rate, economic growth rate, the initial proportion of prime and inappropriate land and finally the mix of formal and informal employment in the city. Each simulation experiment was run with three different values for 50 time periods and was repeated 100 times. The simulation outputs presented below are means of these 100 runs for each scenario. Standard deviations were within 2 to 4% range for all of these parameters and hence not reported for clarity. The rationale for choosing these scenarios is first sketched out before presenting the results for each scenario below.

#### ***5.4.5.1 Population Growth Rate***

More and more people are living in cities and this trend is expected to continue in the near future (United Nations 2007) with unprecedented numbers living in slums (UN-Habitat 2003). In this experiment, it is tested how the population growth in the city could impact slum conditions. The population growth rate was set to 2.0%, 3.0% (base scenario) and 4.0%. It is observed that a higher population growth (4%) leads to a higher percentage of slum population (27.9%) whereas a slower population growth leads to a lower percentage slum population (13.0%) as shown in Table 5. Of note is the non-linear relationship between population growth and percentage slum population.

The higher population growth rate also resulted in a greater number of slums as opposed to the densification of existing slums (Table 5). This is a hypothesis worth testing using real world data. It seems that exploring a new location is

preferred over exploiting existing locations during the rapid population growth period. For example, historically, cities have expanded physically during the period of increased migration, and the densification took place much later in their evolution (Sudhira et al. 2004).

**Table 5: Impact of Population Growth Rate on Model Outcomes**

<b>Output Parameters</b>		<b>Population Growth Rate 2.0 %</b>	<b>Population Growth Rate 3.0 % (Base)</b>	<b>Population Growth Rate 4.0 %</b>
Percent Slum Population	City	13.0	19.0	27.9
	Center	14.2	16.3	12.1
	Periphery	12.1	20.0	30.5
Percent Area under Slums	City	7.4	10.1	14.3
	Center	8.1	8.2	4.9
	Periphery	7.0	10.7	15.9
Slum Density	City	2.24	2.30	2.44
	Center	2.43	2.68	3.12
	Periphery	2.09	2.21	2.41
Number of Slums	City	54	126	283
	Center	23	24	14
	Periphery	31	102	269

Rapid urbanization is often cited as a factor in the slum formation process but it is often less understood how it might be affecting formation of new slums. This experiment shows that future slum locations are identified on the new frontier by new migrants during the rapid population growth phase of a city.

#### 5.4.5.2 Economic Growth Rate

Economic growth has a large impact on why people move to cities (UN-Habitat 2010). For example, Mumbai grew exponentially by attracting migrants from rural India as it added new manufacturing jobs (Yedla 2003). In order to study how economic growth impacts on the formation of slums, three different values for the economic growth rate were tested: 2.0% (base scenario), 3.5% and 5% while all other parameters were kept constant. The results are summarized in Table 6.

**Table 6: Impact of Economic Growth Rate on Model Outcomes**

Output Parameters		Economic Growth Rate 2.0% (Base)	Economic Growth Rate 3.5%	Economic Growth Rate 5.0%
Percent Slum Population	City	19.2	16.8	15.9
	Center	16.3	13.5	10.9
	Periphery	20.2	18.0	17.5
Percent Area under Slums	City	10.2	9.0	8.3
	Center	8.2	6.6	4.7
	Periphery	10.9	9.7	9.4
Slum Density	City	2.30	2.28	2.29
	Center	2.67	2.67	2.97
	Periphery	2.21	2.19	2.19
Number of Slums	City	127	112	104
	Center	24	19	14
	Periphery	103	93	91

The proportion of population living in slums decreases from 19.2 to 15.9% and number of slums decreases from 127 to 104. However, there is no spatial

implication as it is evident from the reduction experienced both in the center and periphery. The density of slums remains unaffected.

#### ***5.4.5.3 Initial Land Supply Conditions***

Cities are historically endowed with land parcels that are considered prime in the sense that they have easy access to jobs, recreation, social amenities and have adequate infrastructure services. Whereas some land parcels are naturally unsuitable for development, for example, hazardous sites such as riverbeds, sites near polluting industries or landfills, sites with poor accessibility from major transportation networks or inadequately serviced in terms of water and sanitation etc. How endowment of higher or lower proportion of prime or inappropriate land parcels in a city affect the slum formation process is tested in this scenario. The initial proportion of prime-land was simulated for three test values: 10% (base value), 20% and 30% while all other parameters were kept constant. The results are shown in Table 7.

A notable outcome from this experiment is reduction in the percentage of slums, percentage area of the city under slums and an increase in slum density in the central part of the city. There is also a higher proportion of prime-land in the initial central city that lower-income households cannot afford. Lower-income households accordingly face the supply constraint, which triggers the peripherization of slums or higher densities in relatively lower number of existing slums in the central city. Higher prices are also observed due to the neighborhood effect (sites near prime-land observes price appreciation over time). It would be

worth investigating this result with respect to real world cities to see if there are any path dependencies in the slum formation rate based on proportion of inappropriate land in the city.

**Table 7: Impact of Prime-land on Model Outcomes**

Output Parameters		Prime Land 10% (Base)	Prime Land 20%	Prime Land 30%
Percent Slum Population	City	19.0	19.0	18.6
	Center	15.7	14.5	13.4
	Periphery	20.1	20.4	20.3
Percent Area under Slums	City	10.3	10.1	9.9
	Center	8.2	7.3	6.6
	Periphery	10.9	11.0	10.9
Slum Density	City	2.27	2.28	2.26
	Center	2.59	2.67	2.64
	Periphery	2.20	2.20	2.20
Number of Slums	City	127	126	125
	Center	24	21	19
	Periphery	104	105	106

In the next experiment, the impact of inappropriate land supply is investigated. The supply of prime land was kept constant at the base scenario (10%), but the percentage of inappropriate land was changed to three different test values: 10% (base scenario), 20% and 30%. The results are shown in Table 8.

A higher initial supply of inappropriate land in the center results into a higher slum population in the center as well as higher densities in those slums. It is interesting that while the overall number of slums in the central city declines, the

slum density increases, indicating that the growth of existing slums originally sited on inappropriate locations.

This result depicts the situation in real world cities e.g. Dharavi, the largest slum in Mumbai, which received a large influx of migrants in 1920s (Clothey 2006) on a land parcel that was inappropriate for development (for example, there were no roads in Dharavi and it was an island within marsh land). The slum persists even today despite formal development has taken place in all surrounding areas (MCGM 2005). Similar patterns are found elsewhere e.g. landfill sites, such as those in Manila, Philippines (Abad 1991).

**Table 8: Impact of Inappropriate Land Supply on Model Outcomes**

<b>Output Parameters</b>		<b>Inappropriate Land 10% (Base)</b>	<b>Inappropriate Land 20%</b>	<b>Inappropriate Land 30%</b>
Percent Slum Population	City	18.9	18.9	18.9
	Center	16.3	16.4	17.6
	Periphery	19.8	19.8	19.2
Percent Area under Slums	City	10.2	10.1	10.0
	Center	8.6	8.3	8.8
	Periphery	10.7	10.7	10.4
Slum Density	City	2.27	2.30	2.31
	Center	2.56	2.71	2.82
	Periphery	2.19	2.21	2.18
Number of Slums	City	127	125	124
	Center	25	24	25
	Periphery	102	102	99

#### 5.4.5.4 Informal-formal Sector Mix

It has been noted in literature (e.g. Mitra 2008; Tamaki 2010) that the people employed in the informal sector cannot expect much upward mobility in their incomes compared to those employed in the formal sector. To test this, we explore how the percentage of slum population changes with different mixes of formal and informal sectors in the city economy. Three test values of the informality index were simulated: 0.1 (base scenario, i.e. the majority of the workforce is in the formal sector), 0.4 and 0.7 (i.e. higher proportion of the workforce is increasingly working the informal sector) while all other parameters were kept constant. The results are shown in Table 8.

Table 9: Impact of Informality on Model Outcomes

Output Parameters		Informality Index 0.1 (Base)	Informality Index 0.4	Informality Index 0.7
Percent Slum Population	City	17.0	17.4	18.2
	Center	12.6	13.6	15.6
	Periphery	18.4	18.6	19.1
Percent Area under Slums	City	8.9	9.2	9.8
	Center	6.5	6.9	8.0
	Periphery	9.6	9.8	10.3
Slum Density	City	2.22	2.24	2.27
	Center	2.42	2.49	2.62
	Periphery	2.19	2.19	2.19
Number of Slums	City	116	118	121
	Center	19	20	23
	Periphery	98	98	99

Of note is that both overall densities and slum population increases as the slum expands. This indicates that a greater number of people working in the informal sector increases the income inequalities. However, the affordable housing supply does not necessarily increase which leads to higher slum population.

The results presented here are based on experiments that vary one parameter at a time but many other type of experiments could be run using HDM. For example, varying multiple parameters such as higher formalization combined with higher economic growth. Similarly, all parameters could be changed in order to find a set of parameter values that would reduce the number of people living in slums (or result in no slums).

## **5.5 Integrating PDM and HDM**

The PDM and the HDM in a city were developed in isolation to understand and debug each modules before integrating them. However, real world systems are not purely independent of each other. Therefore, both these modules are integrated in this section to conduct more experiments. For example, once PDM is integrated with HDM, it is possible to study the impact of change in migration patterns on slum formations in a city.

As discussed earlier, the PDM operates at the scale of an individual whereas HDM operates at the scale of a household. In order to create households from individuals, the following assumptions and rules of transformation are made:

*Rule HH<sub>1</sub>:* Create two categories of individuals, *Household Heads* and *Household Members*. Household heads store the household level characteristics (e.g. household income) in addition to their own individual level attributes (e.g. age). The link between household head and household members is created through a common *Household ID*. Average Household size determines the proportion of individuals that will act as household heads. For example, for a population of 100 individuals with an average household size of 5, there may be 20 household heads to represent 20 households whereas the rest 80 individuals will be household members. Of course, household size is not necessarily uniform and it varies across households.

*Rule HH<sub>2</sub>:* the birth event takes place in existing households. Once an agent is generated after the birth event in the PDM, they are randomly assigned to an existing household in the city. For simplicity, the reproduction function is not restricted to specific household structures e.g. only households with a woman in reproductive age group could reproduce etc.

*Rule HH<sub>3</sub>:* the death event takes place in existing households. If an individual dies in an existing household and if she is the head of the household, one of the household members from the same household is transformed into the head of a household category. All household level attributes are transferred to this new head. In contrast, if a household member dies, only household size is reduced by one.

*Rule HH<sub>4</sub>:* When in-migration takes place, the reason for migration determines whether a new household is formed or the new migrant joins an existing household in the city. The census of India provides data on seven major reasons of

migration. Those include: work/employment, business, education, marriage, moved after birth, moved with household and others. The individuals who migrate due to marriage and those who move after birth are assigned to an existing household in the city as household member. The individuals who migrate for work/employment, business, education or other reasons create their own household and become the household head of their household. Those who moved with the households join these newly formed household heads. It is assumed that those who move with the households, arrived at the same time as the household head.

*Rule HH5:* When out-migration takes place (either of a native or a migrant) and if she is the head of the household, one of the household members from the same household is transformed into the head of a household category. All household level attributes are transferred to this new head. However, if a household member out-migrants, only household size is reduced by one to reflect the out-migration.

Following the above rules, households were generated in this integrated module. The key output parameters remain the same as previous versions with an addition of number of households.

The impact of increase in migration rate on the slum conditions is then tested. Migrant arrival rate was set to 20 per year, 30 per year (base scenario) and 40 per year. It is observed that a higher migration rate leads to a higher percentage slum population (16.2%) whereas slower migration rate to a lower percentage slum population (13.6%) as shown in Table 10.

**Table 10: Impact of Migration Rate on Model Outcomes**

Output Parameters		Migrant Arrival Rate (20 per year)	Migrant Arrival Rate (30 per year)	Migrant Arrival Rate (40 per year)
Percent Slum Population	City	13.6	15.3	16.2
	Center	18.1	17.6	16.1
	Periphery	10.0	14.0	17.5
Percent Area under Slums	City	6.5	8.1	9.5
	Center	7.9	7.9	7.4
	Periphery	5.6	8.2	10.2
Slum Density	City	4.1	3.6	3.4
	Center	5.2	5.2	5.1
	Periphery	3.1	3.0	3.0
Number of Slums	City	45	73	105
	Center	21	21	20
	Periphery	25	53	86

The higher migration rate also results in a greater number of slums as opposed to densification of existing slums. The resulting slum formation pattern shows a higher number of peripheral slums as highlighted in Table 10. This is a hypothesis worth testing using real world data, whether the higher pace of migration results into higher peripherization rather than higher densities. It seems that exploring new location is preferred over exploiting existing locations during the rapid migration phase. For example, historically, cities have expanded physically during periods of increased migration, and the densification process took place much later in the evolution of a city (Sudhira et al. 2004).

These results are similar to the population growth scenario in the HDM before integration. However, once the agents are modeled at individual level, it becomes possible to explore several other scenarios. For example, one could now

explore how slum conditions will be impacted if the migration pattern changes from higher proportion of single migrants to the higher proportion of migrants with families. This scenario is explained by changing the proportion of migrants who moved with households (those who cited reason 6 in Migration Tables). The proportion of migrants moving with the households was changed from 24% to 30%. It is observed that this change in migration pattern leads to lower percentage slum population (16.2%) as shown in Table 11.

**Table 11: Impact of Population Growth Rate on Model Outcomes**

<b>Output Parameters</b>		<b>Migrants Moving with HH (24%)</b>	<b>Migrants Moving with HH (30%)</b>
Percent Slum Population	City	318.4	13.3
	Center	15.9	12.7
	Periphery	19.5	13.6
Percent Area under Slums	City	10.4	7.3
	Center	7.6	6.7
	Periphery	11.3	7.5
Slum Density	City	3.35	3.37
	Center	4.85	4.05
	Periphery	3.03	3.16
Number of Slums	City	114	78
	Center	20	18
	Periphery	94	60

A higher proportion of family migrants also results in a smaller number of slums which may be the result of lower number of households and consequent lower demand for housing. The resulting slum formation pattern shows an increase

in density which may be the result of larger household sizes as highlighted in Table 11.

There are several scenarios related to individual level characteristics that could be explored with the added capability in this version such as changes in causes of migration, changes in age structure of migrants, changes in length of stay to name a few.

## **5.6 Empirical Module**

The *Empirical Module* (EM) consists of two components, the *Geodatabase* and the *Empirical Analyzer*. The *Geodatabase* stores both inputs to and outputs of HDM and PDM. Input data includes all relevant data needed to model Ahmedabad based on secondary data of slums. Input data is comprised of base maps of the city, demographic and socio-economic variables for individuals, housing price and infrastructure variables for land parcels. Output data includes maps showing slum locations, population densities, number of slum residents and their origins. The calibration and validation process is carried out using the *Empirical Analyzer* which allows one to conduct further analysis on simulation outputs stored in the *Geodatabase*. *Empirical Analyzer* provides analytical tools and guides as an aid for calibration and validation purpose, but leaves out actual decision-making to modelers. Both components of this modules are discussed in detail in following subsections.

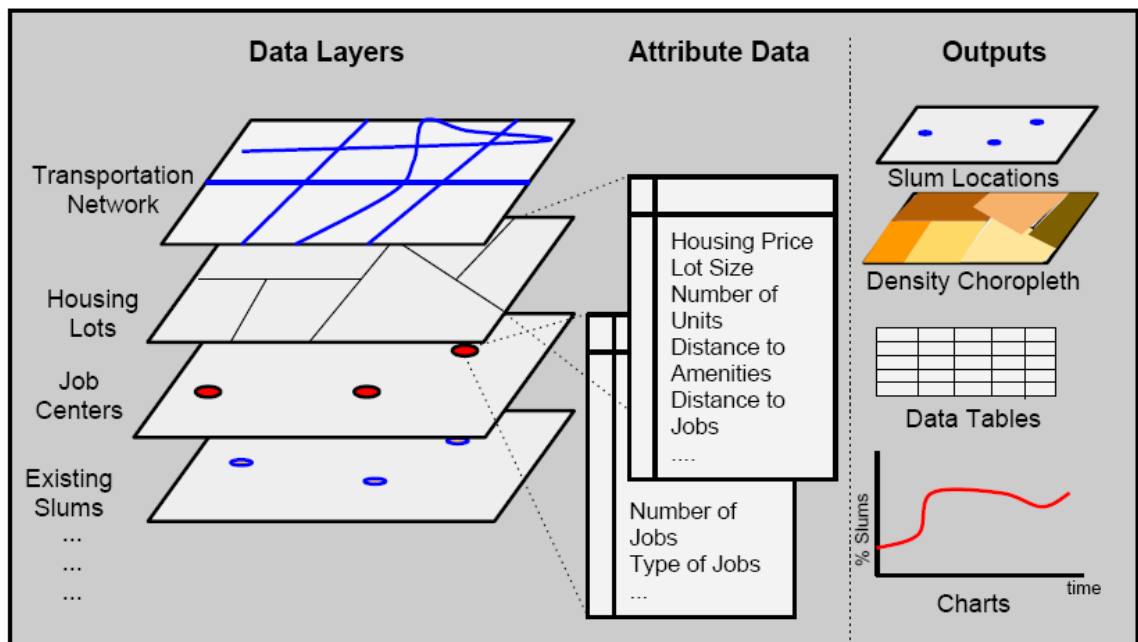
### 5.6.1 Geodatabase

The *Geodatabase* allows a modeler to add numerous datasets of various formats including vector and raster datasets (e.g. Landsat images or ESRI shapefiles), as well as tabular data such as housing price data for land parcels, land records, census geographies for initial population information, gazetteers and non traditional sources of information such as crowd sourced data like OpenStreetMap for road networks. Moreover, this approach aligns itself with the emerging trend towards improving the level of realism in representing space within models, which can lead not only to an enhanced comprehension of model design and outcomes, but also to an enhanced theoretical and empirical grounding of the entire field of agent-based modeling and geography more generally (Stanilov 2012). Some of these datasets were obtained from the local governments of Ahmedabad, GIS consultants and other researchers in Ahmedabad (see chapter 7).

*Geodatabase* also stores simulated outputs from simulation scenarios including location of slums in a map format. Outputs showing temporal dynamics of slum formation and expansion could also be generated using adequate tools (e.g. rank clock (Batty 2006)).

It is argued that slums have always been seen as a "temporal problem" to be dealt with in the "near future" (Abrams 1966). Policies have emphasized social elements in planning for slums but spatial elements are missing (Beaton et al. 1996; Mason et al. 1997). The geodatabase element of the *Slumulation* will enable the connection of slum areas with the rest of the city which is important to break the

dichotomy between slum and non-slum policy-making (Fiori and Brandão 2010). Urban development authorities in developing countries have always overlooked the representation of slums in formal planning documents (Abbot 2002). This dissertation built the geodatabase through the combination of numerous datasets.



**Figure 19:Architecture of Geodatabase with Data layers and Outputs**

It is expected to use this data for deriving input variables for drivers of change. Such as calculating accessibility indexes and land use histories. It is proposed to derive maps of physical networks such as roads, and demographic variables such as population densities. Such data will be then used to define

environments within the various modeling components of *Slumulation*. Moreover, the geodatabase provides a means for calibrating and validating model outputs.

### 5.6.2 Empirical Analyzer

The *Empirical Analyzer* is an identified set of relevant methods to analyze "real" world data as well as simulation outputs. It plays an important role during calibration and validation process. The calibration and validation is done by comparing various spatial and aspatial measures calculated from "real" world data with simulation output parameters as shown in Figure 13.

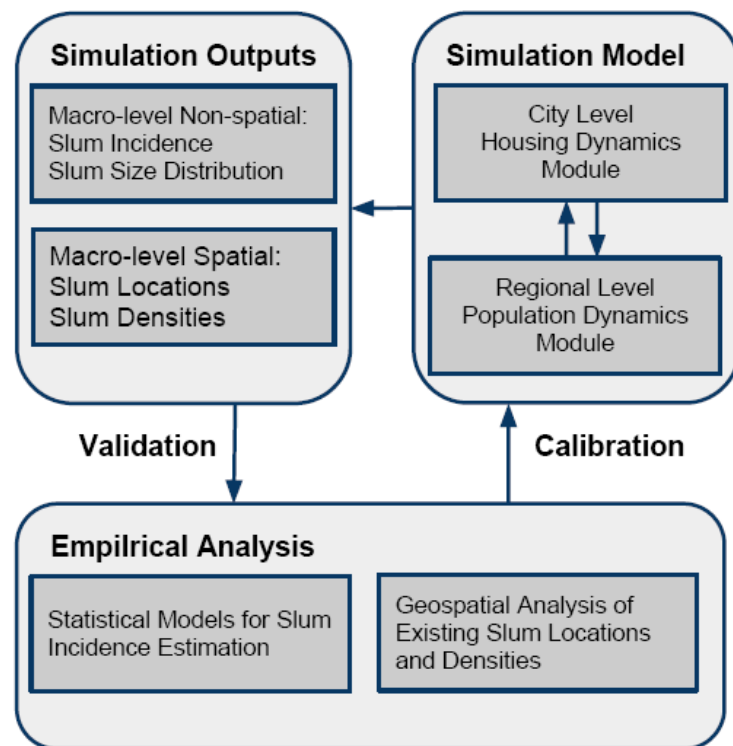


Figure 20: Linking Simulation with EM

Aspatial measures such as percentage slum population, number of slum pockets, etc. are also used for validation. The *Empirical Analyzer* is used to obtain several goodness-of-fit type of measures (D'Agostino and Stephens 1986) for both spatial and aspatial outputs which aid in calibrating the model further. While *Empirical Analyzer* does not calibrate the model automatically, it provides a guide to a modeler as a decision-support tool. This is very handy since calibration and validation of simulation models is rarely automatic and requires the modeler's informed judgment (Ngo and See 2012).

## **5.7 Summary**

This chapter introduced the conceptual framework of *Slumulation*. Various modules of the overall framework were outlined along with their function in *Slumulation* and the underlying methodological framework. Then, two of these modules, namely, PDM and HDM were developed. Intermediate stages of this model development were discussed in detail along with several experiments that were useful in debugging and verifying the modules. Finally, the model integrates DES and ABM in the form of PDM and HDM respectively. The next step is to integrate GIS with this version which requires us to build it for a real world city. Chapter 7 presents such an effort where all three methods are integrated within a single framework of *Slumulation*. However, before turning to the integration, the next chapter introduces the city of Ahmedabad and presents urban dynamics in the city.

## CHAPTER 6. URBAN DYNAMICS IN AHMEDABAD

This chapter introduces the case study city and presents an empirical analysis of population and housing dynamics. The goal of this chapter is threefold: i) to present an overview of the city, ii) to analyze population dynamics and prepare inputs for the simulation model, and iii) to empirically analyze spatial patterns of slum locations that could help us in validating simulation results. Section 6.1 provides an overview of the city; section 6.2 analyzes population dynamics; section 6.3 analyzes spatial patterns of slums observed in Ahmedabad; and, section 6.4 identifies the relevant points for operationalizing *Slumulation*.

