URBAN DEVELOPMENT THROUGH THE LENS OF AGENT-BASED MODELLING

by

Niloofar Bagheri Jebelli
A Thesis
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Master of Arts
Interdisciplinary Studies

Committee:

________________________________ Director

____

____

________________________________ Program Director

________________________________ Dean, College of Humanities and Social Sciences

Date: ____________________________ Fall Semester 2017
George Mason University
Fairfax, VA

Urban Development through the Lens of Agent-based Modelling

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts Interdisciplinary Studies at George Mason University

by

Niloofar Bagheri Jebelli
Bachelor of Anthropology
University of Maryland, College Park, 2013

Director: Andrew Crooks, Associate Professor
Department of Computational and Data Sciences, College of Science

Fall Semester 2017
George Mason University
Fairfax, VA

Dedication

This is dedicated to my dear Parents, Fereshteh and Hassan, and my love, Yaser for all their support and understanding through this journey.

Acknowledgements

I would like to thank the many friends, relatives, and supporters who have made this happen. I would like to thank Dr. Andrew Crooks, for his advise, for continually assisting me to navigate my path through this degree, this thesis and on an academic life. I appreciate your patience, educational guidance and timely advices. I would like to thank Dr. William G. Kennedy, for his advice, being there to answer my questions and agreeing to be part of the committee for this thesis. I would like to thank Dr. Qing Tian, for agreeing to be part of the committee for this thesis. I would also like to thank Dr. Matthew Rice and Aaron Mulhollen for helping me apply the ArcGIS results to the model presented in this thesis.

Table of Contents

List of Tables

List of Figures

List of Equations

List of Abbreviations

Agent-Based Model .... ABM
Cellular Automata .... CA
Central Business District .... CBD
Coldwell Banker Richard Ellis .... CBRE
Capitalized Rent .... CR
California Urban Futures model .... CUF
California Urban and Biodiversity Analysis .... CURBA
Dynamic Urban Evolutionary Model .... DEUM
Economic Policy Institute .... EPI
Floor/Area Ratio .... FAR
Geographical Information System .... GIS
Institute of Spatial Planning of the University of Dortmund .... IRPUD
Mayor Muriel Bowser Office if Planning. .... MMBOP
Monitoring Land Use Change .... MOLAND
Metropolitan Regional Information System .... MRIS
Net Operating Income .... NOI
Net Present Value .... NPV
Potential Rent .... PR
Sprawl Moving Rate .... SMR
Systems Dynamics .... SD
Slope, Land Use, Exclusion, Urban Extent, Transportation, Hill shade .... SLEUTH
United States Census Bureau .... USCB
Urban Land Institute .... ULI

Abstract

URBAN DEVELOPMENT THROUGH THE LENS OF AGENT-BASED MODELLING

Niloofar Bagheri Jebelli, MAIS

George Mason University, 2017

Thesis Director: Dr. Andrew Crooks

Cities are ever changing and growing phenomenon with many underlying complexities. Through its life cycle, a city experiences various forms of dynamics. Models allow for a better understanding of such complexities and dynamics. The model developed in this thesis intends to simulate the dynamics of certain processes such as: an urban market, agent interactions in that market, urban growth, sprawl and shrinkage and gentrification. The purpose of this model is to understand the behavioral pattern of the agents and demonstrate the life cycle of a city based on individual agents' actions. This model is significant in its integration of various subsystems creating a larger system while observing developers' behavior. Specifically, the model explores some well-known issues, including the Smith's rent-gap theory, Burgess's concentric zones model of urban growth, and Alonso's bid rent theory. The main results from the model show that the agents move to and reside in properties within their income range, with similar neighbors. This is one of the first models that provides a new lens to explore urban development.

1 Introduction

1.1 Background and Motivation

All cities experience life cycles. They all undergo periods of rise and fall, growth and shrinkage, development and demolition. From the city of Persepolis in ancient Iran to modern cities like New York, cities transform in size (Batty, 2006), form (Batty & Longley, 1994), density (Fujita, 1989), land value (Alonso, 1964), and other factors over time. The etymology of the word 'city' roots in the Latin word 'civitas'. As the original term has changed, so has the definition. According to the Dictionary of Human Geography, a city is defined as "an urban demographic, economic and above all political and jurisdictional unit, usually bigger than a town (Gregory, Johnston, Pratt, Watts, & Whatmore, 2011)."

Many elements come together to define and shape a city. One of the key decision-maker and stakeholder groups is the developers who seize opportunities that arise in the market and implement their visions (Coiacetto, 2000; Geltner, Miller, Clayton, & Eichholtz, 2001). To study, understand and predict their behavior, is to know the future of a city. To predict and locate the areas of interest for developers' next projects, we need to take a few steps back and study the process that leads to the development motivation.

Over the last two decades, a new modeling approach has emerged to simulate urban environments. This approach is that of Agent-Based Modeling (ABM) utilized in various studies (e.g. Jackson, Forest, & Sengupta, 2008; Otter, van der Veen, & de Vriend, 2001; Parker & Filatova, 2008; Schwarz & Ernst, 2009). Per Parker and Filatova (2008), there are three main elements that make ABM the most suitable platform for modelling land market: “a heterogeneous commodity traded by heterogeneous agents, spatial and agent-agent interactions, and non-equilibrium dynamics.” Until today, ABMs have been focused on examining mainly only one aspect of a city cycle. Here, I examine multiple aspects and their interplay with respect to the life cycle of a city.

1.2 Overview of Approach

In order to explore the life cycle of a city, the model I developed in this thesis will rely on and use various real estate development theories, urban economics theories and urban sociology theories. This model will only focus on residential development due to the availability of supporting market data and to maintain a concentrated research case. While including different land uses (e.g. housing, manufacturing, commerce and services, transform in the form of road networks, and vacant land) that are sometimes used in other models (e.g. Batty & Xie, 2005; Batty, Xie, & Sun, 1999) would make the model more realistic, it also adds to its complexity and bounds the process by precise geographical definitions. A more complex and sophisticated model would require extensive data collection, multiple incentives for each agent group interested in each land use, additional rules and a different landscape structure. To focus on the formation of micro-dynamics between agents, this model is designed in an artificial environment, from stylized facts (Kaldor, 1957; Malik, Crooks, Root, & Swartz, 2015; Patel, Crooks, & Koizumi, 2012). Introduced by Kaldor (1957), stylized facts are empirically based realities that can be generalized but carry exceptions. While utilizing real data to set parameters such as: budget, income, and rent, the model aims to examine the development of urban dynamics using assumptions and behavior rules that simplify and abstract the real-world study of the matter in an ABM framework. Geographical factors such as topology are not studied in the model due to their actual and concrete nature which creates a specified rather than general spatial environment.

Every method and theory applied to the model is structured to build a hypothetical city. Agent-based models are structured with different components including: agents, agent attributes, assumptions, and rules as the framework. To form each of these components, I review relevant literature and use the material to create the various pieces of the model. By using exploration elements such as: plots, switches, sliders, and monitors, the model (as discussed in chapter 3) allows us to follow the evolution of the city throughout a simulation.

As the focus of the model is on the life cycle of a city, its design requires multiple phases of development. All these phases rely on an understanding of the urban land market. The urban land market studies that are included in the literature review use existing cities in their case studies while similar to others (Magliocca, 2012; Parker & Filatova, 2008) in many aspects, this model will present a hypothetical city. The phases of the model are each discussed in depth in chapter 2 and implemented in chapter 3. In the first phase (1) the model will demonstrate urban growth[1] based on the Concentric Zone model of Burgess (1925). The city will have multiple circular rings around the Central Business District (CBD) (Burgess, 1925). Residential land prices are inspired by Alonso (1964). The next phase (2) shows the shrinkage (Haase, Haase, Kabisch, Kabisch, & Rink, 2012; Schwarz, Haase, & Seppelt, 2010; Wiechmann & Pallagst, 2012) and decay (Andersen, 2003; Smith, 1979) of the city visible in certain parts. This is followed

[1] Using an ABM framework rather than the Cellular Automata (CA) used by Batty, Xie, & Sun, (1999)

by the third phase (3) where the invasion and succession occurs in the city. Following the decay of the city, certain neighborhoods become less desirable to rent. The desirability factor effects the neighborhood rent negatively. This is where the next phase arises. In the fourth phase (4) gentrification takes place. Gentrification happens either through a bottom-up process of people attracted to the neighborhoods located near the CBD, with low rent prices (Lees, Slater, & Wyly, 2013); or, by developers who recognize the opportunity in the Potential Rent (PR) of the land.

The focus of this research is on the developers' decision-making process similar to the work of Diappi and Bolchi (2008). The developers' goal is to earn profit and increase their Net Operating Income (NOI) (Miles, Netherton, & Schmitz, 2015). To model the developers' decision-making process, I use Smith's (1979) Rent Gap Theory. A Rent gap explains the supply side of the rise of land value and developers' decision to revitalize. The bottom-up process of the population moving back to the neighborhoods explain the demand side of the rise of land value. The model is not sensitive to changes in the capitalization rate[2]. But patterns of segregation based on economic status emerge. The actions of every agent group effect the actions of other agent groups while the environment and all the agent groups have the same dynamics.

1.3 Research Question

As Epstein and Axtell (1996) note, it is observed in many agent-based models, that the actions in the microscopic level, such as an agent's decision-making on which property to rent, can have macroscopic level effects such as a noticeable segregation rising in a neighborhood. The purpose of the research topic is to implement the dynamics and rules

[2] Capitalization rate (cap rate) is "a rate expressed as a percentage, at which a future flow of income is converted into a present value figure" (Miles, Netherton, & Schmitz, 2015).

within a city and observe the unfolding of emergent behaviors. In a way, this research is weaving previous models and theories in the field to discover their validity in an even more complex set of dynamics. The research intends to answer the question: can multiple processes seen in the life cycle of a city be coupled together within an ABM to understand developers? The model presents a platform for agents to interact with each other, their environment and the patterns emerging throughout the life cycle of the city.

As complex systems with interrelated subsystems, cities can be studied focusing on their seemingly independent subsystems and their interdependent nature. Previous models and theories (as will be discussed in chapter 2) examine the processes and subsystems of an urban environment, but as cities comprise of a variety of interacting processes and subsystems, they show novel results when studied as a whole and not in isolation (Heppenstall, Malleson, & Crooks, 2016). The self-organizing subsystems of cities gives rise to a hierarchy that demonstrates the concept of near-decomposability (Simon, 1996). In such self-organizing subsystems, the parts of each subsystem interact with each other more that interacting with other subsystems. Utilizing previous research, this study aims to explore and understand the interactions of the interdependent subsystems of a city in an abstract space.

1.4 Purpose of Thesis

By implementing key urban processes: urban growth, sprawl and shrinkage, and gentrification within an ABM framework, the effects of each dynamic on the other can be observed. Many works have examined an isolated dynamic within urban markets, but not the combination of these dynamics. The intention of this thesis is to demonstrate micro and macro level emergence of behaviors and patterns of complexity in the form of an abstract model of the life cycle of a city. Tracing and linking each dynamic may provide greater understanding on foundational reasons for their emergence as well as integral parameters that the system is sensitive to.

1.5 Thesis Outline

For effective answering of the research question, the thesis has been divided into various sections. A study on the urban dynamics, models demonstrating them and the urban market is provided in chapter 2. Chapter 2 builds the foundation for the implementation of the model and methodology presented in chapter 3. In chapter 4 the model results are demonstrated by representative runs. Chapter 5 discusses the results and their implications.

2 Literature Review

2.1 Introduction

Various efforts have taken place to explain the dynamics of existing or hypothetical cities. The descriptive and mathematical models include works from Burgess's (1925) *urban growth model* to Alonso's (1964) *bid rent theory* and Smith's (1979) *rent gap theory*. Numerous computer simulations and models have been done to examine the issue as well (e.g. Batty & Xie, 2005; Clarke, Gazulis, Dietzel, & Goldstein, 2007; Crooks, 2006; Gilbert, Hawksworth, & Swinney, 2009; Magliocca, 2012). These efforts have developed a rich literature with contributors across fields such as geography, economics, computational social science, etc. Every one of the descriptive, mathematical or computer models unveils and displays one section of the full mechanism of a city. Each one considers a limited number of agents, parameters, rules and assumptions to form a platform for all aspects of the simulation to come together and create a narrative.

To develop a full picture of the life cycle of a city, several models and theories have to be taken into account. The urban dynamics of growth, sprawl, shrinkage and gentrification have been previously examined by researchers. Urban growth has been a topic of interest among researchers developing descriptive and mathematical models dating back to the early twentieth century, to their latest computer simulations and models (Batty & Xie, 2005; Burgess, 1925; Clarke et al., 2007; Hoyt, 1939). Urban sprawl has been modeled in mainly in the past two decades (e.g. Batty, Xie, & Sun, 1999a; Torrens, 2006). Urban shrinkage has been studied and modeled using case studies of various cities across the globe (e.g. Haase et al., 2012; Schwarz et al., 2010; Wiechmann & Pallagst, 2012). Gentrification (Lees et al., 2013) has been studied both from the supply (Smith, 1979) and the demand (Jackson et al., 2008) aspects and modeled for each aspect. Many of these models have been tested for verification, validation and calibration to ensure their accuracy and precision. For example, Batty and Xie (2005) used predefined rules to fix the model parameter values for calibration. For validation, they fitted the model on three different scenarios with data from 1978 to 1990 and tested its predictions from 1990 to 1995 using data independent of its calibration, and then used the model to make various predictions from 1995 to 2030.

Researchers perform various examinations on their models to ensure its accuracy, relevance and soundness. The three main assessments are verification, validation and calibration. Verification – also known as internal validity – is the process of examining whether a model is working as intended by the conceptual model (Cioffi-Revilla, 2017). Verification includes the processes of code walk through, debugging, profiling, and parameter sweep. Validation is the process of examining whether the results from a model match the empirical data (Cioffi-Revilla, 2017). This process can be conducted in a variety of ways, such as: histograms, distribution moments, time series and special indices. Calibration is the tuning of input values to the simulated values to ensure accuracy (Heppenstall, Crooks, See, & Batty, 2012).

As mentioned in the previous chapter, each of the aforementioned urban systems have subsystems that interact with each other to form the life cycle of a city. To understand this life cycle, we need to understand the models and theories mentioned above. Therefore, in the next section the chosen models and theories will be introduced. Section

2.2 will introduce the three models of urban structure (Burgess, 1925; Harris & Ullman, 1945; Hoyt, 1939) to build a foundation on one chosen for the model presented in this research. Section 2.3 will define land use and introduce relevant theories and research (e.g. Alonso, 1964; Fujita, 1989; Parker & Filatova, 2008; Von Thünen, 1966) that base my study of the urban dynamics. Section 2.4 will include the four aforementioned urban dynamics (urban growth, sprawl, shrinkage and sprawl). This section introduces the various foundational works (e.g. Batty & Xie, 2005; Haase, Lautenbach, & Seppelt, 2010; Smith, 1979; Torrens, 2006) that are used to understand and model the interdependent subsystems of a city and their interactions. Section 2.5 will introduce various spatial environments for modeling CA (e.g. Wilensky, 1997) or ABMs (e.g. Crooks, 2008) and how they impact the behavior of the model. Section 2.6 will delve into the process of real estate development undertaken by developers. This process shapes the decision-making of developers who are an agent group within the model presented in this research.

2.2 Models of Urban Structure

There are three well-known classic models of urban growth and structure. The *concentric zone model* by Burgess (1925), the *sector model* by Hoyt (1939), and the *multiple nuclei model* developed by Harris and Ullman (1945). All of these models belong to the Chicago School in sociology developed between the 1910s and 1930s to study the human behavior in the urban context. They adopted and applied the theories of order and cooperative competition by Darwin to humans in urban environments. The Chicago School set the human-urban foundational studies for researches to follow in various fields such as urban planning, computational social science, urban microeconomics, etc.

Burgess's model also known as the *zonal model*, as shown in Figure 1, considers the city to form in concentric circles with the central business district (CBD) as the core (Burgess, 1925). His case study was the city of Chicago. As Gregory et al. (2011) note, "the process of urban expansion was explained by Burgess in terms of the invasion and succession of one zone (predominant land use) into the next outer zone adjacent to it, with physical expansion of the city the result." The source of urban growth and instability among communities is mobility. The general circles following the CBD (also known as the *loop*) are the factory zone, the immigrant residential zone (low income blue collar residents) and the single-family housing zone (middle and high income white collar residents). The expansion for the CBD results in the invasion and succession of this zone on to the neighboring zone (Burgess, 1925).

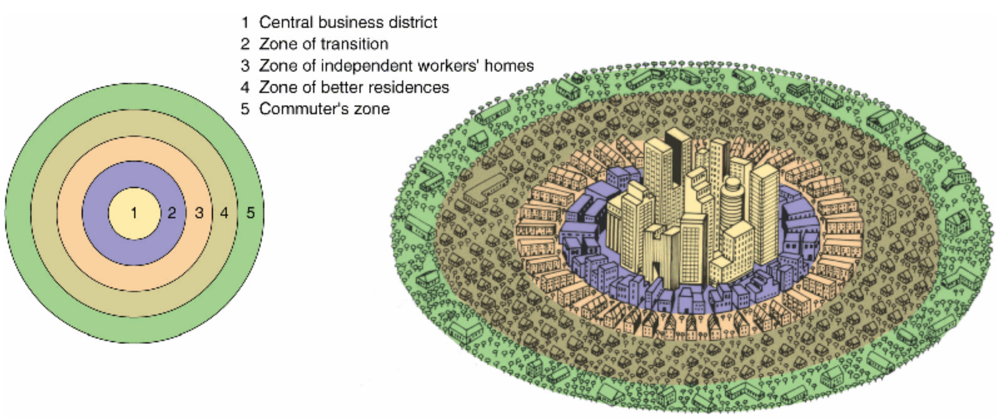

Figure 1. The Zonal Model by Burgess [Source: Pearson Prentice Hall, Inc, 2005]

Hoyt's (1939) model, also known as the *sectoral model,* as shown in Figure 2, built on Burgess's (1925) model by segregation of housing of various quality and value into different sectors stemming from the CBD along major route ways. This model which was developed for American cities is a remodel of the zonal model with consideration for transportation and accessibility as the defining factor of value and economic class. The zones in this model are sectors (mostly in wedge shape) which are adjacent to other sectors relevant to them. Therefore, the higher class is next to the CBD while the lower class is closer to factories and manufacturing land.

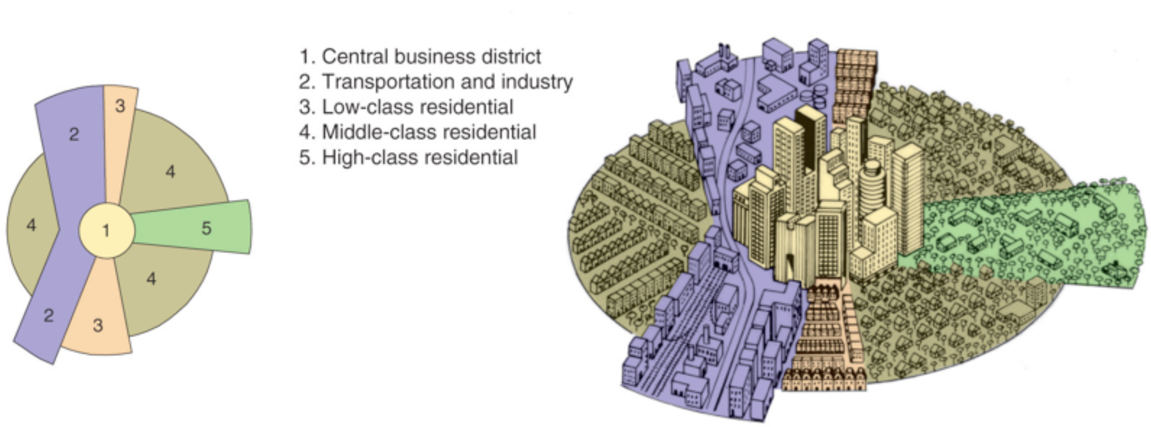

Figure 2. The Sectoral Model by Hoyt [Source: Pearson Prentice Hall, Inc., 2008]

Harris and Ullman (1945) developed a combination and extension of the models to produce the *multiple nuclei model,* as shown in Figure 3. The significance of this model is that instead of a mono-nuclear city structure, it has a multi-nuclei city structure. As Gregory et al. (2011) explain, “this model has land use patterns organized around several nodes on the argument that different uses cluster together (in some cases to share specialized facilities) and wish to avoid other uses, thereby creating a number of nuclei around which the city is organized.”

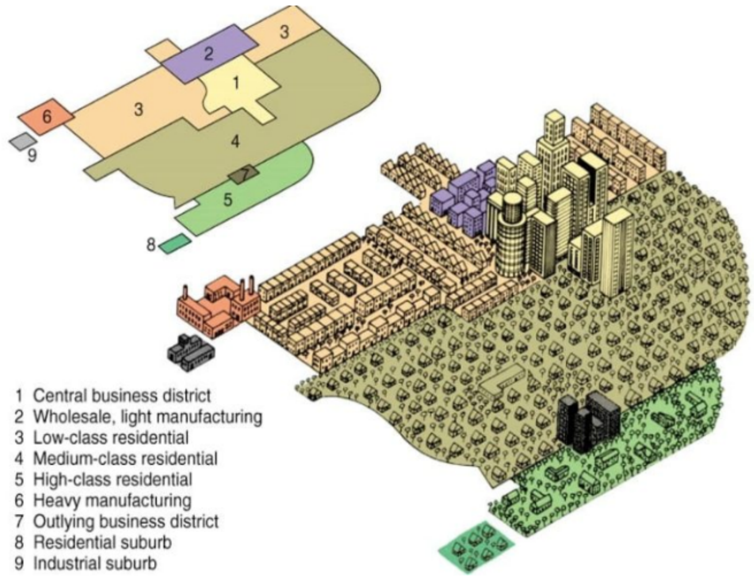

Figure 3. The Multiple Nuclei Model by Harris and Ullman [Source: Pearson Prentice Hall, Inc, 2008]

2.3 Land Markets

Land markets form where land is traded or purchased monetary or through services. Social, political, cultural, economic, legal, environmental factors effect land markets and land markets affect them in return (Gregory et al., 2011). There are two types of land markets; well-functioning and poorly functioning. A well-functioning land market is one that is compatible, efficient, equitable and environmentally sound (United Nations Economic and Social Commission for Asia and the Pacific, 1998). Well-functioning land markets are important factors in economic growth. Land sale and/or rental in well-functioning markets, allows for the transfer of land from less to more efficient users (Qineti, Rajcaniova, Braha, Ciaian, & Demaj, 2014). Poorly-functioning land markets can lead to economic stagnation, misallocation of land and insufficient use of its resources (Norton, Alwang, & Masters, 2014).

Land use is the management and modification of natural and artificial environment (Intergovernmental Panel on Climate Change, 1998). The Von Thünen (1966) and the

Alonso (1964) models are perhaps among the most famous models of land use. Von Thünen's (1966) models, as shown in Figure 4, assumed an isolated state in which the city is located, the surrounding ring of land is unoccupied, flat with no interruptions in topography, the climate and soil quality remain the same throughout the land, farmers intend to increase their profit and they deliver their own goods without using any roads. He envisioned that the distance to the center determined the kind of crops growing in a location and the net rent that location can generate.

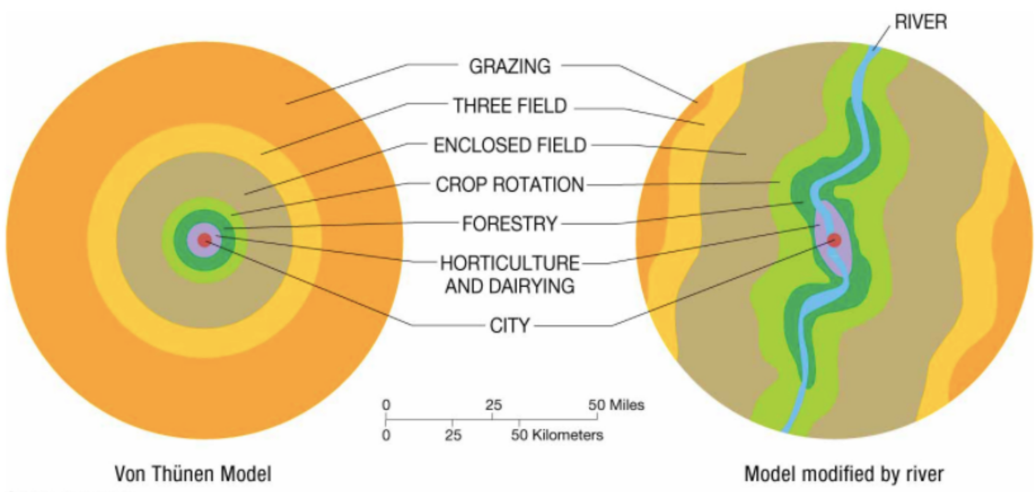

Figure 4. The Von Thunen Model [Source: Pearson Education, Inc., 2014]

The Alonso (1964) model also known as the *bid rent style model*, as shown in Figure 5, forms the urban land market theory. This model is constructed in zones of different land use within an urban area. The model considers accessibility a major parameter in determining variations in land use, land value and intensity. The residential location pattern is organized based on the tradeoff between three main parameters such as travel cost, rent and space needed. Like the Burgess (1925) model, this example focuses on the

CBD, as shown in Figure 5. The Bid Rent Style Model by Alonso [Source: Knights, 2008], as the agent destination. The model, grounded in location choice feedback loops, adaption and evolution, demonstrated a bidding and competing process between firms and firms, residents and residents, and firms and residents (Crooks, 2006). Alonso's (1964) model forms a distance-decay relationship between "location-rent and distance from the center," where residential properties with the lowest bid rent curves are positioned in the outer zone.

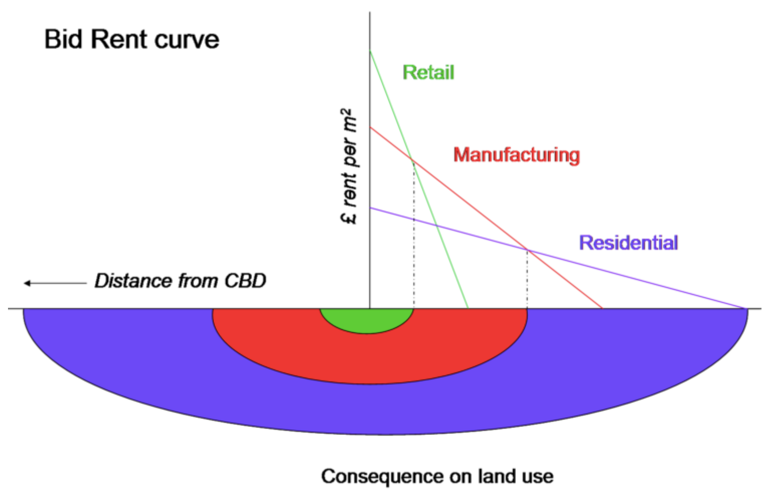

Figure 5. The Bid Rent Style Model by Alonso [Source: Knights, 2008]

Both the aforementioned models have limitations due to their mono-centric city structure that because of static time handling, create static atmospheres. However, the abstract spatial representation in such models allows for a more general example that intends to demonstrate the dynamics and interactions of a system and its subsystems rather than examining a specific geographically detailed case. Spatial economists such as Fujita & Krugman (1995), have built on the Von Thünen (1966) model by developing a monopolistic competition model of an ‘isolated state’ and investigating the model with multiple towns in the isolated state to achieve an equilibrium model of urban systems.

Efforts at developing dynamic models of land markets have also taken place. Parker and Filatova (2008) conceptually explain the agent-based land market with heterogeneous economic agents where land has various characteristics (accessibility, biophysical sustainability, environmental amenities, neighborhood characteristics). The agents of this model are households, developers and rural land owners. The interaction between supply and demand sides plays out through the buyers’ willingness to pay and the sellers’ willingness to ask which creates a bid and ask dynamics where agents can negotiate on prices (Parker & Filatova, 2008). At the end of this process market transaction occurs by determining actual land prices and exchanging the ownership rights on land. In this model agents are heterogeneous due to their behaviors (utility and profit satisfaction), resources (budget) and preferences (dwelling type). The model demonstrates that the developers are motivated by the market while being constrained by policy (Parker & Filatova, 2008).

In another research Filatova, Parker, and Van der Veen, (2009), present a bilateral agent-based land market model which is structurally validated by previous theoretical models (Alonso, 1964; Von Thünen, 1966), but explicitly examines the behavioral drivers of land market transactions on the buyer and seller sides. The model demonstrates the formation of the buyers’ bid prices and the sellers’ ask prices and their gains from the transaction. This model explores the shift of relative market power from a sellers’ market to a buyers’ market by studying the changes in urban dynamics and land rents.

2.4 Urban Dynamics

2.4.1 Urban Growth

Urban growth is described as a spatial system growing by expansion and compaction. The expansion results from a geometric extension caused by an increase in space occupied, while the compaction results from an increase in mass density or intensity. Urban growth and urban sprawl are highly interlinked. However, it is important to note that urban growth can occur without leading to sprawl, while urban sprawl must be generated from urban growth (Bhatta, 2010). Bhatta, (2010) notes population and economic growth, industrialization, physical geography, lack of affordable housing, transportation, and failure to enforce planning as some of the causes of urban growth. Bhatta (2010) full table of causes of urban growth which may result in compact and/or sprawled growth is demonstrated in Appendix 1. Population growth which is a significant factor in urban growth can occur by natural increase in population and migration (both internal and external). Wurster (1963) describes these simultaneous processes in cities as "concentration-deconcentration or centralization-decentralization, sometimes with reference to centrifugal-centripetal forces." Until the 1960s, the approach to understanding urban systems such as urban growth was mainly focused on mathematical applications. The urban growth process demonstrated in such models corresponded the behavior of real cities. These models relied on physics and biology analogies of cities and due to the lack of computation power, were limited to assessing their explorations on an aggregate level (Heppenstall et al., 2016).