There are several reasons for choosing Ahmedabad as a test case for *Slumulation*. First, availability of data on individual slum locations in Ahmedabad. Second, salience of slum policy efforts in India makes this research timely (as discussed in section 3.8). In addition, discussions with slum experts and policymakers in India indicated that a second-tier city like Ahmedabad is an appropriate test case for *Slumulation* since these cities will be at the forefront of rising slum population in India in coming decades (Author's discussions with slum experts and policymakers in India 2011). The Ministry of Housing and Urban Poverty Alleviation have also chosen India's second-tier cities as high-priority cities for RAY, the largest slum improvement program of India (Government of India

2010). Thirdly, author's field visit in India indicated that Ahmedabad is one of the leading cities in documenting its slums and hence it is an ideal case from data availability point of view. It is hoped that Ahmedabad will encourage other cities to collect similar data which may make it possible to test *Slumulation* in other cities in future work. Finally, city's moderate size makes it computationally more feasible to run the simulation experiments and exploring the research questions identified in section 1.3.

## **6.1 Introduction: Ahmedabad**

The city of Ahmedabad is named after the medieval ruler of Gujarat, Ahmed Shah, and has been inhabited since the 11<sup>th</sup> century AD. Ahmedabad is located at 22° 58' N and 72° 35' E in the state of Gujarat in the western part of India as shown in Figure 21. Once known as a textile hub and "Manchester of the East", the city is experiencing a shift in its economic base from manufacturing to services sector (AMC 2006).

River *Sabarmati* divides the city into two physically distinct parts. The Eastern part of Ahmedabad is predominantly characterized by old housing stock often dating back to the first inhabitants of the city. The outer areas of Eastern Ahmedabad have industries (e.g. old textile mills, new chemical industries) and residences of lower income households. The recently developed Western area of the city is generally characterized by more recent buildings and higher income groups (Adhvaryu 2011).



**Figure 21: Location of Ahmedabad in India**

(Source: Ministry of Earth Sciences 2012)

Ahmedabad is located on an important development axis, popularly known as "Golden Corridor" of India, that connects Mumbai with Delhi – the two major cities of India. The city acts as a terminal, rather than as a mere intermediate node in this corridor. It is also connected with the larger region via seven major roadways, one expressway and five rail networks. A new corridor between Ahmedabad and Pune has recently emerged, connecting the city to other cities including Vadodara, Surat and Mumbai. All these factors have resulted in the axial growth of the region. (AMC 2006).

### 6.1.1 Demographic Overview

Ahmedabad is currently the fifth-largest city of India with a population of approximately 5.5 million people (Census of India 2011). Ahmedabad accounts for 7% of the state's total population and around 20% of its urban population. The Ahmedabad Urban Agglomeration (UA) is the seventh-largest metropolitan area in the country with a population of 6.4 million (Census of India 2011)<sup>15</sup>.

Being a regional hub, Ahmedabad attracts a large number of migrants from the rural hinterlands of Gujarat and neighboring states. The Ahmedabad Urban Agglomeration (UA)'s population grew from 3.3 million in 1991 to 4.5 million in 2001 (Bhatt 2003) of which 1.5 million were migrants (Census of India 2001). Ahmedabad UA housed 23.25 % of the state's urban population in 1991, which had increased by about 25% by 2001.

**Table 12: Population, Sex Ratio, Literacy Rate and Work Participation**

	<b>Ahmedabad Municipal Corporation (AMC)</b>	<b>Ahmedabad UA</b>
Population	3520085	4525013
Households	692257	901949
Household Size	5	5
Sex Ratio	884	885
Literacy Rate	72.50%	73.50%
Work Participation	32%	32%

(Data Source: Census of India 2001)

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<sup>15</sup> Only provisional data from the latest Census conducted in 2011 is available as of August 2012. Detailed data at disaggregated level is not yet published. Therefore, in most parts, this dissertation uses data from Census 2001 or earlier. Data from other sources was also collected for the same time-period for comparability and consistency. Of course, this poses a limitation that despite availability of many other datasets for the current time period such as publicly available map data from Google and OpenStreetMap could not be used for consistency reasons.

The average decadal growth rate of population in the AMC area since 1901 has been 37.55% against a national average of 25%. As shown in Table 13, city registered the highest growth after independence of India. The cities became destinations for large number of refugees following the partition of India and Pakistan in 1947. Between the 1950s and the 1960s, city grew at 37% decadal growth rate following the growing manufacturing jobs especially when textile mills were thriving. Subsequent decline of mills in the city may have led to slowed down migration in 1960s and 1970s as reflected in the declining growth rate. However, the growth rate has shown an increase in 1990s again with employment growth in service sector (AMC 2006).

**Table 13: Population Growth: Ahmedabad Municipal Corporation**

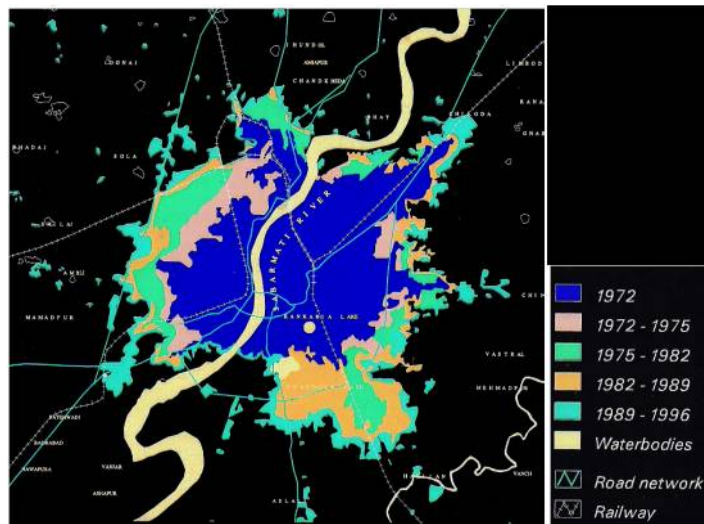
<b>Census Year</b>	<b>Population</b>	<b>Decadal Growth Rate %</b>
1951	837,163	41.59
1961	1,149,918	37.36
1971	1,586,544	37.88
1981	2,059,725	29.90
1991	2,876,710	20.80
2001	3,515,361	22.20

(Source: AMC 2006)

### **6.1.2 Urban Form and Spatial Structure**

Ahmedabad has a geographic area of approximately 192 sq km. Established in the year 1950, area under Ahmedabad Municipal Corporation (AMC) grew from

52.49 sq km. (in 1950) to 190.84 sq km. (in 1991) divided in 43 administrative wards. The urban agglomeration is spread over 259.63 sq km. The spatial distribution of population in the city over the decades shows that until 1981 most of the new population added to the city was concentrated within the old AMC limits, especially in the eastern part. As shown in Figure 22, expansion of the peripheral areas began in the 1980s and has continued since then. Before the 1980s, only the eastern periphery registered faster growth rate compared to other parts of the city, but lately both the eastern and the western periphery has expanded and grown rapidly. Since 1990s, the Western part of the city has experienced a rapid growth (AMC 2006).



**Figure 22: Spatial Growth of Ahmedabad**

(Source: Haran 2005 cited in AMC 2006).

This spatial growth is also accompanied by increasing densities in the peripheries. As highlighted in Table 14, overall density in the city has increased from 11300 persons per sq km to 18420 persons per sq km in last three decades. Interestingly, Central Business District (traditionally known as Walled City of Ahmedabad) has seen a decline in residential density whereas both, the eastern and western peripheries have seen an increase.

**Table 14: Residential Density in Ahmedabad**

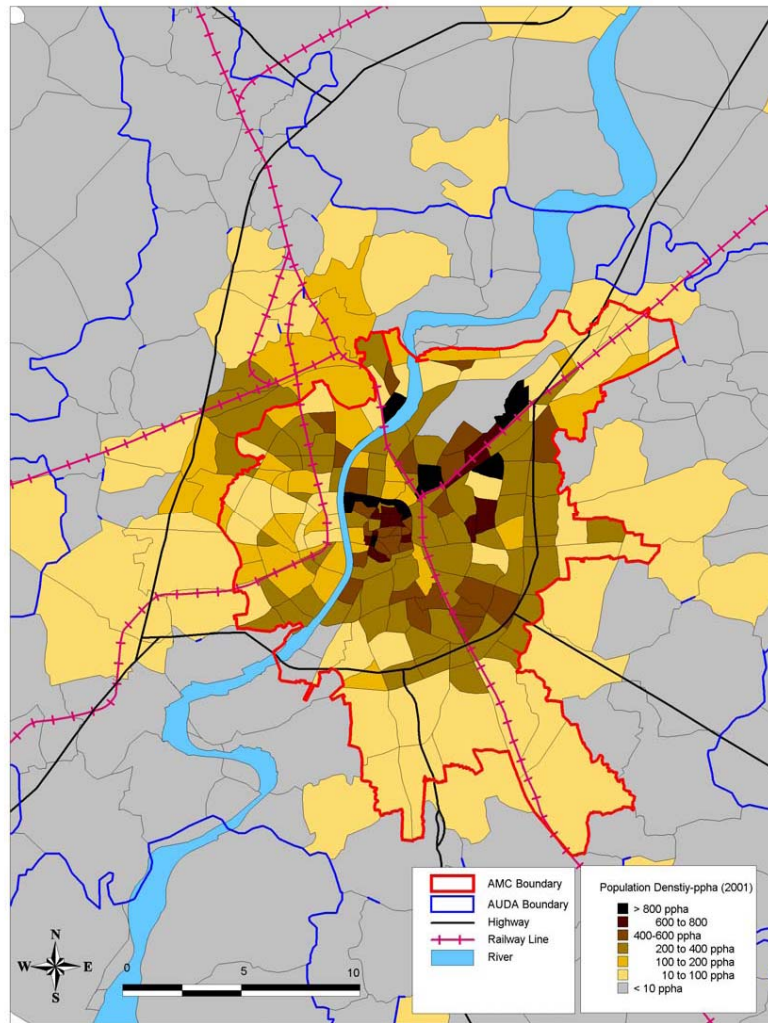
<b>Density (Person/sq km)</b>			
<b>Year</b>	<b>1981</b>	<b>1991</b>	<b>2001</b>
Ahmedabad Municipal Corporation (AMC)	11300	15100	18420
1.a Walled City	71600	59900	56000
1.b. East AMC	7900	13400	17800
1.c West AMC	10900	13500	15900

(Source: AMC 2006)

In a systematic study of change in spatial structure of Ahmedabad, Adhvaryu (2011a) finds decline in density gradients and suggests that Ahmedabad's population is gradually dispersing. The author also finds a strong correlation between density gradient and increasing vehicle ownership in Ahmedabad. It is clear that existing population is moving out from the center to peripheries.

While the population is dispersing in general, there is a large spatial variation in densities across different wards as shown in Figure 23. The residential density range from the highest of 85120 persons per sq km in Dariapur ward located in the central city, to 3,709 persons per sq km in Vatva ward, in the south eastern

periphery of the city. It is of note that higher densities exist in outer peripheries skipping some of the inner wards, an indicating "leap frog" suburbanization of the city.



**Figure 23: Residential Density in Ahmedabad**

(Source: AMC 2006)

### **6.1.3 Urban Economy**

The city of Ahmedabad is an important center of Gujarat owing to the concentration of economic activities. Ahmedabad was once known for its textile mills. The textile industry of Ahmedabad generated half of the total industrial employment in the state before 1960s (Mahadevia 2002). Prior to 1985, there were 85 textile mills in Ahmedabad city which declined to 23 mills by 1994 due to structural shift in textile industry that forced many of these mills to face liquidation (Bhatt 2003). While Ahmedabad still accounts for 21.5% of factories in the state employing 18% of workers (Mahadevia 2002), its economic base is shifting. There are around 4859 factories in Ahmedabad, of which chemical and petrochemical industries have the largest share (29%). However, the economy is now being dominated by a growing service sector that includes trade and commerce, transportation and communication, construction activities, etc. (AMC 2006).

### **6.1.4 Urban Governance and Planning**

Administratively, Ahmedabad agglomeration is governed by two Urban Local Bodies (ULB), namely, Ahmedabad Municipal Corporation (AMC) and Ahmedabad Urban Development Authority (AUDA). AMC is the elected local government responsible for the governance of the city. In contrast, AUDA is an agency of the state government responsible for planning and managing the peripheral areas outside AMC limits.

Urban planning and delivering of serviced land in Ahmedabad is governed by the Gujarat Urban Development and Town Planning Act 1976 (GUDTP). The Act has

a two-fold provision: Development Plan (DP) for macro-level planning and Town Planning (TP) Schemes for area-level planning. The DP has a 10 year horizon and it prescribes land use zoning. The DP also specifies Development Control Regulations including plot sizes and Floor Space Index (FSI).

With regard to the area-level planning, 'land re-adjustment and pooling' is followed in order to deliver serviced land to the residents. The DP area is divided into several TP Schemes covering about 100 ha area each. Under this statutory process, land from different ownership is first pooled together and then, redistributed properly in a reconstituted form after deducting areas for roads and public purposes<sup>16</sup> (Adhvaryu 2011b). This indicates that the government acts as a facilitator in pooling and providing the serviced land. Once the land is reconstituted, it is transferred to the land owner. Although, the government is only a facilitator, the supply of serviced land is not purely market based.

*Slumulation* model could be used to explore the implications of the proposed supply of serviced land on slums. The model could also be a helpful tool to assess the impact of change in plot sizes or FSI on the supply of housing and slum formation.

### **6.1.5 Housing**

There are 925,644 census houses in Ahmedabad Municipal Corporation limits. Out of which, about 15% of the houses are vacant. The various uses of

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<sup>16</sup> For a detailed analysis of the Development Plan making process in Ahmedabad, please see Adhyaru, B. (2011). The Ahmedabad Urban Development Plan-Making Process: A Critical Review

occupied houses are shown in Table 15. The largest category of housing stock is within residential category (71.3%), followed by commercial use such as shops and offices (18.9%).

**Table 15: Housing Stock in Ahmedabad**

<b>Ahmedabad Municipal Corporation</b>	<b>Number</b>	<b>Percent</b>
<b>Total Census Houses</b>	925,644	100.0
Vacant Houses	141,681	15.3
Occupied Houses	783,963	84.7
<b>Occupied Houses used as:</b>		<b>% of Occupied Houses</b>
Residence	558,664	71.3
Residence-cum-other use	10,629	1.4
Shop, Office	147,967	18.9
School, College	2,093	0.3
Hotel, Lodge, Guest House	1,948	0.2
Hospital, Dispensary	4,527	0.6
Factory, Workshop, Workshed, etc.	30,481	3.9
Place of Worship	4,944	0.6
Other non-Residential Use	22,710	2.9

(Data Source: Census of India 2001)

## 6.2 Population Dynamics in Ahmedabad

Ahmedabad UA's population grew from 3.3 million in 1991 to 4.5 million in 2001 out of which 1.5 million were migrants (Census of India 2001). This section assesses the general pattern of migration to the city and the characteristics of migrants. The goal is to construct input parameters for the PDM. Section 6.3.1 discusses the data sources used for this analysis; section 6.3.2 present a demographic profile of the migrants; section 6.3.3 provides an overview of the

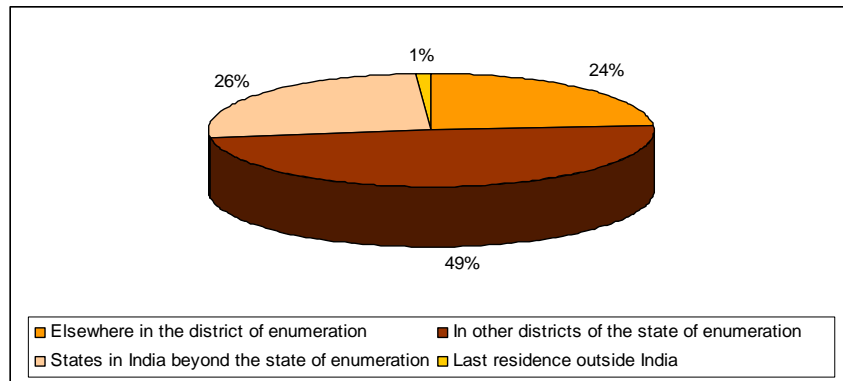
migration pattern based on the place of origin; section 6.3.4 discusses reasons for migration; while section 6.4.5 sheds light on type of employment they pursue.

### **6.2.1 Data**

The Census of India (2001)'s standard migration tables provide migration characteristics at the district level. However, some of these characteristics are also provided separately for urban agglomerations. The analysis that follows is conducted using the Census of India's Migration tables (D-Series) for UAs. In particular, Table D-3, D-8 and D-9 constructed for UA are used for most of this analysis. A few characteristics (e.g. age-group) are not available at the UA level and hence they are analyzed based on tables available at district level. The urban population of Ahmedabad district is considered for this analysis which is mainly Ahmedabad UA (barring only a few small towns elsewhere in the district). In fact, Ahmedabad UA constitutes 92% of the urban population of the district.

### **6.2.2 Places of Origin**

Ahmedabad attracts most migrants from the state of Gujarat itself. Approximately three quarters of the migrants is from the state of Gujarat and roughly a quarter is from within the Ahmedabad district. Ahmedabad has also been an attractive destination for migrants from other states in India. About 26% of the migrants come from other states in India as shown in Figure 24.

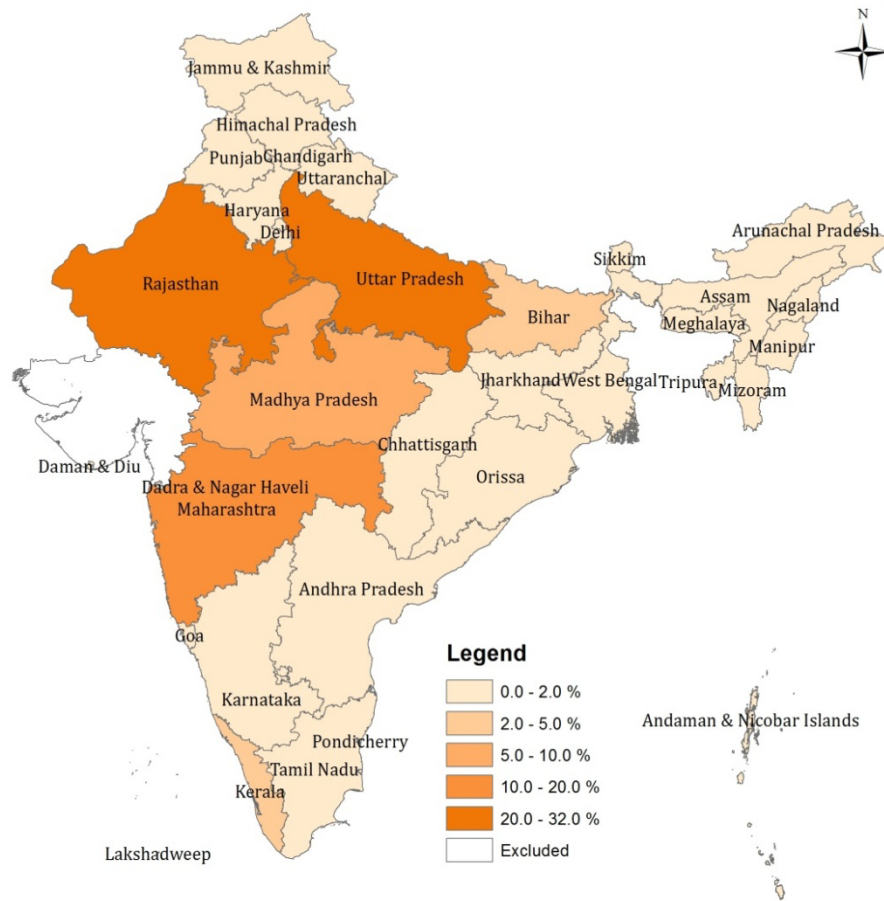


**Figure 24: Migration by Places of Origin**

(Data source: Census of India 2001)

Approximately 400,000 migrants originated from outside the state of Gujarat. As it is evident from Figure 25, highest shares of migrants are from neighboring states of Rajasthan (32%), Maharashtra (18%), and Madhya Pradesh (6%). Migrants from far away states Uttar Pradesh (26%) and Bihar (4%) also constitute a large share. Mainly because the later two states have large rural population and hence they are net out-migration states of India.

Usually, laborers from these states migrate to Ahmedabad to join workforce in labor-intensive and relatively low-skilled industries such as construction, transportation and other manufacturing industries in the city. Ahmedabad has not attracted a large number of migrants from the Southern states. This is partly because there are other competing cities such as Chennai, Bangalore and Hyderabad in Southern India that are geographically as well as culturally closer to potential migrants.



**Figure 25: Migration to Ahmedabad by State of Origin**

(Source: Shapefile from Geocommons.com; Migration data from Census of India 2001; Map prepared by Author<sup>17</sup>)

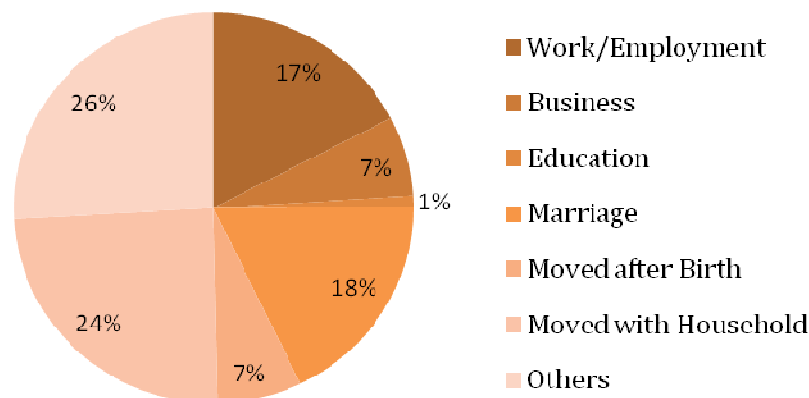
The place of origin of the migrants could be used as an input parameter in the PDM when combined with other parameters such as reasons for migration discussed in section 6.2.3. The migrants coming from certain origin might show distinct characteristics. For example, the data shows that those who arrive in the city in search of employment, the majority of them are male migrants from other

<sup>17</sup> All maps are prepared by the author unless specified otherwise.

states in India (44%), while the majority of those who came after the marriage were female migrants coming from within the state (35%).

### 6.2.3 Reasons for Migration

Individuals migrate to cities for various reasons. Ahmedabad, being the economic center of the state, attracted a large share of migrants who came for either work/employment (17%) or business (7%). Social reasons such as marriage (18%), moving to join the family after birth (7%) equally contribute to migrant population as shown in Figure 26. Approximately a quarter of migrants moved to maintain the family structure (e.g. one of the household member migrated to the city for work and the rest of the household members migrated with her).