After the 1960s, the effects of globalization changed the face of cities. Since then, with the massive transportation and income changes, cities have grown and transformed rapidly. Batty and Xie (2005) claim that “the emergence of a global market place, almost zero population growth, and rising congestion in the central city, all manifest themselves in the form and structure of the typical western city.” These changes have called for a reform in modelling urban environments. Agent-based modeling (ABM), system dynamics (SD) and cellular automata (CA) have been argued to be more suited tools to simulate the dynamics of urban land markets and observe behaviors (e.g. Batty & Xie, 2005; Clarke et al., 2007; Filatova et al., 2009; Gilbert et al., 2009; Han, Hayashi, Cao, & Imura, 2009; Heppenstall et al., 2016; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003). A comprehensive review of such models has been done by Schwarz, Haase, and Seppelt (2010), and is presented in Appendix 2.

In the last 25 years of the twentieth century, theories about the emergence of cities changed. Prior to that date, micro-economic theory and social physics had a top-down approach to understanding a city and considered a city to be in equilibrium (Batty, 2008). The top-down approach considers urban growth into a predetermined number of components which is fixed throughout the model. This approach does not allow for the emergence of new regions or regional boundary change. The role of innovation, creativity and surprise as factors affecting the form and structure of a city was not quite addressed. With more data collection, observation and modelling, a new approach to modelling emerged. This is the bottom-up approach. With this new approached, macro was moved to micro and static to dynamics (Batty, 2008). Benenson (1998) describes the bottom-up approach as a method that “represents the city as a potentially infinite collective of simple elementary units whose interactions define the dynamics of the urban system at large.” The bottom-up approach allows for a complex adaptive system to flourish throughout the model. Various models have been simulated to demonstrate different aspects of urban growth (e.g. Batty & Xie, 2005; Benenson, 1998; Clarke et al., 2007; Landis, 1994).

The SLEUTH model – a bottom-up approach – of urban growth is among the most prominent in simulating land use changes that are caused by urbanization (Clarke et al., 2007). The model is named after its six input layers (slope, land use, exclusion, urban extent, transportation, and hillshade). This CA model was initially simulated by Clarke, Hoppen, and Gaydos, (1997) and was first applied to the San Francisco Bay Area, demonstrating the historical urban cartographic and remotely sensed data from 1850 to 1990. The entities in this model are individuals, the behavior of the model is mathematical, spatial scale is neighborhood and the temporal scale is years. Forecasts of urban extent, animations of spatial growth patterns and spatial growth statistics were calculated as a part of this model. The SLEUTH model was later applied to Alexandria in Egypt, Porto Alegre in Brazil, Yaoundé in Cameroon, and others (Clarke et al., 2007). The SLEUTH model is one of the many models created to demonstrate the dynamics of urban growth from the bottom up.

The California Urban Futures Model (CUF) is designed to replicate the realistic process of urban growth with regards to development and policy (Landis, 1994). The entity in this model is a city, the behavior of the model is mathematical, spatial scales is a city and the temporal scale is years. The model considers accessible and therefore profitable areas for development. The population grows in these areas through a bottom-up process. The model represents the dynamics in San Francisco Bay Area. The CUF model consists of four submodels: The *bottom-up population growth submodel* which generates the model with regards to the demand side; The *spatial database* which includes the supply side and the location attributes based on Geographical Information System (GIS); The *spatial allocation submodel* which focuses on every user's function and decision rule to allocate population growth based on potential profitability of the land; The *annexation-inncorporation submodel* which incorporates rules for newly developed cities. The interesting aspect of the CUF model is that it considers spatial parameters as specific as wetland, earthquakes, etc. and creating a topology (Landis, 1994).

Benenson (1998) presents a more abstract model of a city where the residents who are characterized by cultural identity and economic status are free to migrate and behave based on the properties of their neighborhood, neighbors and the whole city. The entities in his model are individuals, the behavior of the model is cognitive and mathematical, spatial scales are neighborhood and city and the temporal scale is years. He considers the economic status as a uni-dimensional and quantitative factor while the cultural identity is multidimensional and qualitative. Benenson's (1998) agents rely on information gathered at different levels of the urban structure. His results showed that while the economic status factor held a slowly varying spatial pattern and maintained the economic variation of the residents, the cultural identity factor revealed a general instability in the cultural code of the city residents with emergence and extinction of cultural groups on one side and the lack of simultaneous existence of some groups on the other (Benenson, 1998).

The agent-based model of residential choice dynamics which was developed by Devisch et al. (2009), is based the on the assumption that the agents have incomplete and imperfect knowledge (i.e. Bounded Rationality) and therefore their decision-making is based on beliefs. The entities in the model are individuals, the behavior of the model is cognitive and mathematical, spatial scale is neighborhood, and the temporal scale is years. The model unveils the actions that agents make at the individual level and at the group level during house price negotiations based the information they acquire. The factor *lifestyle utility* is one of the central parameters of this model. This utility consists of sub-section utilities which derive from living in a house, daily activities in a house and budget that is spent on non-housing expenditures (Devisch et al., 2009). Agent decision-making and movement occurs in the following process: agents choose an action (stay, search, visit or move) and execute the chosen action. Then they evaluate the action (update demands and needs, update beliefs, update resources) and based on their evaluation choose an action and follow the cycle again. This model shows that the agents behave both reactively and proactively; having in mind their available budgets, they make decisions and update their beliefs and strategies based on the resulted outcomes (Devisch et al., 2009). When the city grows to its limits and capacity, the process of sprawl occurs.

2.4.2 Urban Sprawl

As mentioned in section 2.4.1, urban sprawl occurs when a city grows and is induced and generated by urban growth. However, sprawl is based on population mobility and occurs in a process called suburbanization. It is observed as a demand for greater space and lower density (Batty & Xie, 2005) and among car-dependent communities (Glaeser & Kahn, 2004). Some of the measures of sprawl are decentralization, average number of residential properties per acre of an area and discontinuity of development (Chin, 2002). Based on the static model of cities, residents want to be closer to the CBD; but, sprawl occurs when the residents desire to be closer to the CBD while being further from the congestion as feasible. Therefore, this growth in mobility is observed at the edge of the city. Sprawl generally carries a negative connotation for causing, environmental degradation and affecting segregation and has been used as a term for managing urban growth (James et al., 2013).

Batty and Xie (2005) and Batty et al. (1999a, 1999b) works examine models such as DUEM (Dynamic Urban Evolutionary Model) to understand the emergence of urban sprawl, growth and decay. They use Detroit as their study area and develop their model by means of GIS data. DUEM is interesting in that it holds three different spatial scales (neighborhood, district and region) and uses multiple asset classes to model properties (Batty & Xie, 2005). The entity in this model is a city, the behavior of the model is mathematical and the temporal scale is years.

Urban sprawl happens simultaneously as a city grows or shrinks. Sometimes it acts as the event connecting urban growth to urban shrinkage. Once the households decide to move to the edge of the city or residential development occurs in that area, population increases at the fringe of the city and patterns of urban sprawl start to appear. This causes a vacancy in the CBD which decreases land value and drops the housing prices in and adjacent to the CBD (Schwarz et al., 2010). The development of urban sprawl would be damaging to the agricultural land located adjacent to the sprawling land in some cities. This process could also harm the wildlife in the region.

Gregory et al. (2011) argues that "while sprawl is often associated with a lack of planning, others suggest that government policies and public agencies, influencing decisions about road construction, housing financing and zoning, for instance, have shaped the rise of sprawling cities." Some of the features of urban sprawl are commuter population increasing at the edge of the cities and creating a segregated landscape. Models such as MOLAND (a CA model) by Engelen et al. (2007) which examined various European cities and CURBA (a CA model) by Landis (1994) which examined the San Francisco Bay Area of California, are examples of models demonstrating the impact of urban sprawl. Urban sprawl spreads the population from the centrality if the CBD and may lead to decay (Batty et al., 1999a) and/or shrinkage (Haase et al., 2012).

2.4.3 Urban Shrinkage

To understand urban shrinkage, one needs to understand the social events and phenomena forming it. Urban shrinkage is a product of population decline caused by deindustrialization and out migration from the inner-city. Urban shrinkage can have economic (i.e. long-term industrial transformation in the USA) or demographic (i.e. falling birth rates in Germany) reasons (Wiechmann & Pallagst, 2012). Suburbanization and de-economization are some of the causes of this occurrence, while vacancies, demolition and deconstruction of residential properties are some of the effects (Schwarz et al., 2010). Suburbanization can be described as a process throughout which, people, housing, industry, commerce, and retailing extend beyond traditional urban areas and shape isolated landscapes that are linked to cities by commuting (Gregory et al., 2011).

Urban Shrinkage results in an oversupply of housing and a decline of housing prices which accelerates migration in the region and causes an increase in the housing prices of the areas where migration happened. This process creates "islands of growth in a sea of shrinkage" (Schwarz & Ernst, 2009). Schwarz and Ernst (2009). argued that analyzing the housing price oscillation resulting from the urban growth and shrinkage mirrors the dynamics between supply and demand. Haase et al. (2010) also notes that the increase in household diversification and decrease in population ‘forces the city’ to attract new residents or maintain the current ones. This brings about stable neighborhoods that form in fragmented parts in a shrinkage that causes land market instability (Haase et al., 2010). In their model, Haase et al. (2010) use households as entities. The behavior of the model is mathematical, spatial scales are neighborhood and city and the temporal scale is years.

Schwarz et al., (2010) note that urban shrinkage has significant effects that will be even more considerable in the future. Some of these spatiotemporal outcomes are: rising spatial segregation between the growing and the shrinking section of cities along with vacancies throughout the urban environment, land-abandonment and out migration of suburban residents, appearance of large-scale urban brownfields in the urban and suburban landscape, etc. (Schwarz et al., 2010). Urban shrinkage is also known to cause challenges of underutilization and deficiency due to the lack of infrastructure in the area that host a population as a result of urban sprawl and shrinkage. Various models have developed to evaluate the process of urban growth and shrinkage but only a few focused-on processes of decline and demolition of houses. Among these are urban dynamics by Forrester (1969) on Alfield, the Rotterdam social housing market simulation on the Haaglanden region of Netherlands between 1998 and 2010, and the Institute of Spatial Planning of the University of Dortmund (IRPUD) model by executed by Wegener (1982) on Dortmund, Germany cited by Schwarz et al. (2010).

Wiechmann and Pallagst (2012) examine urban shrinkage in the four cities of Schwedt and Dresden in eastern Germany and Youngstown and Pittsburgh in the USA. They study and differentiate the cases by economic and demographic factors which both play significant roles in urban shrinkage. The study suggests new policy and planning strategies that need to take place to remedy the negative consequences of shrinkage. Haase et al. (2012) utilized social science and land use knowledge to create a joint SD-CA model and an ABM to include the main characteristics, processes and patterns of urban shrinkage. They apply this knowledge and modeling on the city of Leipzig in Germany.

2.4.4 Gentrification

Gentrification is described as the "middle-class settlement in renovated or redeveloped properties in older, inner-city districts formerly occupied by a lower-income population" (Gregory et al., 2011). There are two sides to gentrification which each individually or both concurrently can result in gentrification. The demand side argues that the return of the middle class to the lively lifestyle of the inner-city brings about gentrification (Diappi & Bolchi, 2008). Urban geographers and sociologists such as Ley (1996) emphasize that the "new class of private- and public-sector professionals and managers in post-industrial societies" are interested in migration into the city. The Supply side argues that the opportunity arising from the rent gap (explained below) attracts developers and ultimately grows the population in a neighborhood. The supply side, developed by , is supported by the urban economics community (Diappi & Bolchi, 2008). With the rise of deindustrialization, gentrification had been used as a policy strategy to revitalize and reshape the urban economics and landscapes (Gregory et al., 2011).

The significance of gentrification study is due to its engagement of various "categories including class, gender, and, most recently, race, patterns and styles of consumption, housing and other service needs, social polarization and the governance practices of neo-liberalism in the global city" (Gregory et al., 2011). When modelling gentrification, two factors are considered as effective measures of gentrification. One is the displacement or decreased presence of a group of the population and the other is the increase in property value of the area compared to the region or the zone modeled (Jackson et al., 2008).

Rent gap theory was developed by Smith (1979). This theory explains the supply side of the process of gentrification. Smith analyzed every land rent to have a capitalized and a potential rent. The capitalized rent (CR) is the actual rent on the land under current use while the potential rent (PR) is the possible rent under the highest and best use. Initially the capitalized and the potential rent are equal, but in time, the property loses value as it becomes obsolescent which causes the capitalized rent to decrease. At the same time the potential rent of the property remains the same or increases as the investments within the city increase. This process creates a rent gap which is the opportunity ground for developers to gentrify the land by "injecting new capital," rehabilitate buildings and invest in large-scale residential projects (Diappi & Bolchi, 2008). This chain of events leads to gentrification and changes the land market in the aggregate level by increasing the potential and capitalized rent of the neighborhood (Smith, 1979). The developers owning higher capital than individual households, find the rent gap a profitable opportunity.

Diappi and Bolchi (2008) developed a stylized model to study the housing market dynamics with regards to gentrification. Their study is focused on representing the supply side of the revitalization process. They developed a model where agents (homeowner, landlord, tenant, developer and the property unit) behave in relation to the following parameters: size of the neighborhood, rent gap threshold and amount of capital invested. Emergence occurs in this model as a result of agents and their economic behavior and the cells influenced and changing based on the behavior of its neighboring cells. The model determines CR locally through land use analysis and socio-economic characteristics of the neighborhood while determining PR globally. The interesting feature in this model is that the property unit is defined by the two aspects of spatial location and state of decay. The model also considers transition rules where the evolution of PR can be observed and the rent gap calculates (Diappi & Bolchi, 2008).

The model designed by Jackson et al. (2008) demonstrates the emergence of gentrification by using Boston as a case study. The agents in the model are divided into three main groups: young professionals (college students and business professionals), non-professionals and elderly (Jackson et al., 2008). The agents vary in status/class make their location decisions based on occupancy, accessibility to desired locations (CBD or college), affordability, existence of at least one neighbor of the same class, recommendations of friends and attractiveness. The agents move when necessary (economically feasible) or at their leisure (attraction) with reliance on communication and memory. The element of memory in this model is used as a motive to relocate based on attraction to an area where the agent has lived before (while in college). This element pushes a number of young professionals to move back to neighborhoods where they used to live, thus changing the landscape of the city and gentrifying the neighborhoods previously dominated by non-professionals (Jackson et al., 2008). This model is an example of the demand side of gentrification.

O’Sullivan (2002) designed a model of gentrification using the concept of proximal space in irregular CA architecture and the geographical theory of gentrification. The model uses Smith's (1979) rent gap theory for cell transition rules. Graph-based cells representing individual buildings have one of the four following states; not for same, for sale, seeking tenants and rented. The state of a building at a time is determined by its discrete state, the property's current physical, condition and the income of the current occupants. The model was applied to a part of Hoxton in London, United Kingdom, where gentrification has been increasing over the years. The model shows that high and low neighborhoods stay that way until the neighborhood status falls due to the entrance of a household of the opposite income property.

Torrens and Nara (2007) presented a hybrid automata model that tests ideas and hypotheses about urban gentrification with a focus on the agency of relocating households in the property markets. The environment of the model allows for the interaction of fixed and mobile entities. The model is applied to Salt Lake City in Utah, USA. The three main variables of the model are market, property, and resident which are each consistent of various attributes. The results show that a hybrid approach is useful in investigating human behavior in complex adaptive urban systems such as gentrification.

2.5 Spatial Environment

The spatial environment of a model largely impacts the narrative and results. The neighborhood where an agent resides or is deciding to reside in, paints a local picture which creates global patterns. Both abstract and geographically detailed spatial representations have their utilities and purposes. While the specificity in geographically detailed spatial representations allows for an accurate and extensive study of a given case, abstract spatial representations allows for a more general study that aims to exhibit the dynamics and interactions of a system and its subsystems. Both of these representations are practical and applicable depending on the subject of research. Various frameworks such as ABMs and CA models provide the means for implementing the aforementioned spatial representations.

ABMs and CA models are both computational simulating tools with finite states. however, in ABMs, the approach is to examine the actions and interactions of agents within the system and assess their effects on the system as a whole, while CA models operate on a discrete approach with fixed cells forming neighborhoods (Niazi & Hussain, 2011). While in an ABM, agents directly interact, in CA models, there are no agents, only cell transition rules. ABMs and CA models both aim at modelling complexity and emergence; however, ABMs are more applicable for computing emergence and self-organization in a complex adaptive system and CA models are more applicable for computationally simple systems (Toffoli & Margolus, 1987).

CA models are built with cells as the foundation of the model. The traditional cellular spaces define neighborhoods either in the Von Neumann style with agent in the center cell and four neighboring cells covering each *side* or the Moore style with the center cell and nine neighboring cells covering each *side* and *corner*. Both of these definitions fit within a regular lattice structure. Perhaps the most famous CA model is the *game of life* model devised by mathematician Conway (Gardner, 1970). There are no players and interactions in the game. The game evolves based on its initial state. The Schelling *dynamic models of segregation* is one of the most famous ABM models. The entities in his model are individuals, the behavior of the model is mathematical, spatial scale is neighborhood, and the temporal scale is not specified. In this model, agents make individual choices and move based on their preference of living with their own kind (Schelling, 1971). The agents' decision-making with consideration for its neighbors, takes on an action which determines whether the agent will be in a happy or unhappy state. Various studies have utilized this model (e.g. Clark, 1991; Laurie & Jaggi, 2003; O'Sullivan, MacGill, & Yu, 2003). The segregation model was simulated in NetLogo by Wilensky (1997). with parameters such as 'similar-wanted' which controls the percentage of same color agent that every agent wants in their individual neighborhood.

To examine the effects of spatial structure on segregation, Flache and Hegselmann, (2001) applied Schelling's (1971) model to irregular grids using a Voronoi tessellations. Voronoi tessellations are made of a number of randomly located points on a surface called generators which are corresponding to the number of cells in a grid. The cell of a particular generator is considered as the area covering all points of the rectangle that are closer to its core than to any other nearby generator in terms of Euclidian distance (Flache & Hegselmann, 2001). The neighbors in this model are defined as cells that share 'common borders' with the main cell (Flache & Hegselmann, 2001). The results of the Flache and Hegselmann model showed that size and structure of neighborhood does not affect the outcome of segregation. The landscape designed for the agents to interact and behave and the decision-making rules followed by agents both affect each other and determines the result of a model.

2.6 Real Estate Development

Real estate development is one of the factors that influences the cycle of a city. Real estate developers are stakeholders that by investing, effect the land use of an urban environment (Coiacetto, 2000). Real estate development can act as a key parameter in population movement and a subsystem within the urban dynamics previously mentioned in section 2.4. While models utilize a simplified version of this complex process, the real-world process of real estate development occurs in multiple stages. According to Miles et al. (2015) the process of property development includes eight main stages; idea inception, idea refinement, feasibility, contract negotiation, commitment point, construction, initiation of operation and asset management.

Idea inception occurs when the developer tests a generated idea by estimating the preliminary costs, and the project Net Operating Income (NOI) by writing and assessing the pro-forma (financial statement of the developer's overall project assessment) (Adams & Tiesdell, 2012; Walzer & Hamm, 2012). Then, he/she refines and tests the idea again, identifies the site, studies the physical feasibility of the site, studies the market, and calculates the potential finances of the project. At the feasibility stage, the developer needs to insure his/her return from a project; therefore, in this stage, he/she studies the market, puts together the preliminary design, construction cost estimate and the entitlement assessment, consults with a lender and arrives at a more refined cost and value statement (Nelson, 2014). Next, the developer enters a written agreement, acquires the loan commitment, confirms the construction process and makes decisions on the equity and the pre-leasing. Once the contracts are signed, partnership and equity agreements are closed, detailed construction budget is prepared, pre-leasing is formalized and leases are executed, construction loans are closed, an accounting system is initiated, and time control is established through scheduling, the developer has fully committed to the project (Allen & Iano, 2011). At this point the construction starts and the developer begins to act as the manager. The construction loans are drawn, construction manager (ensures building according to plan, space, time and budget), marketing representative (manages leasing function) and financial officer (manages money) start working together.

Once the construction is completed, operation is initiated. At this stage, operating personnel are brought to the project while pre-opening advertising takes place. Utilities are connected, inspections are taken place and permanent loan may be closed. At the last stage maintenance is provided, re-leasing and tenant retention or repositioning the asset occurs (Miles et al., 2015).

Developers find a location based on land use. They employ an approach called *land residual analysis* which calculates land value by determining the value of improvements minus the costs of construction. Using the land residual analysis and market analysis[3], they arrive at the potential price of a property at highest and best use. If the developer decided to initiate the investment, the supply side of gentrification is generated per Smith (1979).

Developers wish to acquire land by undertaking the least amount of risk and having the most amount of time to research for the most feasible option (Duany, Speck, Lydon, & Goffman, 2011). Sellers on the other hand, wish to earn the highest price in the least time for their property. As a part of the feasibility research, the developer studies the site's physical characteristics such as the useable area, geology, hazardous materials, cultural resources and infrastructure. Another side of this research consists of market study.

The total area of a site is known as the gross area, while the area utilized for development is known as net area. Both of these areas are calculated using the floor/area ratio (FAR). Sometimes developers purchase surrounding sites to their target site to

---

[3] Market study examines "national economic conditions (including international influences) and projected trends, in light of characteristics of the region, locality, neighborhood, site, population forecast, job growth" (Miles et al., 2015).

increase the return on their investment. Miles et al. (2015) explains that the interaction of a project and its surrounding site uses is of great importance.

To estimate the value of a property, an appraisal takes place. Appraisal is an opinion of value on a specific date valid for a period of time. This assessment shows the value of the property in its highest and best use. The three main appraisal approaches include; the market data (sales comparison) approach for residential properties, the cost (replacement) approach for public service properties, and the income (capitalization) approach for commercial properties. Although the appraisal demonstrates the value of the target property, developers consider other calculations such as the Net Operating Income (NOI), Cash Inflow and Outflow, Net Present Value (NPV). Developers use the information from the appraisal, their financial calculations and feasibility study to make land development decisions. These decisions shape the community and the city as a whole while affect its life cycle in time (Coiacetto, 2000).

2.7 Chapter Summary

In this chapter, land market, urban dynamics, real estate development processes and the significance of utilizing ABMs to simulate them was introduced. An overview of the literature was explained in section 2.1, while section 2.2 covered a number of urban structure models that are used in the following chapter as foundations of the model. Section 2.3 provided a brief overview of the creation and dynamics of land markets while section 2.4 expanded on urban dynamics such as, urban growth, sprawl, shrinkage and gentrification. Both of these sections are utilized in the application of previous works to the model logic and structure. Through the use of ABMs and CA models, spatial environment was introduced in section 2.5 to provide an understanding of the abstract environment of the model while section 2.6 delved into the details of real estate development and its role in the urban environment. These main sections lay the foundation to what will be the basis of the ‘city life cycle’ model represented in chapter 3.

3 Methodology

3.1 Introduction

This chapter provides information on the approach, data and the model design implemented to address the thesis central question mentioned in Sections 1.3 and 1.4. Section 3.2, will describe the implemented model, while Section 3.3 will introduce environment and lead to Section 3.4 which expands on the agent classes, the data related to them and their attributes. In Section 3.5, the properties in the model are explained. Section 3.6, provides a detailed explanation on the dynamics within the model. Section 3.7, discusses efforts to verify the model, while Section 3.8 describes model outputs. Finally, the chapter concludes with the Section 3.9, the summary of the chapter.

3.2 Model Background

The agent-based model demonstrating the life cycle of a city is designed containing various elements based on the research presented above. Building on the theories and models discussed in chapter 2, this NetLogo model, which is designed in version 5.2.1, intends to simulate the dynamics of a land market, agent interactions in that market, urban growth, sprawl and shrinkage and gentrification. The purpose of this model is to understand the strategy and behavioral pattern of the agents and the emergent dynamics. The overview of the model is illustrated in Figure 6.

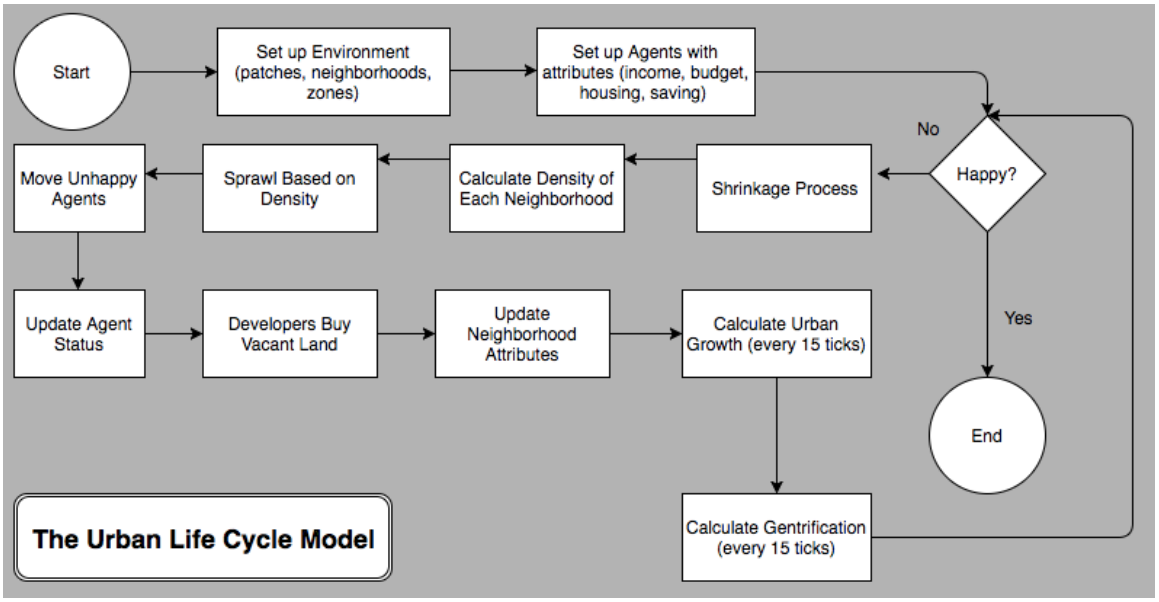

Figure 6. Creative Flow Diagram of the Urban Life Cycle Model

Utilizing various theories and models mentioned in chapter 2, the model of an abstract city space stylized on Washington D.C. was designed. The following models in Table 1 were used as inspiration to develop this model.

Table 1. Summary of Researched Models

Author	Application	Entity	Behavior	Spatial Scale	Temporal Scale	Verification (Y/N)	Validation (Y/N)	Calibration (Y/N)
Benenson, 1998	City Dynamics	Individual	Cognitive & Mathematical	Neighborhood & City	Years	Y	N	N
Crooks, 2006	Residential Segregation	Individual	Mathematical	Neighborhood & City	Years	Y	Y	Y
Devisch et al., 2009	Residential Choice	Individual	Cognitive & Mathematical	Neighborhood	Years	N	Y	N
Landis, 1994	Urban Growth	City	Mathematical	City	Years	Y	Y	N
Schelling, 1971	Segregation	Individual	Mathematical	Neighborhood	Not Specified	Y	Y	Y
Haase et al., 2010	Urban Shrinkage	Household	Mathematical	Neighborhood & City	Years	Y	Y	Y
Batty & Xie, 2005	Urban Growth & Sprawl	City	Mathematical	Neighborhood & City & Regions	Years	Y	Y	Y
Clarke et al., 2007	Urban Growth	Individual	Mathematical	Neighborhood	Years	Y	Y	Y

3.2.1 Data

The data used in the model is stylized on the real-world data of Washington D.C. The data concerning income, budget, housing and land rent prices are extracted from the websites of United States Census Bureau (2016), Mayor Muriel Bowser Office of Planning (2015), Economic Policy Institute (2015) and the Urban Land Institute (2012). This data is focused on Washington D.C. (131 neighborhoods) for modeling with realistic amounts. According to the Census Bureau between 2010 and 2014, from the 306,184 housing units in the District, 37.6% were single-family units while 62.4% were multi-family units. There were 277,378 occupied housing units or households of which 40.6 percent were owner-occupied and 59.4 percent were renter-occupied. Average household size was 2.2 persons. Median value of an owner-occupied unit was $486,900. Median household income with a mortgage was $125,870.

All the data is gathered for the creation of the model. The data is then used as a reference for the input parameters of the model. Adopting real data for simulation input and development has great effect on the validity of the process and output. Table 2 will demonstrate in detail the input parameters, their range of values, default settings and references. The majority of the default values of the developers, professionals, non-professionals, and properties are initiated at the beginning of every simulation. Therefore, these values are not presented in Table 2.

Table 2. Input Parameters of the Urban Life Cycle Model

Parameter	Value	Default	Reference
Developer	Normal Distribution (mean, standard Deviation): $\mathcal{N}(\mu, \sigma)$		
State	Happy/Unhappy	Happy	Benenson (1998);

			Schelling (1971)
Income	$\mathcal{N}(5{,}000{,}000,\ 4{,}000{,}000)$		Adopted from Miles et al. (2015)
Budget	69% of annual income		Adopted from Miles et al. (2015)
Saving	Income - Budget		Adopted from Miles et al. (2015)
NOI	≥ 0	0	Adopted from Miles et al. (2015)
Professional			
State	Happy/Unhappy	Unhappy	Benenson (1998); Schelling (1971)
Income	$\mathcal{N}(137{,}814,\ 20{,}728)$		EPI, MMBOP, ULI, USCB
Budget	69% of annual Income		EPI, MMBOP, ULI, USCB
Saving	Income - Budget		EPI, MMBOP, ULI, USCB
Housing	28% of Budget		EPI, MMBOP, ULI, USCB
Non-Professional			
State	Happy/Unhappy	Unhappy	Benenson (1998); Schelling (1971)
Income	$\mathcal{N}(42{,}814,\ 10{,}938)$		EPI, MMBOP, ULI, USCB
Budget	69% of annual Income		EPI, MMBOP, ULI, USCB
Saving	Income - Budget		EPI, MMBOP, ULI, USCB
Housing	28% of Budget		EPI, MMBOP, ULI, USCB
Properties			
State	Occupied/Vacant	Vacant	Author's estimation
Zone	Inner-city/Suburban		Adopted from Ernest Watson Burgess et al. (1925)
Type	C: Condo/S: Single Family House		MRIS
Size	C: $\mathcal{N}(926.96, 31.26)$ S: $\mathcal{N}(1650.40, 504.14)$		MRIS
Price	C: $\mathcal{N}(492{,}867,\ 14{,}715.43)$ S: $\mathcal{N}(769{,}387,\ 201{,}379.80)$		MRIS
age	$[0 - 100]$		Author's estimation

Potential Rent	> 0		Adopted from Diappi & Bolchi (2008); Smith (1979), Author's estimation
Capitalized Rent	> 0		Adopted from Diappi & Bolchi (2008); Smith (1979), Author's estimation
Environment			
Cap Rate	$[4.75 - 7.75]$	7.50	Adopted from CBRE
Urban Growth Rate	$[0 - 1]$	0.17	Adopted from CBRE
Initial Population	$[100 - 1000]$	300	Adopted from CBRE
Gentrification Rate	$[0 - 1]$	0.26	Adopted from CBRE
Sprawl Density Threshold	$[0 - 1]$	0.2	Adopted from CBRE, Author's estimation
Sprawl Moving Rate	$[0 - 1]$	0.1	Adopted from CBRE
Shrinkage Rate	$[0 - 1]$	0.0050	Adopted from CBRE

3.3 Environment

Using the information mentioned in section 2.5, the environment is modeled with the bottom layer of 'patches' as houses in a Moore neighborhood definition of 3x3 cells to generate an abstract spatial representation. The middle layer will hold Voronoi tessellations representing a region in the city. To form the abstract urban structure, the top layer is formed according to the zonal model by Burgess (1925) – introduced in section 2.2. The zones are designed (from the center out) with the CBD in the core, inner-city and suburbia. CBD and suburbia are considered as more expensive zones while the inner-city is less expensive.

The landscape was created by designing a hypothetical city in ArcGIS[4]. The city center is in the center point with (0,0) coordinates. By buffering the area at equal interval distances from the center point constrained by the study area, erasing the overlapping portions and appending the three created zones into one concentric zone, the city structure based on the zonal model was produced. To create the 131 neighborhoods of Washington D.C., I generated random points constrained within the largest buffer zone and tessellated the points to get Voronoi/ Thiessen polygons. Next, I clipped the polygons to the extent of the largest buffer. Then, by using the attribute table in ArcGIS, we assigned zonal IDs to the polygons through their original point centroids. Lastly, I imported the ArcGIS shape file to NetLogo as the base map for our city. Voronoi polygons have a closer shape to real neighborhoods and they ease the appraisal calculation to arrive at a land value estimate by comparing properties neighboring our designated polygon. Generating converted dimensions from exact polygons that form the neighborhoods in Washington D.C., on an abstract space, would not be applicable. Therefore, the polygons are randomly generated. The purpose of this spatial representation is not to examine the effects of the polygon-shaped neighborhoods of Washington D.C. on the behavior of the agents, but to utilize a spatial representation that is stylized on the real-world to create an abstract environment for the hypothetical city of the model.

3.4 Agent Classes

Agents are designed in three categories: professionals, non-professionals, and developers. These categories are chosen by being inspired from various studies (e.g. Diappi & Bolchi,

[4] The coordinate system used in the model is GCS_North_American_1983, the datum is D_North_American_1983, the spheroid is GRS_1980 with unit as Degree 0.017453.

2008; Gilbert et al., 2009; Jackson et al., 2008; Magliocca, 2012). Professionals and non-professionals both have agents of colors red, green and blue. Both agent groups have incomes, budgets and preferences. Professional and non-professional agents are randomly located in the inner-city and suburbia (the two rings around the CBD). The agents, that are initialized by a random income and a budget, then move around based on their preferences, as discussed further in section 3.6 and examined in section 4.2. Developers are in the CBD symbolizing working in the city center. The developers also have randomly assigned budgets and preferences, as will be discussed in section 3.6 and examined in section 4.2.

Although the agents are limited by their incomes and budgets, their decision-making process determines a large portion of their movements. Professional and non-professional agents check unoccupied properties based on their available budget for renting the property, preference of being closer to the CBD, inspired by Alonso (1964) with at least one neighbor of the same class in their neighborhood, inspired by Schelling (1971) choose a housing type with travel cost in relation to their budget. The parameters of travel cost, rent and space – introduced in section 2.3 – that play central roles in Alonso's (1964) bid rent theory, are used as inspirations for the preference setting of the professional and non-professional agents. As discussed in section 2.6, the developers are driven by profitability of a land. They check their available saving, the vacancy of their interested residential type (single family house or multi-family), assess market demand, get an appraisal of the property value using a neighborhood index and using the methods explained in section 2.4.4, search for the rent gap using a rent gap threshold (Diappi & Bolchi, 2008; Smith, 1979). The movements arising from the interaction of the agents with each other and their environment shapes the state (growing, sprawling, shrinking or gentrifying) of the city modeled. The movement of the agents is portrayed in Figure 7.

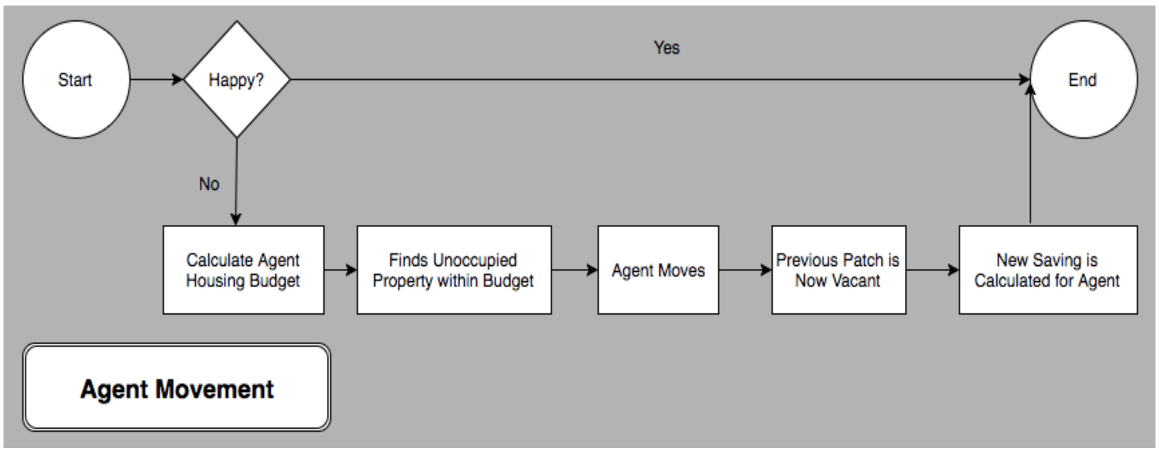

Figure 7. Flow Diagram of the Movement of Professionals and Non-professionals

3.4.1 Professionals & Non-Professionals

Professional agents who are represented by colors green, red, and blue (displayed as such for representational purposes), have ‘incomes’ within a general range of $75,628 (the average of highest and lowest income based on the Census data) to $200,000 (highest amount recognized for the model). Using the United States Census Bureau (2016a) income estimation and distribution methods, their income is generated randomly using the random-normal feature with mean of $137,814 and standard deviation of $20,728 This brings their ‘lowerbound’ (mean - std of income distribution) to $117,086 and their ‘upperbound’ (mean + std of income distribution) to $158,542.

Non-professional agents are also represented by colors green, red and blue (displayed as such for representational purposes), have ‘incomes’ within a general range of $10,000 (lowest amount recognized for the model) to $75,628 (the average of highest and lowest income based on the Census data). Their income is generated randomly using the random-normal feature with mean of $42,814 and standard deviation of $10,938 This brings their 'lowerbound' (mean - std of income distribution) to $31,876 and their 'upperbound' (mean + std of income distribution) to $53,752.

To calculate the total budget of professional and non-professional agents, I assign 69% of their income to their total budget. This percentage is arrived at by using the 'family budget calculator' of the Economic Policy Institute (EPI) for monthly and annual costs of two adults in Washington D.C. Table 3. Annual Costs based on EPI Data [Source: Economic Policy Institute, 2015] demonstrates the numbers.

Table 3. Annual Costs based on EPI Data [Source: Economic Policy Institute, 2015]

ANNUAL COSTS

2 adults *and* no children

Washington, DC

HOUSING	$14,868
FOOD	$5,957
CHILD CARE	$0
TRANSPORTATION	$7,373
HEALTH CARE	$5,438
OTHER NECESSITIES	$10,059
TAXES	$8,653
Annual Total	**$52,347**

From the total budget, the housing budget that is allocated to rents and mortgages can be calculated. The housing budget is calculated as 28% of the total budget. Agents also have savings which is calculated by subtracting their budget from their income. The agents make their decision of residing in a location based on all their preferences being satisfied.

The model was extended utilizing Benenson's (1998) CA model, Schelling's (1971) segregation model and Zhou's (2015) segregation model to use the color and income of agents as a part of their location decision-making process. When the model starts, the agents check their state. If they are 'happy', it means that they are satisfied and will not move. If they are not happy, they will calculate their housing budget – as described earlier –, look for an unoccupied property near an agent with the same income range or same color and move to that property. The agent's relocation changes the state of the previous property to unoccupied, turn the color of the patch to the color of the developer who developed the property – will be explained in detail in section 3.4.2 – and transfers the payment of the property from the agent to the relevant developer, which changes the saving of the agent and the developer.

3.4.2 Developers

In the model, the developers make their decisions based on available budget, vacancy of their preferred residential type, appraisal of value, rent gap and market demand.

Properties are considered as attributes of patches. With a total of 25,899 patches within the three zones, the model assumes that there are same number properties on the landscape. Using the Miles et al. (2015) real estate development stages – introduced in section 2.6 – the developers in the model employ the stages of idea inception, idea refinement and feasibility for conceptual decision-making and the stages of construction and asset management for their actions.

The five developers who are only found in the CBD, are shown in yellow, violet, white, orange and gray. The reason for choosing five developers is that a higher or lower number would affect the model's running time. More developers overshadow the emergence process of the urban dynamics by fast development, while fewer developers would slow down this process. The developers are fixed agents because their movement is not essential to the model and it is only their decision-making and developments that effect the model. They depend on the property value and the capitalization rate (cap rate) to earn their NOIs. The cap rate determines the rate of return on a real estate investment based the income generated by the property. Based on the 2014 CBRE cap rate survey report (Ludeman et al., 2014), Washington D.C. cap rates for multi-family housing market are between 4.75% and 7.75%. This range is used in the model as a slider which can affect the developers' NOI and the market condition.

Developers buy vacant properties if the rent gap (Smith, 1979) is high and the property age is 60 or higher. By doing so, inspired by Gilbert et al., (2009) model of the English housing market – introduced in section 2.4.1 – they change the properties' ages to zero which makes it a great option for agents to buy. The properties that are developed take the color of their developer. When an agent purchases a property from a developer, that agent is paying the price of the property from its savings. This transfer, places the purchased money in the developer's savings and adjusts the NOI. Continuing with Diappi and Bolchi's (2008) method, introduced in section 2.4.4, neighborhood IDs were used to count the patches within them, apply the summation of their capitalized rents to arrive at the neighborhood rent parameter. This method helps the developers make better assessments of the market value of their properties.

3.5 Properties

The properties in this model are divided into single family houses developing in the outer circle and condominiums developing throughout the three zones. The properties each have a spatial location, occupancy, a CR and PR and a state of decay. According to the (Metropolitan Regional Information System, 2016) (MRIS) data gathered by ShowingTime, the average sold price of a two or less bedroom detached property in 2015 was $553,782, while an attached property was $512,290. Same market analysis showed that a condo with the same characteristics sold for an average of $492,392. According to this data, shown in Table 4. **2015 Average Dollar per sf Price of Detached, Attached, and Condo/Coop in Washington D.C.** and Table 5. 2015 Average Sold Price of Detached, Attached, and Condo/Coop in Washington D.C., the 2015 average sold price per square feet for all property types averaged at $491 and ranged from $453 to $509 (Metropolitan Regional Information System, 2016).

Table 4. 2015 Average Dollar per sf Price of Detached, Attached, and Condo/Coop in Washington D.C. [source: Metropolitan Regional Information System, 2016]

Months	Detached: all	Attached: all	Condo/Coop
Dec 2015	$418	$484	$526
Nov 2015	$472	$510	$546
Oct 2015	$462	$500	$528
Sep 2015	$441	$500	$521
Aug 2015	$479	$488	$511
Jul 2015	$468	$515	$540
Jun 2015	$473	$517	$555
May 2015	$432	$520	$545
Apr 2015	$463	$503	$541
Mar 2015	$418	$485	$517
Feb 2015	$422	$490	$527
Jan 2015	$418	$484	$526

Table 5. 2015 Average Sold Price of Detached, Attached, and Condo/Coop in Washington D.C. [Source: Metropolitan Regional Information System, 2016]

Months	Detached: all	Attached: all	Condo/Coop
Dec 2015	2,238.90	1,185.64	956.96
Nov 2015	2,164.46	1,200.31	922.39
Oct 2015	2,194.09	1,184.53	902.99
Sep 2015	1,828.12	1,223.14	947.38
Aug 2015	2,099.44	1,143.51	943.67
Jul 2015	2,199.52	1,182.19	928.81
Jun 2015	2,234.78	1,137.19	885.76
May 2015	2,553.26	1,190.00	943.04
Apr 2015	2,135.62	1,129.32	856.36
Mar 2015	1,827.44	1148.2	929.70
Feb 2015	2,003.39	1,206.48	963.97
Jan 2015	2,025.09	1,175.03	942.48

Table 6. 2015 Average sf of Detached, Attached, and Condo/Coop in Washington D.C. [Source: Metropolitan Regional Information System, 2016]

Months	Detached: all	Attached: all	Condo/Coop
Dec 2015	$935,862	$573,853	$503,361
Nov 2015	$1,021,628	$612,159	$503,629
Oct 2015	$1,013,671	$592,269	$476,783
Sep 2015	$806,205	$611,574	$493,585
Aug 2015	$1,005,634	$558,034	$482,216
Jul 2015	$1,029,379	$608,828	$501,558
Jun 2015	$1,057,054	$587,929	$491,598
May 2015	$1,103,009	$618,802	$513,958
Apr 2015	$988,793	$568,048	$463,295
Mar 2015	$763,874	$556,877	$480,657
Feb 2015	$845,432	$591,176	$508,017
Jan 2015	$846,490	$568,719	$495,748

To create the pseudo housing market for agent groups to buy, rent, develop and sell in, I used the data above and added new parameters. The new parameters shape the properties and their characteristics. Properties have ages, types based on their zones, sizes based on their types, renting and buying prices based on their sizes. Property age is randomly assigned between zero to one hundred. Properties in the inner-city zone are condos and coops and are labeled as “C” type, while properties in the suburban zone are attached and detached single family houses labeled as “S” type. To determine the sizes of each property type, shown in Table 6, I took the average and their standard deviation from Table 4 and Table 5. Once the sizes were achieved and randomly assigned to patches in the defined zones, the prices were applied to them using the same randomness.

3.6 Urban Dynamics

From the prices determining total value, rental prices were achieved using United States Census Data on the 32.02 price-to-rent ratio in Washington D.C. (Wallace, 2016). As mentioned by Smith (1979), the property capitalized and potential rents are equal. In time, the capitalized rent declines and create a rent gap which explains the supply side of gentrification. This decline is demonstrated by applying a decay rate to the age of the property using Diappi and Bolchi's (2008) method. Governing (2016) analysis from American Community Survey and Longitudinal Tract Database shows a 51.9% gentrification occurring in Washington D.C. between 2000 and 2015.

Gentrification by supply occurs in the model as follows; for a patch that is unoccupied, the PR is calculated as follows:

Equation 1. Potential Rent

$$PR = p/(r \times 12)$$

Where p is the property price and r is the price-to-rent ratio. We estimate the CR using the PR and a decaying function over the age of the property:

Equation 2. Capitalized Rent

$$CR = PR \times e^{-\lambda * a}$$

where λ is the decaying parameter and a is the age of property. I use $\lambda = 0.04$ throughout the experiment since it provides a more realistic value for the CR. Using the PR and the CR, rent gap is calculated as:

Equation 3. Rent Gap

$$rent\ gap = (PR - CR)/PR$$

Then the developer with a saving higher than the property value, buys the property. This is demonstrated by a decrease in the developer's budget and the changing of the patch color to the color of the developer. Once the developer becomes the owner, the property age changes to zero, symbolizing new construction and development. Finally, the developer's NOI is calculated as follows:

Equation 4. Developers' NOI

$$NOI = (NOI\ +\ ((PR_v \times 12 \times r) \times (cr/100))$$

where PR_v is the vacant property's PR, r is the price-to-rent ratio, and cr is the cap rate. Figure 8 demonstrates this process.

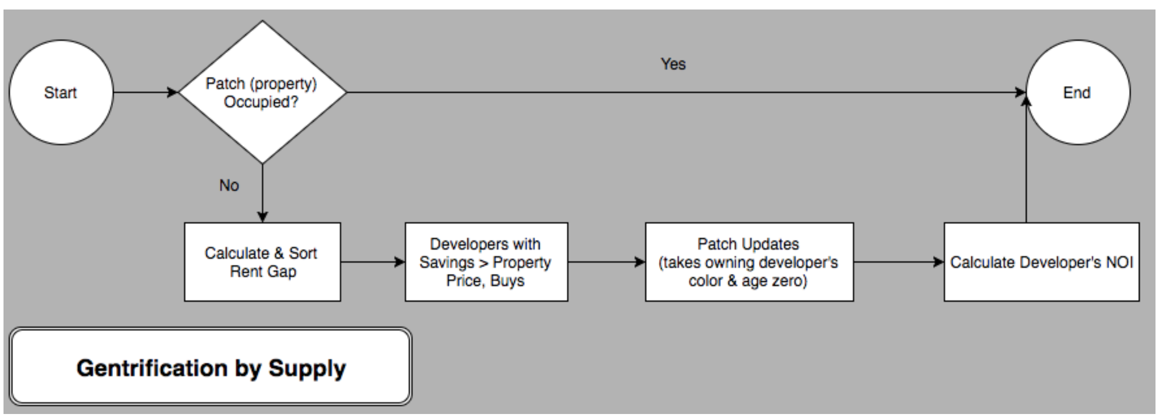

Figure 8. Flow Diagram of Gentrification by Supply

An important element in the model is neighborhood density. Let the number of agents in an area be n and the number of possible agents in an area as np, neighborhood density is calculated as:

Equation 5. Neighborhood Density

$$density = n/np$$

As the density increases, the property prices increase as follows:

Equation 6. Price Change by Density

$$p = (1 + density) \times (CR \times r \times 12)$$

Density is a significant parameter, for gentrification and urban sprawl (Chin, 2002; Lees et al., 2013). Utilizing the data presented in section 3.21, the demand side of gentrification is demonstrated by 26% (half of the 51.9% overall gentrification rate adopted from the CBRE report (Ludeman et al., 2014)) of the middle class (represented by the lower range of professional) moving to the inner-city. The gentrified population is calculated by setting gentrification rate as gr and number of agents in suburbia as s, resulting in:

Equation 7. Gentrification Population

$$gentrification\, population = gr \times s$$

This movement symbolizes the demand of the higher income class for living near the CBD for the various reasons mentioned in section 2.4.4. This clustering of agents increases the density, hence the price increase. The price increase makes the land unaffordable for the lower income agents in the inner-city. Figure 9 shows such processes. Incorporating both sides of gentrification in this model creates a unique perspective that previous models examining only one side, don't include.

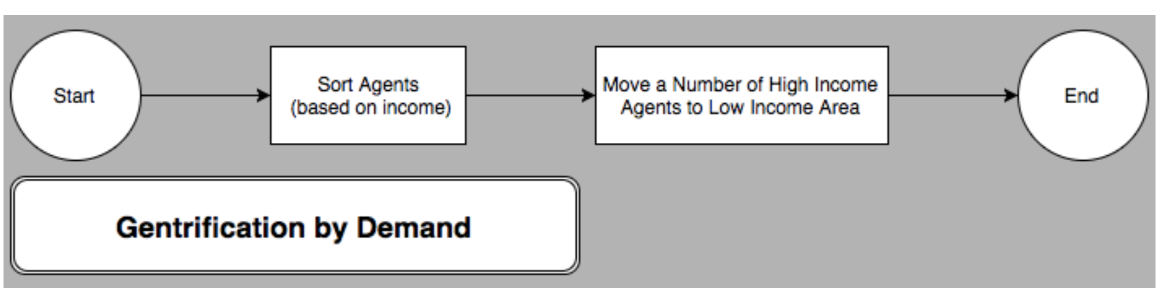

Figure 9. Flow Diagram of Gentrification by Demand

Once every neighborhood reaches the density threshold – adopted from CBRE (Ludeman et al., 2014) –, certain percentage of the agents, based on the sprawl moving rate (SMR), move from that neighborhood to a location with greater property size than their current property, lower density than their current neighborhood and within their housing budget. This creates urban sprawl. Let the number of agents in an area be n, the sprawl moving population is calculated as follows:

Equation 8. Sprawl Moving Population

$$sprawl\ moving\ population = (SMR \times n)$$

The CBRE data (Ludeman et al., 2014) demonstrates a 10% sprawl rate which is demonstrated in section 3.2.1. Using this data, along with the population density, a sprawl threshold was estimated to allow for the flow of this process within the model. The urban sprawl designed in the model occurs due to population mobility. The process of sprawl is illustrated in Figure 10.

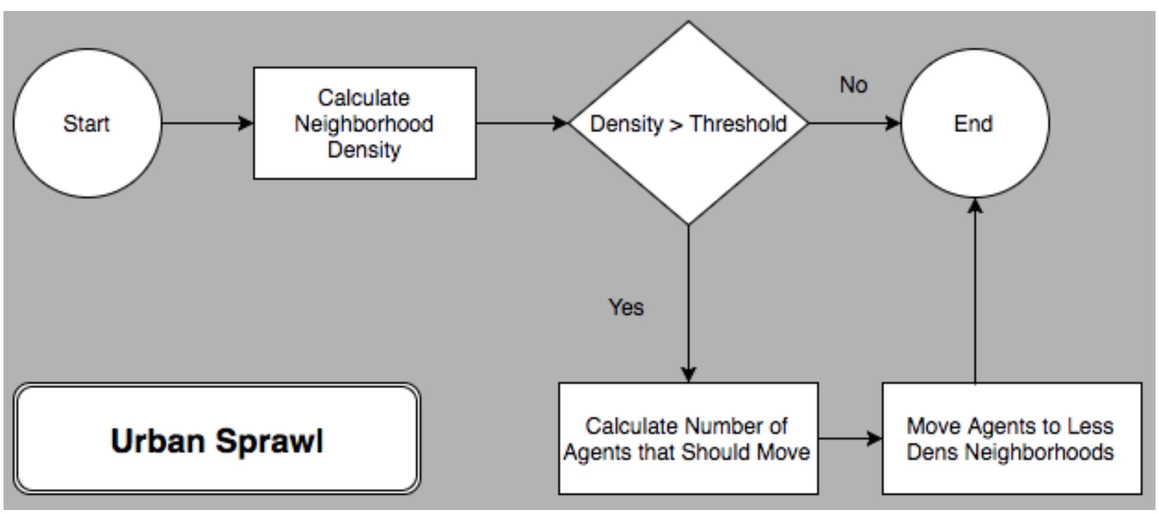

Figure 10. Flow Diagram of Urban Sprawl

Per the District of Columbia Office of Planning (2016), report on population trends, between 2000 and 2015, the district added 100,000 people. Per the United States Census Bureau (2016b), in 2000, the population was 572,046 which grew to 672,228 in 2015. This shows a 17% growth rate in the Washington D.C. population. This is demonstrated in the model by a population growth of 17% every 15 years. This data was used to design the urban growth dynamic based on empirical facts while ensuring the correct procedure of the model. The new agents follow the same rules as the rest of the agents. This process is demonstrated in Figure 11.

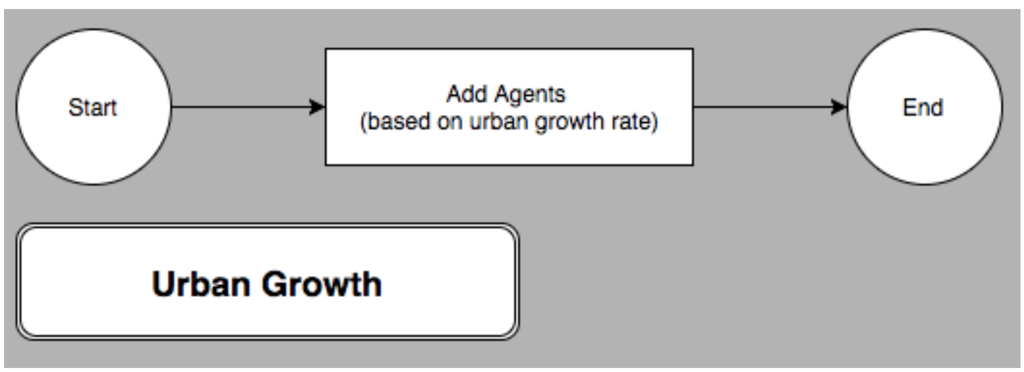

Figure 11. Flow Diagram of Urban Growth

There are other dynamics in the model that do not depend on density, such as urban growth and shrinkage. The data shows that Washington D.C. has had a 25% urban shrinkage from 1950 to 2015 (Wikipedia, 2015). Every 50 years the population shrinks by 25%. The shrinking means that a population moves to another location; however, due to the lack of extended geography in the model, this process is demonstrated by agents dying. Let sr be the shrinkage rate. The leaving agents are calculated as follows:

Equation 9. Shrinking Agents

$$number\ of\ leaving\ agents = sr \times N$$

where N is the total number of professional and non-professional agents. Figure 12 portrays this dynamic.

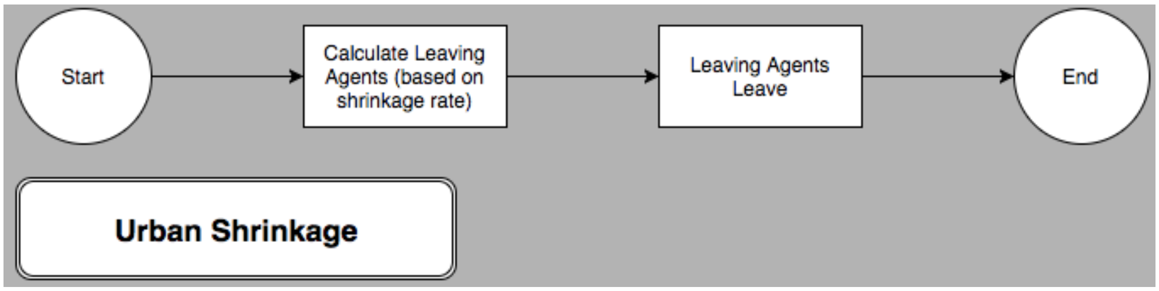

Figure 12. Flow Diagram of Urban Shrinkage

Putting all the agent behaviors and urban dynamics in the model together, the interconnectivity and interactions of the subsystems within themselves and with each other become clear. Figure 13 demonstrates this interconnectivity from initiation of the model for the course of a simulation.