**Figure 26: Classification by Reason for Migration**

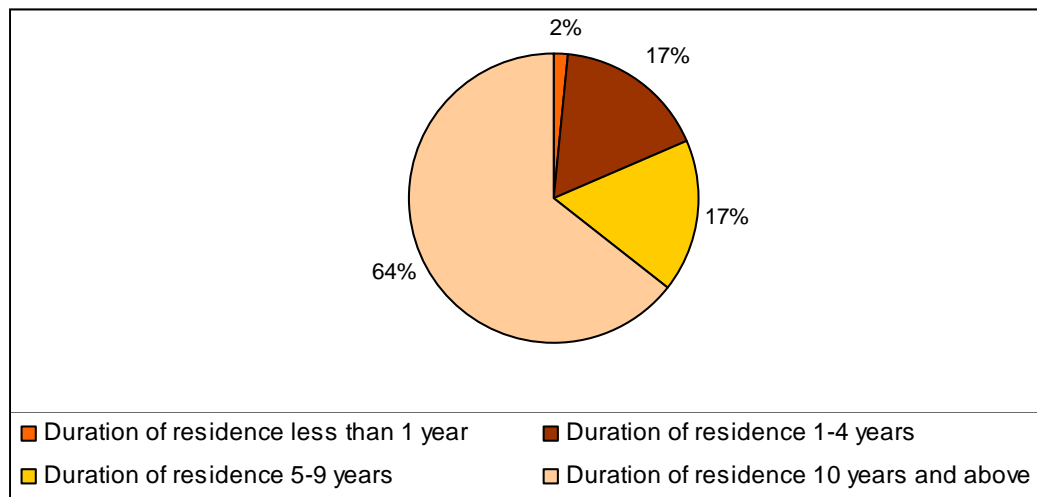
(Data source: Census of India 2001)

The reason for migration could be a useful input parameter for the model to determine household formation patterns. For example, a migrant who reported

moving after birth as the reason for migration, is most likely to join an existing household, and hence may not need another housing unit. Nonetheless, they may trigger a change in type of housing demanded in the city (e.g. two bedroom housing units as opposed to one bedroom housing units). Similarly, a migrant who reported work as the reason for migration would form a new household and hence would need housing almost immediately upon arrival.

#### 6.2.4 Duration of Stay

Ahmedabad has experienced a flow of migrants for past several decades. Of the total 1.5 million migrants, around 64% of them have been living in the city for more than 10 years as shown in Figure 27. About 36% arrived to the city in last ten years indicating that Ahmedabad is still a choice for many as a destination.



**Figure 27: Migration by Duration of Residence in Ahmedabad**

(Data Source: Census of India 2001)

There were 1.12 million migrants in the city in 1991 (Census of India 1991). In 2001, 10.9 million migrants reported that they were in the city for more than ten years i.e. they were enumerated in 1991 census. This suggests that only 21891 migrants (less than 2%), either out-migrated or died during 1991 and 2001. Census data does not provide any estimate of Length of Stay but a comparison of 1991 and 2001 census data indicates that once migrated to Ahmedabad, most migrants spend rest of their life in the city.

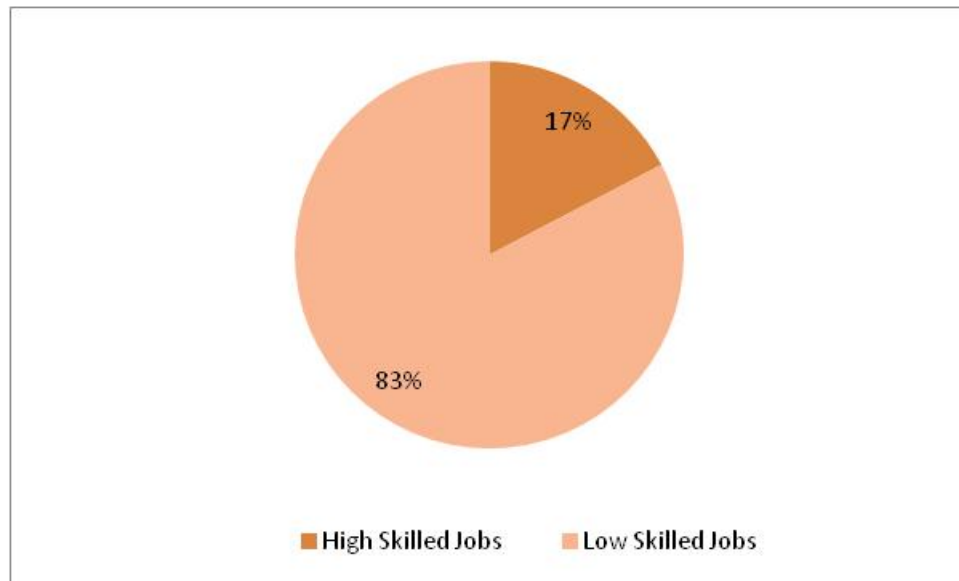
### **6.2.5 Type of Employment**

The migrant population of Ahmedabad exhibits a higher work participation rate (44%) than that of the native population. However, more than 80% of them join a low-skilled occupation<sup>18</sup> such as machine operators and other elementary occupations. Only 17% of the migrants joined a skilled workforce as professionals, managers, clerical staff, technician staff etc.

This proportion could be converted into an input parameter for the model. For example, the type of employment could be used to assign initial income level based on occupation. It could also be used to determine upward mobility in income over time. However, such an assignment of income and upward mobility will require additional information such as average income and salary increase for each type of occupation.

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<sup>18</sup> Census of India (2001) followed National Classification of Occupation 2004 to code occupation data. This classification is based on two concepts: "kind of work performed" and "level of skills involved" (Source: "General Note on D8 and D9 Tables" a note that was supplied with the dataset).



**Figure 28: Occupational Composition of Migrants**

(Data Source: Census of India 2001)

### **6.3 Slums in Ahmedabad**

There are two types of low quality housing typologies predominant in Ahmedabad: chawls, the one room housing units originally constructed in a row to house the textile mill workers, and slums, the illegally occupied marginal areas such as low lying areas along the riverfront occupied by poor (Bhatt 2003; UN-Habitat 2003; Mahadevia 2002). Approximately, 41% of the city's population lives in either slums or chawls in Ahmedabad (AMC 2001). Many of these slums lack access to basic amenities such as water and sewerage. The housing stock in those slums is often built with temporary materials. While chawls are usually permanent structures, they are characterized by overcrowding and lack of individual toilets. These characteristics differentiate them from formal housing in Ahmedabad.

### 6.3.1 Slum Data

AMC carried out its first slum census in 1976. AMC reported total 1200 slums<sup>19</sup> that had 82,177 huts. Ahmedabad Study Action Group (ASAG) conducted another study and reported the status of housing stock in 1990. According to this study, there were 1023 slums with 92,121 housing units and 1409 chawls with 1,36,773 housing units in Ahmedabad.

However, these efforts were independently carried out by the local government and other institutions in the city. The Census of India enumerated slum population only in 2001, first time in Indian history. About 640 cities of India reported slum population in 2001 including Ahmedabad; there were 92,307 slum households (13.5%) in Ahmedabad. In the same year, AMC carried out a slum level survey for their Slum Networking Project (SNP) with the help of NGOs working with slum communities in Ahmedabad<sup>20</sup>. According to this survey, there were approximately 300,000 households (41%) living in those slums. As discussed in section 2.1.4 earlier, such differences in the estimates arise due to the definitions used for enumeration and hence makes it difficult to study the temporal trends. Nonetheless, among all, SNP survey is the most recent and the most comprehensive publicly available data on slums in Ahmedabad. This dataset is used to conduct further analysis.

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<sup>19</sup> Slums and chawls are referred to a place with multiple houses where as huts and housing units are the terms used to refer to individual houses within them.

<sup>20</sup> The author is thankful to SAATH (<http://saath.org/>), the NGOs conducted part of this survey with AMC, for providing this data in digital format.

According to SNP survey data, there are total 710 slums and 958 chawls in Ahmedabad. The main purpose of the data collection was to assist in planning the slum networking projects (discussed in section 3.7), and hence the focus was on the physical aspects of slums such as status of housing and basic infrastructure as opposed to socio-economic characteristics of slum dwellers. The information related to land parcels occupied by slums such as geographic area, ownership, legal disputes on land etc. was also collected. However, data was collected at an aggregate level of a slum community such as total number of houses, distance to nearest public amenities etc., but individual housing unit level data, such as number of rooms etc., was not collected.

### **6.3.2 Mapping of Slums**

There are 1668 slums and chawls in the dataset described above with approximately 300,000 housing units in them. The dataset contained several variables indicating each slum's location. However, data was available only in tabular form and hence mapping of slums was carried out. In absence of standardized street address systems in cities of developing world, it becomes difficult to automate mapping of slums<sup>21</sup>. As a result, all slums and chawls from this dataset were individually mapped by the author to create the GIS database required for spatial analysis.

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<sup>21</sup> In contrast, in developed world where addresses are standardized and base maps are up-to-date, geocoding addresses could be done fairly automatically using tools such as address-locators in ArcGIS.

The set of variables that were used to identify a location of slum were *Survey Number*, *Town Planning (TP) Scheme Number* and *Final Plot (FP) Number*. The *Survey Number* refers to the original land parcel number of the rural land record system before it became the part of urban agglomeration. It uniquely identifies land parcels that were originally farmlands of a village. When these land parcels are formally added to the city via town planning schemes, new land parcels are created and assigned a *FP Number*. The *FP number* uniquely identifies a land parcel within a town planning scheme. Some of the land parcels maintain their survey numbers if town planning schemes were not implemented in those areas.

A base map showing boundaries of town planning schemes and final plots within those schemes was obtained from Ahmedabad Urban Development Authority (AUDA). A snapshot of base-map (shown at the top of Figure 29) and tabular data (shown at the bottom of Figure 29) illustrates the format in which data was available.

FP number in combination with TP Scheme number were used to locate individual slums and chawls. In some cases, Survey Number in combination with village name were used for this purpose. When information on both FP number and Survey number were available, it was used to validate locations. There were several records that either missed the Survey number or the FP number or both. For those cases, address in conjunction with electoral ward numbers were used to identify the land parcel. Often, slums with missing precise location data were cross-referenced another slum in address line (e.g. a slum called "Maneknagar Shaktikunj na

Chhapra" did not have location data but had a reference to another slum, i.e. "Near Premnagar Na Chhapra" in the address line).

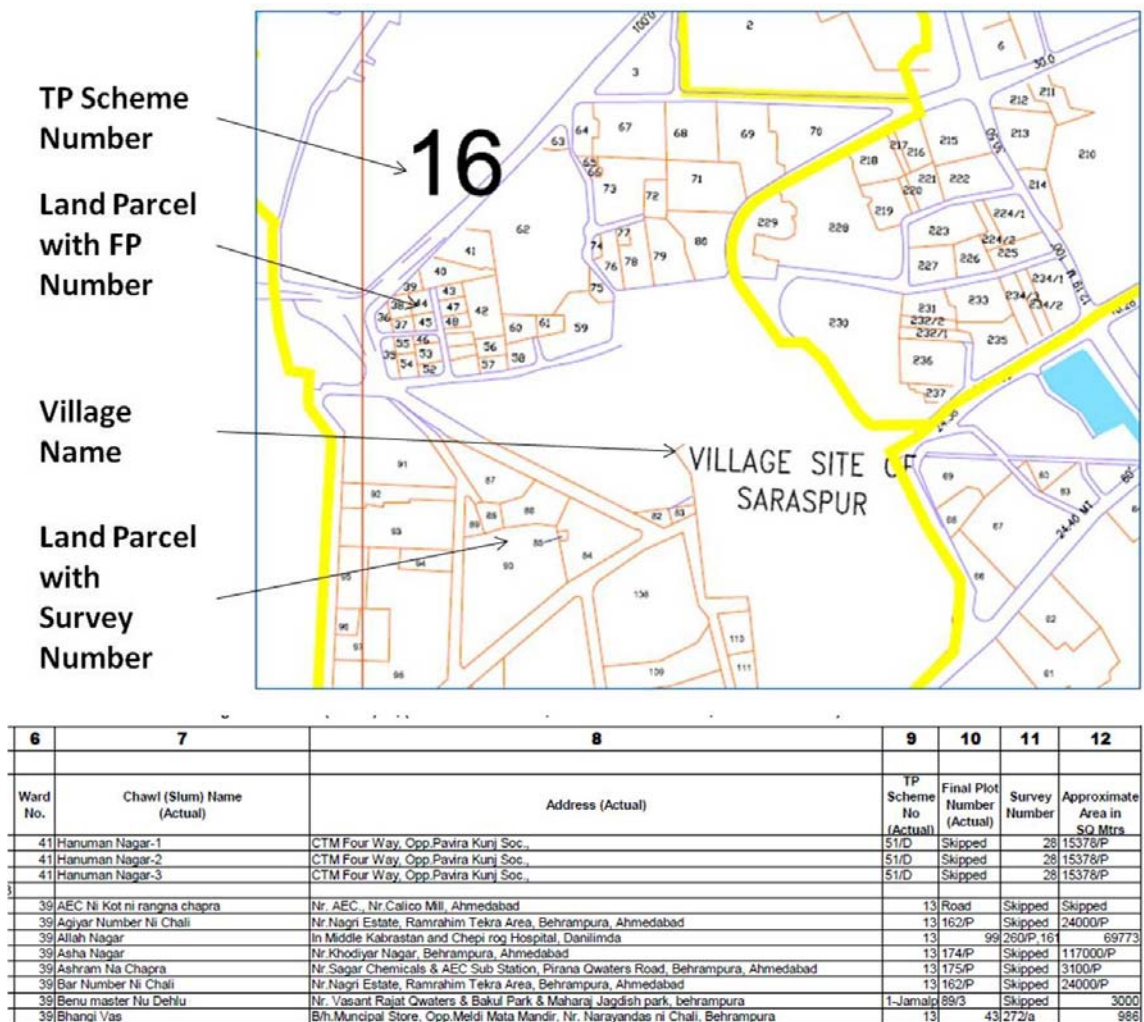
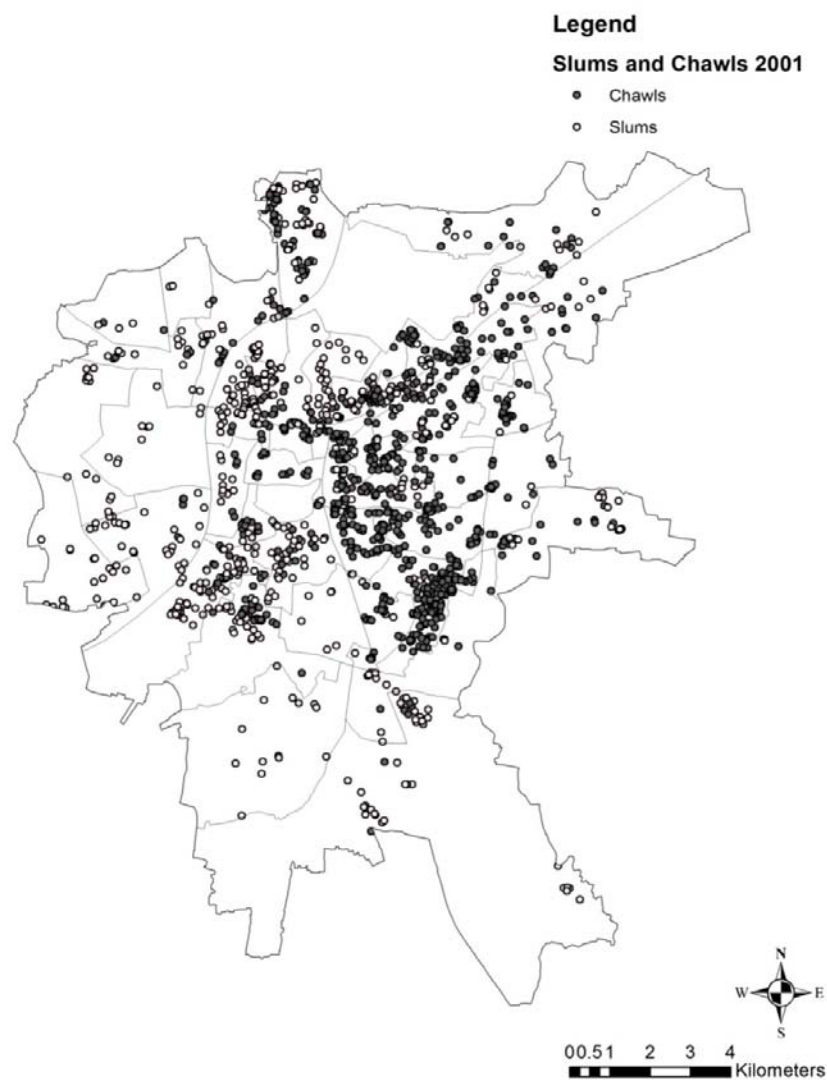


Figure 29: Mapping of Slums of Ahmedabad using Base Map (Top) and Tabular Data (Bottom)

At limited occasions, the researcher applied his personal knowledge of the city to identify the location of slums. Addresses often indicated the proximity to

other slums or known landmarks. Using combination of these methods, 641 of 710 slums and 896 of 958 chawls could be located. As shown in Figure 30, total 1537 of total 1668 slums and chawls were located (92.1 %). Total 131 slums and chawls could not be located due to insufficient information.



**Figure 30: Slum and Chawl Locations in Ahmedabad**

The original base map used for identifying slum locations lacked spatial references. The known physical features such as water-bodies and bridges were used to provide a spatial reference to the map. Bing ®'s maps and imageries available within ArcGIS® 10 were used as a basis for this spatial referencing. While a precise fit for individual features is not possible, a reasonable accuracy was achieved at the overall city scale. This georeferenced map was then used to conduct spatial analysis presented in this chapter.

### 6.3.3 Characteristics of Slums

The slum data was analyzed to identify general characteristics of slums in terms of area occupied, densities, land ownership, and housing conditions such as availability of basic infrastructure. Approximately 80% of slums and chawls are located on privately owned land, compared to only 16% of them on government land (including local government, AMC) as shown in Table 16. Chawls are largely on privately owned land (90%) whereas slums are distributed between private land (66%) and government land (28%).

**Table 16: Land Ownership of Slums and Chawls**

	Land by Ownership				
	AMC	Government Land	Private Land	Others	Total
Chawls	51	19	806	20	896
Slums	129	51	427	34	641
Total	180	70	1233	54	1537

This is primarily because chawls were often built by landowners themselves to generate rental income from their land which eventually turned into a dilapidated housing. Whereas slums required individual households to illegally occupy these land parcels which may pause a risk of eviction by private land-owners.

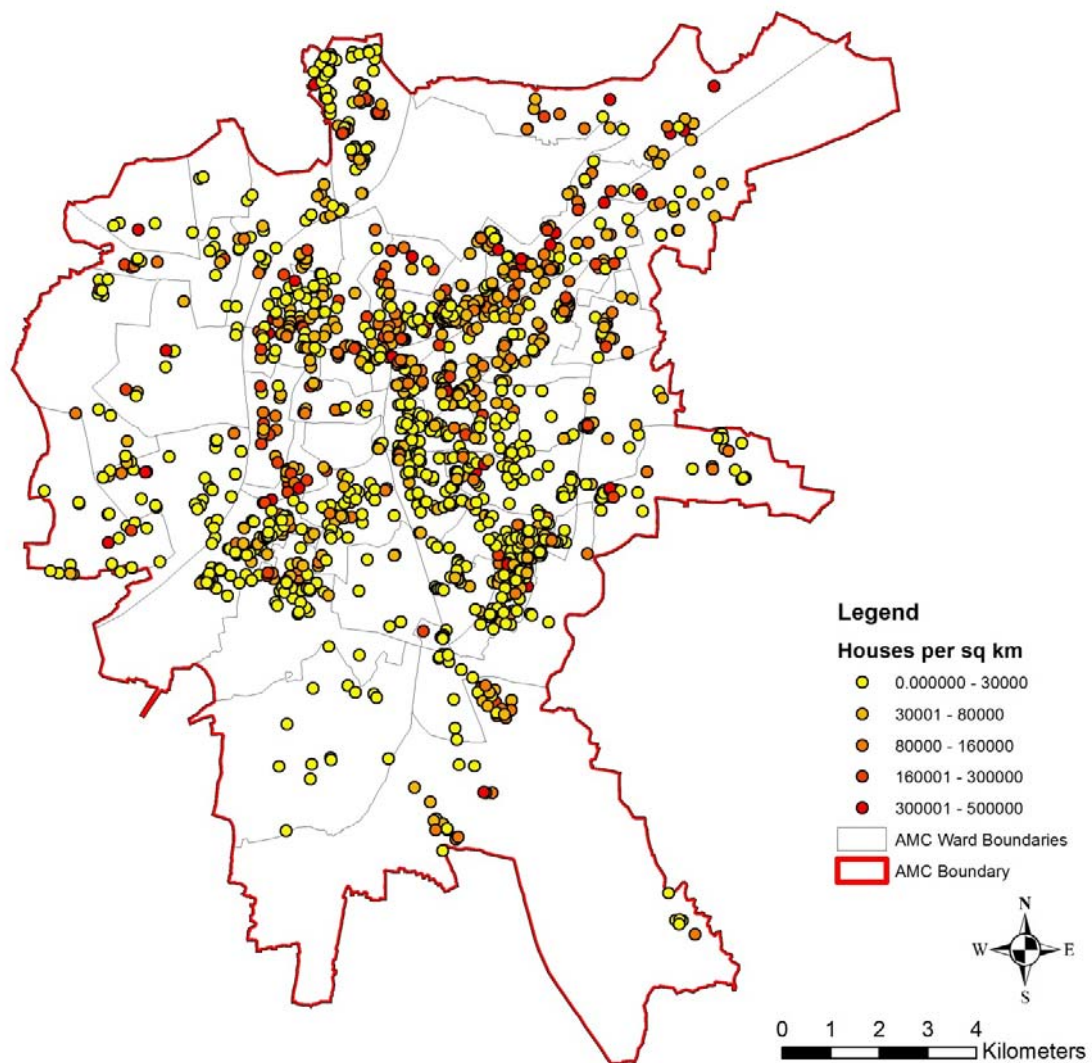
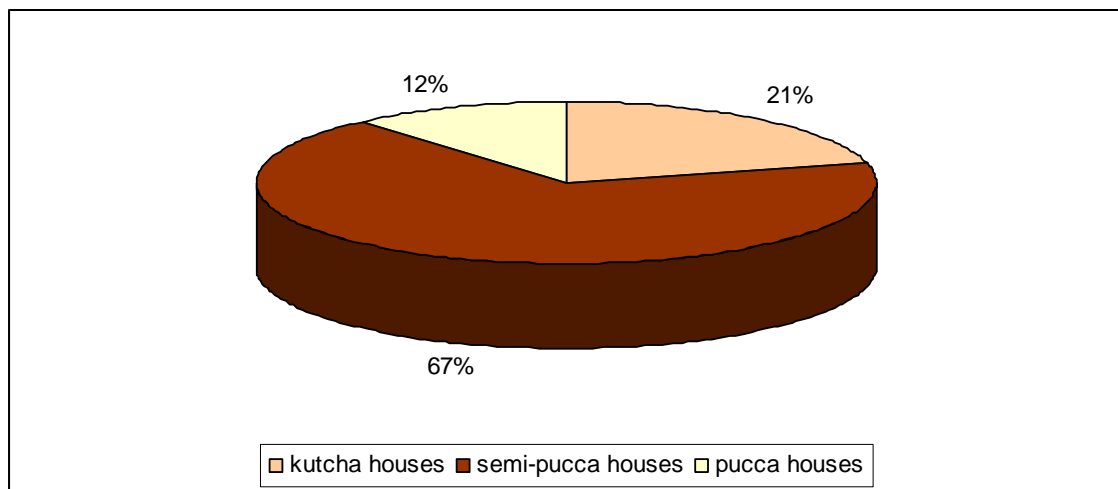


Figure 31: Residential Density in Slums of Ahmedabad

While all slums were dense, the density across slums varied widely as shown in Figure 23. Many of the slums had a density higher than 500,000 houses per sq km.

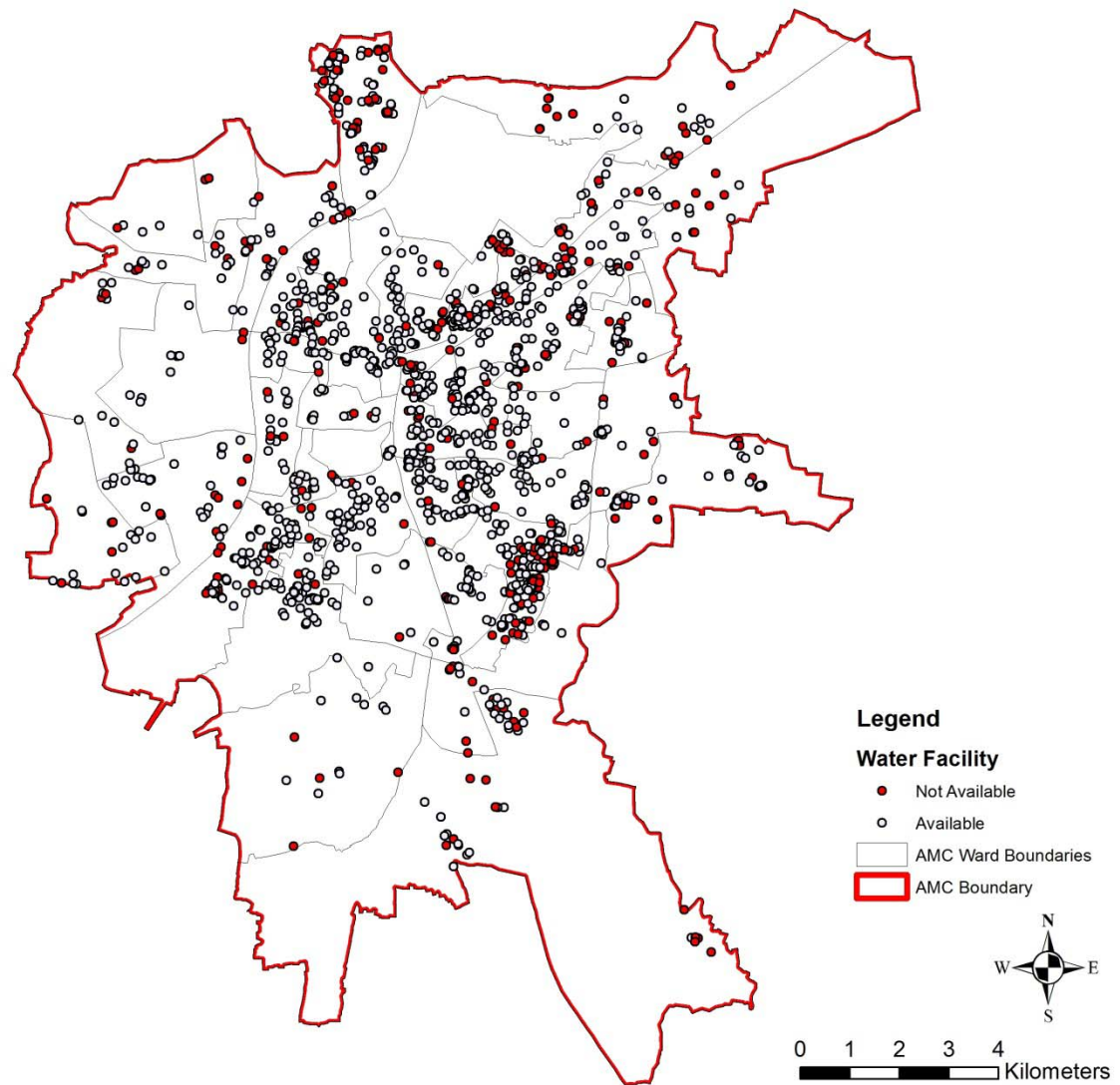
Of the total 300,000 houses in these slums and chawls, 88% of the houses are *kutcha*, i.e. built with temporary materials, or *semi-pucca*, i.e. constructed with semi-temporary material as highlighted in Figure 32. These houses constitute almost half of Ahmedabad's total housing stock.



**Figure 32: Type of Dwelling Structures in Slums**

In terms of basic infrastructure such as water, sanitation and individual toilets, many of the slums and chawls were deprived of these necessities. In particular, eastern slums and chawls lacked access to water as shown in Figure 32. It is of note that slums with and without access to water were in close proximity to each other. Slum Networking Project could have provided water to these slums if

the policy would have not failed due to institutional reasons as highlighted in Chapter 3.



**Figure 33: Lack of Access to Water in Ahmedabad Slums**

Slums in eastern periphery lacked sanitation services as shown in Figure 34. Multiple depravity is present in those slums since those areas lack both water and sanitation.

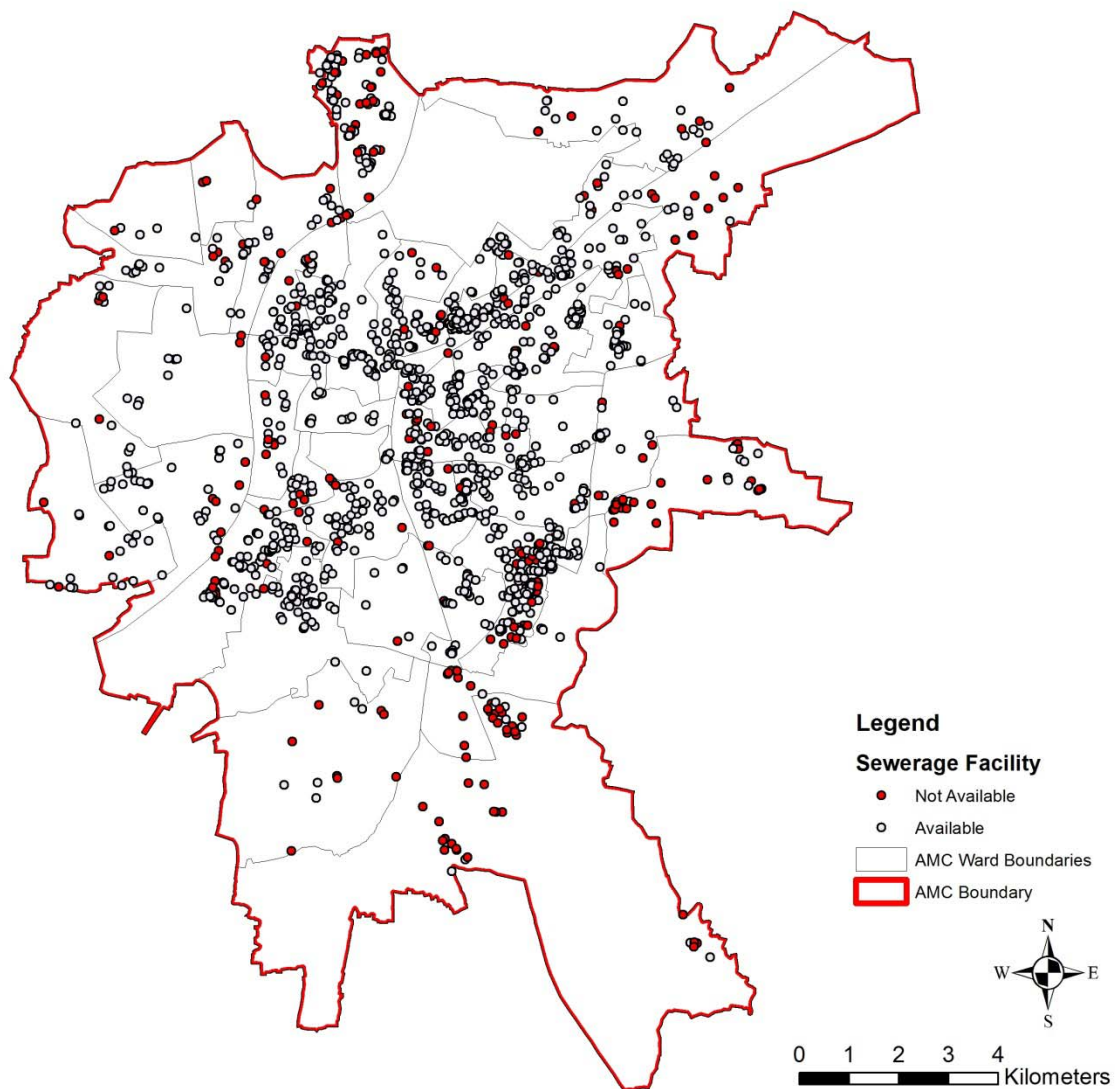
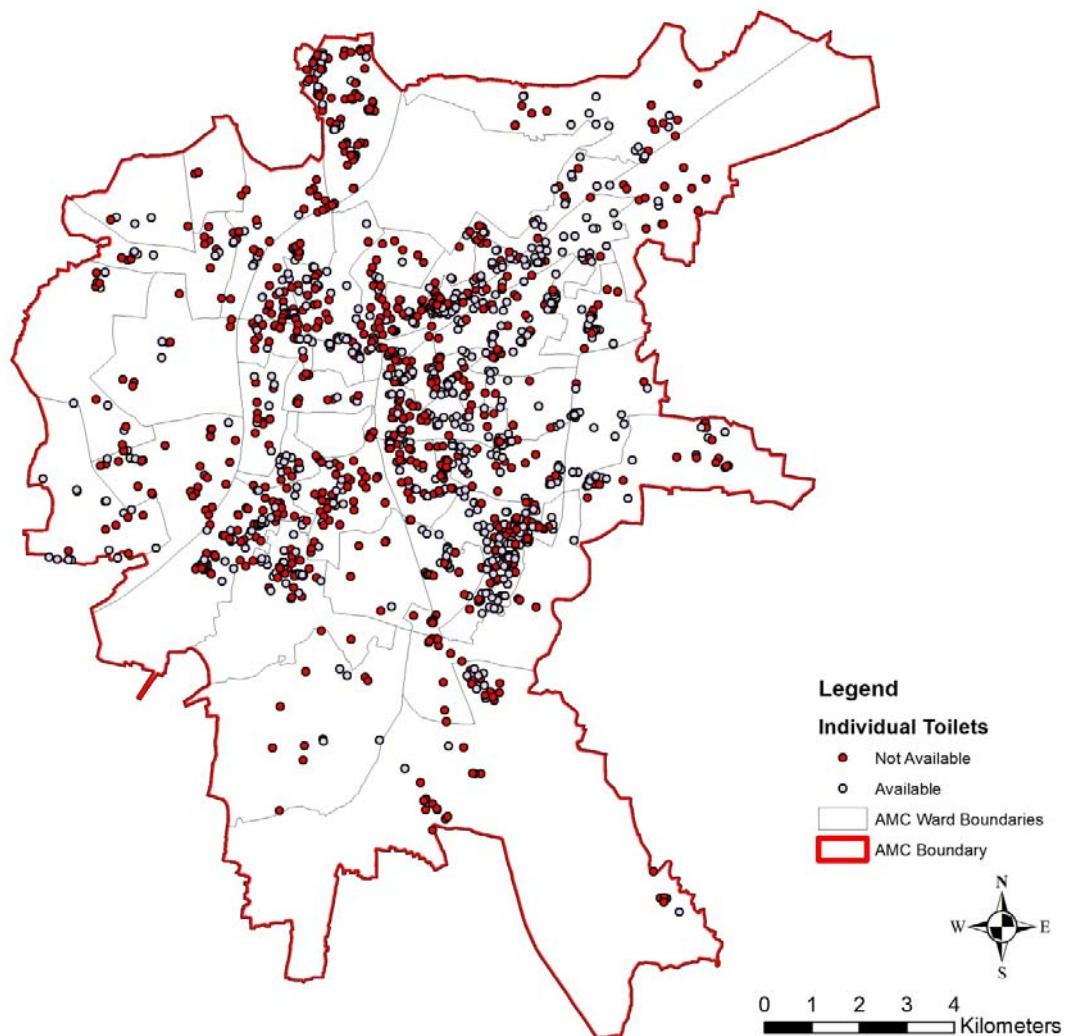


Figure 34: Lack of Sewerage in Ahmedabad Slums

In terms of individual toilets, almost everywhere slums lacked individual toilets as shown in Figure 35. Many of these slums had public toilets or shared toilets, especially in chawls where the housing typology typically included common toilets shared by many households.



**Figure 35: Lack of Individual Toilets in Slums of Ahmedabad**

#### **6.3.4 Descriptive Spatial Analysis of Slum Locations**

An exploratory spatial analysis was conducted to understand the spatial patterns of slum locations in Ahmedabad. Slums and chawls were not differentiated for the purpose of this analysis. Classical text describing methods of point pattern analysis include Bailey and Gatrell (1995), Diggle (1993), Diggle (1983), Cuzick and Edwards (1990). The purpose of this analysis is to develop a general understanding of slum location patterns that could be used to guide the model design in early development phase. Often, a complete validation of a simulation model is not carried out especially when the model is "Level1" such as the one presented in Chapter 5 or "Level 2" model in Axtell and Epstein (1994) schema. The measure such as relative position of slum centroid with respect to the city centroid, nature of spatial distribution etc. are used to qualitatively validate the macro structure that emerges in the simulation. Such an approach is common in agent-based modeling e.g. Barros (2004; 2012) compares abstract model's outcomes with the empirically observed patterns in Latin American cities for qualitative validation.

A commonly used summary statistics to understand spatial pattern of slums is a centroid (often referred as "Mean Center"). A centroid is a point which is most centrally located from all other points in the dataset and is constructed from the average of X and Y coordinates of individual slums. It is a measure of central tendency similar to the statistical mean. The difference is in dimensions, the statistical mean is univariate (e.g. number of houses in a dataset of slums) whereas

centroid is a measure of central tendency of spatial point patterns in planer systems (e.g. with two variables indicating X and Y coordinates of each slum location).

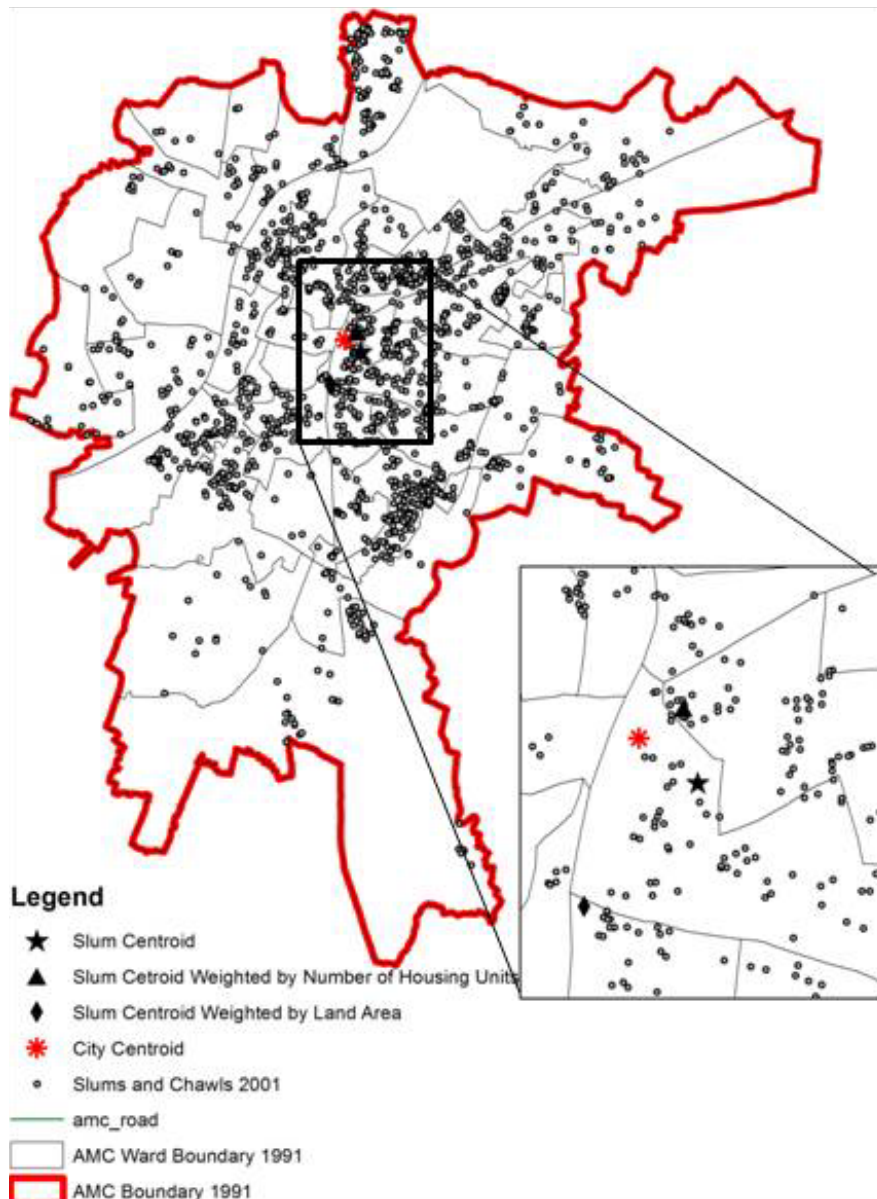
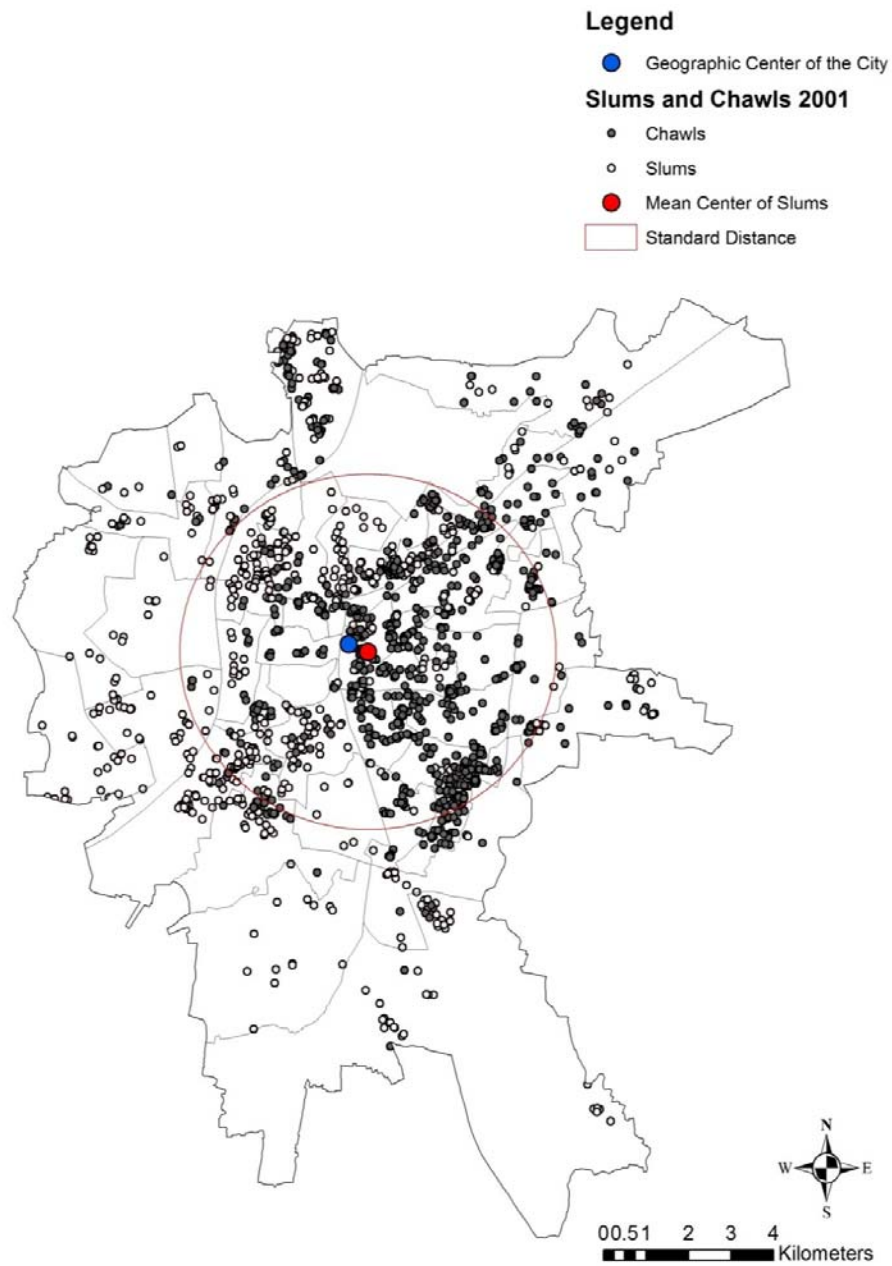


Figure 36: Spatial Balance of Slum Locations in Ahmedabad

Spatial imbalance could be measured using the centroid of a distribution and the centroid of a region to indicate the relative position of the distribution in the region. The spatial imbalance of a distribution in a region is defined as the distance of the centroid of the distribution from the centroid of the region (Zhao et al 2010; Tellier 1995). As shown in Figure 36, the centroid of the slums in Ahmedabad is in proximity to the centroid of the city (Euclidian distance: 0.5 km).