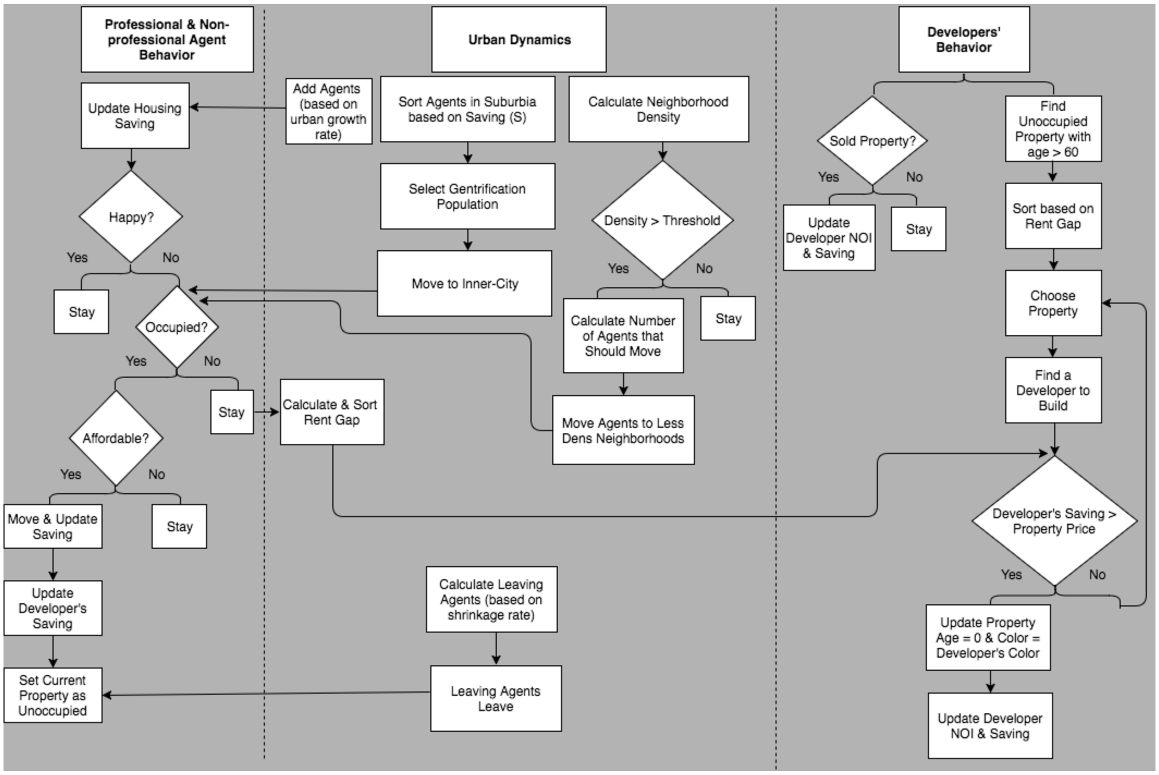

Figure 13. Model Logic and Interactions Between Entities During a Simulation

Assembling all the mentioned parameters creates a dynamic that shows the model's sensitivity to certain elements. The parameters of the model are used to generate emergence along with the life cycle of a city. An example of which is the urban growth rate which is determined based on the previously mentioned data. Since population growth needs to be enforced in the model in some manner, I utilized this urban growth rate to define a parameter that the model is sensitive to. The same logic is applied to the gentrification rate, cap rate, sprawl density threshold, sprawl moving rate and shrinkage rate which are examined and recorded in section 4.2.

3.7 Verification

As mentioned in section 2.1, an essential part of building an ABM is verifying the model for correct performance (Cioffi-Revilla, 2017). To implement the model, various verification procedures have taken place. I walked through the code to ensure the matching of the model inputs with the background data. Then, I performed testing measures such as printing the outputs of each section of the code for debugging. Once I gathered the output data and results, I visually inspected the tables, figures and plots to track the behavior of the variables and verify their intended performance. Finally, by observing the behavior change demonstrated through the interface of the model, I traced the model's dynamics to detect emergent behavior.

3.8 Model Outputs

ABMs have the ability to collect data at the agent and the system level and of any agent or agent group and the environment. This chapter has delved in the inner functions of the model at the agent and system level. Chapter 4 will examine these functions by testing various parameters. The model collects this data for further analysis. For every run, plots reporting various elements are produced for further analysis.

The plots demonstrate the saving of professionals, non-professionals, the number of each of these agent groups in the inner-city and suburbia, each developer's average saving and NOI, and the growth, gentrification, sprawl and shrinkage population over time. A monitor also tracks the number of properties developed. These are general data collected for analysis. However, the model is constantly gathering data with respect to the processes. For example, the model calculates the density of each neighborhood. Such examples can be reported on a plot and analyzed for further understanding.

NetLogo's BehaviorSpace tool and report command allow for the data collected to be sorted and published in the form of tables, figures and plots. This feature was used to gather, organize and visualize the data produced by the model in every examination step.

3.9 Chapter Summary

This chapter provided information on the approach, data and the model design implemented to address the thesis central question. The model represented in this chapter extends and weaves previous theories and models on urban dynamics together (e.g. Batty & Xie, 2005; Benenson, 1998; Clarke et al., 2007; Crooks, 2008; Devisch et al., 2009; Diappi & Bolchi, 2008; Gilbert et al., 2009; Haase et al., 2010; Jackson et al., 2008; Landis, 1994; Magliocca, 2012; Schelling, 1971; Smith, 1979; Zhou, 2015). As discussed in chapter 2, the model design is focused on providing a picture of the life cycle of a city by linking various sub-processes together. Sections 4.2 will highlight the results of the experiments executed on the model and delve into the details of the findings of every dynamic.

4 Results and Analysis

4.1 Introduction

To test the methodology and data, an environment with agents was simulated in NetLogo 5.2.1. To examine various aspects and dynamics the model was tested for 300 time-steps. Per section 3.3, the environment of the model is demonstrated as zones that represent the CBD (central circle), inner-city (middle ring) and suburbia (outer ring), and the polygons represent regions that form the neighborhoods. As explained in section 3.4, professional and non-professional agents of all colors are randomly placed in the inner-city and suburbia (gray background) while the developers are placed fixed in the CBD. Figure 14 shows the model at setup.

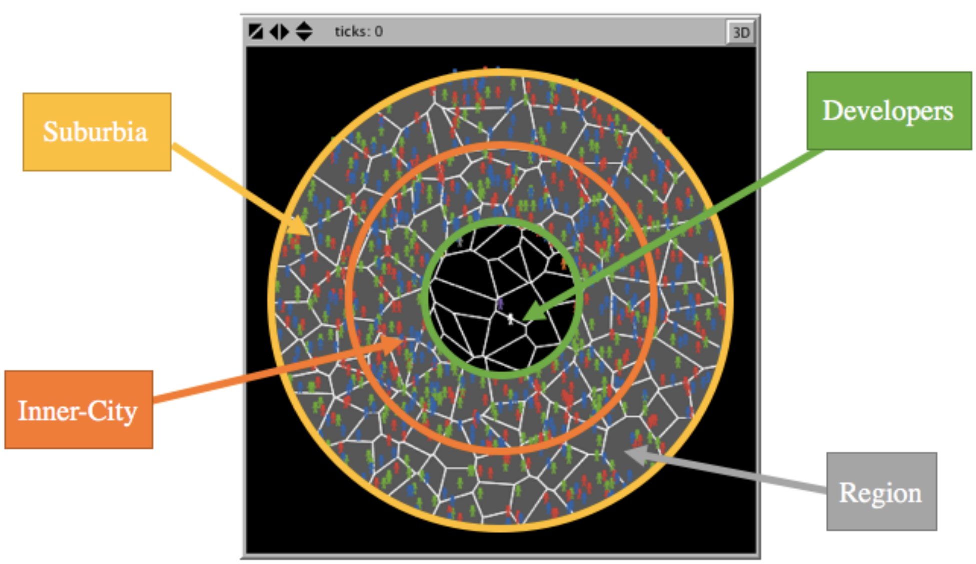

Figure 14. Model at Default Settings

The cap rate, urban growth rate, gentrification rate, shrinkage rate, sprawl moving rate, sprawl density threshold and initial population ranges appear as sliders to ease sensitivity analysis. The developed properties are demonstrated on a monitor. There are six plots that display various information such as developers' average savings, developers' NOI, professional and non-professional agents in the inner-city and in suburbia and their savings. These details are illustrated in Figure 15.

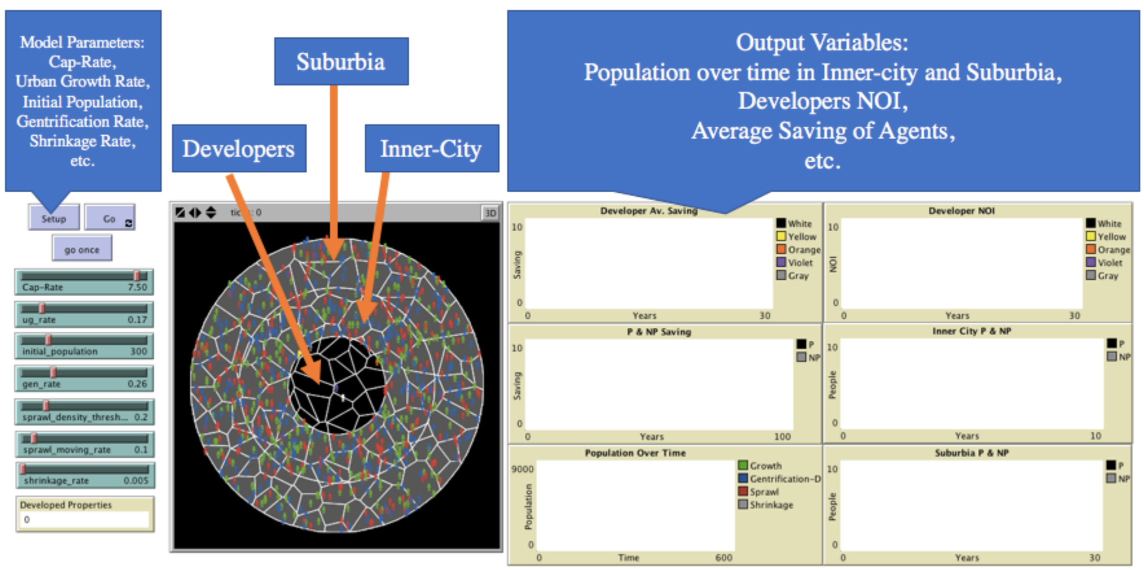

Figure 15. Graphical User Interface of the Model

To examine the outcome of decision-making based on economic status runs dependent on examination parameters were conducted with the same seed, for 300 time-steps – notionally interpreted as years in the model. As mentioned in section 3.4, one of the preferences of professional and non-professional agents, is having at least one neighbor of their income status. In some cases, the agents with similar economic background cluster adjacent to the cluster of a different economic group. This pattern shows that the agents on the edge of these two clusters chose their neighbors by economic status. Running the model for 300 time-steps shows that development and the occurrence of the urban dynamics, effects the stabilization of the model. Time is an important element of the model, because the interactions and behaviors of agents and urban dynamics play out the urban structure in time. The Figure 16 demonstrates the results achieved with the default settings as shown in Table 2, for a respective run of 300 time-steps.

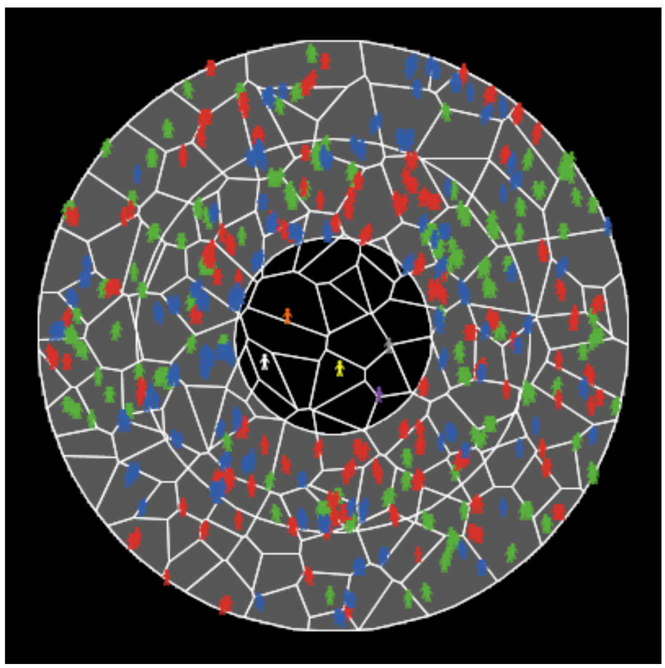

Figure 16. Model at Stabilization

The model was examined with the default parameters and the parameters influencing the various urban dynamics. I estimated the minimum and maximum ranges and used the default values based on data mentioned in chapter 3. All the plots in this chapter illustrated as figures of the results are in the log scale for concise and cohesive representation. As explained in section 3.6, the parameters of the model are used to generate emergence. I utilized the real-world data to define parameters that the model is sensitive to. This logic is applied to the urban growth rate, gentrification rate, cap rate, sprawl density threshold, sprawl moving rate and shrinkage rate which are examined and recorded in this chapter. When testing the model for each combination of parameters, all the other parameters remain at default value. Table 7 shows these parameters and their tested ranges. All the results in this chapter show representative runs.

Table 7. Parameter Examination Chart

Parameter	Min	Default	Max	Urban Dynamics Used for
Initial Population	100	300	1000	Gentrification by Supply, Gentrification by Demand, Urban Sprawl, Growth & Shrinkage
Gentrification Rate	0.1	0.26	0.4	Gentrification by Supply & Demand
Cap Rate	4.75	7.50	7.75	Gentrification by Supply
Sprawl Density Threshold	0.05	0.2	0.5	Urban Sprawl
Sprawl Moving Rate	0.05	0.1	0.3	Urban Sprawl
Urban Growth Rate	0.1	0.17	0.3	Urban Growth
Shrinkage Rate	0.001	0.005	0.01	Urban Shrinkage

4.2 Experiments

4.2.1 Default Settings

The model ran for 20 times with seed for the random generator on default settings of 300 initial population for every color, urban growth rate of 0.17, gentrification rate of 0.26, sprawl density threshold of 0.2, sprawl moving rate of 0.1, shrinkage rate of 0.25

every 50 time-steps which yields to 0.005 for each time-step, and cap rate of 7.50. Figures in this section demonstrate the results of this test.

The default settings show a rise and fall in agents' savings every 15 time-step which correlates with the urban growth that occurs every 15 years – per section 3.6. The savings reflect the income and budget of agents in each agent group. Figure 17 illustrates the agent saving.

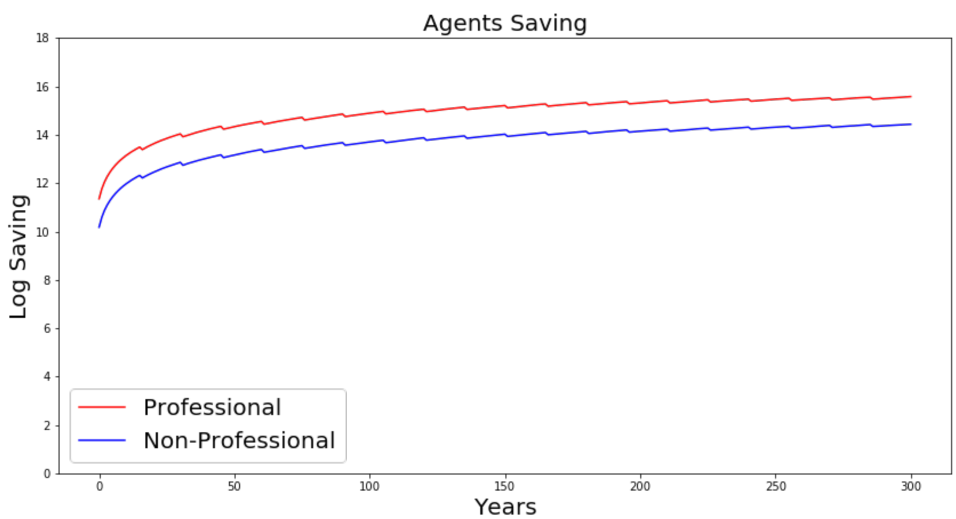

Figure 17. Agent Saving with Default Setting

The developers' savings demonstrate a sharp drop at the beginning of the simulations, then plateau until about the time-step 80. The sharp drop at the beginning is due to the starting process of buying and selling properties that occurs upon the starting of the simulations. About time-step 80, the developers' savings take a rise which is due to the professional agents gaining eligibility to buy a property and increasing the developers' portfolio and savings. Figure 18 shows this trend.

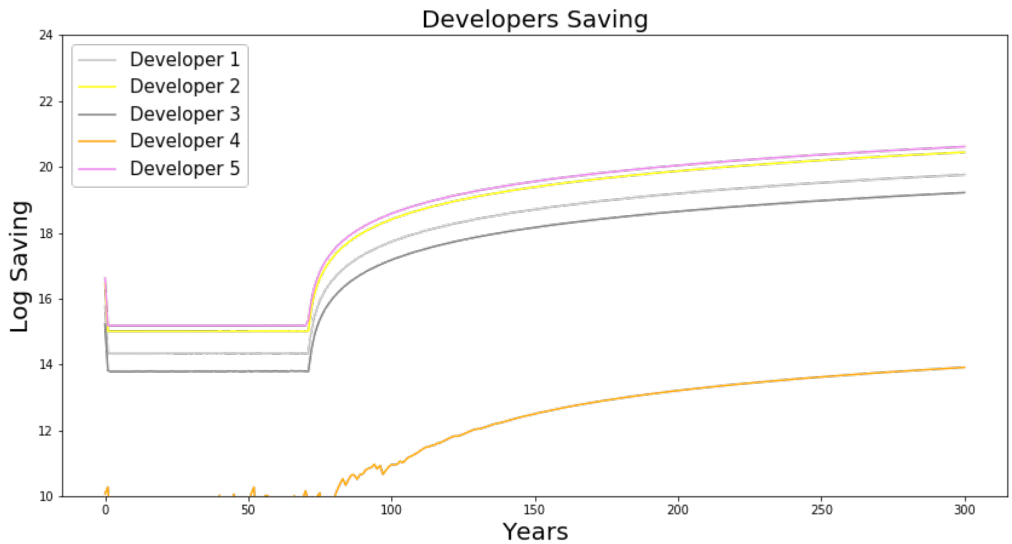

Figure 18. Developers' Saving with Default Settings

The developers' NOI shows a sharp peak at the beginning of the run and a slow rise after. The peak represents the random allocated budget that is the base for developers' savings. The slow rise is due to the constant buying and selling that is occurring. In every run, one developer dominates the simulation. Hence, the developer's saving falls lower than the rest. Figure 19 demonstrates the NOI while Figure 20 shows an example of the dominant developers (developer 2 and 5 in this case).

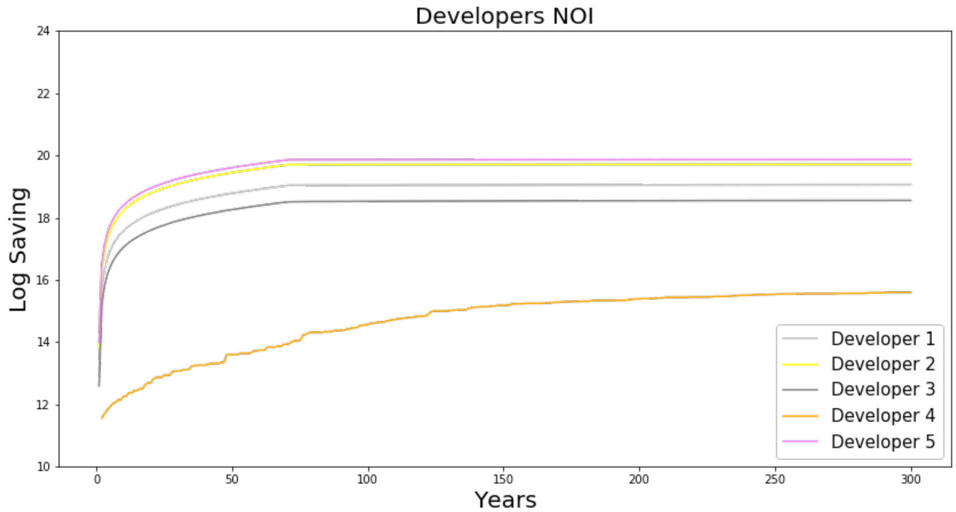

Figure 19. Developers' NOI with Default Settings

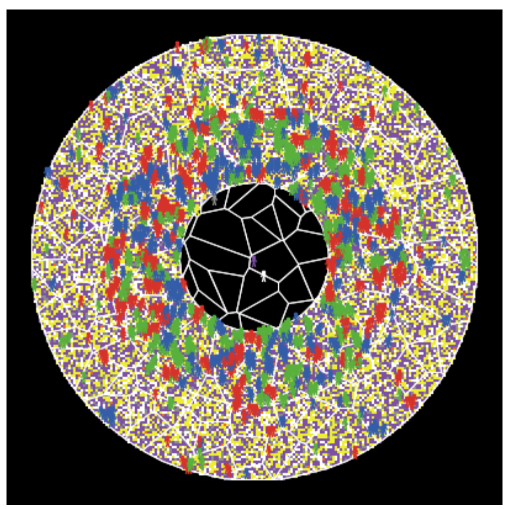

Figure 20. Example of a Dominant Developer

The inner-city population shown in Figure 21 plots the rise of the professional agents into the inner-city while the non-professional residents of the zone remain the dominant population. This rise occurs because the professional agents increasingly find their desired properties in the inner-city.

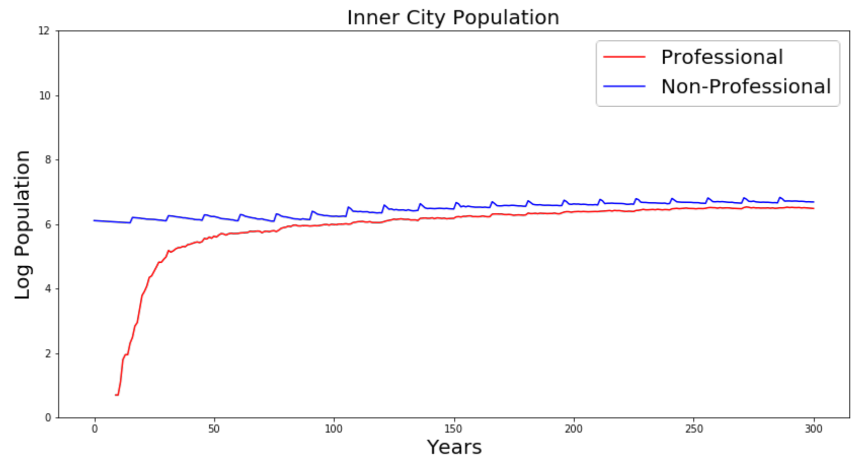

Figure 21. Inner-City Population with Default Settings

Figure 22 shows almost the opposite behavior to Figure 21. The suburbia population represented in Figure 22, shows an increase in the non-professional agent population in suburbia. This is due to the non-professional agents' increase in savings to afford properties in suburbia.

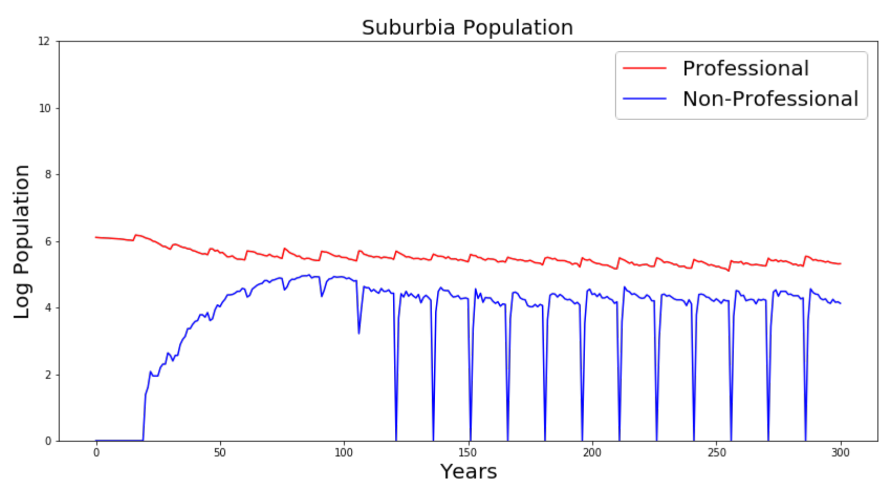

Figure 22. Suburbia Population with Default Settings

Figure 23 plots the growth, gentrification, sprawl and shrinkage population over the 300 time-steps. While the urban growth and gentrification have gradual increases, shrinkage occurs rapidly as the population increases. As mentioned in section 2.4, urban growth and sprawl are interlinked. However, urban growth can occur independently of sprawl, urban sprawl is induced and generated from urban growth. As explained in section 3.6, the sprawl parameters facilitate the transition from urban growth to sprawl. It is interesting to note that urban sprawl does not occur until after 100 time-steps. This is due to all the settings of these parameters (initial population, sprawl density threshold, sprawl moving rate and urban growth rate) effecting this dynamic to emerge. At this time-step, a neighborhood has become dense enough for sprawl to occur. After time-step 150 and due to the increase in population density, sprawl constantly happens. The movement of professional and non-professional agents based on sprawl parameters, is considered urban sprawl in the model. However, urban growth is considered to occur by the increase in population, every 15 years – per data in section 4.2.2 – based on the urban growth rate.

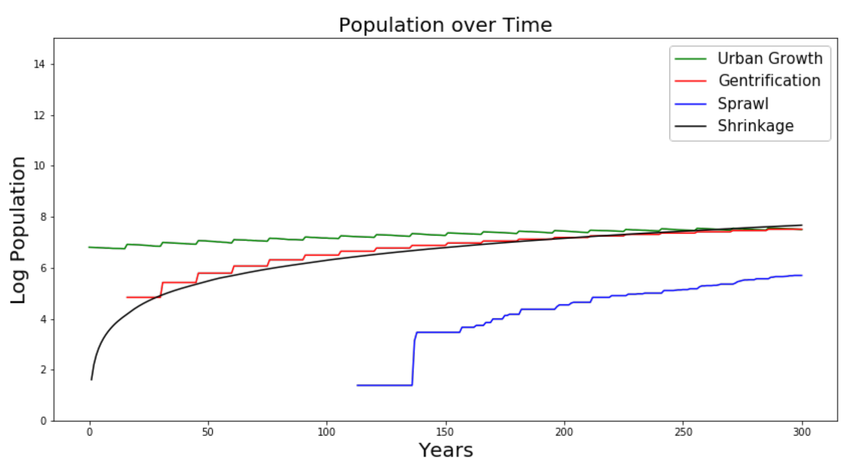

Figure 23. Population over Time with Default Settings

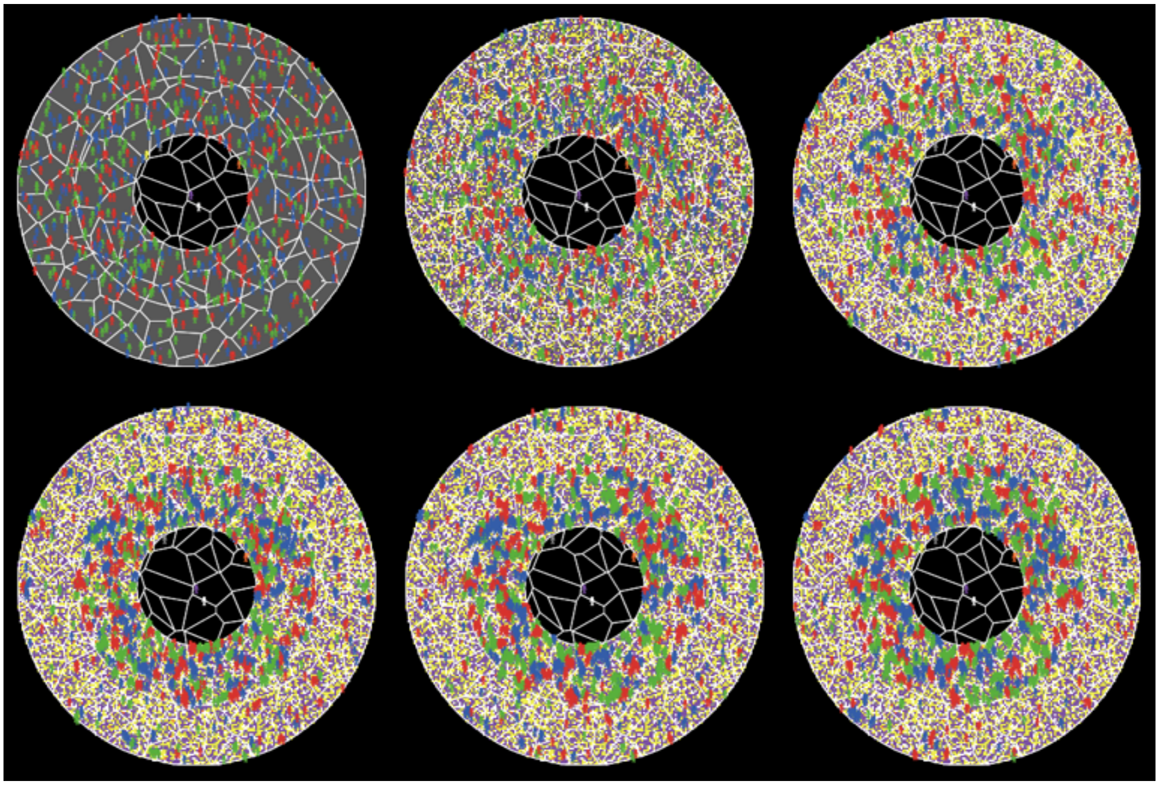

Figure 24. Evolution of the Model at Default Settings: Top Left at 0 Time-Step, Top Middle at 50, Top Right at 100, Bottom Left at 150, Bottom Middle at 200 and Bottom Right at 250

The results collected from the model cohesively show the evolution of the city. The model evolves from a landscape with scattered, randomly placed professionals and non-professionals, to a highly dense, gentrified and segregated landscape with the majority located in the inner-city. Figure 24 demonstrates this in a representative model run.