The finding holds even after weighting slum locations with number of houses (Euclidian distance from the centroid of the city: 0.3 km) or the land area occupied (Euclidian distance from the centroid of the city: 1.3 km). The land area weighted slum centroid is the farthest and southwards from the city centroid which indicates larger land parcels occupied by relatively less dense slums in southern wards. This analysis suggests that an underlying spatial process driving the locations of slums might be related to the process that drives the development of formal parts of the city. This finding could serve as a basis for qualitative validation of the simulation outcomes especially in conceptual development stage presented in Chapter 5.

Another useful statistic is the standard distance. The standard distance provides a single summary measure of feature distribution around their center similar to the way a standard deviation measures the distribution of data values around the statistical mean. The Standard Distance is usually represented as a circle centered on the mean. The circle is drawn with a radius equal to the standard distance (Bachi 1962).



**Figure 37: Spatial Summary Statistics for Slum Locations in Ahmedabad, 2001**

In general, if the underlying spatial pattern of the input features is concentrated in the center with fewer features toward the periphery (in other

words, spatial normal distribution of locations<sup>22</sup>), a one standard deviation circle will cover approximately 68.27% of the features; a two standard deviation circle will contain 95.45% of the features; and three standard deviations will cover 99.73% of the features in the cluster. As a simple back-of-the-envelope test, it is useful to check whether these three values are observed for slum data in Ahmedabad. The standard distance was 4.7 km (2.92 miles) which was then used as a radii to draw the circle from the centroid slums as shown in Figure 37.

When intersected with the slum locations, the circle of one standard distance covered total 1001 slums accounting for 65.12% of total 1537 slums; a circle of two standard distance covered 1520 slums (98.89%); and a circle of three standard distance radius covered all 1537 slums (100%). This pattern indicates that distribution of slums in Ahmedabad approximates to a spatial normal distribution. As shown in Table 17, back-of-envelope test suggests that slums are concentrated around the centroid of the city whereas there are fewer slums in the peripheries.

**Table 17: Simple Test for Spatial Normal Distribution of Slum Locations in Ahmedabad**

<b>Distance from the Center (Standard Distance)</b>	<b>Expected Number of Slums (Spatial Normal Distribution)</b>	<b>Observed Number of Slums</b>
4.7 km ( $1\sigma$ )	1049 (68.27%)	1001 (65.12%)
9.4 km ( $2\sigma$ )	1467 (95.45%)	1520 (98.89%)
14.1 km ( $3\sigma$ )	(99.73%)	1537 (100.00%)

---

<sup>22</sup> This is different from testing for normality of a variable of spatially clustered points. It simply means nature of distribution of point patterns around the centroid in a planar system.

Formally, this can be tested using the Doornik-Hansen (2008) test which is an omnibus test for multivariate normality. Doornik-Hansen test is a multivariate version for normality, using skewness and kurtosis based on Shenton and Bowman (1977). Spatial point data could be conceived as a dataset with two variables, namely, X and Y coordinates of these points, distributed over continuous Euclidean space. The Doornik-Hansen test for X and Y coordinates of slum locations in Ahmedabad was conducted to test normality of the spatial distribution. Hence, the null hypothesis for the test is:

$H_0$ : X and Y coordinates of slum locations follow normal distribution

$H_a$ : X and Y coordinates of slum locations follow non-normal distribution

The Doornik-Hansen test statistic,  $\chi^2(4)$  is 9.414 and hence the null-hypothesis of normality cannot be rejected at 95% confidence level ( $p > 0.05$ ). The two more multivariate normality tests developed by Mardia (1970) provides tests for skewness and kurtosis separately. These tests suggested that Mardia's kurtosis statistic,  $\chi^2(1)$  is 1.884 and hence the null-hypothesis of normality cannot be rejected at 95% confidence level ( $p > 0.05$ ). However, Mardia's skewness statistic,  $\chi^2(4)$  is 9.639 and hence the null-hypothesis of normality is rejected at 95% confidence level ( $p < 0.05$ ) but cannot be rejected at 99% confidence level ( $p > 0.01$ ). These tests suggest that the data is spatially normally distributed. The reason for non-normality in one of the test is skewness but not the kurtosis as suggested by

Mardia's skewness and kurtosis test. This might be resulting from the uneven boundary effects. Since the data was not collected outside the city boundaries, data is not collected in a regular circular area. There may be slums outside the boundaries which may make it less skewed but they were not recorded in the slum census.

Such tests provide us a stylized understanding of slum location pattern. Until one reaches to the stage of simulating a real world city and compare it with observed data for validation, stylized facts could serve as a benchmark and guide the simulation model development. In early phases of simulation tool development, especially in ABM, modelers often start with an abstract model and rely on scale-free measures of patterns such as fractal dimension (e.g. Barros 2004; 2012) to gain confidence in early stage of model development. The purpose of checking for normality is to develop one such stylized understanding of slum patterns. However, this finding is based on slum locations in only one city and hence needs to be used as a basis for validation carefully. It is hoped that slum location data becomes available for many other cities to conduct similar analysis in the future that could help us to devise robust guiding principles for validating spatial distribution of slums.

### **6.3.5 Slum Size Distribution in Ahmedabad**

Slums vary in size as defined by number of houses in each slum<sup>23</sup>. The largest slum in Ahmedabad has more than 10000 houses and the smallest slum has as low

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<sup>23</sup> Population measures such as number of households or number of persons were not available at slum level in SNP dataset. Nonetheless, number of houses roughly corresponds to number of households.

as 3 houses. As shown in Figure 38, there are large number of smaller slums (with less than 250 houses) and only small number of large slums (with more than 250 houses). Average slum size in Ahmedabad is 197 houses per slum (SD: 553 houses). The size of a slum could be varying based on the availability of vacant land at that location, age of the slum, accessibility to other amenities etc. Slum size distribution provides another stylized understanding of slum formation pattern: there are large number of smaller slums and small number of large slums. It could provide us the basis for validation during development stage of the abstract model.

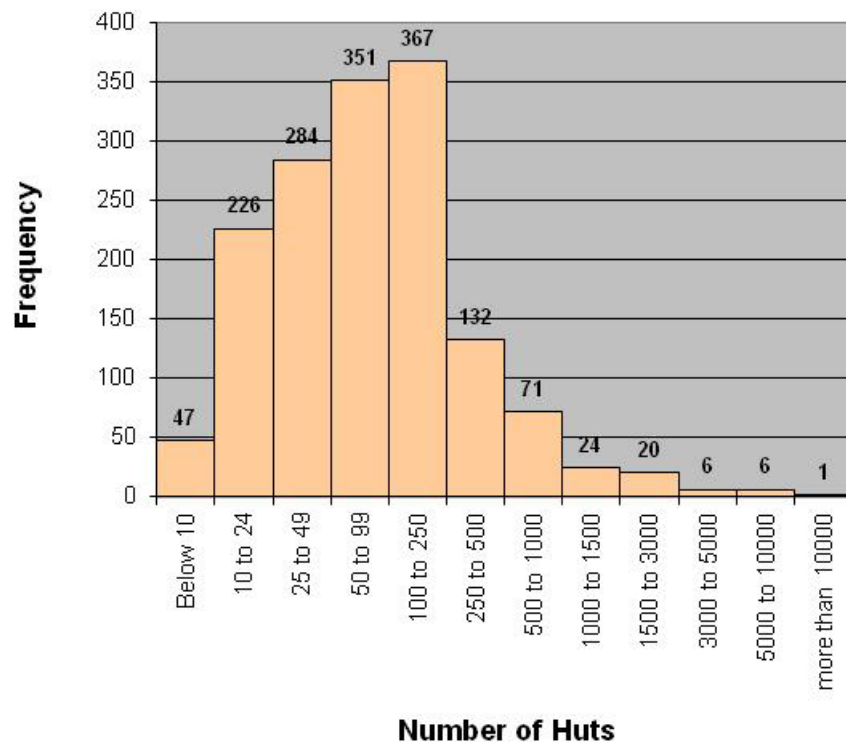
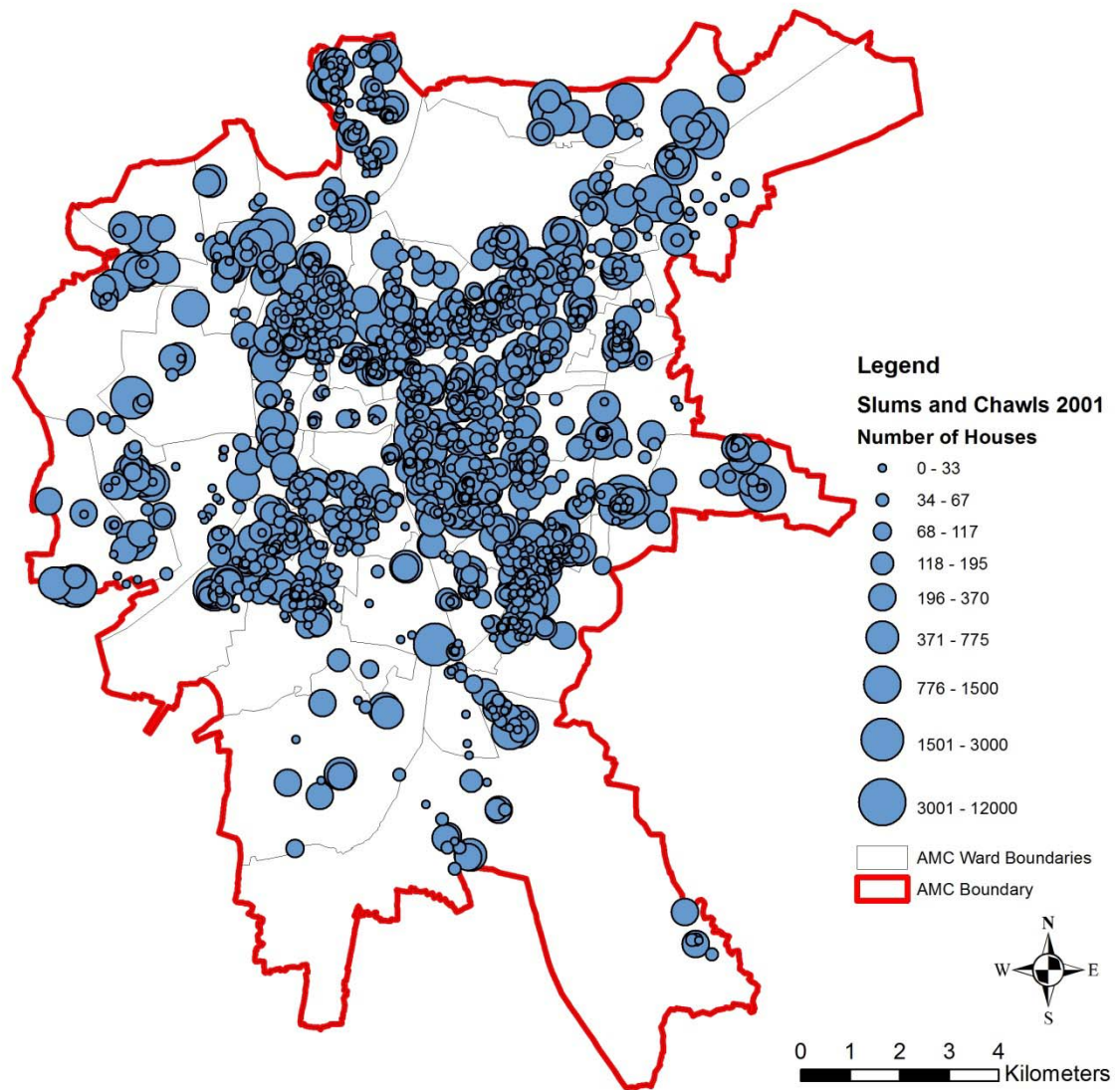


Figure 38: Size Distribution of Slums in Ahmedabad



**Figure 39: Slum Size Distribution in Ahmedabad**

As shown in Figure 39, smaller slums are concentrated in central part of the city whereas larger slums are in the peripheries. This may be simply because the contiguous land parcels of larger size are not available in the central city and hence instead of larger slums, we observed multiple smaller slums. It is of note that CBD

("Walled City") has nearly no slums which may be a reflection of higher opportunity cost associated with land use in CBD for residential purposes.

#### **6.3.6 Spatial Clustering of Slums in Ahmedabad**

Slum locations were further analyzed to explore the underlying spatial patterns. Particularly, the dataset was analyzed to see if slums were randomly located, clustered or dispersed within Ahmedabad. A spatial statistic called the Nearest Neighbor Index (NNI) was calculated for revealing underlying pattern of slum locations.

The NNI is expressed as the ratio of the Observed Mean Distance to the Expected Mean Distance (Cressie 1991). The Expected Mean Distance is the average distance between the nearest neighbors a hypothetical random distribution referred as distribution with Complete Spatial Randomness (CSR) whereas the Observed Mean Distance is the average of observed distances between the nearest neighbors for the features under study. If the index is less than 1, the pattern exhibits clustering; if the index is greater than 1, the trend is toward dispersion or competition.

Further, it is useful to test if such a clustering or dispersion is by chance or if there is any underlying spatial process at work. Similar to hypothesis testing for one-dimensional variable in statistics, spatial statistics also employs Z-score and p-values to determine statistical significance. The null hypothesis for the spatial pattern analysis is CSR, either of the features themselves or of the values associated with those features.

If the null hypothesis of CSR is rejected, it indicates that rather than a random pattern, slums exhibit statistically significant clustering or dispersion. The p-value is a probability that the observed spatial pattern was generated from some random process. When the p-value is very small, it means it is very unlikely (small probability) that the observed spatial pattern is a result of random processes, so we can reject the null hypothesis. Whenever we see spatial structure, like clustering or dispersion of slums in the city, it provides an evidence of some underlying spatial processes at work, and as a spatial scientist or urban planner, this is often what we are most interested in. For example, a program like Slum Networking Project (SNP) which aims to connect slums with existing city infrastructure such as water and sewerage networks could target these clusters. Given the nature of network infrastructure, it may be feasible to serve spatially clustered slums than spatially dispersed slums. Services like urban transportation also benefits from concentrated demand resulting from high densities. For example, a bus route could have higher utilization if population is clustered within walking distance from a station as opposed to a dispersed population.

The Nearest Neighbor Index was calculated with Spatial Statistics extension of Arc View 10. The NNI for the slum locations in Ahmedabad was 0.46 indicating spatial clustering. The Nearest Neighbor Index was calculated as a ratio of Observed Mean Distance which was 0.10 km and Expected Mean Distance which was 0.22 km. The Expected Mean Distance was calculated as an average of distance between nearest neighbors under CSR assumption. Clearly, slums were not located randomly

as it is evident from the much smaller average distance between nearest neighbors. As shown in Figure 40 created with the help of ESRI's ArcView 10, the value of Z-score (-40.3) and p-value < 0.01 suggests that there is less than a 1% likelihood that this clustered pattern could be a result of random chance.

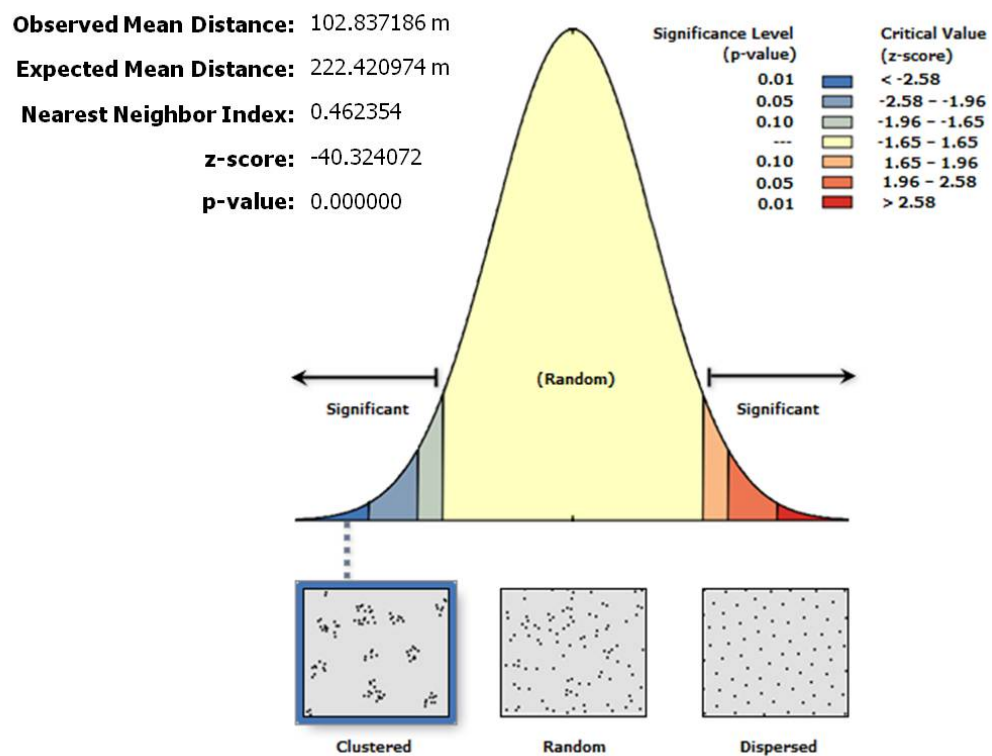


Figure 40: Spatial Clustering of Slums in Ahmedabad

### 6.3.7 Hot-Spot Analysis

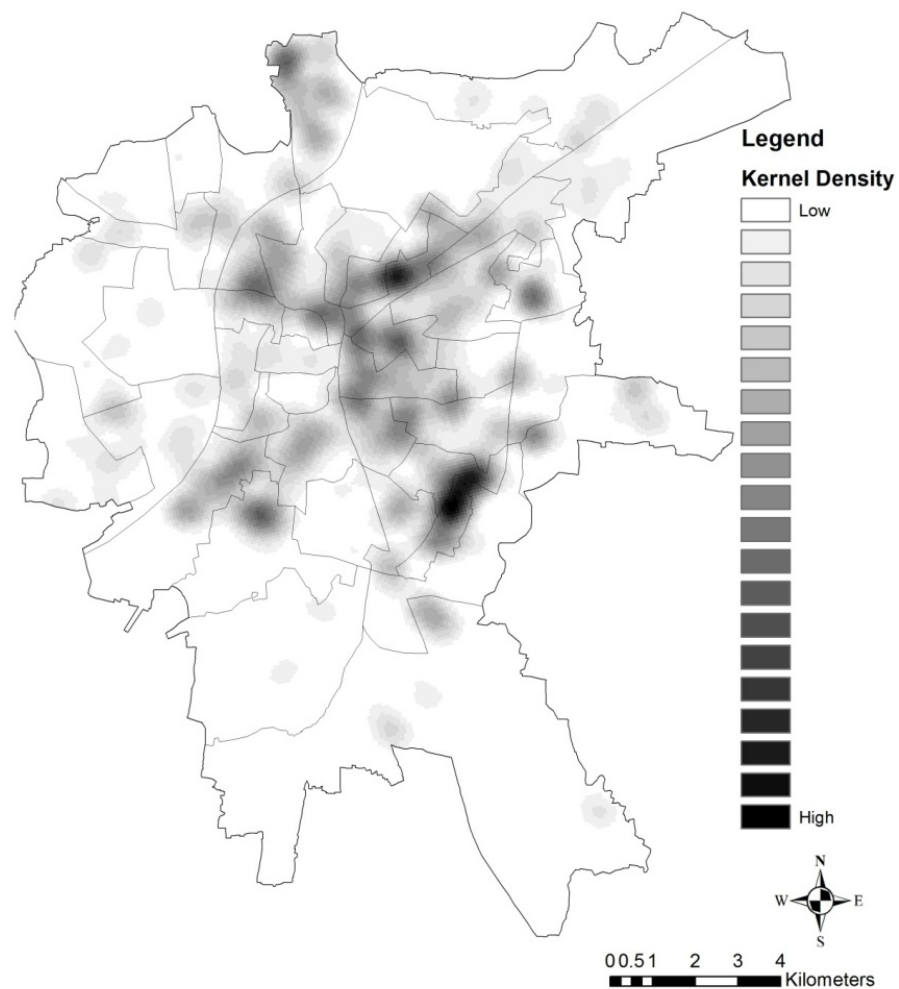
Once it is identified that there exists a spatial clustering of slums in Ahmedabad, it is worthwhile to explore where these clusters are in the city. Kernel

density estimation method was used to identify such clusters (often referred as "hot-spots"). The classic texts for kernel estimation include Silverman (1986) and Gatrell (1994).

Kernel Density calculates the density of point features around each output (raster) cell. Conceptually, a smoothly curved surface is fitted over each point. The surface value is highest at the location of the point and diminishes with increasing distance from the point, reaching zero at the specified search radius distance from the point. The density at each output cell is calculated by adding the values of all the kernel surfaces where they overlay the cell center. The kernel density is then presented in the form of a choropleth map of densities.

Figure 41 allows us to identify the areas where slums are clustered as well as the areas where slums are sparse. As it is evident from the map, there are several hot-spots of slums in Ahmedabad. Particularly, in the Eastern part of the city, the kernel density of slums is high compared to the western part of the city. There are few clusters in the Northern part but North-eastern and South-eastern parts have sparsely distributed slums. It is anecdotally known that some of these hot-spots are around the major job centers (e.g. textile mills) and areas unsuitable for formal development (e.g. river bed, land along the railway track etc.) which may have influenced the emergence of such hot-spots. However, in order to establish a formal relationship of these hot-spots with other environmental variables, spatial data on job centers, land suitability, accessibility etc. could be obtained in the future to

advance this analysis. It could also improve the model with the inclusion of these parameters in the spatial environment of the model.



**Figure 41: Hot-Spots of Slum Clusters in Ahmedabad**

## 6.4 Summary

This chapter has provided an introduction to the case study city, Ahmedabad. The chapter briefly explored the general profile of the city in terms of socio-economic and physical environment. Then population dynamics, in particular, migration patterns to Ahmedabad were analyzed using census data. The basis for input parameters were identified for customizing *Slumulation* for Ahmedabad. Finally, the slum location patterns in Ahmedabad were analyzed using SNP data. To the best of the author's knowledge, this is the first attempt to systematically analyze spatial patterns of slum locations in Ahmedabad using measures of spatial equality and clustering. This analysis provides the basis for validation of *Slumulation* in the next chapter.

## CHAPTER 7. IMPLIMENTING SLUMULATION ON AHMEDABAD

The goal of this chapter is to exemplify the use of *Slumulation* for a real world city using Ahmedabad as a test case. We attempt to customize the model for a particular city without losing the general framework presented in Chapter 5. This chapter starts from the model presented in section 5.5 and completes the integration of all three methodological approaches, namely, DES, ABM and GIS. Analysis presented in Chapter 6 for Ahmedabad provides inputs for the model as well as the basis for comparing simulation outputs for validation purposes. In Axtell and Epstein (1994)'s schema of classification, we now attempt to take *Slumulation* to a "Level 2" model which could generate patterns that are in quantitative agreement with the observed macro-structure of slums in a real world city.

Section 7.1. provides the details on how the model was customized and adapted for the case study city. In particular, section 7.1.1 describes the preparation of the *Geodatabase* for integration with PDM and HDM. Section 7.1.2 calibrates and validates the PDM for micro-simulating agent population for the case of Ahmedabad. Section 7.2 simulates the city with several initial conditions to explain the formation and expansion of slums in Ahmedabad. The model outcomes are then compared with macro-level empirical analysis (presented in section 6.3) to

comment on validity of the model. Section 7.3 uses this model to generate policy scenarios that could be useful to predict slum location under various conditions.

## **7.1 Slumulation: Customization and Adaptations**

The first step is to complete the conceptual framework presented in section 5.2 by integrating GIS with the model. The GIS extension of NetLogo 5.0 was used to incorporate the spatial environment in the model. The GIS extension allows us to read data from ESRI's shapefiles, a commonly used GIS data format (Crooks and Castle 2012).

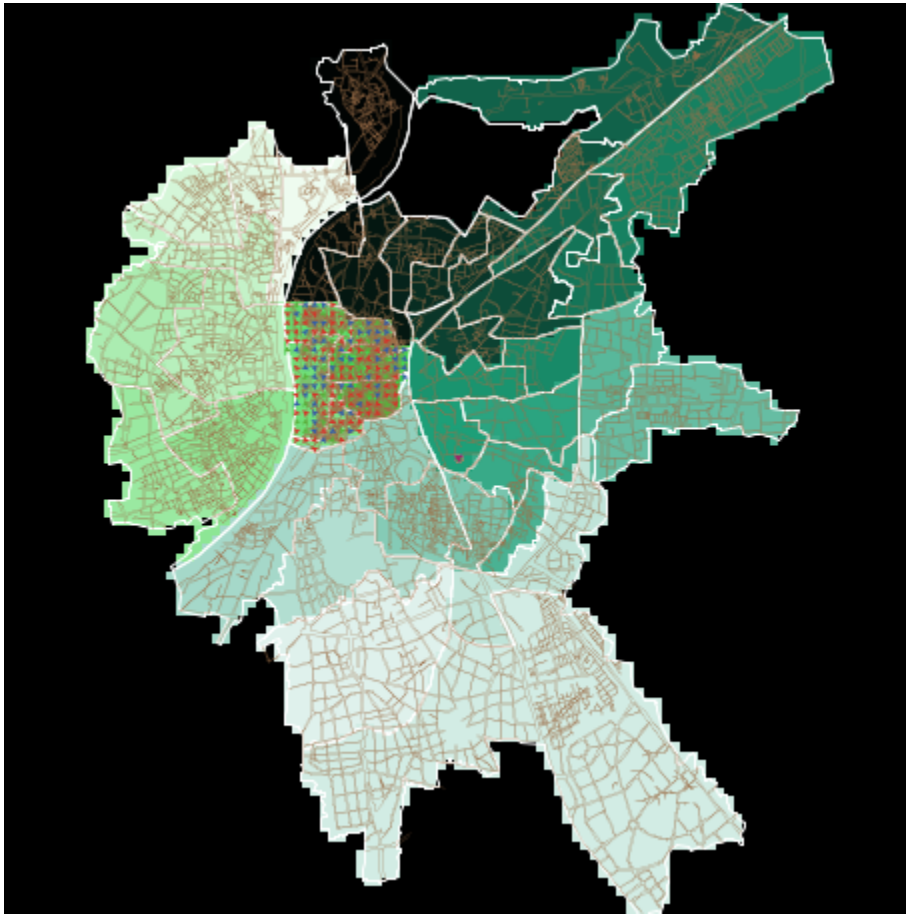
### **7.1.1 Configuring Spatial Environment**

As shown in Figure 42, the electoral ward map of Ahmedabad is first incorporated in the model presented in section 5.5 to construct the spatial environment relevant for the politician agents<sup>24</sup>. In the second step, the spatial scale of the model is set by relating GIS data layer with the NetLogo's cell-based environment. The cell grid of the size 101 x 101 cells was created for the spatial environment resulting into 10201 total cells. Of which 5804 cells were within spatial extent of Ahmedabad city. These 5804 cells represented Ahmedabad's entire geographic area of 190.84 sq km. This translates to each cell representing 180m x 180m area of Ahmedabad. Once, the size of each cell is determined, the number of available dwelling units on each of those cells could be assigned. There were more than half-a-million dwelling units in Ahmedabad in 2001. Therefore, each of the

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<sup>24</sup> The digitized electoral ward boundary map of Ahmedabad in GIS format was provided by Spin Systems Private Limited (<http://www.spin-india.com/>), based in Ahmedabad, India. The author is grateful to Ms. Shetal Shah, the founder and CEO of the company, for the permission to use the digitized map for this research.

5804 cells in our environment represents approximately 100 dwelling units. These calculations are based on the census data presented in Chapter 6.



**Figure 42: Incorporating Political Wards of Ahmedabad in Spatial Environment of Slumulation**

The city of Ahmedabad is large both in terms of its population and area to simulate in NetLogo. Simulating an entire population at a fine geographical scale becomes intensive on computer memory as well as poses computational limitations. In particular, NetLogo cannot parallelized the computing processes within model

and hence relies on one computer processor at a time for a single model run. To overcome this limitation, the approach suggested by Vincent (2009) is adopted and a 1% random sample of agent population is taken to overcome computational limitations of a large sized models. In essence, the entire city was represented at the scale of 1 to 100 both geographically and demographically. For example, to represent 3.31 million residents of Ahmedabad in 1991, only 33100 representative agents are created in the model. Consequently, the spatial environment should also represent 1/100th of the number of housing units available in the city. Therefore, each cell has one housing unit representative of 100 actual dwelling units in Ahmedabad. However, this approach is not free of limitations. For example, the model cannot generate outputs at fine scale and hence slums with smaller than 100 housing units will be predicted as slums with at least 100 housing units by the model.

#### **7.1.2 Calibrating Population Dynamics**

The conceptual PDM presented in section 5.3.3 which generates agents through natural growth and migration was further calibrated and validated for the case of Ahmedabad. The model was initiated with the population data from 1991 census and then simulated for next 10 years. The simulated outputs were then compared with observed data from 2001 census to validate the model. We initiated the model with input parameters shown in Table 18. As proposed in section 5.3.3, the Inflationary Index ( $I$ ) was iteratively calibrated to generate the outputs that match with the observed parameters. The model was run 1000 times for 10 years. The

simulated total population, native population and migrant population was used to compare the model outcomes in making a choice of calibration parameter  $I$ .

**Table 18: Input Parameters for Population Dynamics in Ahmedabad**

Input Parameter	Value
Initial Population <sup>a</sup>	33121
Initial Native Population <sup>a</sup>	21970
Initial Migrant Population <sup>a</sup>	11151
Crude Birth Rate (CBR) <sup>b</sup>	23.7
Life Expectancy at Birth in Years <sup>c</sup>	64
Annual Migration Rate <sup>d</sup>	428
Length of Stay (LOS)	30

(Source: <sup>a</sup> Census 1991; <sup>b</sup> Statistical Outline of Ahmedabad d2004-05; <sup>c</sup> World Bank's estimate for India <sup>d</sup> Author's Calculations from Migration Tables (Census 2001)

As shown in Table 19, the simulation results are in quantitative agreement with the observed data in Census 2001. A small overestimate of the total population (less than 1%) is observed which arises as the net effect of an overestimate of total migrants (4%) and an underestimate of natural growth (0.6%). Such inconsistencies could arise because the input parameters are assumed to be static during simulated time period. However, in reality, they may exhibit some fluctuation and measurement may have lack of precision. Nonetheless, the PDM generates sufficiently accurate population that could serve the purpose of this model.

**Table 19: Comparison of Simulated Parameters and Observed Parameters**

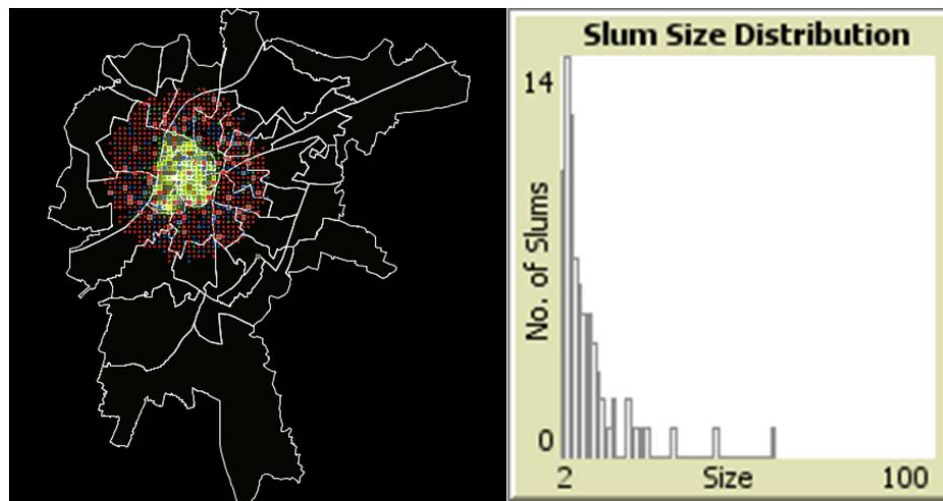
Output Parameters	Simulated Population (Mean)	95% CI Range	Population as per Census 2001
Total Population	45668	45660 - 45677	45250
Total Natives	29845	29838 - 29852	30029
Total Migrants	15823	15818 - 15828	15221

The calibrated and validated model provides the value of calibration parameter  $I$  which is then use in the integrated framework. The main advantage of calibrating and validating individual components is the computational efficiency. For example, reaching to the parameter value for  $I$  requires several iterations of the model. While such a calibration could also be done in the integrated model, the computational burden involved in running other modules is an inefficient modeling approach. This is one of the advantages of loosely-coupled models. It allows the modeler to understand and debug the model at the development stage as well as provides an efficient use of computing power to the users of a final product (Crooks and Castle 2012).

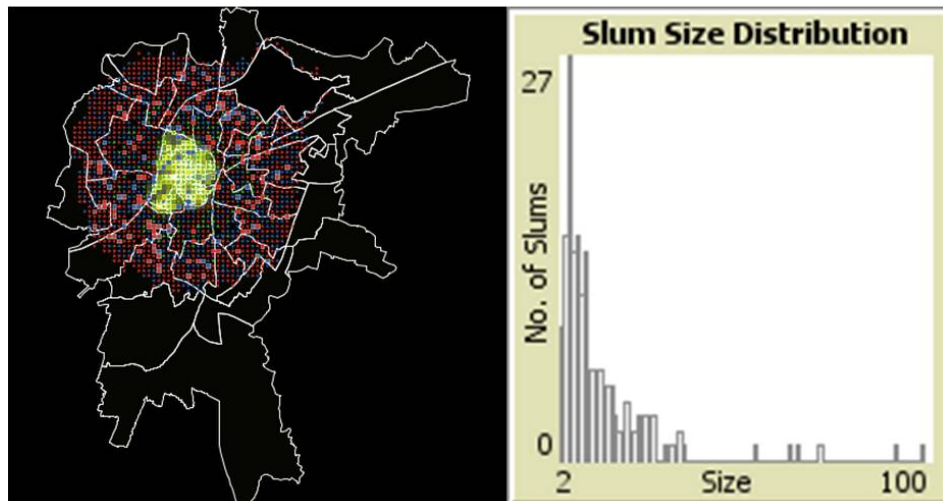
## **7.2 Simulation Experiments**

The model was tested with several initial conditions. In the first such hypothetical scenario, the model was initiated with populating the "Walled City" without any pre-existing slums. As the simulation progresses, the emergence of slums was observed, purely as a result of human-environment interaction. Such an experiment partly explains how slums came into existence in a city over time. As

seen in Figure 43, the simulation first showed formation of new slums within walled city in first few years and eventually slums were dispersed to peripheries. Such a pattern is observed in the city of Ahmedabad as shown in previous chapter.



T = 10 Years



T = 20Years

Figure 43: Hypothetical Scenario with "Walled City"

In order to assess if a city grows to its current extent, the city was populated with more wards in initial condition and then the model was run for longer period. It was observed that the model reaches to the spatial extent of the city in 30 years as shown in Figure 44 after which it attains population growth with increased density as discussed in Chapter 6.

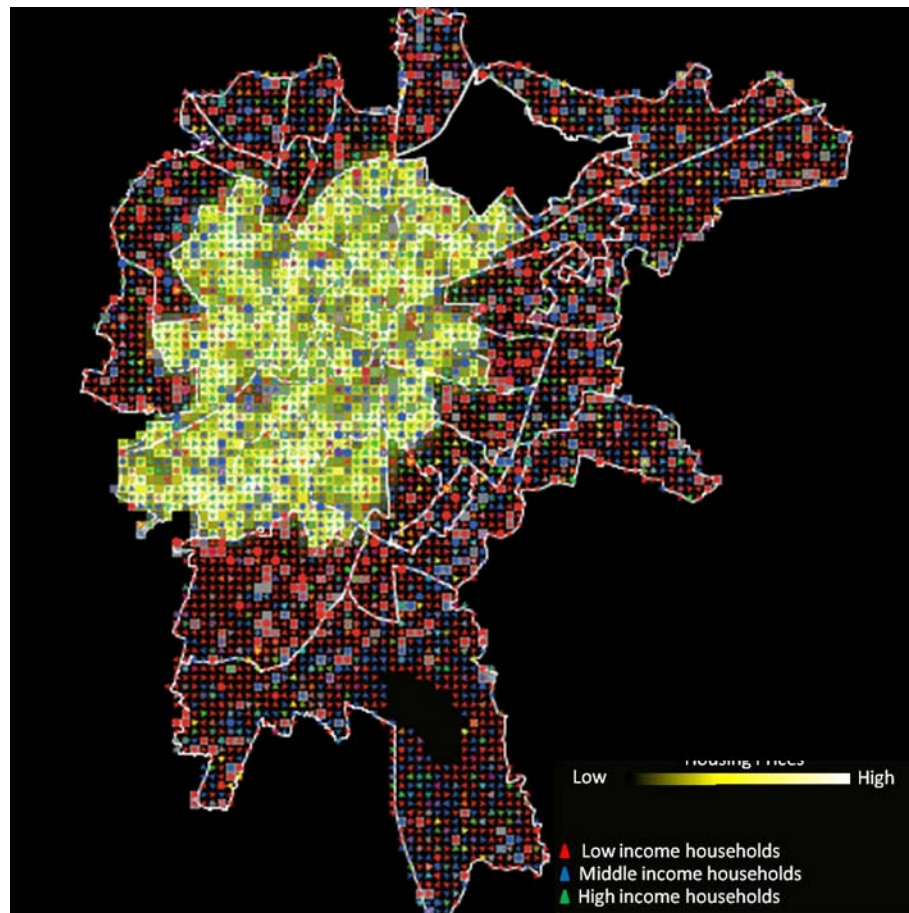


Figure 44: Spatial Sprawl Experiment

Once the model behavior was understood, some policy experiments were conducted in order to assess effectiveness of *Slumulation* as a policy support tool. In one such experiment, the value of number of housing units allowed per unit area were varied. Ahmedabad's Development Plan (AUDA 1997) imposes development control regulations which stipulate Floor Space Index (FSI, also known as Floor Area Ratio). FSI controls how much built area can be added per unit area. The residential density is thus determined by this policy measure. While this policy does not restrict the supply of housing in totality i.e. housing market can produce the same number of units over larger area to meet with the demand, it does restrict the supply of housing at particular locations. The values tested were the existing housing stock (base scenario), twice the current conditions and in an extreme scenario 3, five times current conditions in Ahmedabad.

As shown in Table 20, the increase in FSI induces lower slum population (55% in base scenario to 45% in higher FSI scenario). However, slums still emerge but in lower numbers. They tend to be larger and more dense as highlighted in Table 20. As we increase FSI to 5 times from base scenario, slum density almost doubles from 47000 to 88000 persons per sq km. This trend might be indicative of the fact that when the formal development happens at a higher density (as reflected in higher FSI), slum density also increases. The area under slum has also observed a decline. It is possible that slums follow the pattern of formal development and hence if formal development happens in a compact area (as reflected by higher FSI), slums tend to be compact as well. In other words, slums will follow the spatial

development patterns of the formal city. However, empirical analysis of slums in cities with varying levels of compactness is required to further validate this hypothesis.

**Table 20: Impacts of Floor Space Index on Simulation Outcomes**

	<b>100 Units per site (base scenario)</b>	<b>200 units per site</b>	<b>500 units per site</b>
<b>Percent slums</b>	55%	50.2%	45%
<b>Smallest slum (population)</b>	200	300	600
<b>Largest slum (population)</b>	27600	28900	32000
<b>Number of slums</b>	401	220	171
<b>Area under slums (percent of total area of the city)</b>	14.5%	8.5%	6.4%
<b>Slum Density (Persons per sq km)</b>	47400	76543	88889

A typical urban planning approach requires exploring various population growth scenarios in order to assess the future demand for land, housing and other amenities in the city. In order to assess the impact of migration rate on slum formation, three scenarios were explored: i) migration rate equals 1.5% of initial population, ii) 2.5% of initial population, and iii) 3.5% of initial population.

As shown in Table 21, lower migration rate reduces the percentage slum population and the average slum density. The reverse is also true, higher migration rate increases the percentage slum population and the average slum density. Such a pattern may have emerged since higher rate of migration also induces higher

demand for formal housing. This may lead to increased consumption of available land for formal development and hence, reducing areas available for potential slum locations. While the area available for potential slums reduces, the density of existing slums increases as they accommodate new migrants.

**Table 21: Impact of Migration Rate on Simulation Outcomes**

	<b>Migration Rate 1.0% of Population</b>	<b>Migration Rate 1.5% of Population (base scenario)</b>	<b>Migration Rate 2.5% of Population)</b>
<b>Percent slums</b>	49.3%	52.4%	62.2%
<b>Smallest slum</b>	200	200	200
<b>Largest slum</b>	26200	31500	107800
<b>Number of slums</b>	404	376	337
<b>Area under slums</b>	17.7%	13.1%	10.0%
<b>Slum Density (Persons per sq km)</b>	33950	48417	92283

### **7.3 Slumulation: A Critical Appraisal**

*Slumulation* aims to aid policymaking as a decision support tool and hence it is important to understand the limitations of this model. For example, to move towards a truly "comprehensive" understanding is beyond the scope of the dissertation as many variables and factors such as political will, economic dynamics and "unforeseen forces" cannot be fully modeled and captured in a modeling and simulation exercise (Evans 2012).

As discussed above, computational limitations does not allow the current model to simulate entire city. A practical approach to scale it to a smaller size was implemented. However, such a scaling is not without limitation. For example, smaller slums cannot be modeled due to lack of spatial resolution. Second, some of the output parameters are not scale-free, such as the number of slums in a city. This limitation could be overcome by modeling spatial environment in entirety using hardware and software that could provide required computing capacity.

For simplicity, characteristics of initial population were drawn from a normal distribution with respect to income. While, a normal distribution is a conservative approach, more realistic income distributions such as log-normal and exponential need to be tested. It is believed that such distributions are closer to reality and it will help to advance future versions of this model to more closely match the real world. Nonetheless, the model did generate real world patterns of slum formation and sustenance over space and time. As Epstein 1999 describes, there could be many "candidate explanations" for the emergence of observed patterns. This model is one of the "candidate explanations".

It should also be noted that a detailed calibration and validation of this model is not carried out due to lack of consistent data for multiple time-periods. In addition, the goal of this chapter was to conduct exploratory research and test the feasibility of the model framework. It is hoped that the 2011 census and slum mapping under RAY will provide comparable data which can be used to calibrate and validate the model. In the future, the model could be initiated with slum

locations in 2001. The simulation could then be carried out for the period between 2001 and 2011 with population growth and migration estimates from the Census 2011 data. Although, Census 2011 has already been carried out in India, detailed ward level data is still being compiled and are likely to be available by mid-2013 (Census of India 2011). The simulated outputs could then be compared to the observed slum locations in 2011 (new data has been already collected under RAY in 2011 but it is uncertain when it will be publicly available).

Furthermore, model development, calibration and validation could also benefit from extending the spatial analysis presented in Chapter 6. For example, the data on the year in which each slum came into existence could provide temporal evolution of the slum pattern observed in year 2001. This analysis could be further enriched if the year of construction for each housing unit within those slums is also obtained. Such data could show when each slum came into existence, whether those slums increased or decreased in size etc. Temporal variable could provide a dynamic view of evolution of slum system in the city which could then be used to validate dynamic patterns generated within simulation.

The model presented here is an effort to develop a theoretical framework which is capable of generating slum patterns similar to that observed in the real world. Ideally, if it is to be considered as a good urban planning support tool, it should be able to predict slum locations with precision. However, such a system inherently requires data on several aspects that are often not available in developing countries. For example, *Slumulation* could produce better results if

housing price data is available for multiple years. This would therefore allow for several assumptions to be replaced with actual data that can help in calibrating and validating this model further. Data availability is improving in developing countries (e.g. massive data collection under RAY in India) and hence it is hoped that *Slumulation* will benefit in the future from improved data.

Such modeling work could benefit from collaborations with local governments, for example with AMC and AUDA for the case of Ahmedabad, and provide two mutual advantage to the researchers and policymakers: i) access to the required data becomes possible for the model development, and ii) the model becomes more relevant for the policymakers (e.g. Clarke and Gaydos 1998; Engelen et al. 2003). For example, spatial environment of the model could be enhanced with the inclusion of transportation network, public transit route information etc. which could add accessibility dimension in household agents' location choice behavior. Similarly, each housing site could also be configured with the status of availability of basic amenities such as water and sewerage. Incorporating this information in the spatial environment could help in determining slum status of a household in a comprehensive way as suggested by UN-Habitat (2006)'s definition of a slum household. Such a collaboration between researchers and policymakers could also make the model relevant for the policymaking purpose. For example, the model could be tailored to study the impact on slums of the proposed development plan, a primary urban planning mechanism in Ahmedabad.

Finally, it may be challenging to create a generic model that could be tailored to the needs of any city in India, let alone in other developing countries due to differences in context, policy environment and data availability. However, this is a dilemma that many models face (Crooks et al. 2008; Webster et al. 1988), nevertheless some spatial models have been successfully applied to many different cities (Clarke et al. 2006). To overcome this issue, the model is well documented in this dissertation, all the assumptions are made explicit and *Slumulation* model code is made available along with all source data at <http://tinyurl.com/SlumulationDissertation>. The dissertation has followed the modeling protocols such as those advocated by Grimm et al. (2006) and improved upon by Grimm and Railsback (2012).

## **CHAPTER 8. POLICY IMPLICATIONS AND CONCLUSIONS**

This dissertation develops an integrated framework to explore the spatio-temporal dynamics of slum formations that is suitable for cities in developing countries. A case study is also provided to exemplify how *Slumulation* could be customized and adapted for policymaking in the real world. This chapter provides concluding remarks (section 8.1) followed by research and policy implications of this research (section 8.2) and future directions for the extension of *Slumulation* (section 8.3).