The default settings are used as a benchmark to compare the results of runs with parameters at various settings. These results are representative runs from 20 simulations with seed for the random generator on default settings. Sections 4.2.2 to 4.2.6 will cover results examining the urban dynamics. The testing parameters are introduced in tables while the plots illustrating the results are in the figures associated with the tables.

4.2.2 Urban Growth

In this section, the urban growth dynamic of the model is examined. As mentioned in section 3.6, agents are randomly added to the model at random locations in the inner-city or suburbia every 15 time-steps. This data was used to design the urban growth dynamic based on empirical facts (the 17% growth rate in the Washington D.C. population) This while ensuring the correct procedure of the model. The parameters initial population and urban growth rate were used to plot the data gathered for this dynamic. A seed was fixed for the random generator to maintain all the parameters of the model with default setting and track the change of the parameters being examined. The model ran for each of the nine possible configurations of the parameter settings (each of the three minimum, default and maximum settings of each two parameters) as shown in **Error! Reference ource not found.**. Although all the results are interesting to study, due to large possible parameter combination, only a select group of resulted dynamics will be reported. Table 8 lists the parameters that are tested for urban growth.

Table 8. Urban Growth Test Parameters

Scenario	Urban Growth Rate	Initial Population	Subject of Test	Figure
A	0.1	100	Inner-city	Figure 25
B	0.3	100	Inner-city	Figure 26
C	0.1	1000	Inner-city	Figure 27
D	0.3	1000	Inner-city	Figure 28
E	0.1	100	Suburbia	Figure 29
F	0.3	100	Suburbia	Figure 30
G	0.1	1000	Suburbia	Figure 31

H	0.3	1000	Suburbia	Figure 32
I	0.1	100	Population over Time	Figure 33
J	0.3	100	Population over Time	Figure 34
K	0.1	1000	Population over Time	Figure 35
L	0.3	1000	Population over Time	Figure 36

Figure 25 and Figure 26 compare the urban growth within the inner-city with 100 initial population and urban growth rates of 0.1 (minimum) and 0.3 (maximum). While the behavioral pattern of the professional agents shows an increasing presence in the inner-city, the non-professional agents seem to be less dominant in the inner-city when the growth rate is lower. As the population grows the divide between agent groups becomes more visible.

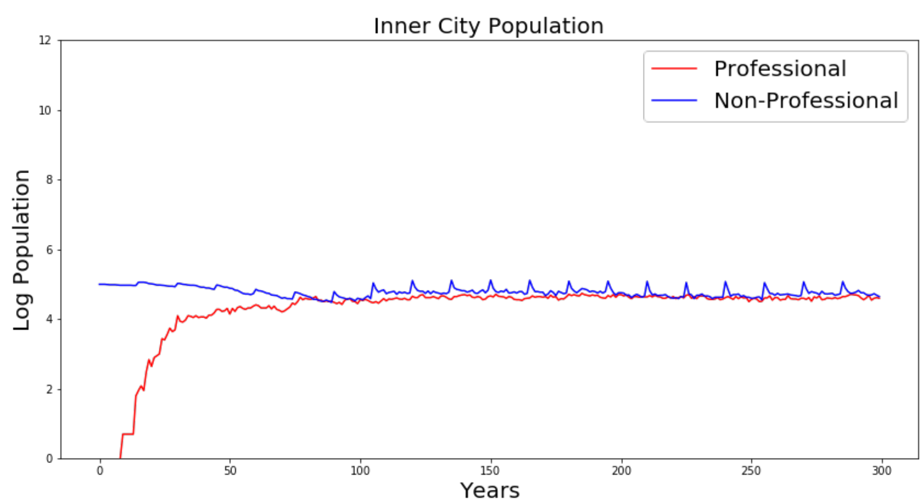

Figure 25. Urban Growth: Scenario A

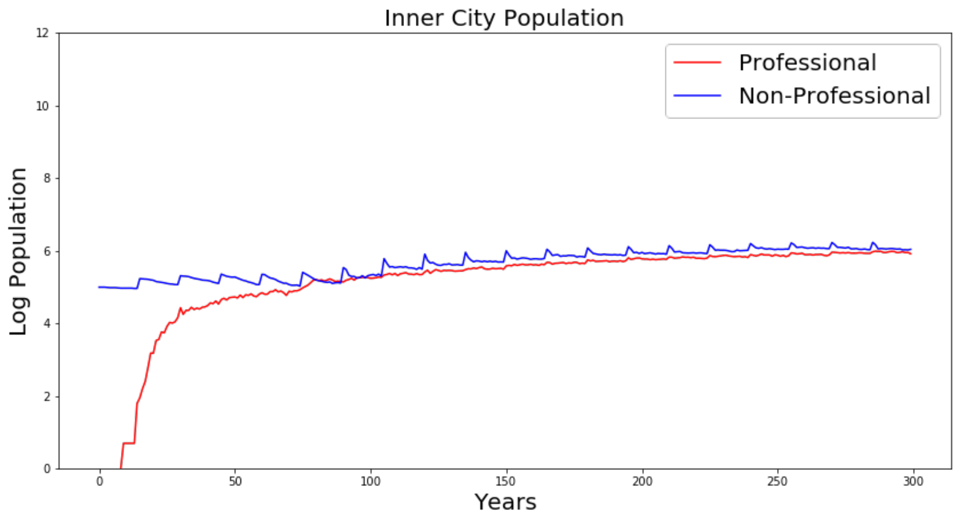

Figure 26. Urban Growth: Scenario B

Figure 27 and Figure 28 show the effect of population increase on the inner-city demographics then slowly decreases after over 100 time-steps. Another point in these two figures is that by increasing the growth rate, we see that the number of professionals and non-professionals reach the same in the inner city while with a lower growth rate there is a gap between the two populations. As you will see in Figure 35 and Figure 36, the reason for a decrease in the population after year 150, is due to the dominance of shrinkage population. Basically, after this point, the shrinkage rate removes slightly more people than the amount of people which are added to the model by urban growth. With 1000 people as the initial population, the general pattern of the plots follows the same as 100 people. The difference appears in the rising population difference with higher initial population. Comparing Figure 25 and Figure 26 with Figure 27 and Figure 28, the higher the population the higher the dominance of the non-professional agents in the inner-city.

The lower the population the higher the chances of integration and equal dominance of groups over a territory.

Figure 27. Urban Growth: Scenario C

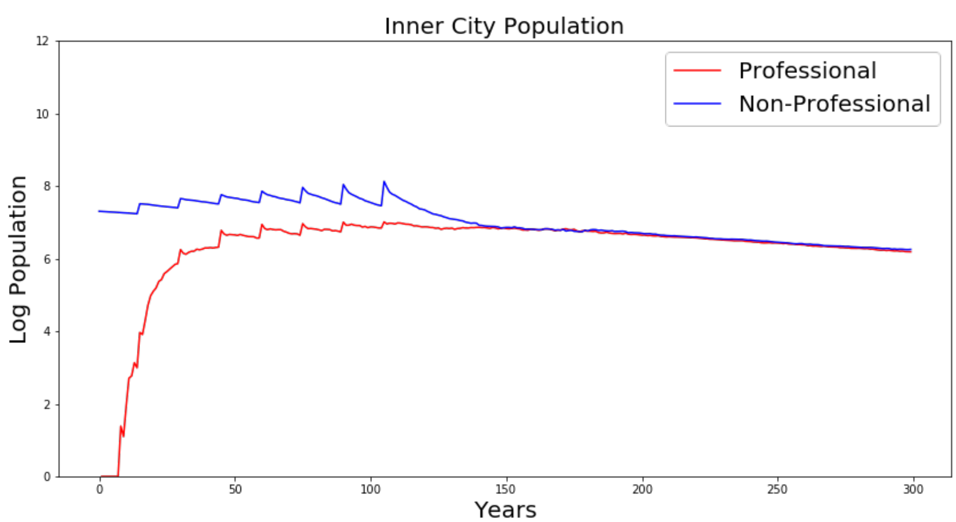

Figure 28. Urban Growth: Scenario D

Figure 29 and Figure 30 compare the urban growth within the suburbia with 100 initial population and urban growth rates of 0.1 (minimum) and 0.3 (maximum). While the behavioral pattern of the non-professionals agents shows an increasing presence in the suburbia, the professional agents seem to slowly lose dominance in the suburbia when the growth rate is lower. As the population grows the divide between agent groups becomes more visible.

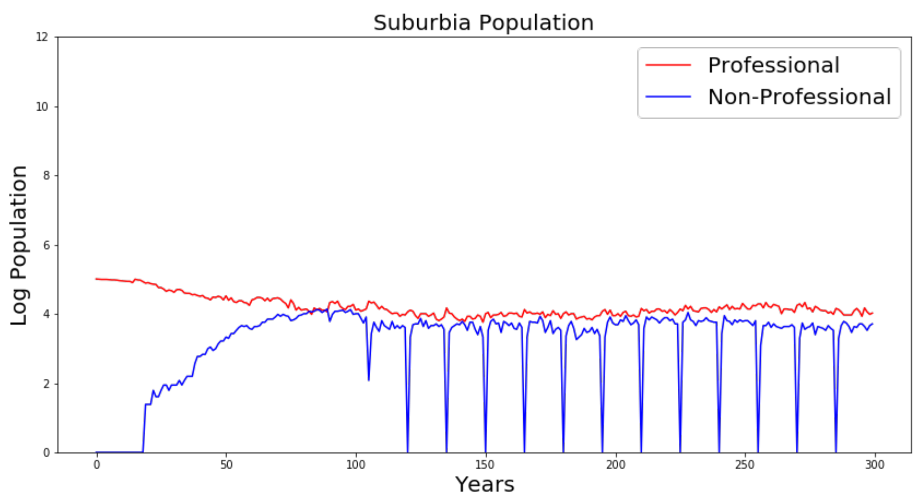

Figure 29. Urban Growth: Scenario E

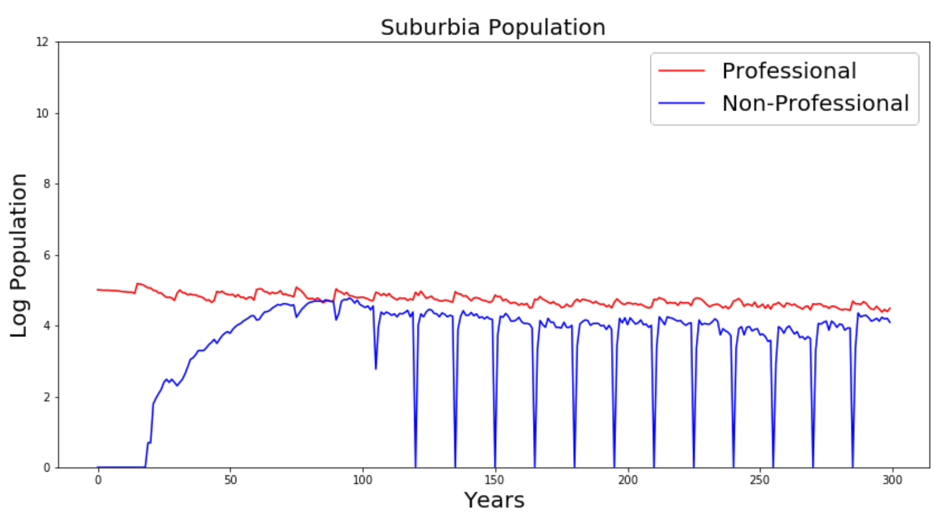

Figure 30. Urban Growth: Scenario F

Figure 31 and Figure 32 show the effect of population increase on the suburbia demographics. With 1000 people as the initial population, the pattern of the plots shows the steady dominance of professionals in this region while the non-professionals have a constant rise and fall. Although the rise and fall for the non-professionals seems to stop after time-step 120 which shows that most of the agents reached a state where they are not moving around anymore. This could come from the fact that they are already reached a state of happiness and their saving is enough for buying houses in the suburbia. As the urban growth rate increases, the divide among the agent groups seem to lower. The sharp drop of non-professionals in suburbia is due to the model's gentrification setting – that enforces the dynamic every 15 years – which moves professional agents with the lowest income in suburbia to the inner-city – explained in detail in section 4.2.5.

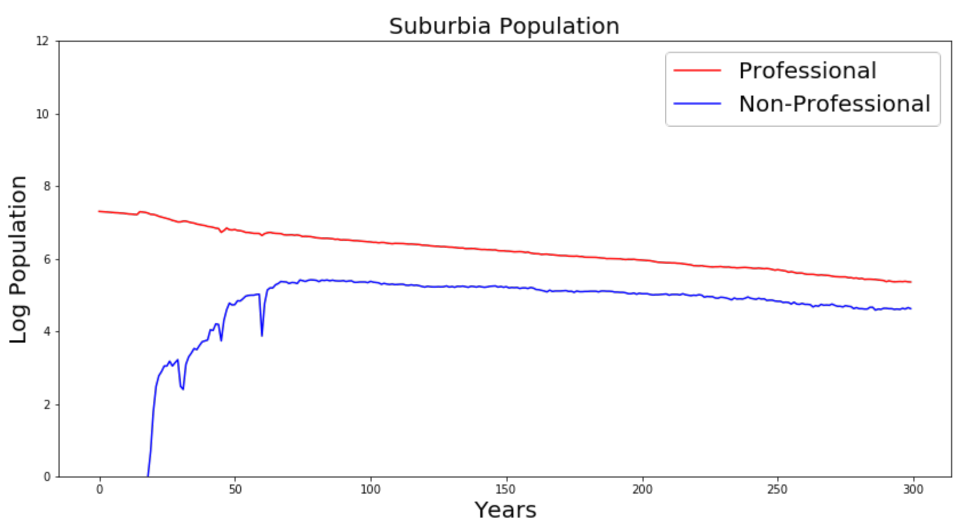

Figure 31. Urban Growth: Scenario G

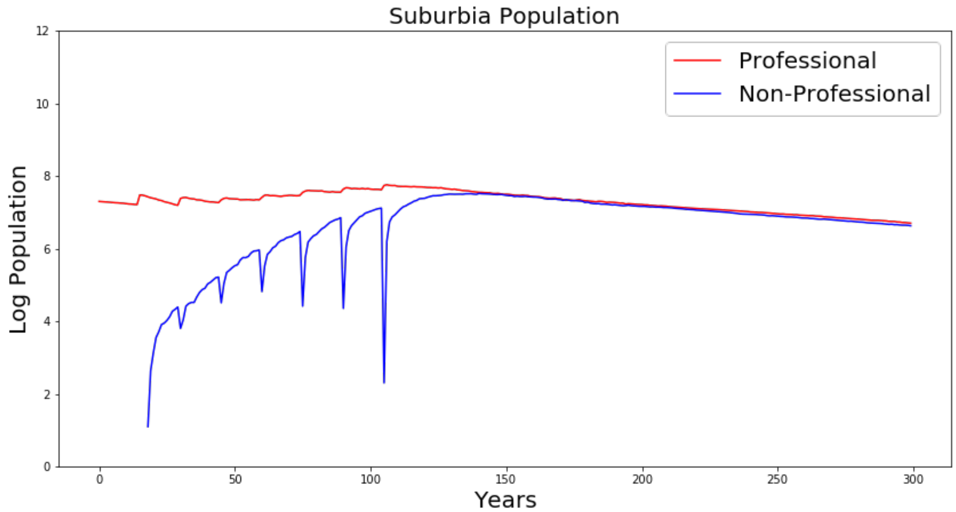

Figure 32. Urban Growth: Scenario H

Figure 33 and Figure 34 show almost identical results for initial population of 100 and urban growth rates of 0.1 and 0.3. In both cases, urban growth and gentrification are steady and similar to the model results with default settings. The shrinkage population slowly increases as the years pass and the overall population increases.

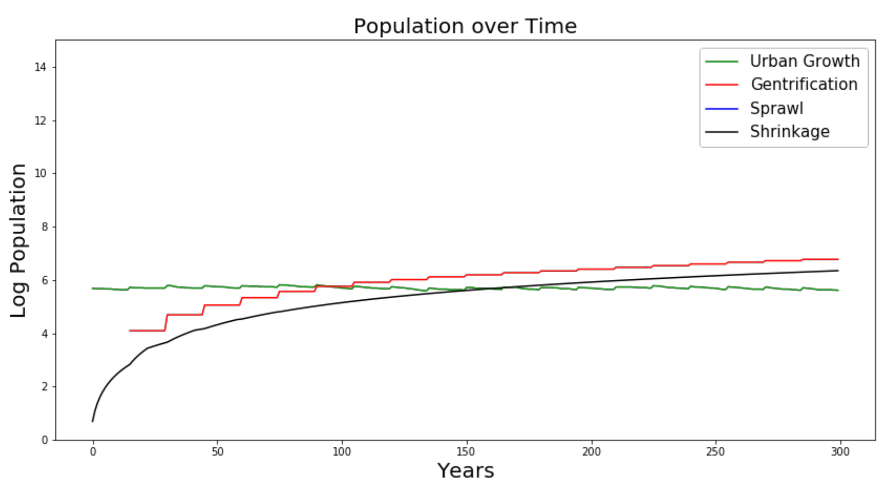

Figure 33. Urban Growth: Scenario I

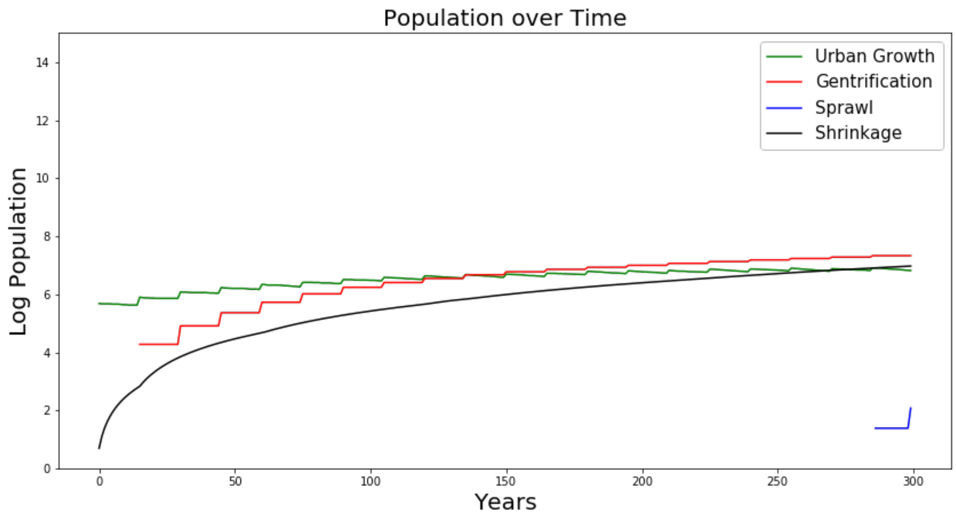

Figure 34. Urban Growth: Scenario J

Figure 35 and Figure 36 illustrate noteworthy results. While the population increase has elevated the start point of urban growth, shrinkage and gentrification, the relation between these dynamics has remained the same. The interesting observation in these figures is the rise of urban sprawl. The plots show that even with the default sprawl, given a large population with a high percentage of growth, sprawl can occur at a major scale. This highlights the aforementioned – in sections 2.4.1 and 2.4.2 – interlink between urban growth and sprawl and the inducing of sprawl from growth. Figure 37 shows urban growth at maximum and minimum settings in two representative simulations.

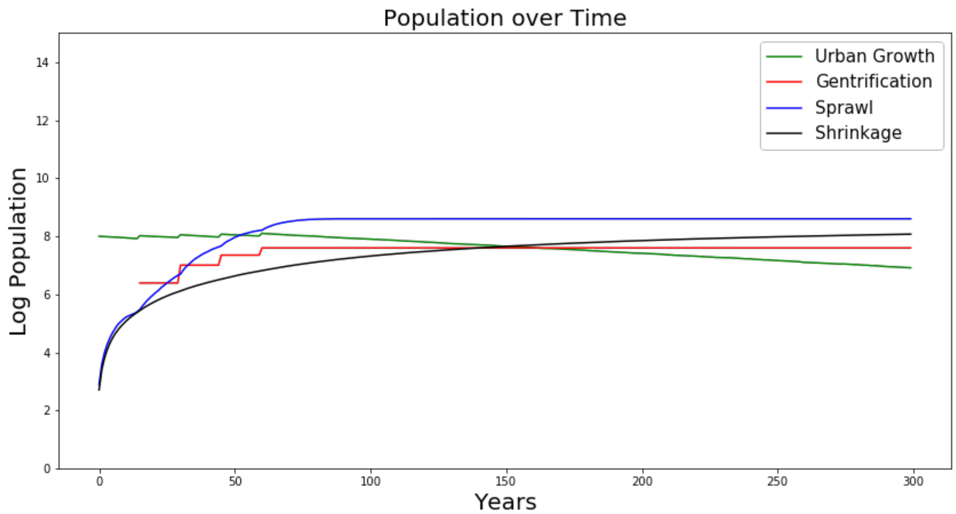

Figure 35. Urban Growth: Scenario K

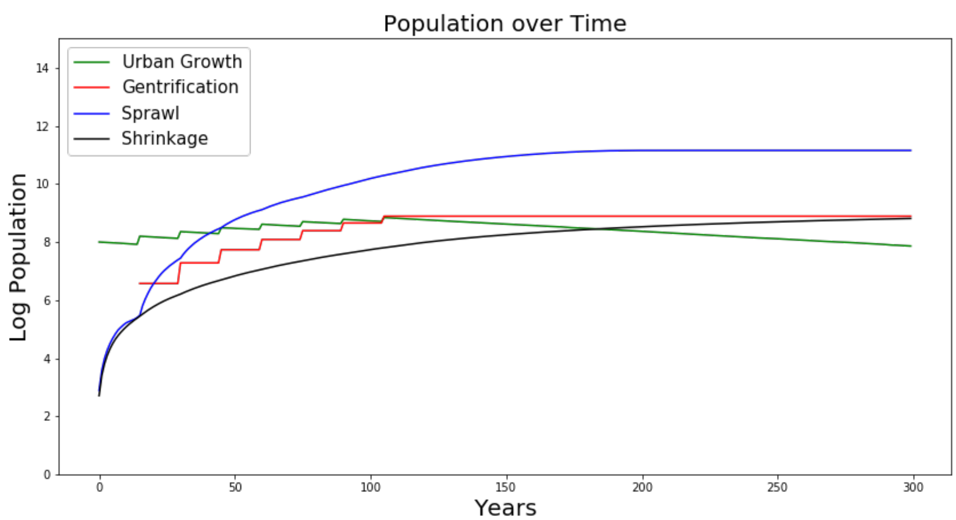

Figure 36. Urban Growth: Scenario L

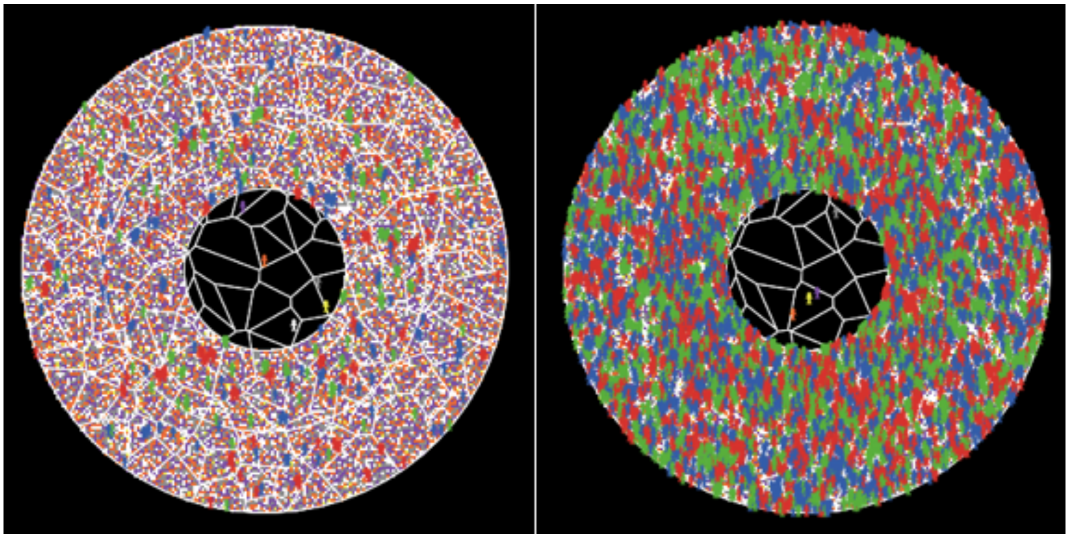

Figure 37. Representative Urban Growth Results at Minimum (left) and Maximum (right) Settings

4.2.3 Urban Shrinkage

In this section, the urban shrinkage dynamics of the model is examined. As introduced in section 3.6, data shows that Washington D.C. has had a 25% urban shrinkage from 1950 to 2015 (Wikipedia, 2015). Using this data, the model population shrinks by 25% every 50 time-steps. The shrinking means that a population moves to another location; however, due to the lack of extended geography in the model, this process is demonstrated by agents dying. The parameters initial population and shrinkage rate – introduced in section 3.6 – were used to plot the data gathered for this dynamic. A seed was fixed for the random generator to maintain all the parameters of the model with default setting and track the change of the parameters being examined. The model ran for each of the nine possible configurations of the parameter settings (each of the three minimum, default and maximum settings of each two parameters) as highlighted in Table 7. Although all the results are interesting to study, due to large possible parameter combination, only a select group of resulted dynamics will be reported. Table 9 lists the testing parameters for urban shrinkage.

Table 9. Urban Shrinkage Test Parameters

Scenario	Urban Shrinkage Rate	Initial Population	Subject of Test	Figure
A	0.001	100	Inner-city	Figure 38
B	0.01	100	Inner-city	Figure 39
C	0.001	1000	Inner-city	Figure 40
D	0.01	1000	Inner-city	Figure 41
E	0.001	100	Suburbia	Figure 42
F	0.01	100	Suburbia	Figure 43
G	0.001	1000	Suburbia	Figure 44
H	0.01	1000	Suburbia	Figure 45
I	0.001	100	Population over Time	Figure 46
J	0.01	100	Population over Time	Figure 47
K	0.001	1000	Population over Time	Figure 48
L	0.01	1000	Population over Time	Figure 49

Figure 38 and Figure 39 demonstrate gradual appearance of professionals in the inner-city with low and high shrinkage rates. The plots also demonstrate that at high and low shrinkage rates, the professionals and non-professionals seem to coexist in the inner-city. It seems that at low population, shrinkage allows professionals to enter the inner-city due to the availability of unoccupied and preferred properties – based on the concepts introduced in section 3.4.1.

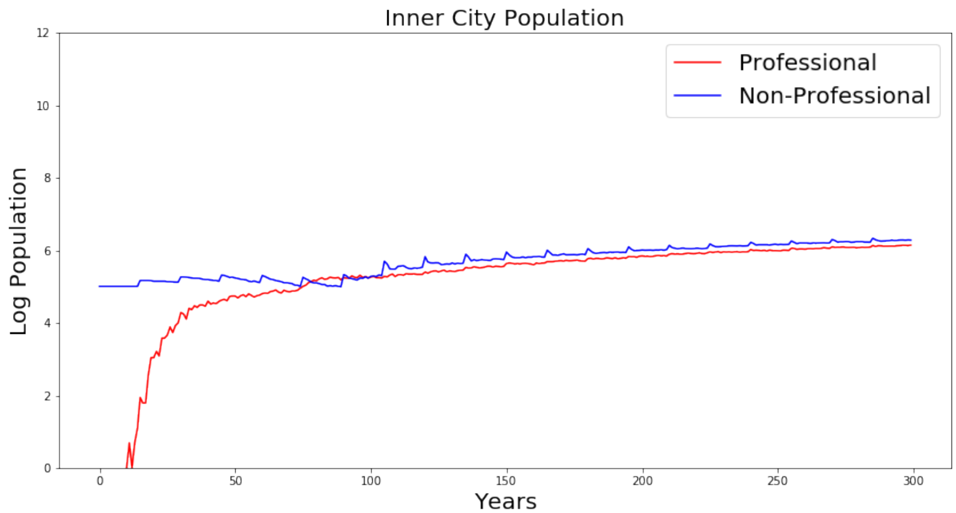

Figure 38. Urban Shrinkage: Scenario A

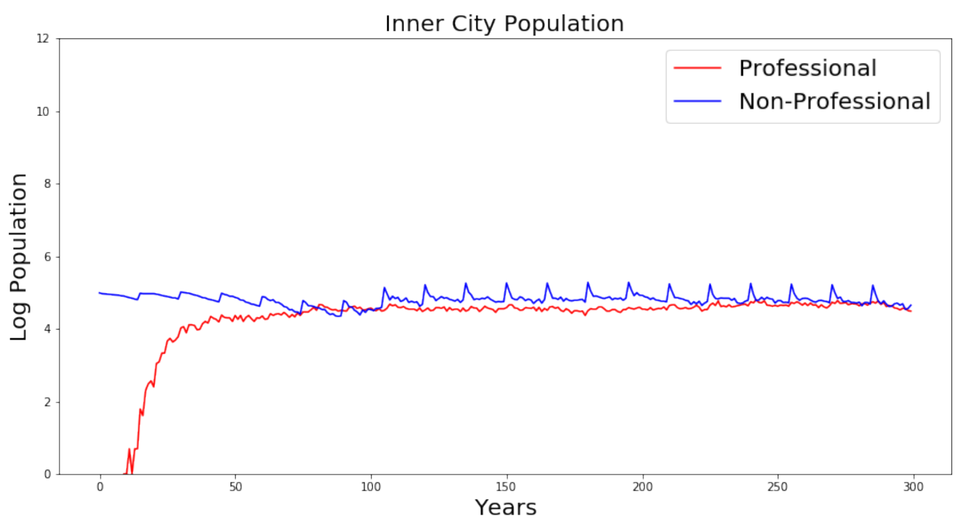

Figure 39. Urban Shrinkage: Scenario B

Figure 40 and Figure 41 show the effect of population increase on the inner-city demographics. With 1000 people as the initial population, the general pattern of the plots follows the same as 100 people. The difference appears in the rising population difference with higher initial population. Comparing Figure 38 and Figure 39 with Figure 40and Figure 41, the higher the population the higher the dominance of the non-professional agents in the inner-city. The lower the population the higher the chances of integration and equal dominance of groups over a territory. The comparison shows that initial population effects the intensification of urban shrinkage. Both the professional and non-professional agents are bound by their economic statuses. Therefore, when the population increases, the possibility of options and movement decreases based on their statuses.