### **8.1 Concluding Remarks**

As Wilson (2000) writes, understanding cities represent one of the greatest challenges of our time. As more than a third of the world's population currently live in slums (UN-Habitat 2003), slums represent a great challenge. Integrated simulation framework developed here may evolve into an useful tool to study questions relating to how slums come into existence, how do they expand, and test effectiveness of policy options to address the challenge of slums by improving housing conditions for urban poor.

This dissertation has built an exploratory integrated framework to model slum formation using existing understanding of urbanization processes, housing

market dynamics, politics of slums and households' behavior within an integrated framework. Specifically, the model adds to the small but growing body of literature (discussed in section 4.3) that uses spatial simulation models to aid our understanding of slum formation. Slums are results of a combination of conditions present at various spatial scales, coupled with the interplay of different actors, ranging from the individual household to local politicians and developers, all of which influence the emergence or persistence of the slums. This approach to model slum formation and expansion is unique as it explicitly incorporates political behavior with regard to political protection of slum communities by explicitly modeling politicians as agents.

Similarly, the role of developers who transform low-density housing into high-density housing is modeled to analyze the impact on both the formal housing market growth and slum formation. Agent-based models of slum formation have ignored these two important actors and their roles in slum formation and expansion process. Incorporating these agents also required our model to be multi-scalar which is then lacking in prior modeling efforts with regard to slums.

The model suggests that higher protection of slum dwellers in the form of subsidies in lieu of slum votes results into slums with high densities. While peripherization of slums slows down as the formation of new slums decreases, several slums persist on the prime-land for a longer amount of time in the center. Virtually, none of the slum households get evicted despite the rising prices in the central city when politician agents are active. This model provides an explanation

for persistence of slums on highly priced land which is counter-intuitive in prior modeling efforts that do not incorporate politics of slums in their models. It should be noted that it is not claimed that slums are more likely in democratic societies. It is only to highlight that political representation of slum dwellers in the form of voting rights allow them to resist economic forces by building an electorate. In simulating cities where slum dwellers are not given voting rights, the model could easily be adapted by turning off the politics provided as a switch in the model interface as demonstrated in Chapter 5. The developers provide a central role in converting low-density middle-income neighborhoods into high-density middle-income neighborhoods. This central function of developers releases the upward pressure on real estate.

Moreover the experiments from Chapter 5 suggest that economic growth and informality has a direct impact on slum formation. It seems that economic growth alone cannot alleviate slum issues in developing world cities. It is necessary to increase formality which has a two-pronged effect: i) reducing income inequality and ii) housing prices are within affordability limits for all sections of society. These effects are well captured in the model and suggest that economic growth combined with reduced inequality may reduce slum growth in developing world. Similarly, the fast pace of urbanization is often considered a driving force for slum formation. However, the experiments suggested that cities expand and increase the sprawl resulting into lower density during a rapid population growth phase.

## 8.2 Research and Policy Implications

*Slumulation* provides an integrated framework that is both dynamic through space and time, with the various modules interacting with each other. The framework also showcases how one can couple various research techniques and scientific methods (which are often used separately) for geographical research and significantly add to our current understanding of slums. Individuals within the model have behavioral characteristics and they take actions accordingly which leads to collective outcomes, apparent at larger spatial scales and over longer periods of time. Slums emerge from the bottom-up, rather than the more traditional top-down normative constraints of classical models (Clifford 2008).

In addition, the framework could serve as a urban laboratory in which one can explore links between individual behaviors and aggregate outcomes (Casti 1999) in a spatially explicit environment utilizing both quantitative and qualitative methods. The main product of this dissertation is a visual *Slumulation* software that could be used by policy makers to test the outcomes of various potential slum management policies. It is hoped that the methodological framework developed for Ahmedabad, India, could be tailored with efforts and used in other cities within India and potentially in other developing countries to formulate effective slum policies in future.

The model has received a positive feedback from the scholars from various disciplines, policymakers and NGOs working in the field with slum communities. The conceptual model was first presented to urban planners and field NGOs in India

to test the usefulness of this tool for urban planning purpose (Patel & Shah, 2009). The model was further improved and presented in scholarly conferences for geographers and ABM scholars to receive feedback on methodological aspects (Patel, 2010a; 2010b). The prototype model was also presented to the policymakers in India during the field visits to collect their views on how to make it more useful for policymaking. The experience suggests that model building process greatly improves with inputs from other slum scholars, potential users i.e. planners and policymakers, people closely working with slum communities i.e. field NGOs. This model shows a promise to be enriched further both in terms of its utility, relevance to real problems and feasibility of model development with such collaborations and consultations.

It is believed that a greater understanding of slum behavior via *Slumulation* will lead to more effective policy interventions that could contribute not only to the living condition, but also to the general welfare of the slum population including health, education and environment of slums. Moreover, it is believed that by integrating these research techniques within a single framework, the theoretical and empirical grounding of the entire field of slums is enhanced. The dissertation also demonstrates the utility of geographically explicit models focusing on cities and how such models can be used to investigate one of the major and under-studied challenges faced by society in the coming decades.

### **8.3 Future Extensions**

The purpose of this model is explanatory and it simply explores theories and generates new hypotheses. However, future work will attempt to predict precise slum locations and take it to a "Level 2" and possibly "Level 3" model in terms of Axtell and Epstein's (1994) classification system. In order to do so, the model needs to build on the empirical works of slum researchers who explore issues relating to: management of informal settlements with the aid of geographical information systems (e.g. Sliuzas et al. 2004); housing transformation (e.g. Sheuya 2004); as well as issues pertaining to informal land management (e.g. Kombe and Kreibich 2000).

Another direction of the model extension is to incorporate more complex behaviors and interactions. For example, it might be interesting to explore the competition between the developers for the sites. However, this would involve developing a more complicated land market mechanism than that currently implemented in the model. The work of Filatova et al. (2009) could be a good starting point for this. Similarly, the competition between two political parties could be introduced that would work in both directions rather than simply protecting the poor (Kim 2011; Muis 2010).

The role of government is also important in developing new green-field sites by providing infrastructure, which is currently absent in the model. The economic growth and formal-informal mix determines the level of budget available for such a development and may become more important parameters once the role of government is introduced in supply of serviced land. Data on some of these input

parameters might not be available readily for cities in developing countries.

However, one can hope that the model may precede and guide empirical work in this area as is the case with many other theoretical and exploratory works (Epstein and Axtell 1994).

It is also important to distinguish between renters and owners within household agents in the model. This distinction will enable the model to test the policy ideas such as security of tenure which distinctly benefits owners of housing units in slums. This becomes more relevant as secured tenure is considered the critical component of RAY (MHUPA 2010). This leads to another point that the model should have mechanism to turn policy interventions into the input parameters. For example, basic infrastructure extended to existing slums through SNP could be converted into input parameters such as "service level" for each housing site in the model. Similarly, a public transport projects such as Bus Rapid Transit System (BRTS) of Ahmedabad could be incorporated as input parameters such as "accessibility" for each housing site in the model.

Another extension could be the improved interaction between the PDM and HDM. As envisaged in section 5.2, the PDM could interactively receive feedback from the HDM to dynamically change its outputs. For example, if the slum population reduces in the city i.e. housing conditions improve, it could provide a pull factor for potential migrants resulting in the increase in the migration arrival rate. However, the relationship between increase in the migration rate and improved housing in the destination needs to be empirically established. A study similar to Lall et al (2007)

could provide the basis for such a relationship. Similar relationship may also exist between number of new jobs added in the city and the migration rate. The employment projections could be linked in the model that could change the migration rate dynamically.

## APPENDICES

### Appendix 1A: Natural Growth Component

```
;;INITIATLIZATION OF NATURAL GROWTH MODULE
to setup
  _clear-all-and-reset-ticks ;clear everything from previous runs
  set time 0
  crt InitPop [set age random-normal 30 10 set los age + random-normal 30 10]
  set meanage (sum [age] of turtles / InitPop )
  set pop count turtles
  set everpop 0
end
;;VARIABLE DECLARATION
globals
[time ; keep track of simulation run time
 pop ; total population at time t
 everpop ;total population including those who outmigrated
 newpop ; total population after the tick is over
 nb
 meanage
]
turtles-own
[age
 los
]
;;SIMULATION RUN OF MIGRATION MODULE
to go
  set pop newpop
  create-citizens
  set everpop everpop + nb
  kill-citizens
  set newpop count turtles
  tick
  update-citizens
  set meanage (sum [age] of turtles / newpop )
  set time time + 1
  if (time = T) [stop]
end
;; TO CREATE MIGRANTS
to create-citizens
  let x CrudeBirthRate
  set nb x * pop / 1000
  crt nb
[set los random-normal avglifeexpectancyatbirth 30
 set age 0
]
end
;; UPDATE-MIGRANTS
```

```
to update-citizens
  ask turtles
    [set age age + 1]
end
;;Death
to kill-citizens
  ask turtles [if age > los [die]]
end
;;update variables
```

## Appendix 1B: Migration Module

```

;;VARIABLE DECLARATION
globals
[time ; keep track of simulation run time
 pop ; total population at time t
 everpop ;total population including those who outmigrated
 newpop ; total population after the tick is over
 nm ; number of migrants
 statelist ; list of states of origin
 originstatepr ; cumulative probability of migrant's state of origin
 stateruralpr ; state specific probability of rural or urban status
 stateruralfemalepr ;state specific rural migrants gender probability
 stateurbanfemalepr ;state specific urban migrants gender probability
 reasonlist ; reason for migration list
 stateruralreasonpr ; state specific rural-urban migrants reason probability
 stateurbanreasonpr ; state specific rural-urban migrants reason probability
 stateruralreasonfemalepr ;state specific rural-urban migrants reasonwise female probability
 stateurbanreasonfemalepr ;state specific rural-urban migrants reasonwise female probability
 y ; temp variable
 za ; temp variable
 zb ; temp variable
 numstate ; number of states
 numreason ; number of reasons
]
turtles-own
[reasonmig
 ru ; rural or urban. rural = 1 and urban = 2
 gender ; migrant's gender. female = 1 male = 2
 originstate ;migrant's state of origin
 los ; length of stay
 stay ;stay so far
]
;;INITIALIZATION OF MIGRATION MODULE
to setup
__clear-all-and-reset-ticks ;clear everything from previous runs
set time 0
set pop 100
set everpop 100
crt pop
set numstate 5 ; number of origin states
set statelist [0 1 2 3 4 5] ; test with five states. add "0" on zeroth position to simplify reference to elements.
Eventually expand it to 34
set originstatepr [0 0.2 0.5 0.7 0.9 1.0] ; cumulative probability of migrant's state of origin. Start with "0" and
items will be exactly one more than number of states
set stateruralpr [0 0.1 0.2 0.3 0.4 0.5] ; state specific probability of rural or urban status
set stateruralfemalepr [0 0.7 0.7 0.7 0.7 0.7] ;state specific rural migrants gender probability
set stateurbanfemalepr [0 0.3 0.3 0.3 0.3 0.3] ;state specific urban migrants gender probability
set numreason 7; number of reasons for migration
set reasonlist [0 1 2 3 4 5 6 7]
set stateruralreasonpr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0; first zeros
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0 ; first zero;reason probability for state 1 rural
    0 0.2 0.4 0.6 0.7 0.8 0.9 1.0 ; first zero ;reason probability for state 2 rural
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
];rural reasons stop here

```

```

set stateurbanreasonpr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 ;urban reasons start here. first zeros
    0 0.2 0.5 0.6 0.7 0.8 0.9 1.0 ;first zero;reason probability for state 1 urban
    0 0.3 0.5 0.6 0.7 0.8 0.9 1.0
    0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
    0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
    0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
]; start with "0"
set stateruralreasonfemalepr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0; first zeros
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0 ; first zero;female probability for state 1 rural;
    0 0.8 0.6 0.6 0.7 0.7 0.8 1.0
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
    0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
]; rural reasons stop here
set stateurbanreasonfemalepr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
    0 0.4 0.2 0.6 0.7 0.8 0.9 1.0 ;urban reasonwise females state 1
    0 0.2 0.5 0.6 0.7 0.8 0.9 1.0 ;urban reasonwise females state 2
    0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
    0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
    0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
]; start with "0"
end
;;SIMULATION RUN OF MIGRATION MODULE
to go
set pop newpop
create-migrants
set everpop everpop + nm
out-migrate
set newpop count turtles
tick
update-migrants
set time time + 1
if (time > T) [stop]
end
;; TO CREATE MIGRANTS
to create-migrants
set nm random-poisson AnnualMigrationRate
set nm nm * (1 + InflationaryIndex)
crt nm
[ set los random-exponential avglos
set stay 0
let s random-float 1 ; state of origin starts here
set y 1
while [y < (numstate + 1)]
[if (s < item y originstatepr) and (s > item (y - 1) originstatepr)
[set originstate item y statelist
let sr random-float 1 ; rural urban status starts here
ifelse sr < item y stateruralpr
[set ru 1
let rrm random-float 1; reason for migration starts here
set za 1
while [za < (numreason + 1)]
[if (rrm < item (((numreason + 1) * y) + za) stateruralreasonpr) and (rrm > item (((numreason + 1) * y) + (za
- 1)) stateruralreasonpr)
[set reasonmig item za reasonlist
let rrmg random-float 1; gender starts here
ifelse (rrmg < item (((numreason + 1) * y) + za) stateruralreasonfemalepr) and (rrmg > item (((numreason
+ 1) * y) + (za - 1)) stateruralreasonfemalepr)

```

```

        [set gender 1][set gender 2]
      ]
      set za za + 1]
    ]
    [set ru 2
    let urm random-float 1; reason for migration starts here
    set zb 1
    while [zb < (numreason)]
      [if (urm < item (((numreason + 1) * y) + zb) stateurbanreasonpr) and (urm > item (((numreason + 1) * y) +
(zb - 1)) stateurbanreasonpr)
        [set reasonmig item zb reasonlist
        let urmg random-float 1; gender starts here
        ifelse (urmg < item (((numreason + 1) * y) + zb) stateurbanreasonfemalepr) and (urmg > item
(((numreason + 1) * y) + (zb - 1)) stateurbanreasonfemalepr)
          [set gender 1][set gender 2]
        ]
        set zb zb + 1]
      ]
    ]
    set y y + 1
  ]
]
end
;; UPDATE-MIGRANTS
to update-migrants
  ask turtles
    [set stay stay + 1]
  end
;;OUT-MIGRATION
to out-migrate
  ask turtles [if stay > los [die] ]
end

```

## Appendix 1C: Population Dynamics Module

```
;;INITIALIZATION OF MIGRATION MODULE
breed [natives native]
breed [migrants migrant]

to setup
  _clear-all-and-reset-ticks ;clear everything from previous runs
  set n 35
  set k 0
  set m 2 * (lifeexp - n)
  crt InitNativePop [set breed natives set age random n set life n + random m set los random-exponential avglos
  set stay 0]
  crt InitMigrantPop [set breed migrants set age random n set life n + random m set los random-exponential
  avglos set stay 0]
  set meanage mean [age] of turtles
  set pop count natives
  set everpop 0

set time 0
set pop 0
set everpop 0
set numstate 5 ; number of origin states
set statelist [0 1 2 3 4 5] ; test with five states. add "0" on zeroth position to simplify reference to elements.
Eventually expand it to 34
set originstatepr [0 0.2 0.5 0.7 0.9 1.0] ; cumulative probability of migrant's state of origin. Start with "0" and
items will be exactly one more than number of states
set stateruralpr [0 0.1 0.2 0.3 0.4 0.5] ; state specific probability of rural or urban status
set stateruralfemalepr [0 0.2 0.2 0.2 0.2 0.2] ;state specific rural migrants gender probability
set stateurbanfemalepr [0 0.7 0.7 0.7 0.7 0.7] ;state specific urban migrants gender probability
set numreason 7; number of reasons for migration
set reasonlist [0 1 2 3 4 5 6 7]
set stateruralreasonpr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0; first zeros
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0 ; first zero;reason probability for state 1 rural
  0 0.2 0.4 0.6 0.7 0.8 0.9 1.0 ; first zero ;reason probability for state 2 rural
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
];rural reasons stop here
set stateurbanreasonpr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 ;urban reasons start here. first zeros
  0 0.2 0.5 0.6 0.7 0.8 0.9 1.0 ;first zero;reason probability for state 1 urban
  0 0.3 0.5 0.6 0.7 0.8 0.9 1.0
  0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
  0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
  0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
]; start with "0"
set stateruralreasonfemalepr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0; first zeros
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0 ; first zero;female probability for state 1 rural;
  0 0.8 0.6 0.6 0.7 0.7 0.8 1.0
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
  0 0.1 0.2 0.3 0.4 0.5 0.6 1.0
]; rural reasons stop here
set stateurbanreasonfemalepr [0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
  0 0.4 0.2 0.6 0.7 0.8 0.9 1.0 ;urban reasonwise females state 1
  0 0.2 0.5 0.6 0.7 0.8 0.9 1.0 ;urban reasonwise females state 2
```

```

0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0 0.4 0.5 0.6 0.7 0.8 0.9 1.0
]; start with "0"
update-variables
end
;;VARIABLE DECLARATION
globals
[time
pop ; total population at time t
everpop ;total population including those who died
newpop ; total population after the tick is over
death ;death
everdeath ;total deaths
nb ;number of new births placeholder for each tick
nm ;number of new migrants placeholder for each tick
deathrate
migrantpop
nativepop
numcitizens

statelist ; list of states of origin
originstatepr ; cumulative probability of migrant's state of origin
stateruralpr ; state specific probability of rural or urban status
stateruralfemalepr ;state specific rural migrants gender probability
stateurbanfemalepr ;state specific urban migrants gender probabiliy
reasonlist ; reason for migration list
stateruralreasonpr ; state specific rural-urban migrants reason probability
stateurbanreasonpr ; state specific rural-urban migrants reason probability
stateruralreasonfemalepr ;state specific rural-urban migrants reasonwise female probability
stateurbanreasonfemalepr ;state specific rural-urban migrants reasonwise female probability
y ; temp variable
za ; temp variable
zb ; temp variable
numstate ; number of states
numreason ; number of resason

n
m
k
meanage
]
turtles-own
[age
stay
reasonmig
ru ; rural or urban. rural = 1 and urban = 2
gender ; migrant's gender. female = 1 male = 2
originstate ;migrant's state of origin
life
los
]
;;SIMULATION RUN OF NATURAL GROWTH MODULE
to go
set pop newpop
newbirth
newmigrants
set everpop everpop + nb + nm

```

```

kill-citizens
out-migrate
set newpop count turtles
set time time + 1
update-citizens
set meanage mean [age] of turtles
update-variables
if ticks = T [stop]
tick
end
;; TO CREATE natives
to newbirth
set nb random-poisson (CrudeBirthrate * pop / 1000)
crt nb
[set breed natives
set life n + random m
set age 0
set los random-exponential avglos
set stay 0
]
end
to newmigrants
set nm random-poisson avgmigrationrate
set nm nm * (1 + InflationIndex)
crt nm
[set breed migrants
set age k + random n
set life n + random m
set los random-exponential avglos
set stay 0

let s random-float 1 ; state of origin starts here
set y 1
while [y < (numstate + 1)]
[if (s < item y originstatepr) and (s > item (y - 1) originstatepr)
[set originstate item y statelist
let sr random-float 1 ; rural urban status starts here
ifelse sr < item y stateruralpr
[set ru 1
let rrm random-float 1; reason for migration starts here
set za 1
while [za < (numreason + 1)]
[if (rrm < item (((numreason + 1) * y) + za) stateruralreasonpr) and (rrm > item (((numreason + 1) * y) + (za
- 1)) stateruralreasonpr)
[set reasonmig item za reasonlist
let rrmg random-float 1; gender starts here
ifelse (rrmg < item (((numreason + 1) * y) + za) stateruralreasonfemalepr) and (rrmg > item (((numreason
+ 1) * y) + (za - 1)) stateruralreasonfemalepr)
[set gender 1][set gender 2]
]
set za za + 1]
]
[set ru 2
let urm random-float 1; reason for migration starts here
set zb 1
while [zb < (numreason)]
[if (urm < item (((numreason + 1) * y) + zb) stateurbanreasonpr) and (urm > item (((numreason + 1) * y) +
(zb - 1)) stateurbanreasonpr)

```

```

    [set reasonmig item zb reasonlist
    let urmg random-float 1; gender starts here
    ifelse (urmg < item (((numreason + 1) * y) + zb) stateurbanreasonfemalepr) and (urmg > item
(((numreason + 1) * y) + (zb - 1)) stateurbanreasonfemalepr)
    [set gender 1][set gender 2]
    ]
    set zb zb + 1]
  ]
]
set y y + 1
]
end
;; UPDATE-NATIVES
to update-citizens
  ask turtles
    [set age age + 1]
  end
to update-migrants
  ask migrants
    [set stay stay + 1]
  end

;;DEATH
to kill-citizens
  set death count turtles with [age > life]
  set everdeath everdeath + death
  ask turtles [if age > life [die]]
end

;;OUT-MIGRATION
to out-migrate
  ask turtles [if stay > los [die] ]
end

to update-variables
  if pop > 0 [
    set deathrate death / (pop / 1000)]
  set migrantpop count migrants
  set nativepop count natives
  set numcitizens count turtles
end

```

## Appendix 2: Housing Dynamics Module

```
;;SECTION 1. INITIALIZATION
;*****
breed [developers developer] ; developers hold a vacant property. Add to existing housing stock on that site.
Holds it until all units are occupied.
breed [households household] ; households. Make their housing decisions.
to setup ;initial population and environment setup
  ;; (for this model to work with NetLogo's new plotting features,
  ;; _clear-all-and-reset-ticks should be replaced with clear-all at
  ;; the beginning of your setup procedure and reset-ticks at the end
  ;; of the procedure.)
  _clear-all-and-reset-ticks ;clear remains of previous runs
  set max-rent 1000 ; to set maximum rent of a land-parcel at the start of simulation
  set min-rent max-rent / initialinequality ; to set minimum rent of a land-parcel at the start of simulation.
  Calculated based on initial inequality level.
  ask patches [set num-units 1] ;to set initial number of housing units per patch. the value changes for some
  patches as simulation progresses.
  ask patches [set available? true] ;to set initial availability
  ask patches [set occupied? false] ;to set initial occupancy status
  ask patches [set num-occupants 0] ;to set initial occupancy levels
  ask patches [set slum-occupants 0] ;to set initial slum occupancy
  ask patches [set slum? false] ;to set initial slum status
  ;;CREATE POLITICAL WARDS
  ask patches with [pxcor > -26 and pxcor < -8 and pycor > -26 and pycor < -8] [set ward 1 set pcolor 71] ;ward 1
  - peripheral ward
  ask patches with [pxcor > -9 and pxcor < 9 and pycor > -26 and pycor < -8] [set ward 2 set pcolor 72] ;ward 2 -
  peripheral ward
  ask patches with [pxcor > 8 and pxcor < 26 and pycor > -26 and pycor < -8] [set ward 3 set pcolor 73] ;ward 3 -
  peripheral ward
  ask patches with [pxcor > -26 and pxcor < -8 and pycor > -9 and pycor < 9] [set ward 4 set pcolor 74] ;ward 4 -
  peripheral ward
  ask patches with [pxcor > -9 and pxcor < 9 and pycor > -9 and pycor < 9] [set ward 5 set pcolor 75] ;ward 5 -
  central ward
  ask patches with [pxcor > 8 and pxcor < 26 and pycor > -9 and pycor < 9] [set ward 6 set pcolor 76] ;ward 6 -
  peripheral ward
  ask patches with [pxcor > -26 and pxcor < -8 and pycor > 8 and pycor < 26] [set ward 7 set pcolor 77] ;ward 7 -
  peripheral ward
  ask patches with [pxcor > -9 and pxcor < 9 and pycor > 8 and pycor < 26] [set ward 8 set pcolor 78] ;ward 8 -
  peripheral ward
  ask patches with [pxcor > 8 and pxcor < 26 and pycor > 8 and pycor < 26] [set ward 9 set pcolor 79] ;ward 9 -
  peripheral ward
  ;;INITIAL LAND PARCEL AND POPULATION CREATION
  ask n-of ((percent-prime-land * count patches with [abs pxcor <= initialcitylimit and abs pycor <=
  initialcitylimit] / 100) + (percent-inappropriate-land * count patches with [abs pxcor < initialcitylimit and abs
  pycor < initialcitylimit] / 100)) patches with [abs pxcor < initialcitylimit and abs pycor < initialcitylimit] ;set up
  patches within user-specified initial city limit
  [ifelse random-float 1 < (percent-prime-land / (percent-prime-land + percent-inappropriate-land)) ;to declare
  randomly selected patches in the city-center as prime or inadequate land (proportion is user-specified)
  [set rent max-rent sprout 1 [set breed households set old 0 set stay 0 set num-houses 1]] ;create initial land
  parcels with highest-rent
  [set rent min-rent sprout 1 [set breed households set old 0 set stay 0 set num-houses 1]] ;land parcels with
  lowest-rent
  ask patches with [rent = 0 and abs pxcor <= initialcitylimit and abs pycor <= initialcitylimit]
  [set rent random-float 1 * (max-rent - min-rent) sprout 1 [set breed households set old 0 set stay 0 set num-
  houses 1]] ;patches with rent varying (normally distributed) between highest-rent and lowest-rent
```

```

ask patches [set rent-payable rent] ;initially rent is the rent-payable. rent-payable changes and varies from
rent during simulation.
ask households [set income 3.3 * [rent] of patch-here
  ifelse random-float 1 < informalityindex [set informal? true][set informal? false]
] ;initially the incomes are sent in accordance with the housing unit they are occupying. i.e. most prime land
occupiers are rich, inadequate land occupiers are poor.
ask households [update-class update-searching update-willingnesstoshare]
ask patches [update-occupancy update-availability update-resicat update-slumstatus]
;;INITIATE GLOBAL VARIABLES
set time 0
set cityincome sum [income] of households
update-variables
end
;;RENDER INITIAL RENT AS CHOROPLETH
to RentMap
  ask patches [recolor-patch]
end
;;END OF SECTION 1. INITIALIZATION
,*****

;;SECTION 2. VARIABLE DECLARATION
,*****
;GLOBAL VARIABLE DECLARATION
globals
[
  num-developers ;number of developers in the city (for monitoring purpose during model development and
verification)
  max-rent ;initial maximum rent
  min-rent ;initial lowest rent (calculated based on inequality level specified by the user).
  highestrent;highest rent in the city during the simulation (most prime property)
  lowestrent;lowest rent in the city during the simulation (most inappropriate property)
  red-averagerent; to keep track of average rents of poor people in the city
  green-averagerent; to keep track of average rents of rich people in the city
  blue-averagerent; to keep track of average rents of middle-class people in the city
  red-count; to keep track of number of poor people
  blue-count; to keep track of number of middle-class people
  green-count; to keep track of number of rich people
  red-density; to keep track of poor people's housing density
  blue-density; to keep track of middle-class people's housing density
  green-density; to keep track of rich people's housing density
  slum-density; to keep track of density in slums
  central-slum-density
  periphery-slum-density
  avg-density; average density in the city
  num-searching ;to keep track of how many people are searching house during simulation
  time ;to keep track of simulation time lapsed. Unit is a year.
  cityincome ;total income of the entire economy. updated every iteration.

  income-red ;share of income of lower income group people
  income-blue ;share of income of middle income group people
  income-green ;share of income of higher income group people
  avg-income ;average income
  avg-income-red ; average income of poor
  avg-income-blue ;average income of middle-class
  avg-income-green ;average income of rich
  population ;total population of the city
  slumpop ;total slum population of the city

```

```

centralslumpop ; slum population in the central city
peripheralslumpop ;slum population in the periphery
slumpoppercent ; percentage slum population  of the city
num-slums ; number of slums in the city
smallest-slum
largest-slum
central-num-slums ; number of slums in central city
peripheral-num-slums ;number of slums in peripheral city
centralslumpoppercent ; central city slum population
peripheralslumpoppercent ; peripheral slum population
slumareapercent
centralslumareapercent
peripheralslumareapercent
ward1pop ;ward 1 population
ward2pop ;ward 2 population
ward3pop ;ward 3 population
ward4pop ;ward 4 population
ward5pop ;ward 5 population
ward6pop ;ward 6 population
ward7pop ;ward 7 population
ward8pop ;ward 8 population
ward9pop ;ward 9 population
ward1slumpop ;ward 1 slum population
ward2slumpop ;ward 2 slum population
ward3slumpop ;ward 3 slum population
ward4slumpop ;ward 4 slum population
ward5slumpop ;ward 5 slum population
ward6slumpop ;ward 6 slum population
ward7slumpop ;ward 7 slum population
ward8slumpop ;ward 8 slum population
ward9slumpop ;ward 9 slum population
ward1slumpoppercent ;ward 1 slum population in percent
ward2slumpoppercent ;ward 2 slum population in percent
ward3slumpoppercent ;ward 3 slum population in percent
ward4slumpoppercent ;ward 4 slum population in percent
ward5slumpoppercent ;ward 5 slum population in percent
ward6slumpoppercent ;ward 6 slum population in percent
ward7slumpoppercent ;ward 7 slum population in percent
ward8slumpoppercent ;ward 8 slum population in percent
ward9slumpoppercent ;ward 9 slum population in percent
]
;TURTLES (AGENTS) VARIABLE DECLARATION
developers-own ;developer agents' variables
[
no-role? ; to see if they have no role on that patch
]
households-own ;household agents' variables
[
income ;households income
informal? ; household works in informal sector? bulion.
searching? ; if migrant is searching for new house - set to true when migrant arrives first time or dissatisfied
with the place and set to false once found the place
willing? ; if resident is willing to share the house in face of rising rents
class-updated? ;temporary variable to make sure that each person's class is updated at the end of each iteration
old ; to record how long resident has been at this city? ;for further analysis on residential mobility
stay; to record how long resident has been at this site? ;only available for the current residence; for further
analysis on residential mobility
num-houses ;to record how many houses households have changed ;for further analysis on residential mobility

```

```

]
patches-own
[
  occupied? ; occupancy status of a property
  available? ; availability status of housing units. a patch might be available even if there are occupants if number
of units on that patch is higher than current occupancy
  num-occupants ; number of occupants on a particular property
  num-units ; number of possible units if a developer holds the property
  slum-occupants ; number of poor occupants on a particular property
  rent ; economic rent of the property
  rent-payable ; if people start sharing the house, this variable shows the rent that each person is paying on that
property (used for people making decision on housing - they are not worried about the complete rent, they are
worried how much they would pay in a shared accommodation) rent payable is lower for poor people if they live in
slums (in proportion with how many poor people live there)
  slum? ; if site is squatted set to true otherwise false (shared facilities are shown as squatted - however, sharing
also means apartment building on a land-parcel, not differentiated in this model yet)
  rescat ; to record residential category. category 3 if occupied by poor, 2 if by middle-class and 1 if rich (useful to
calculate density)
  ward ; to record political ward number of city
]
;;END OF SECTION 2. VARIABLE DECLARATION
,*****

;; SECTION 3. SIMULATION
,*****
,
to Slumulate
  create-new-households ; to create new set of agents based on population growth rate
  settle-households ; to get homes for people who are searching home
  update-households ; update all households at the end of the iteration
  update-patches ; update all patches at the end of the iteration
  update-developers ; update all developers at the end of the iteration
  update-cityincome
  update-variables ; update all variables at the end of the iteration
  update-time
  if (time > SimulationRuntime) [stop] ; to stop at user-specified time period.
  tick
  if time > 3 [do-plots] ; to ignore initial burn-in period, we start plotting after 3 time periods.
end
;PROCEDURES RELATED TO TURTLES (AGENTS)
,*****
;HOUSEHOLDS
,*****
;CREATE NEW HOUSEHOLDS
to create-new-households
  crt (popgrowthrate * population) / 100 ; create new households based on user-specified population growth rate
  [
    set breed households
    set income random-exponential avg-income ; assign income to new agent based on current income
distribution
    ifelse random-float 1 < informalityindex [set informal? true][set informal? false] ; set job-type
    update-class
    update-willingnesstoshare
    set searching? true
    set old 0
    set stay 0
    set num-houses 0

```

```

] ; new arrival of a migrant on a random place in the city center. set to start searching a house and initially not
willing to share. migration rate set by the user.
end
;SETTLE HOUSEHOLDS
to settle-households
  ask households with [searching?]
  ; move-to patch 0 0; start from center
  [move-to patch 0 0
   find-house] ;and then roam around to search a house that is within income-constraints
end
;HOUSE SEARCH PROCESS
to find-house
  rt random-float 360 ;all directions
  fd random-float 1 ;one step at a time
  if (any? households-here with [color != [color] of myself])
    or (rent-payable > 0.3 * income)
    or (not available?) ;;
    [find-house] ;if rent is higher than a person can pay or already occupied by people who wouldn't want to
share, keep searching
    move-to patch-here ; once found a patch, move here
    set searching? false ;update search status
    set stay 0 ;restart how long household has lived here
    set num-houses (num-houses + 1); number of houses a household has changed after arriving in the city. for
further analysis on residential mobility.
    ask patch-here [update-occupancy update-availability update-slumstatus update-resicat update-rent-payable]
  ; to update the newly occupied patch before the next agent starts the search.
end
;UPDATE HOUSEHOLDS
to update-households
  ask households [update-income update-willingnesstoshare update-searching update-class update-old update-
stay]
end
;UPDATE INCOME OF HOUSEHOLDS
to update-income
  if (informal? = true) and (color = red) [set income income + (economicgrowthrate / 100) * 0.1 * income]
  if (informal? = false) and (color = red) [set income income + (economicgrowthrate / 100) * income]
  if (color = green) or (color = blue) [set income income + (economicgrowthrate / 100) * income]
end
;UPDATE WILLINGNESS TO SHARE
to update-willingnesstoshare
  ifelse rent-payable > ((1 - price-sensitivity) * 0.3 * income)
    [set willing? true]
    [set willing? false]
  if (color = green or color = blue) [set willing? false]
end
;UPDATE SEARCH STATUS
to update-searching
  ifelse rent-payable > (1 + staying-power) * 0.3 * income
    [set searching? true create-developer]
    [set searching? false]
  if (any? other households-here with [color != [color] of myself])
    [set searching? true]
end
;UPDATE INCOME CLASS
to update-class
  if income > (mean [income] of households + 1.1 * standard-deviation [income] of households) [set color green
set class-updated? true]

```

```

    if income < (mean [income] of households - 0.1 * standard-deviation [income] of households) [set color red
set class-updated? true]
    if (income < (mean [income] of households + 1.1 * standard-deviation [income] of households))
        and (income > (mean [income] of households - 0.1 * standard-deviation [income] of households))[set color
blue set class-updated? true]
    end
;UPDATE NUMBER OF YEARS STAYED IN THE CITY
to update-old
    set old (old + 1)
end
;UPDATE NUMBER OF YEARS STAYED IN THIS PLACE
to update-stay
    set stay (stay + 1)
end
;UPDATE RENT CHOROPLETH
to recolor-patch ; patch procedure -use color to indicate rent level
    set pcolor scale-color yellow rent lowestrent highestrent
    if (slum? = true) [set pcolor grey]
end
;DEVELOPERS
,*****
to create-developer
    ask households-here
    [if not any? developers-here
        and not any? other households-here
        and Develop = true
        [
            hatch 1
            [
                set breed developers set no-role? false set num-units num-units + int random-float 3 set available? true
set resicat 0
            ]
        ]
    ]
end
to update-developers
    ask developers [check-no-role? exit]
end
;CHECK ROLE
to check-no-role?
    ask developers [if (num-units = num-occupants)[set no-role? true]]
    ask developers [if (num-units < num-occupants)[set no-role? true]]
end
;EXIT
to exit
    if (no-role? = true) [die]
end
;;END OF PROCEDURES RELATED TO TURTLES (AGENTS)
,,*****

;;PROCEDURES RELATED TO PATCHES (SPATIAL ENVIRONMENT)
,*****
to update-patches
    diffuse rent diffusion-rate ;neighborhood effect of property prices.
    ask patches [update-rent update-occupancy update-resicat update-slumstatus update-availability update-rent-
payable recolor-patch]
end
;UPDATE RENT

```

```

to update-rent
  set rent rent + ((0.5 * economicgrowthrate) / 100) * rent
end
;UPDATE OCCUPANCY LEVEL AND OCCUPANCY STATUS
to update-occupancy
  set num-occupants count households-here ;number of occupants sharing the property
  ifelse num-occupants > 0 [set occupied? true][set occupied? false]
end
;UPDATE RESIDENTIAL CATEGORY
to update-resicat
  if num-occupants > num-units [set resicat 4]
  if (any? households-here with [color = red]) and (slum? = false) [set resicat 3]
  if (any? households-here with [color = blue]) and (slum? = false) [set resicat 2]
  if (any? households-here with [color = green]) and (slum? = false) [set resicat 1]
  if num-occupants = 0 [set resicat 0]
end
;UPDATE SLUM STATUS
to update-slumstatus
  if num-occupants > num-units [set slum? true set slum-occupants num-occupants]
  if num-occupants < num-units [set slum? false set slum-occupants 0]
  if num-occupants = num-units [set slum? false set slum-occupants 0]
end
;UPDATE AVAILABILITY
to update-availability
  if (any? developers-here)
  [
    if num-occupants < num-units [set available? true]
    if num-occupants = num-units [set available? false]
  ]

  if (not any? developers-here)
  [
    ifelse num-occupants > 0
      [if (any? households-here with [willing? = false]) [set available? false]] ; to declare a land parcel as
      occupied (and hence not available for people searching home)
      [set occupied? false set available? true]
    ] ;otherwise show property as available
  end
;UPDATE RENT PAYABLE PER UNIT
to update-rent-payable
  if (any? developers-here) [set rent-payable (rent / num-units)]
  if (not any? developers-here)
  [
    if not slum? [set rent-payable rent / num-units]
    if slum?
    [
      set rent-payable rent / num-occupants
      if (Politics = true)
      [
        if (ward = 1) [set rent-payable ((1 - ward1slumpoppercent) * (rent-payable))]
        if (ward = 2) [set rent-payable ((1 - ward2slumpoppercent) * (rent-payable))]
        if (ward = 3) [set rent-payable ((1 - ward3slumpoppercent) * (rent-payable))]
        if (ward = 4) [set rent-payable ((1 - ward4slumpoppercent) * (rent-payable))]
        if (ward = 5) [set rent-payable ((1 - ward5slumpoppercent) * (rent-payable))]
        if (ward = 6) [set rent-payable ((1 - ward6slumpoppercent) * (rent-payable))]
        if (ward = 7) [set rent-payable ((1 - ward7slumpoppercent) * (rent-payable))]
        if (ward = 8) [set rent-payable ((1 - ward8slumpoppercent) * (rent-payable))]
        if (ward = 9) [set rent-payable ((1 - ward9slumpoppercent) * (rent-payable))]
      ]
    ]
  ]

```

```

    ]
  ]
end
;;END OF PROCEDURES RELATED TO PATCHES (SPATIAL ENVIRONMENT)
,*****

;;GLOBAL VARIABLES UPDATE
,*****
to update-variables
  set red-count count households with [color = red]
  set green-count count households with [color = green]
  set blue-count count households with [color = blue]

  set red-density red-count / (count patches with [resicat = 3])
  set blue-density blue-count / (count patches with [resicat = 2])
  set green-density green-count / (count patches with [resicat = 1])
  set avg-density (count households) / (count patches with [occupied? = true])

  set red-averagerent mean [rent-payable] of households with [color = red] ;to keep track of rents during
simulation in this developing stage. no analytical interest.
  set green-averagerent mean [rent-payable] of households with [color = green] ;to keep track of rents during
simulation in this developing stage. no analytical interest.
  set blue-averagerent mean [rent-payable] of households with [color = blue] ;to keep track of rents during
simulation in this developing stage. no analytical interest.
  set highestrent max [rent] of patches ;to calculate highest rent in the city
  set lowestrent min [rent] of patches ;to calculate lowerst rent in the city

  set num-searching (count households with [searching?])

  set population (count households) ;total population of the city

  set avg-income-red mean [income] of households with [color = red]
  set avg-income-green mean [income] of households with [color = green]
  set avg-income-blue mean [income] of households with [color = blue]
  set avg-income cityincome / population

  set slumpop sum [slum-occupants] of patches ;total slum population of the city
  set centralslumpop sum [slum-occupants] of patches with [ward = 5]
  set peripheralslumpop sum [slum-occupants] of patches with [ward != 5]
  set slumpoppercent (slumpop / population)
  set num-slums count patches with [slum? = true]; count number of slum patches
  set central-num-slums count patches with [slum? = true and ward = 5]
  set peripheral-num-slums count patches with [slum? = true and ward != 5]
  set slumareapercent (num-slums / count patches with [occupied? = true]) * 100
  set centralslumareapercent (count patches with [slum? = true and ward = 5] / count patches with [occupied? =
true and ward = 5]) * 100
  if count patches with [occupied? = true and ward != 5] > 0
    [set peripheryslumareapercent (count patches with [slum? = true and ward != 5] / count patches with
[occupied? = true and ward != 5]) * 100]

  if num-slums > 0 [set slum-density slumpop / num-slums] ;slum density

  if num-slums > 0 [set smallest-slum min [slum-occupants] of patches with [slum? = true]]
  if num-slums > 0 [set largest-slum min [slum-occupants] of patches with [slum? = true]]

  if central-num-slums > 0 [set central-slum-density centralslumpop / central-num-slums]

```

```

if peripheral-num-slums > 0 [set periphery-slum-density peripheralslumpop / peripheral-num-slums]

set num-developers (count developers) ;keep track of properties held by developers

set ward1pop sum [num-occupants] of patches with [ward = 1] ;ward-wise population
set ward2pop sum [num-occupants] of patches with [ward = 2]
set ward3pop sum [num-occupants] of patches with [ward = 3]
set ward4pop sum [num-occupants] of patches with [ward = 4]
set ward5pop sum [num-occupants] of patches with [ward = 5]
set ward6pop sum [num-occupants] of patches with [ward = 6]
set ward7pop sum [num-occupants] of patches with [ward = 7]
set ward8pop sum [num-occupants] of patches with [ward = 8]
set ward9pop sum [num-occupants] of patches with [ward = 9] ;ward-wise poulation ends

set ward1slumpop sum [slum-occupants] of patches with [ward = 1];ward-wise slum population
set ward2slumpop sum [slum-occupants] of patches with [ward = 2]
set ward3slumpop sum [slum-occupants] of patches with [ward = 3]
set ward4slumpop sum [slum-occupants] of patches with [ward = 4]
set ward5slumpop sum [slum-occupants] of patches with [ward = 5]
set ward6slumpop sum [slum-occupants] of patches with [ward = 6]
set ward7slumpop sum [slum-occupants] of patches with [ward = 7]
set ward8slumpop sum [slum-occupants] of patches with [ward = 8]
set ward9slumpop sum [slum-occupants] of patches with [ward = 9];ward-wise slum poulation ends

if ward1pop > 0 [set ward1slumpoppercent ward1slumpop / ward1pop] ;ward 1 slum population in percent
(0 to 1)
if ward2pop > 0 [set ward2slumpoppercent ward2slumpop / ward2pop];ward 2 slum population in percent
if ward3pop > 0 [set ward3slumpoppercent ward3slumpop / ward3pop];ward 3 slum population in percent
if ward4pop > 0 [set ward4slumpoppercent ward4slumpop / ward4pop];ward 4 slum population in percent
if ward5pop > 0 [set ward5slumpoppercent ward5slumpop / ward5pop];ward 5 slum population in percent
if ward6pop > 0 [set ward6slumpoppercent ward6slumpop / ward6pop];ward 6 slum population in percent
if ward7pop > 0 [set ward7slumpoppercent ward7slumpop / ward7pop];ward 7 slum population in percent
if ward8pop > 0 [set ward8slumpoppercent ward8slumpop / ward8pop];ward 8 slum population in percent
if ward9pop > 0 [set ward9slumpoppercent ward9slumpop / ward9pop];ward 9 slum population in percent

set centralslumpoppercent (ward5slumpoppercent) * 100
if (sum [num-occupants] of patches with [ward != 5] > 0 )
[set peripheryslumpoppercent (sum [slum-occupants] of patches with [ward != 5]) / (sum [num-occupants]
of patches with [ward != 5]) * 100]
end
;;UPDATE TIME
to update-time
set time (time + 1)
end
;;UPDATE CITY INCOME
to update-cityincome
set cityincome cityincome + (economicgrowthrate / 100) * cityincome
end
;; UPDATE PLOTS
,*****
,
to do-plots
set-current-plot "Housing Density"
set-current-plot-pen "Lower Income Group"
plot red-density
set-current-plot-pen "Middle Income Group"
plot blue-density
set-current-plot-pen "Higher Income Group"

```

```

plot green-density
set-current-plot-pen "Slums"
plot slum-density
set-current-plot "Slum Size Distribution"
set-current-plot-pen "Slum Size"
histogram [slum-occupants] of patches with [slum? = true]
set-current-plot "% Slum Population"
set-current-plot-pen "City"
plot slumpop / population * 100
set-current-plot-pen "Central"
plot centralslumpoppercent
set-current-plot-pen "Periphery"
plot peripheryslumpoppercent
end
;; END OF SECTION 3. SIMULATION
*****
;;END OF PROGRAM
*****

```

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## REFERENCES

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