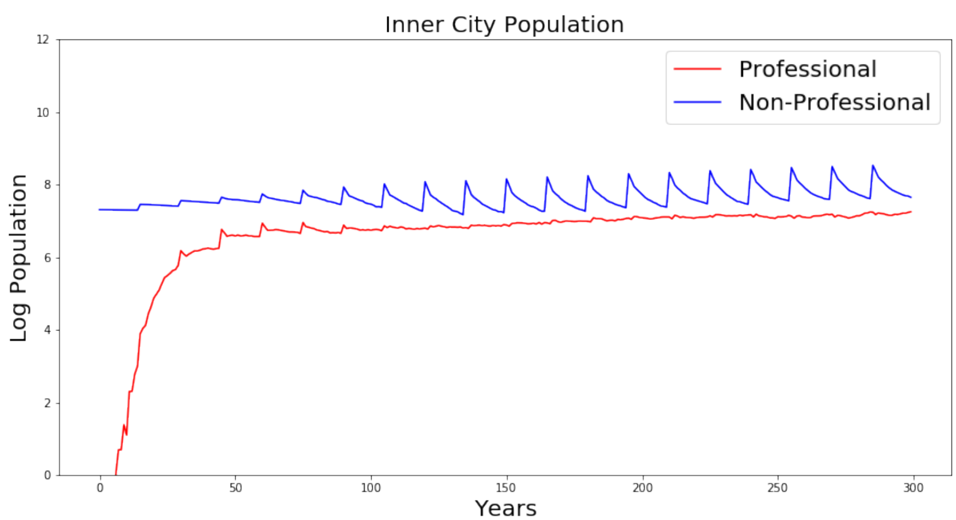

Figure 40. Urban Shrinkage: Scenario C

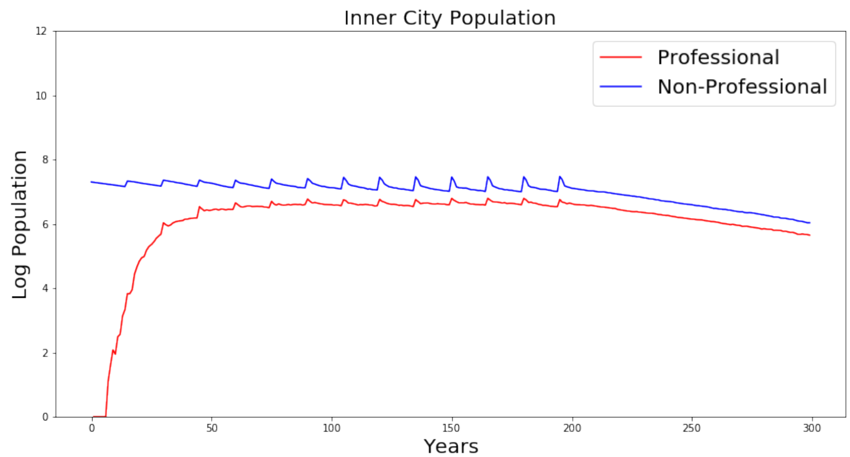

Figure 41. Urban Shrinkage: Scenario D

Figure 42 and Figure 43 show that at minimum shrinkage rate, the number of non-professionals in suburbia increases while high shrinkage rate maintains the geographical divide between them and professionals. The lower shrinkage rate also shows a sudden population rise of the non-professionals from zero. The higher shrinkage rate however, shows a sudden appearance of non-professionals in the suburbia, followed by a sharp rise.

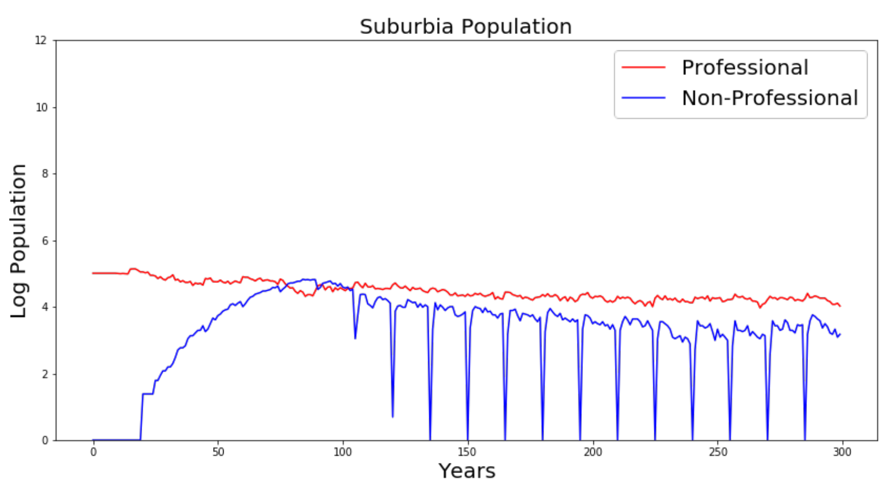

Figure 42. Urban Shrinkage: Scenario E

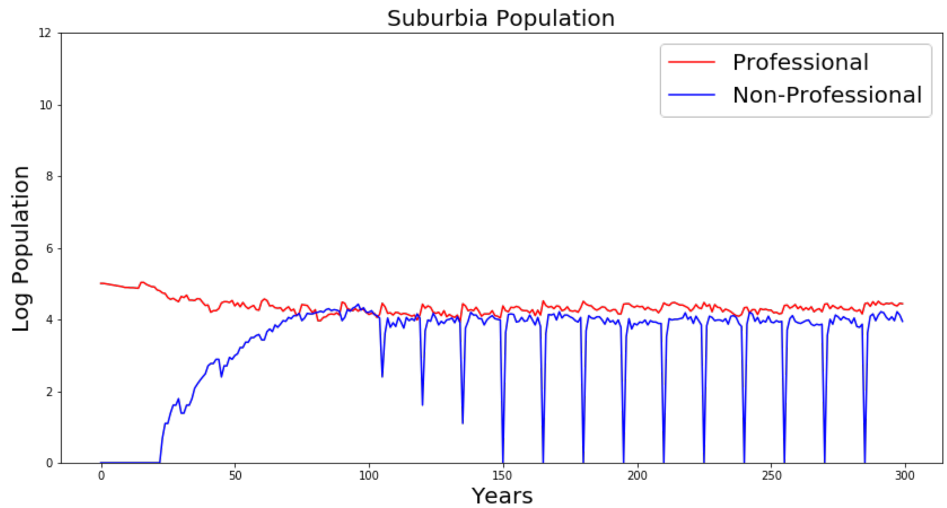

Figure 43. Urban Shrinkage: Scenario F

Figure 44 and Figure 45 illustrate the effects of large population on the suburbia output of the model. The plots of Figure 42 and Figure 43 and Figure 44 and Figure 45 demonstrate that the larger the initial population and the shrinkage rate, the higher the possibility of a divide between professionals and non-professionals in suburbia. Lower shrinkage rate results in non-professionals reaching the same level of population as professionals. As mentioned in section 4.2.2 the sharp drop of non-professionals in suburbia is due to the model's gentrification setting which moves agents with the lowest income within suburbia to the inner-city. This is followed by the growth and entrance of a new population in suburbia.

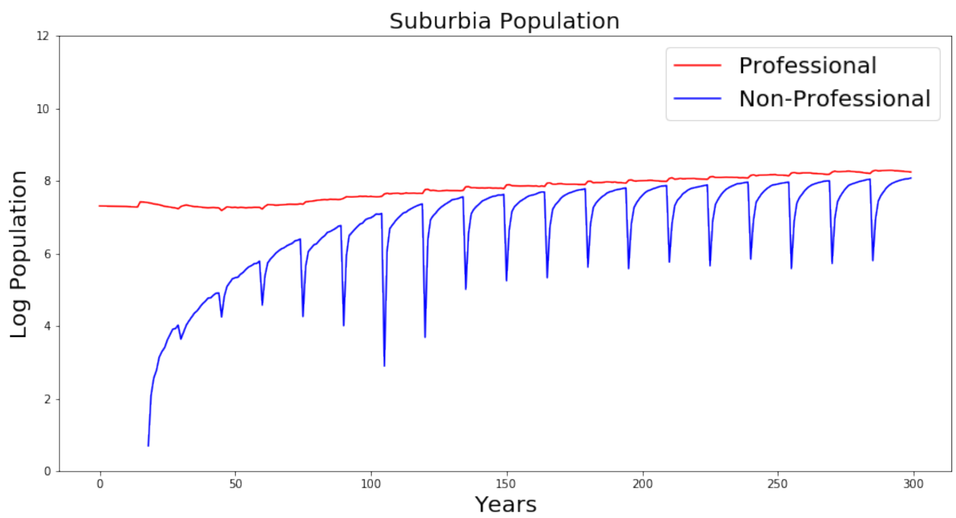

Figure 44. Urban Shrinkage: Scenario G

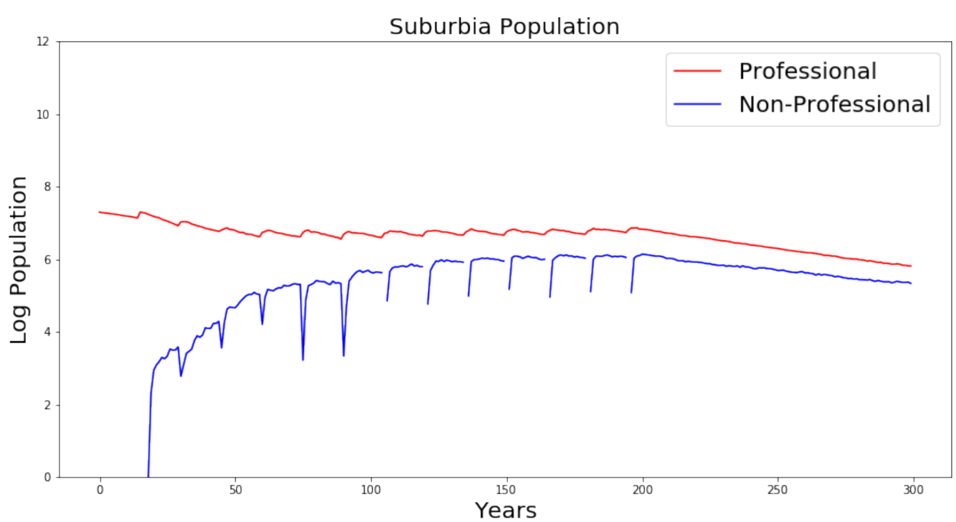

Figure 45. Urban Shrinkage: Scenario H

Figure 46 and Figure 47 illustrates the interesting results of 100 initial population over time and with minimum and maximum shrinkage rates. While urban growth and gentrification remain consistent at both rates, at minimum rate, urban sprawl do not even occur while urban shrinkage starts after year 60. With an increase in shrinkage rate, urban shrinkage begins to occur and develop over time. Sprawl is still not happening at this stage.

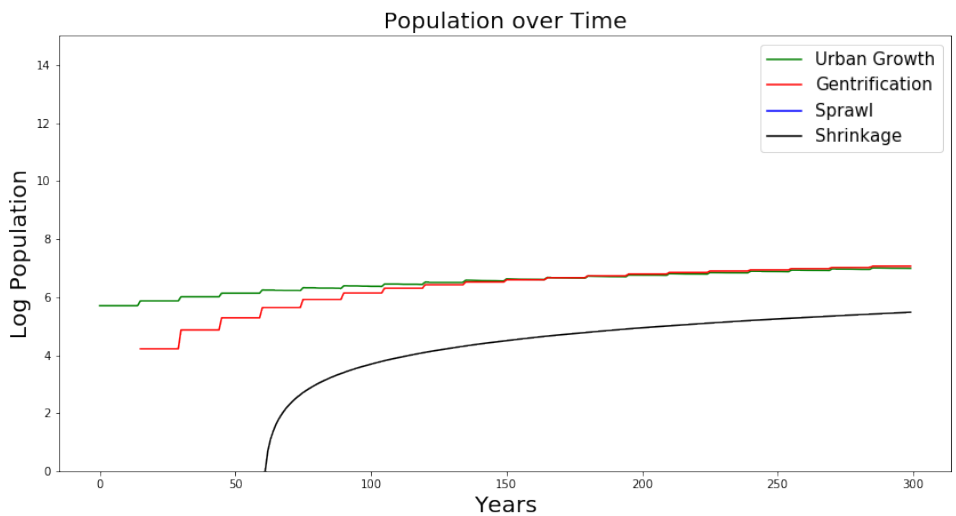

Figure 46. Urban Shrinkage: Scenario I

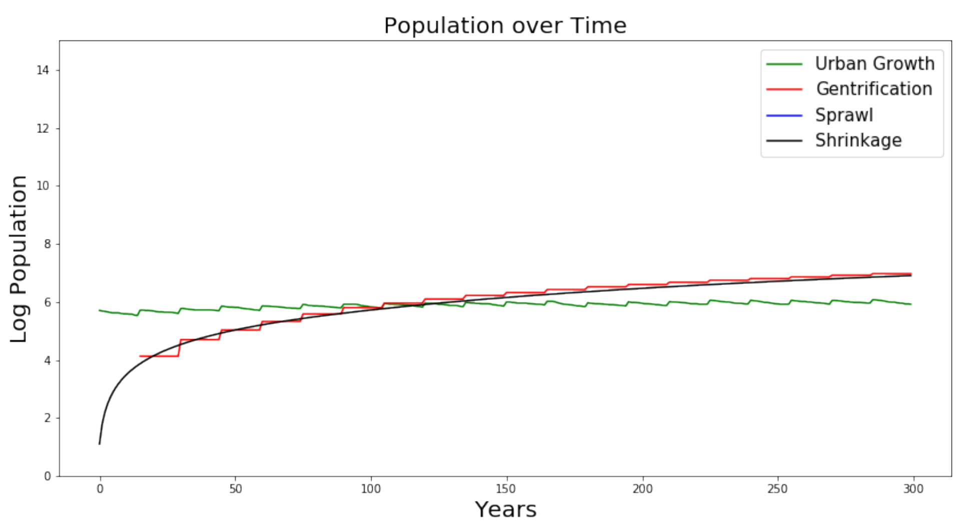

Figure 47. Urban Shrinkage: Scenario J

The 1000 initial population shows different results than previously observed. For these scenarios, the urban growth and gentrification pattern remain similar to the pattern observed in Figure 48 and Figure 49. However, urban shrinkage and sprawl appear as increasing. At lower shrinkage rate the population difference between urban sprawl and shrinkage is significant while at higher shrinkage rate, this difference decreases. As you can see, by increasing the shrinkage rate the urban growth population decreases over time which shows that we remove more agents over time than add new ones to the model. This behavior is demonstrated in detail in section 4.2.4. Figure 50 illustrates representative model simulations the urban shrinkage at minimum and maximum settings.

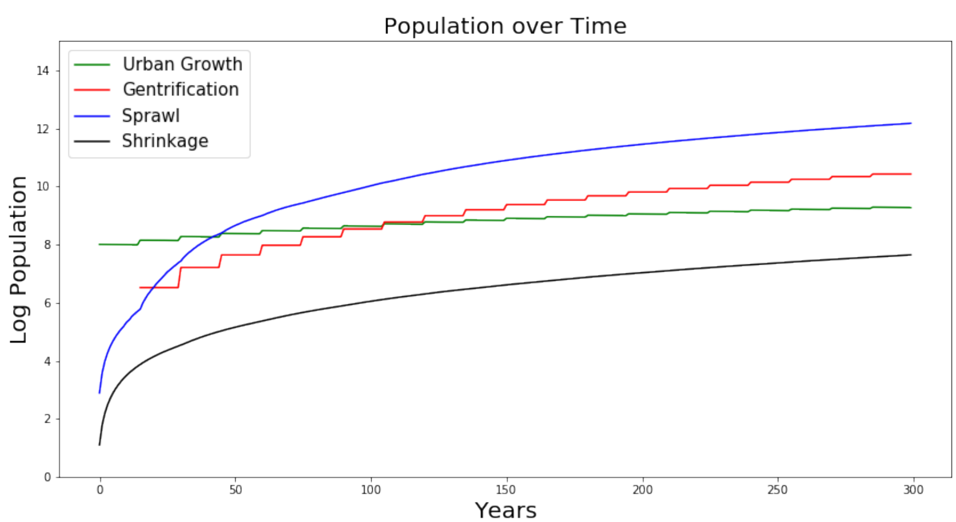

Figure 48. Urban Shrinkage: Scenario K

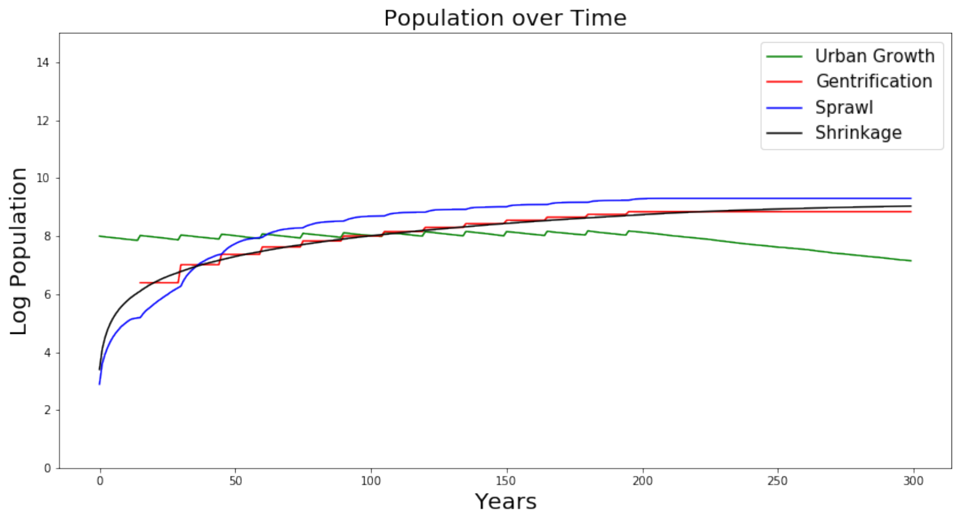

Figure 49. Urban Shrinkage: Scenario L

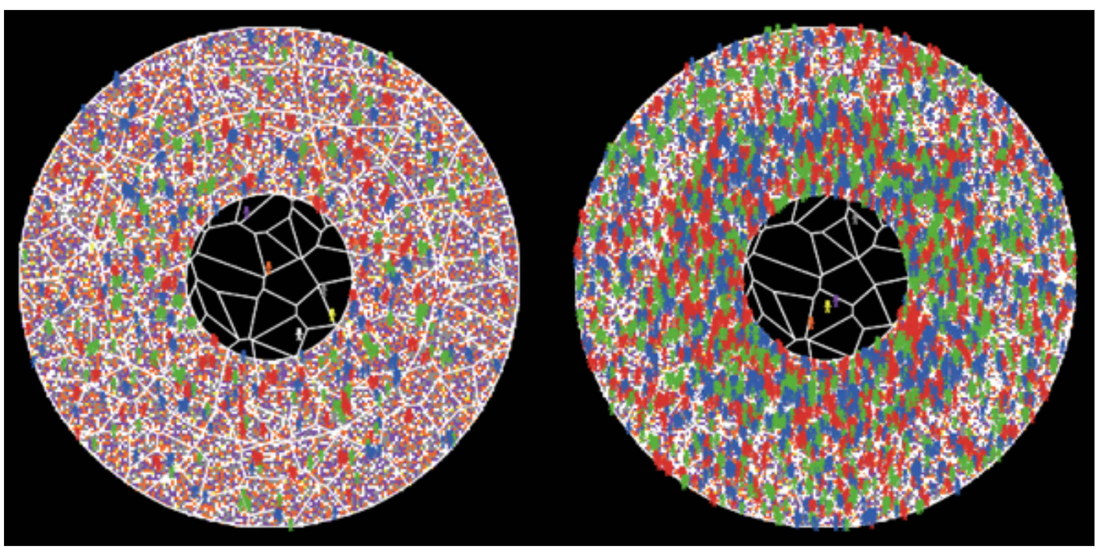

Figure 50. Representative Urban Shrinkage Results at Minimum (left) and Maximum (right) Settings

4.2.4 Urban Sprawl

In this section, the urban sprawl dynamic of the model is examined. As mentioned in section 3.6, the parameters initial population, sprawl density threshold and sprawl moving rate were used to plot the data gathered for this dynamic. A seed was set for the random generator to maintain all the parameters of the model with default setting and track the change of the parameters being examined. The model ran for each of the 27 possible configurations of the parameter settings (each of the three minimum, default and maximum settings of each three parameters) as highlighted in Table 7.

Although all the results are interesting to study, due to large possible parameter combination, only a select group of resulted dynamics will be reported. Due to high similarities found in various recorded results, the urban sprawl results mentioned here will be focused on the population over time and grouped based on similar or different instances.

Table 10. Urban Sprawl Test Parameters

Scenario	Sprawl Moving Rate	Sprawl Density Threshold	Initial Population	Figure
A	0.05	0.5	100	Figure 51
B	0.3	0.5	100	Figure 52
C	0.05	0.5	300	Figure 53
D	0.3	0.5	300	Figure 54
E	0.05	0.5	1000	Figure 55
F	0.3	0.5	1000	Figure 56
G	0.05	0.05	100	Figure 57
H	0.3	0.05	100	Figure 58
I	0.05	0.05	300	Figure 59
J	0.3	0.05	300	Figure 60
K	0.05	0.05	1000	Figure 61
L	0.3	0.05	1000	Figure 62

Figure 51, Figure 52, Figure 53, and Figure 54 demonstrate similar patterns observed when experimenting for urban sprawl with initial populations of 100 and 300, sprawl moving rates of 0.05 (minimum) and 0.3 (maximum), and sprawl density threshold of 0.5. All the plots above follow the same pattern. No sprawl is observed at this level. While urban shrinkage starts with zero population at 100 population, the start point slightly increases at 300 population. As mentioned in section 3.6, the density of neighborhoods has to reach its threshold for population mobility to occur.

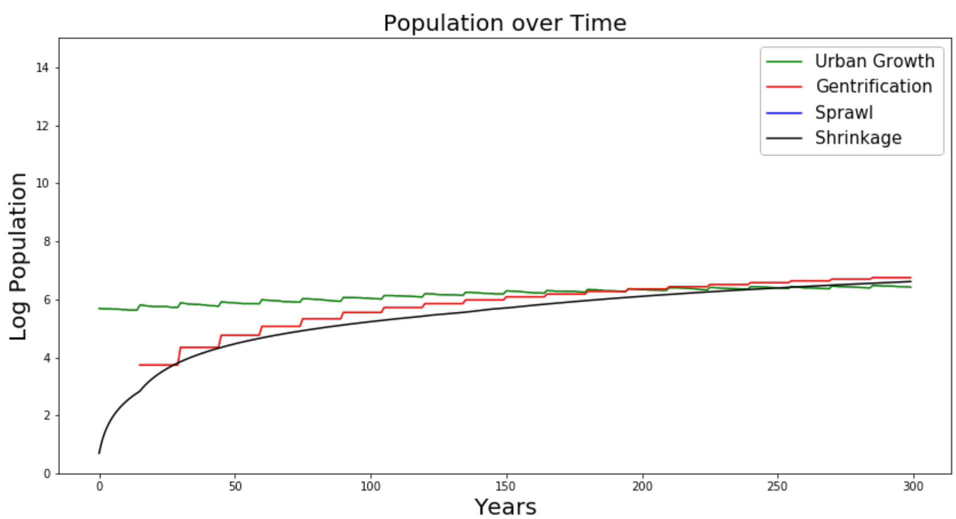

Figure 51. Urban Sprawl: Scenario A

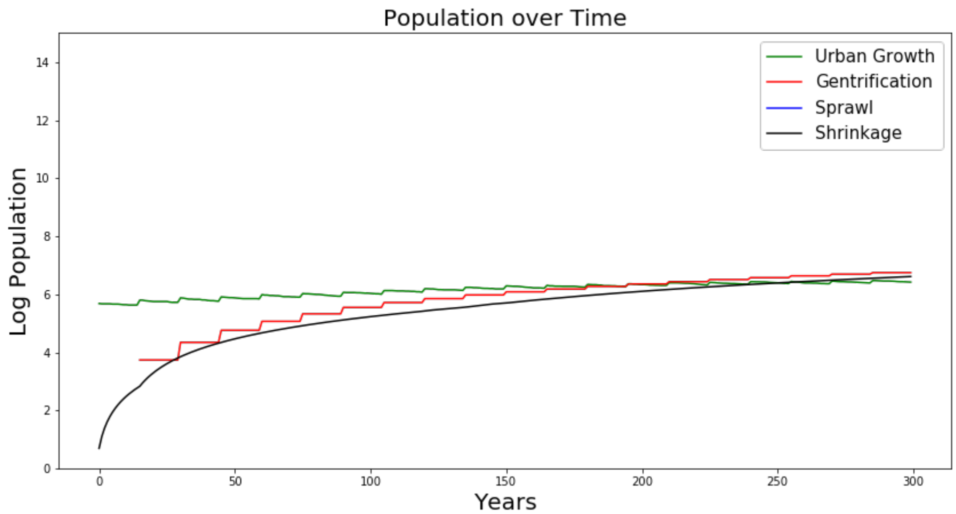

Figure 52. Urban Sprawl: Scenario B

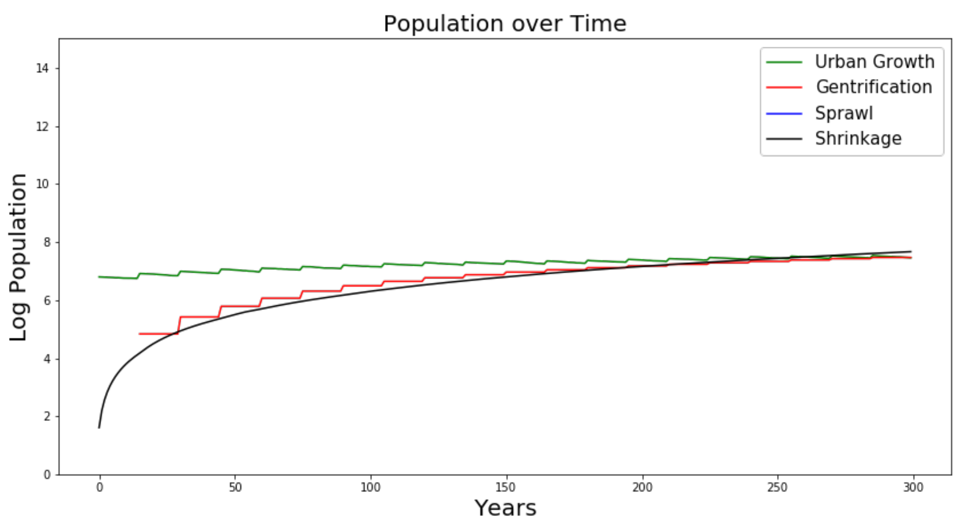

Figure 53. Urban Sprawl: Scenario C

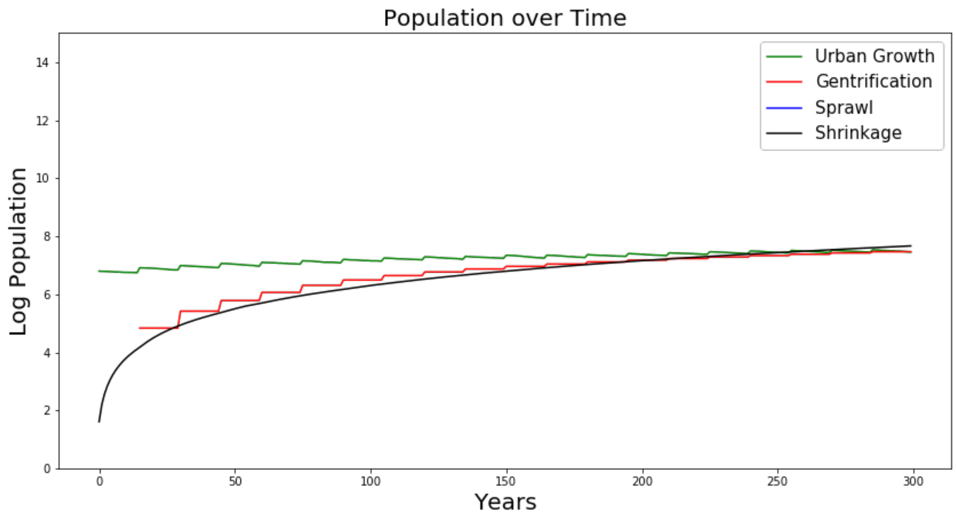

Figure 54. Urban Sprawl: Scenario D

Figure 55 and Figure 56 illustrate similar patterns observed when experimenting for urban sprawl with initial populations of 1000, minimum and maximum sprawl moving rates, and maximum sprawl density threshold. Both plots show the appearance of urban sprawl about the year 80. This sudden appearance is due to the high sprawl density threshold that occurs when patches reach a certain number of agents. The rise in sprawl is due to the increase of urban growth. This confirms the notion of growth inducing sprawl as introduced in section 2.4.1 and 2.4.2 and modeled according section 3.6.

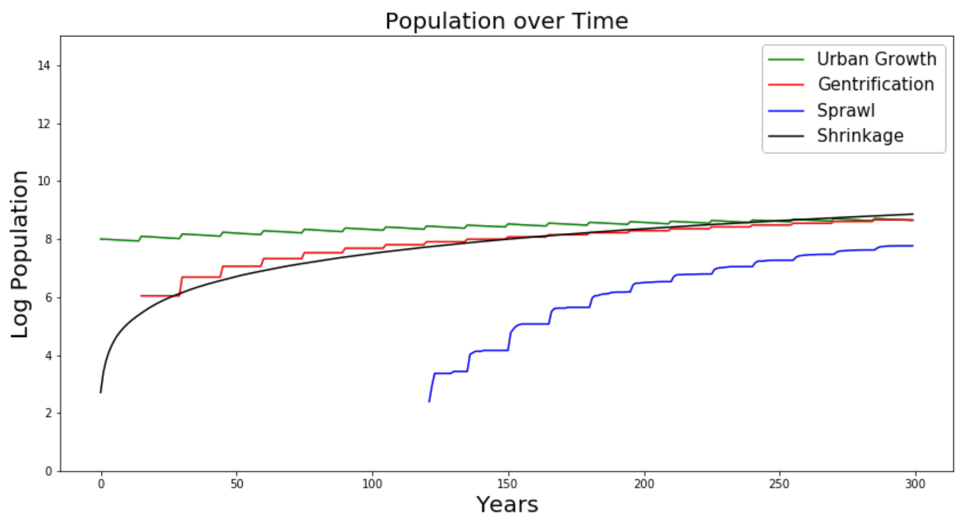

Figure 55. Urban Sprawl: Scenario E

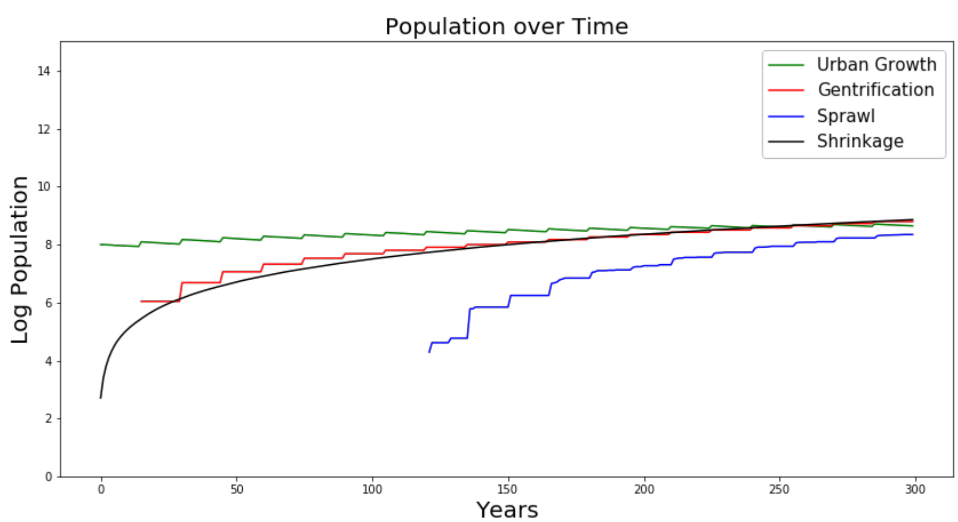

Figure 56. Urban Sprawl: Scenario F

Figure 57 and Figure 58 show how the increase in sprawl moving rate can affect the population. The higher the sprawl moving rate, the earlier the sprawl occurs and the more population it impacts. The urban growth, shrinkage and gentrification follow the same pattern.

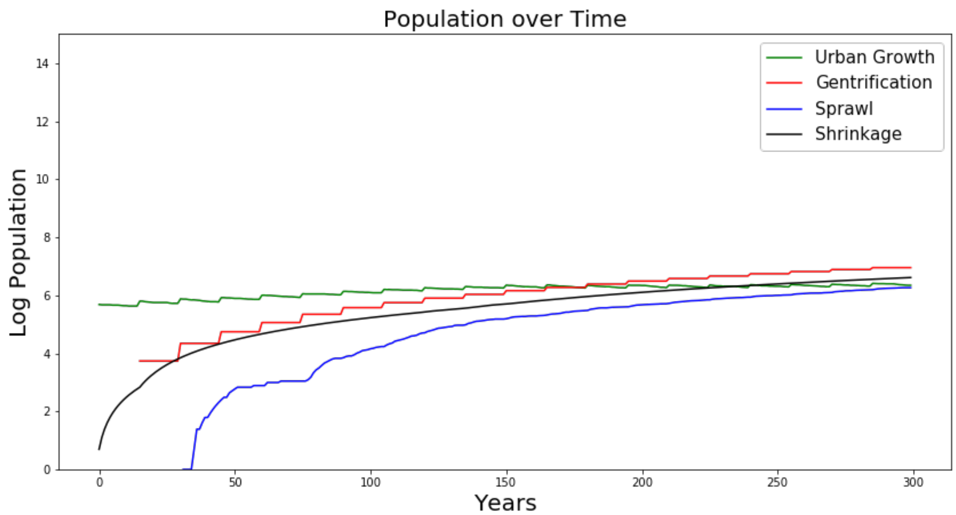

Figure 57. Urban Sprawl: Scenario G

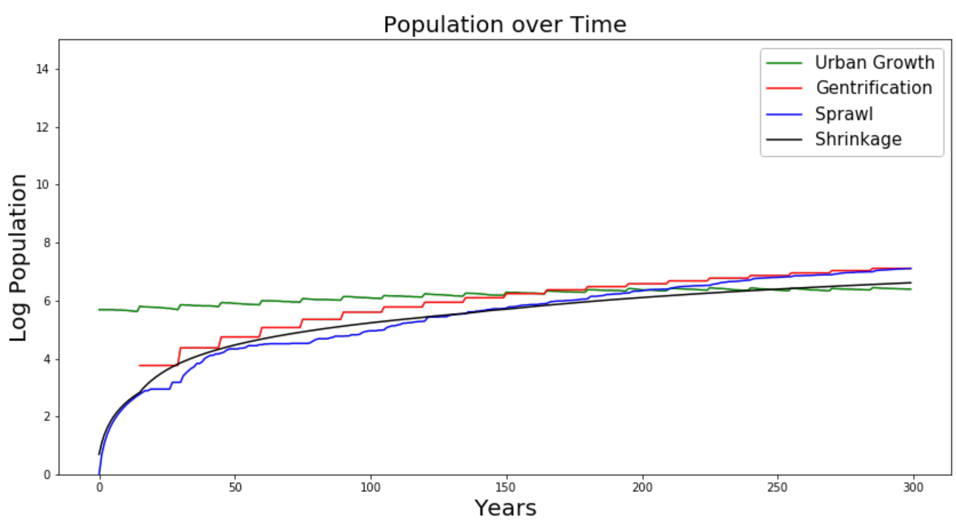

Figure 58. Urban Sprawl: Scenario H

Figure 59 and Figure 60 illustrate the effect of higher sprawl moving rate and population on the consistency and early appearance of sprawl. The urban growth, shrinkage and gentrification follow the same pattern.

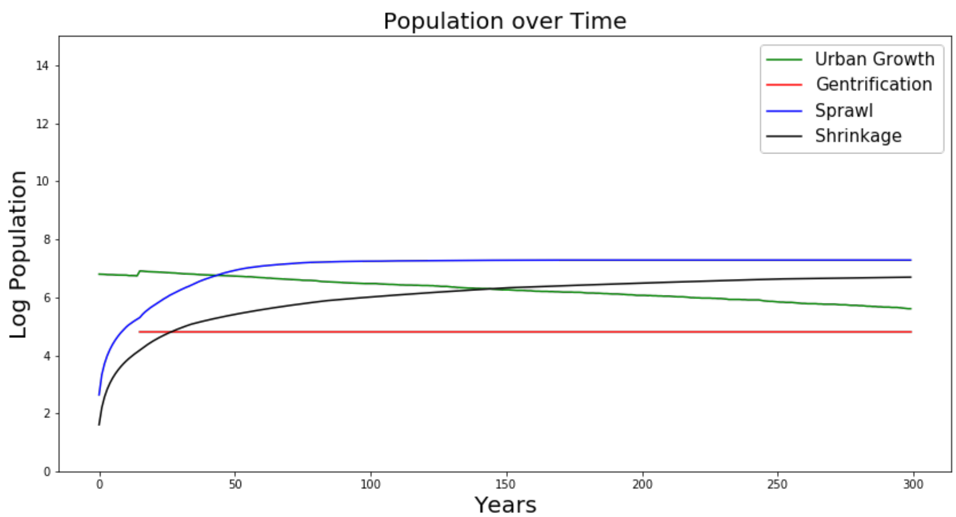

Figure 59. Urban Sprawl: Scenario I

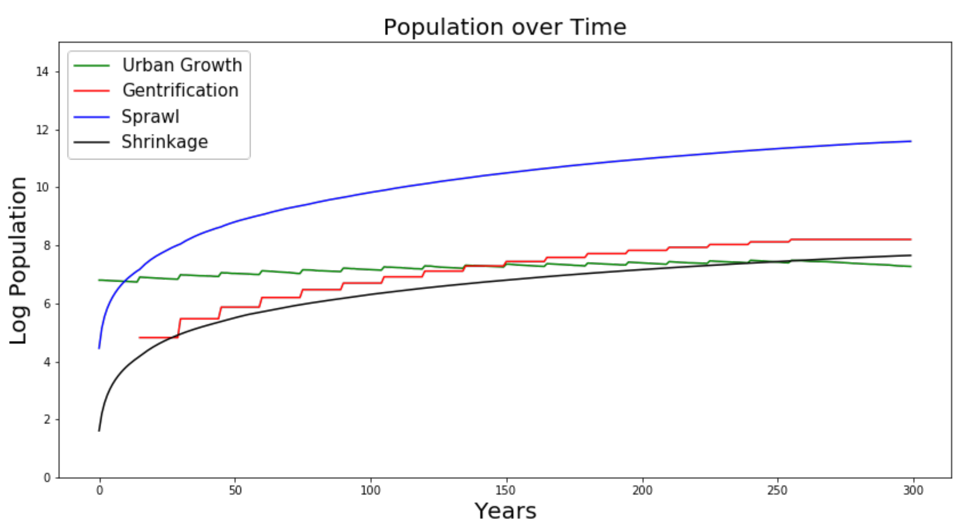

Figure 60. Urban Sprawl: Scenario J

Figure 61 and Figure 62 demonstrate a consistent rising curve of sprawl population. All the three parameters examined in this table play significant roles in the urban sprawl. The urban growth, shrinkage and gentrification follow the same pattern. The behavior observed in examining urban sprawl, follow a logical pattern where higher initial population, higher sprawl moving rate and lower sprawl density threshold give result in an early and significant sprawl. This dynamic which occurs due to the mechanics of the sprawl settings shows a trace of agent movement. Figure 63 shows representative simulations urban sprawl with 1000 initial population, 0.05 sprawl density threshold, 0.05 (left) and 0.3 (right) sprawl moving rate.

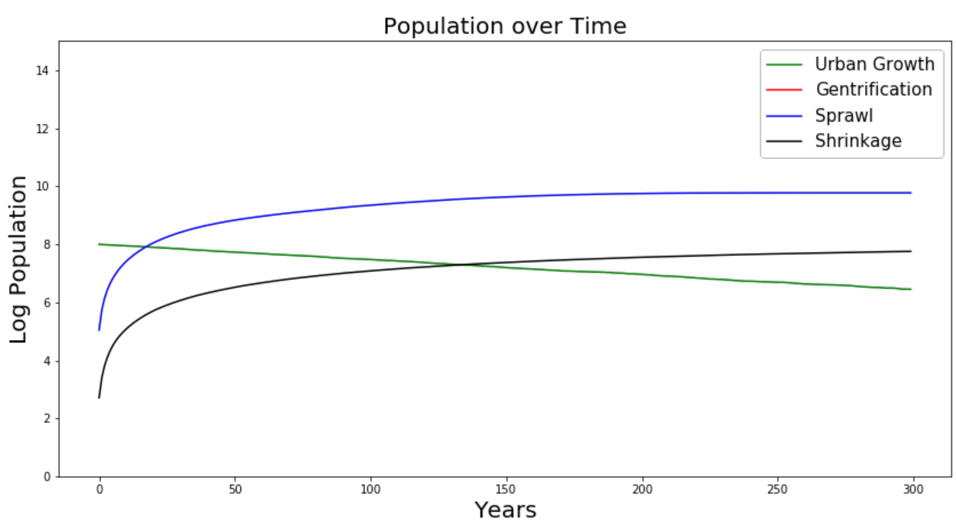

Figure 61. Urban Sprawl: Scenario K

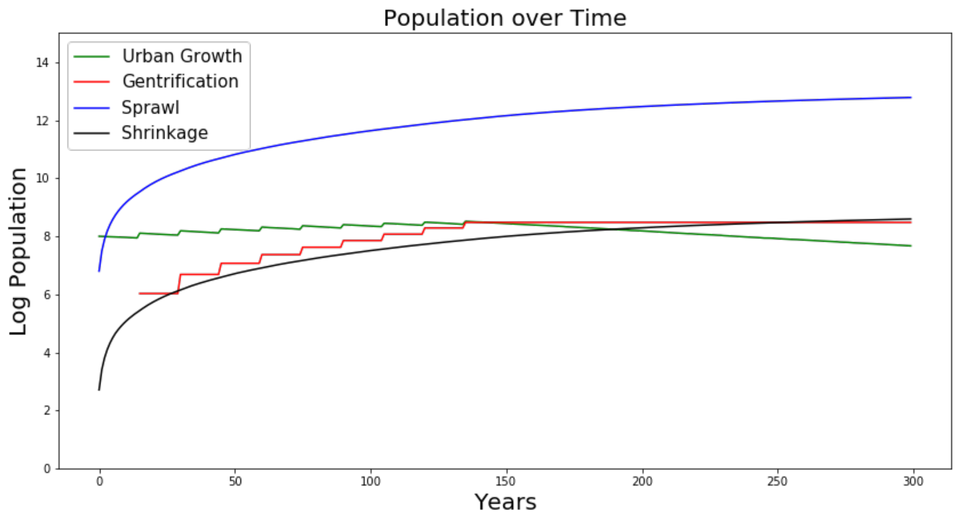

Figure 62. Urban Sprawl: Scenario L

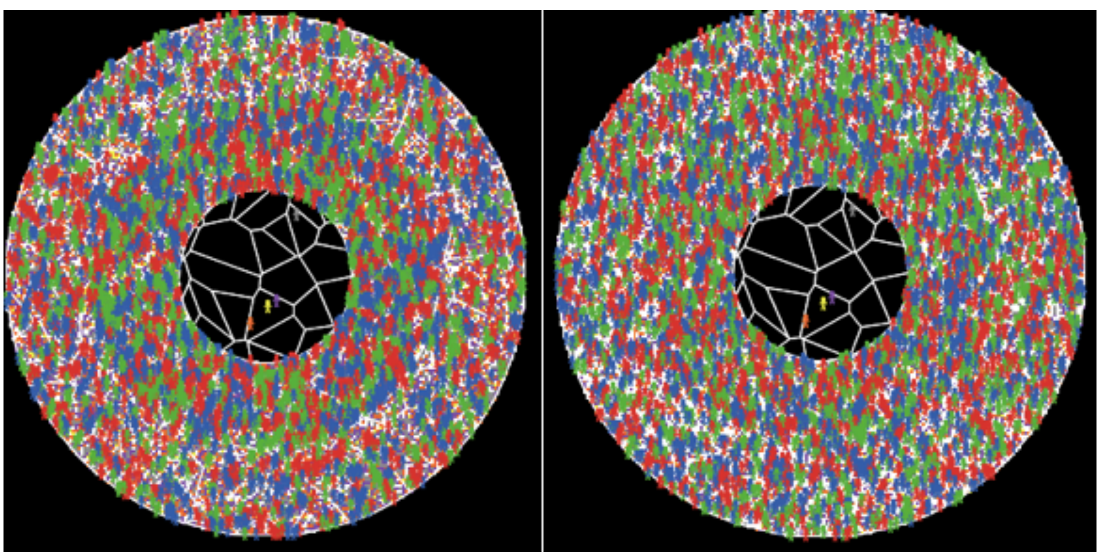

Figure 63. Representative Urban Sprawl: Scenario K (left) and L (right)

4.2.5 Gentrification by Demand

In this section, the gentrification by demand dynamics of the model is examined. The parameters initial population and gentrification rate – based on data and methods introduced in section 3.6 – were used to plot the data gathered for this dynamic. A seed was fixed for the random generator to maintain all the parameters of the model with default setting and track the change of the parameters being examined. The model ran for each of the nine possible configurations of the parameter settings (each of the three minimum, default and maximum settings of each two parameters) as highlighted in Table 7. Due to large possible parameter combination, only a select group of resulted dynamics will be reported. Table 11 lists the testing parameters of gentrification by demand.

Table 11. Gentrification by Demand Test Parameters

Scenario	Gentrification Rate	Initial Population	Subject of Test	Figure
A	0.1	100	Inner-city	Figure 64
B	0.4	100	Inner-city	Figure 65
C	0.1	1000	Inner-city	Figure 66
D	0.4	1000	Inner-city	Figure 67
E	0.1	100	Suburbia	Figure 68
F	0.4	100	Suburbia	Figure 69
G	0.1	1000	Suburbia	Figure 70
H	0.4	1000	Suburbia	Figure 71
I	0.1	100	Population over Time	Figure 72
J	0.4	100	Population over Time	Figure 73
K	0.1	1000	Population over Time	Figure 74
L	0.4	1000	Population over Time	Figure 75

Figure 64 and Figure 65 show the inner-city population for scenarios with the initial population of 100 and gentrification rates of 0.1 (minimum) and 0.4 (maximum). The results follow a generally similar pattern. The professional population has a sudden rise in the inner-city and it quickly reaches the population of non-professionals in the zone. The sudden rise is due to the gentrification settings that enforces the dynamics every 15 years, as discussed in sections 3.4 and 3.6.

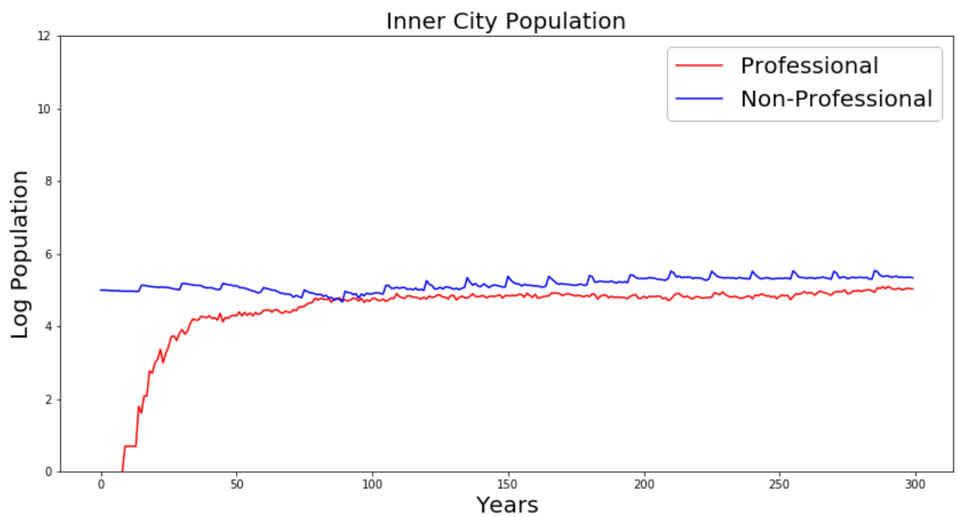

Figure 64. Gentrification by Demand: Scenario A

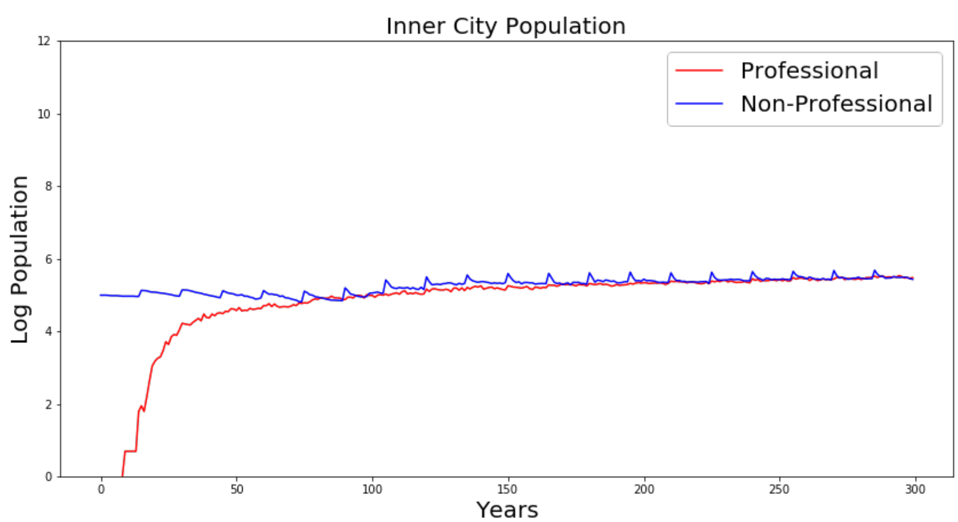

Figure 65. Gentrification by Demand: Scenario B

Figure 66 and Figure 67 demonstrate an earlier increase of the professionals. However, in the higher population of this case maintains a population divide between the professionals and the dominant non-professionals. In time, the higher gentrification rate seems to create a similar pattern in the professional and non-professional population plotted.

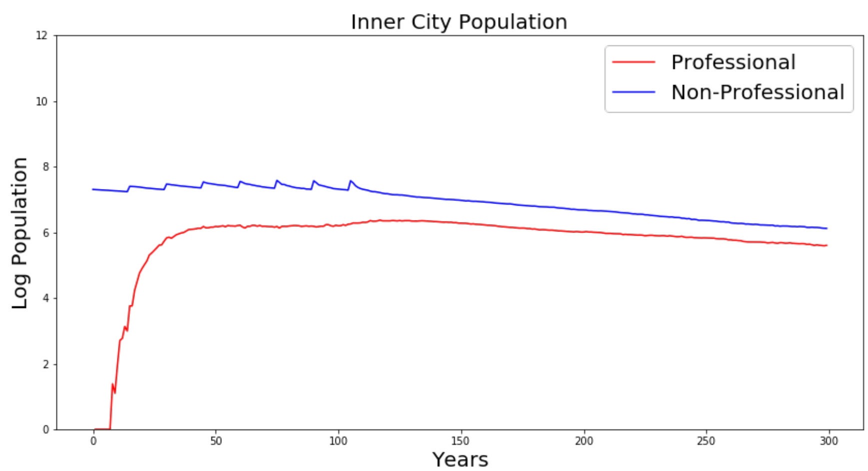

Figure 66. Gentrification by Demand: Scenario C

Figure 67. Gentrification by Demand: Scenario D

Figure 68 and Figure 69 shows the increase of the non-professionals in the suburbia. There is a sharp rise in the non-professionals in suburbia. It is interesting to note that the maximum gentrification rate causes an inconsistency in the pattern of the non-professionals.

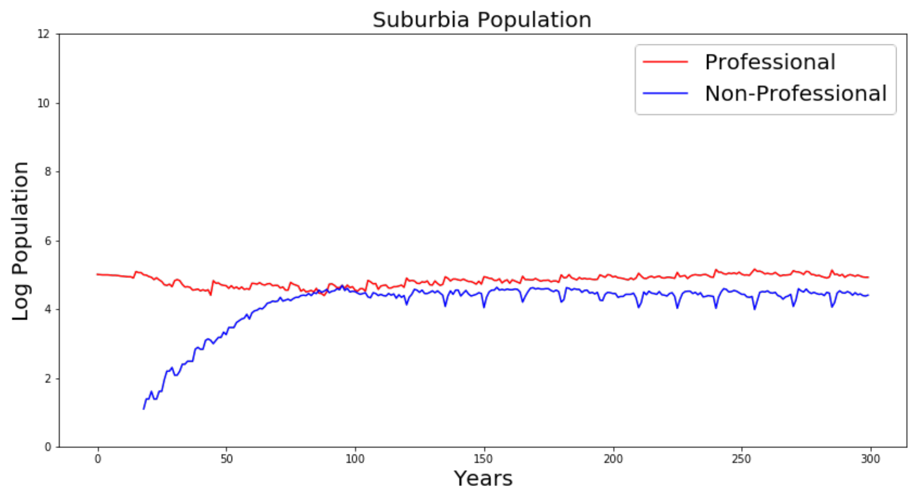

Figure 68. Gentrification by Demand: Scenario E

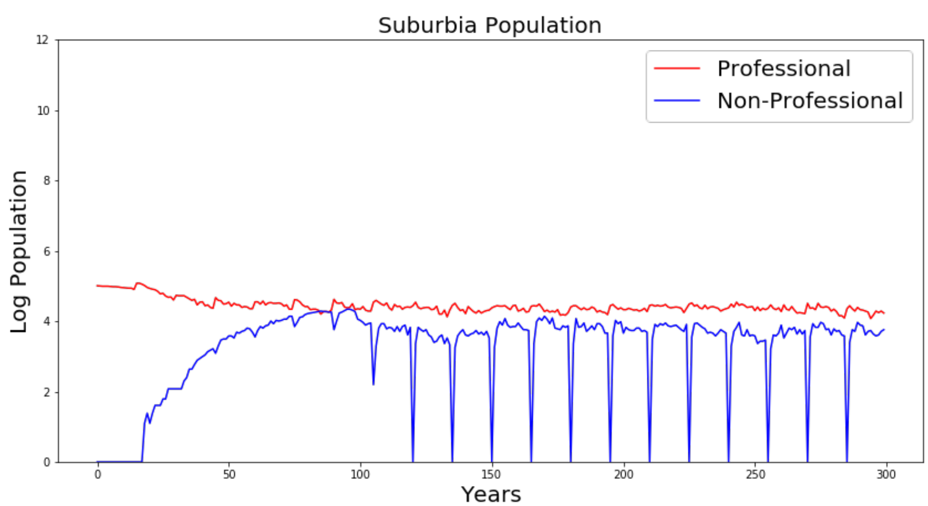

Figure 69. Gentrification by Demand: Scenario F

Figure 70 and Figure 71 illustrate the effects of large population on the suburbia output of the model. The plots in this these figures resemble the plots in Figure 31 and Figure 32 of urban growth in section 4.2.2 and Figure 44 and Figure 45 of urban shrinkage in section 4.2.3 with the same initial population. As mentioned in section 4.2.2 the sharp drop of non-professionals in suburbia is due to the model's gentrification setting which moves agents with the lowest income within suburbia to the inner-city. This is followed by the growth and entrance of a new population in suburbia.

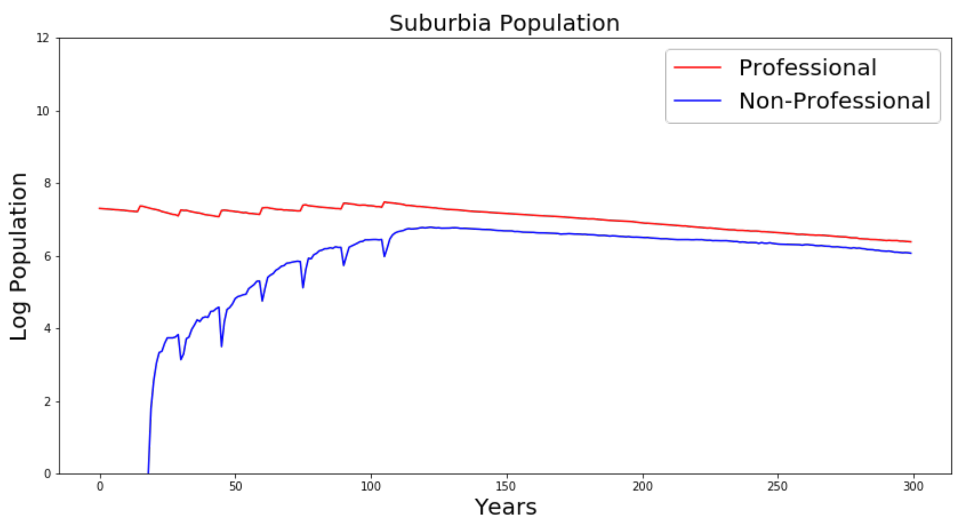

Figure 70. Gentrification by Demand: Scenario G

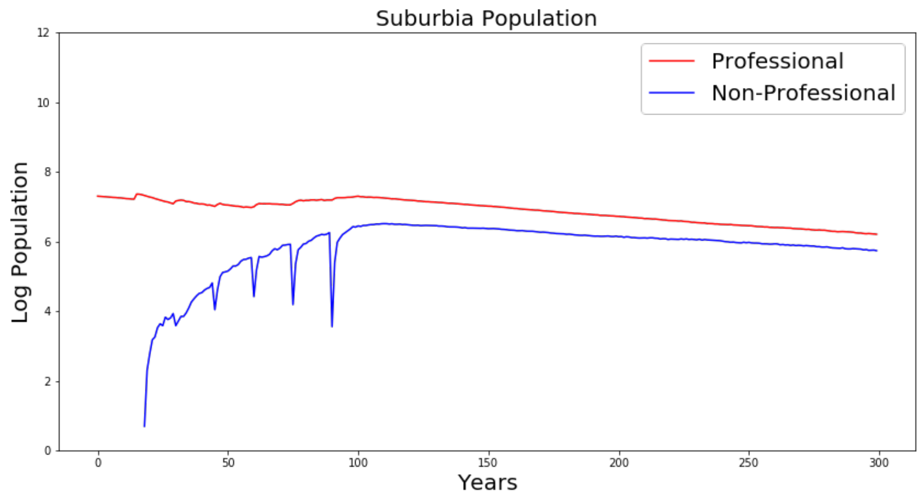

Figure 71. Gentrification by Demand: Scenario H

The low gentrification rate in Figure 72 and Figure 73 is accompanied by the same level of urban shrinkage. The higher gentrification rate results in the gentrification and urban growth population reaching the same population.

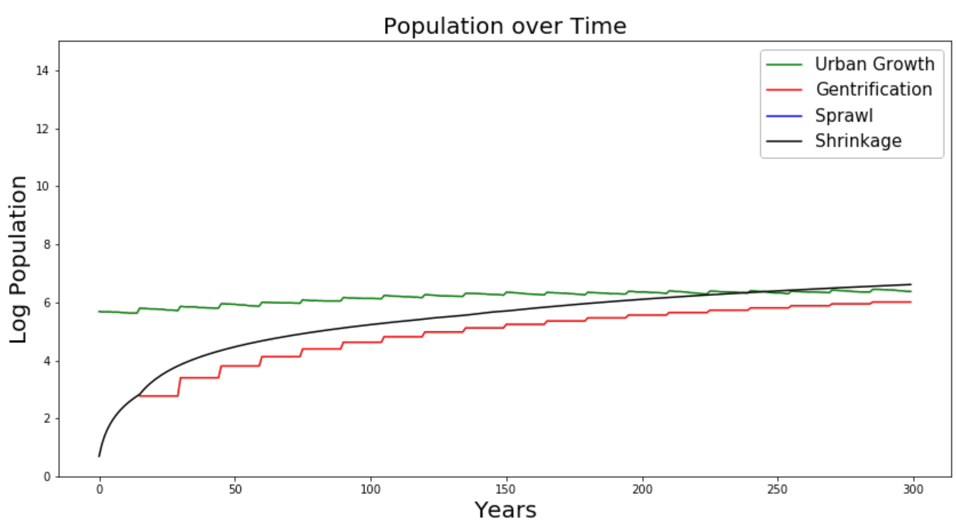

Figure 72. Gentrification by Demand: Scenario I

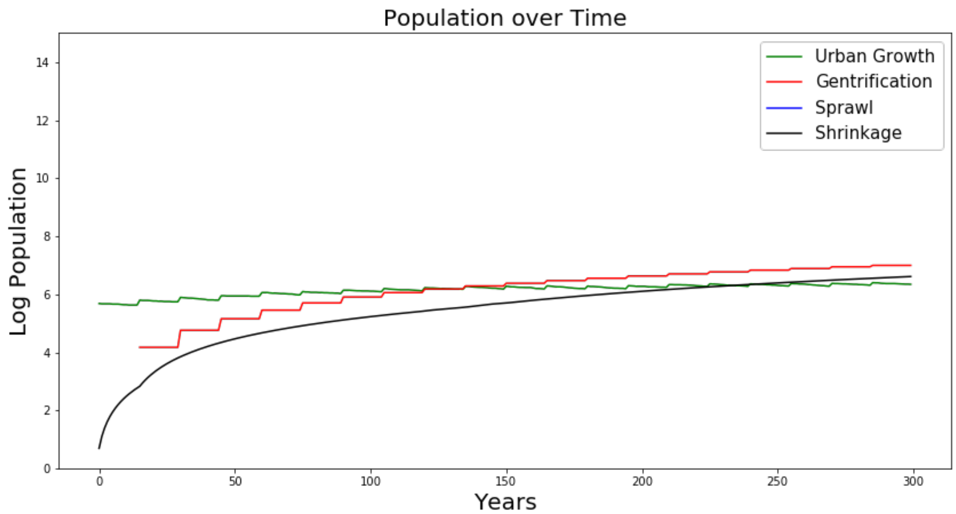

Figure 73. Gentrification by Demand: Scenario J

Figure 74 and Figure 75 show the appearance and increase of urban sprawl at the initial population of 1000 in representative simulations. At minimum gentrification rate for both 100 and 1000 initial population, the gentrification and shrinkage population slowly meet and follow the same path across the plots. As the urban growth introduces new agents to the model, gentrification causes the movement of agents from suburbia to inner-city. Both these events occur every 15 time-steps. At maximum gentrification rate, these dynamics gradually fall on the same line. The developmental process of gentrification by demand with 0.4 Gentrification Rate is shown in Figure 76.

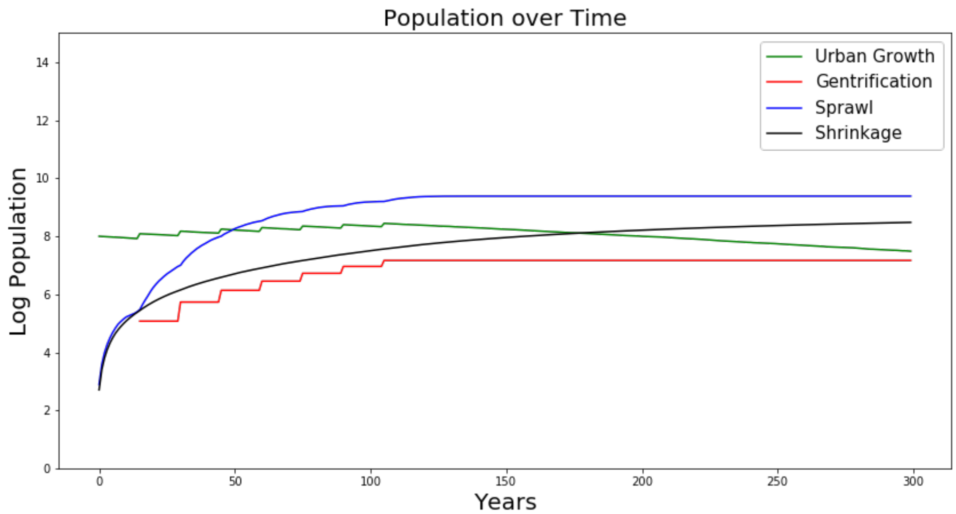

Figure 74. Gentrification by Demand: Scenario K

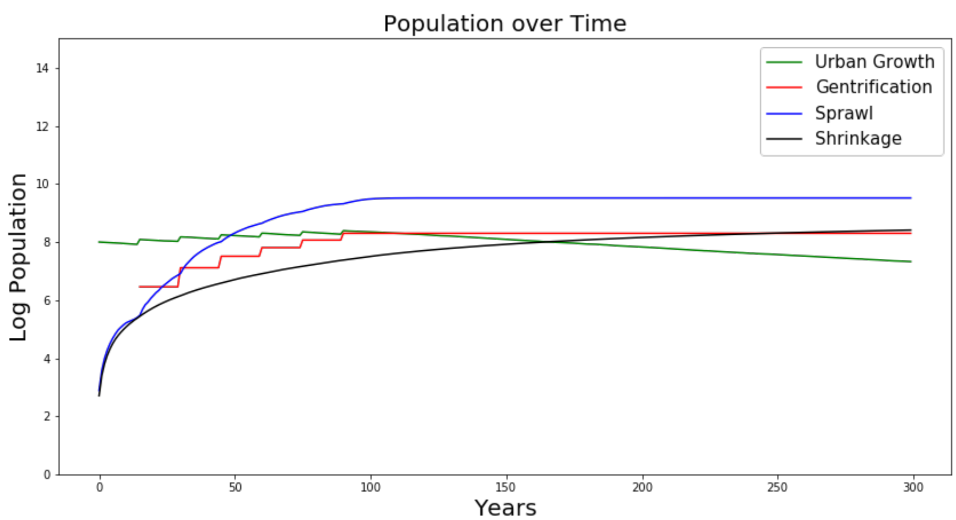

Figure 75. Gentrification by Demand: Scenario L

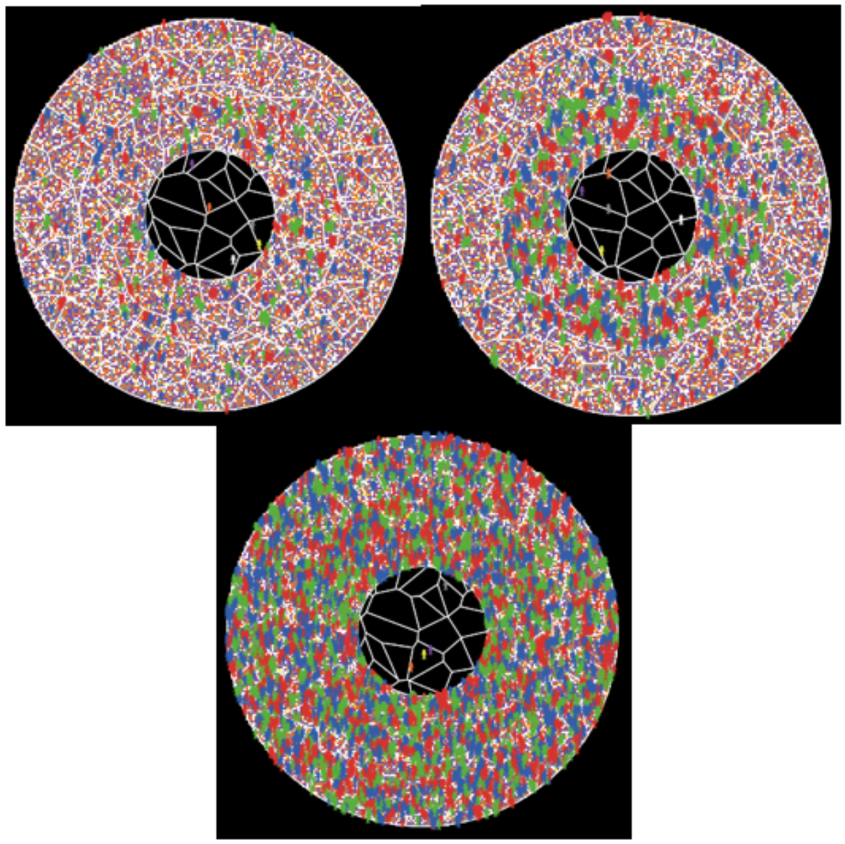

Figure 76. Representative Development of Gentrification by Demand: Top Left 100 initial population, Top Right 300 initial population, and Bottom 1000 initial population

4.2.6 Gentrification by Supply

In this section, the Smith's (1979) rent gap theory is examined as gentrification by supply dynamics. The parameters initial population, gentrification rate and cap rate were used to plot the data gathered and introduced in section 3.6. A seed was fixed for the random generator to maintain all the parameters of the model with default setting and track the change of the parameters being examined. The model ran for each of the 27 possible configurations of the parameter settings (each of the three minimum, default and maximum settings of each three parameters) as highlighted in Table 7.

Although all the results are interesting to study, due to large possible parameter combination, only a select group of resulted dynamics will be reported. Due to high similarities found in various recorded results, the gentrification by supply results mentioned here will be focused on the population over time and grouped based on similar or different instances. Table 12 demonstrates testing parameters of gentrification by supply.

Table 12. Gentrification by Supply Test Parameters

Scenario	Gentrification Rate	Cap Rate	Initial Population	Figure
A	0.1	4.75	100	Figure 77
B	0.1	7.75	100	Figure 78
C	0.1	4.75	300	Figure 79
D	0.1	7.75	300	Figure 80
E	0.4	4.75	1000	Figure 81
F	0.4	7.75	1000	Figure 82
G	0.4	4.75	100	Figure 83
H	0.4	7.75	100	Figure 84
I	0.1	4.75	300	Figure 85
J	0.1	7.75	300	Figure 86
K	0.4	4.75	1000	Figure 87
L	0.4	7.75	1000	Figure 88

Figure 77, Figure 78, Figure 79, and Figure 80 demonstrate similar patterns observed when experimenting for gentrification by supply with initial populations of 100 and 300, gentrification rate of 0.1 (minimum) and cap rates of 4.75 (minimum) and 7.75 (maximum). All the plots above follow the same pattern. No sprawl is observed at this level. While urban shrinkage starts with zero population at 100 population, the start point slightly increases at 300 population. Gentrification and shrinkage seem to follow the same population level. The population difference between urban growth and gentrification is noticeable.

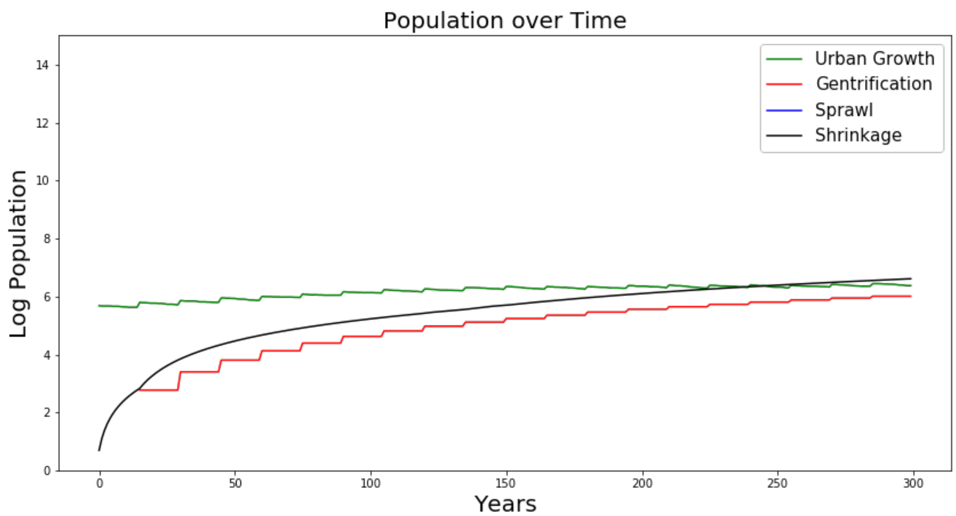

Figure 77. Gentrification by Supply: Scenario A

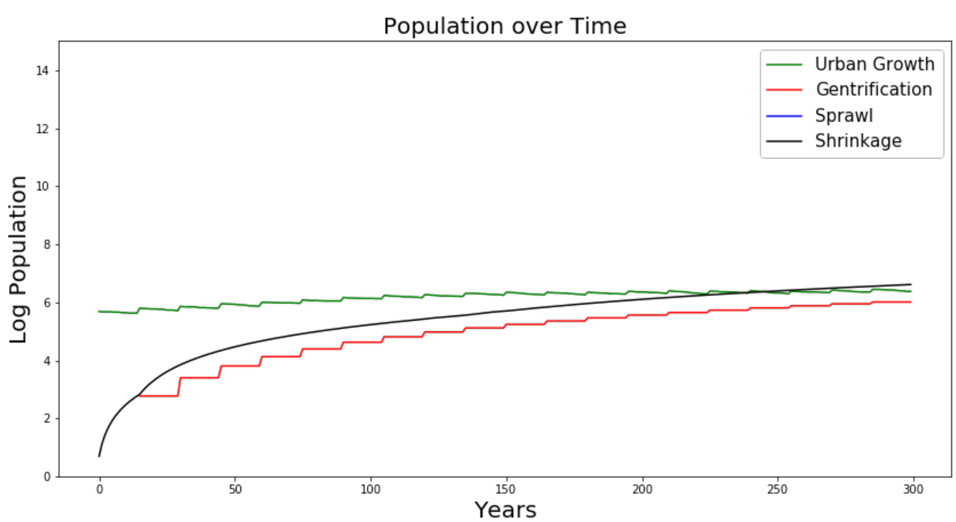

Figure 78. Gentrification by Supply: Scenario B

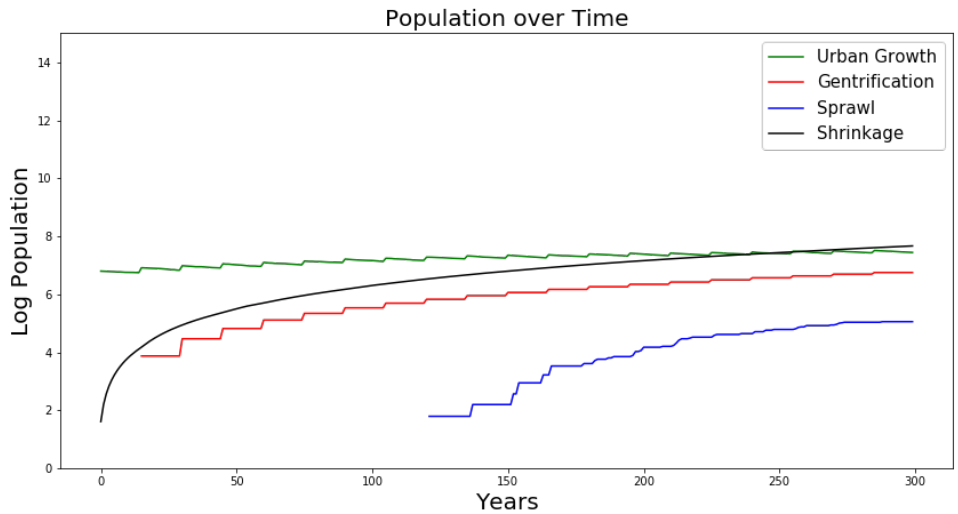

Figure 79. Gentrification by Supply: Scenario C

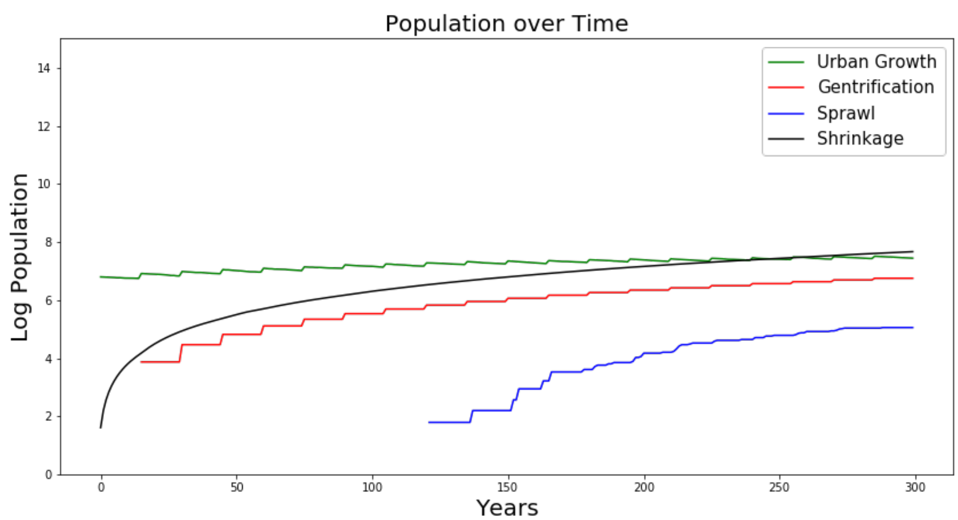

Figure 80. Gentrification by Supply: Scenario D

Figure 81, Figure 82, Figure 83, and Figure 84 illustrate similar patterns observed when experimenting for gentrification by supply with initial populations of 100 and 300, gentrification rate of 0.4 (maximum) and cap rates of 4.75 (minimum) and 7.75 (maximum). All the plots above follow the same pattern. No sprawl is observed at this level. While urban shrinkage starts with zero population at 100 population, the start point slightly increases at 300 population. The population difference between urban growth and gentrification significantly decreases at this cap rate.

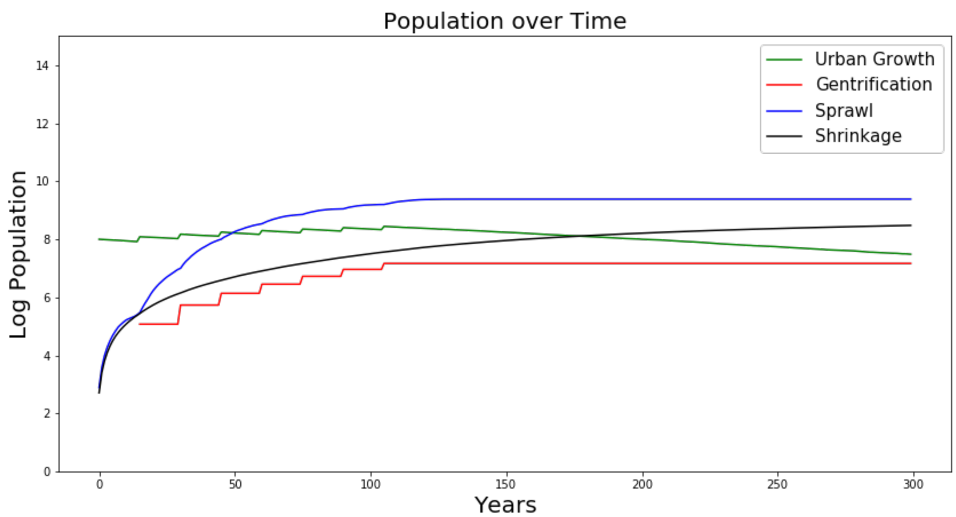

Figure 81. Gentrification by Supply: Scenario E

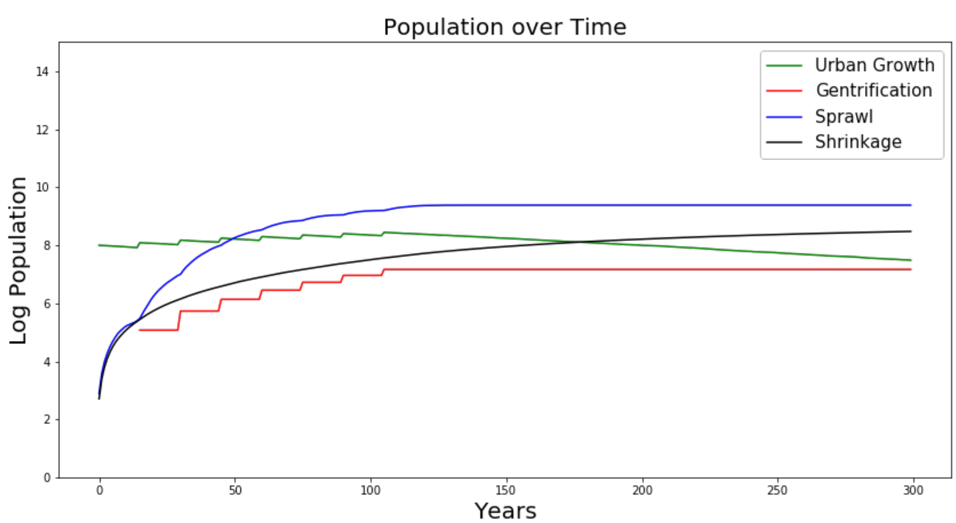

Figure 82. Gentrification by Supply: Scenario F

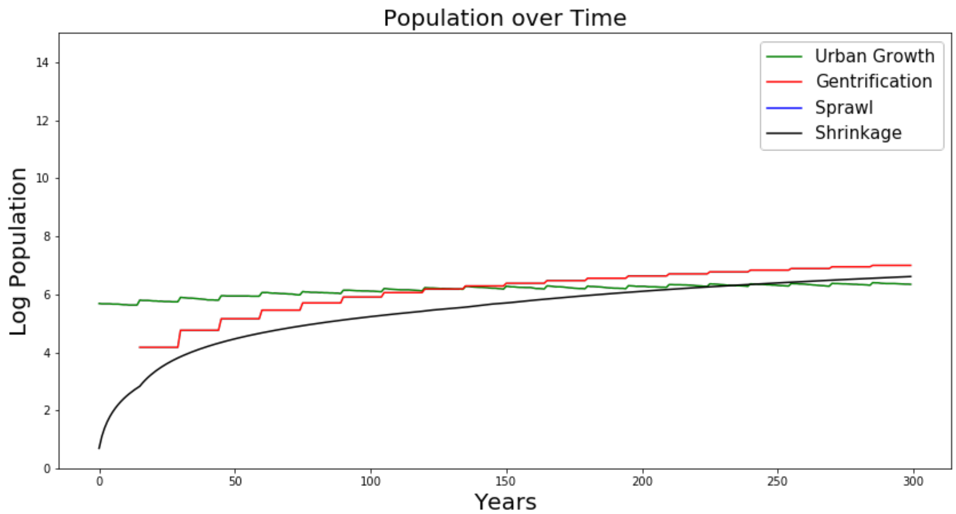

Figure 83. Gentrification by Supply: Scenario G

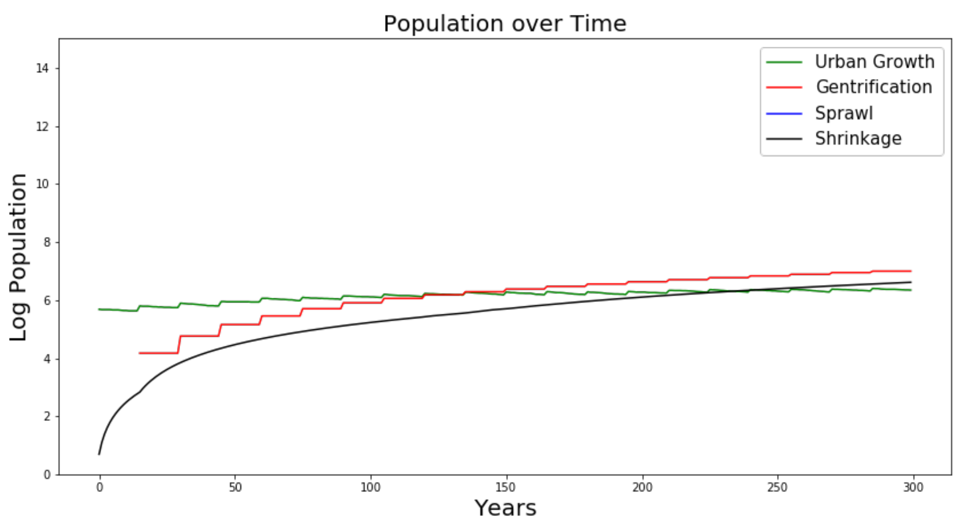

Figure 84. Gentrification by Supply: Scenario H

Figure 85, Figure 86, Figure 87, and Figure 88 show representative simulations of similar patterns observed when experimenting for gentrification by supply with initial populations of 1000, gentrification rates of 0.1 (minimum) and 0.4 (maximum) and cap rates of 4.75 (minimum) and 7.75 (maximum). At minimum cap rate, the population difference between urban growth and gentrification is noticeable. Urban shrinkage follows a slow and consistent population increase. The population difference between urban growth and gentrification significantly decreases at 0.4 cap rate. Urban sprawl has a sudden appearance at this population. Figure 89. Representative Gentrification by Supply: Scenario K (left) and L (right) shows representative simulations of gentrification by supply with 1000 initial population, 0.4 gentrification rate, 4.75 (left) and 7.73 (right) cap rate.

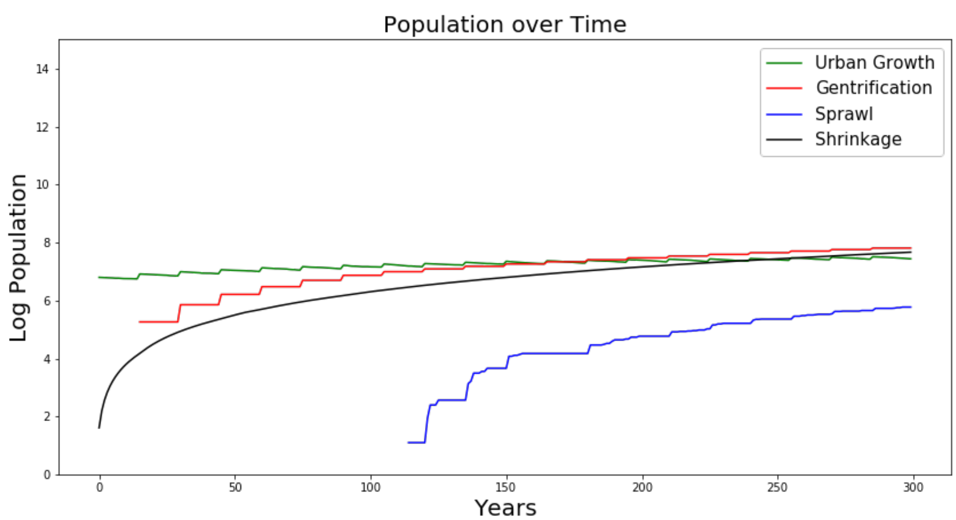

Figure 85. Gentrification by Supply: Scenario I

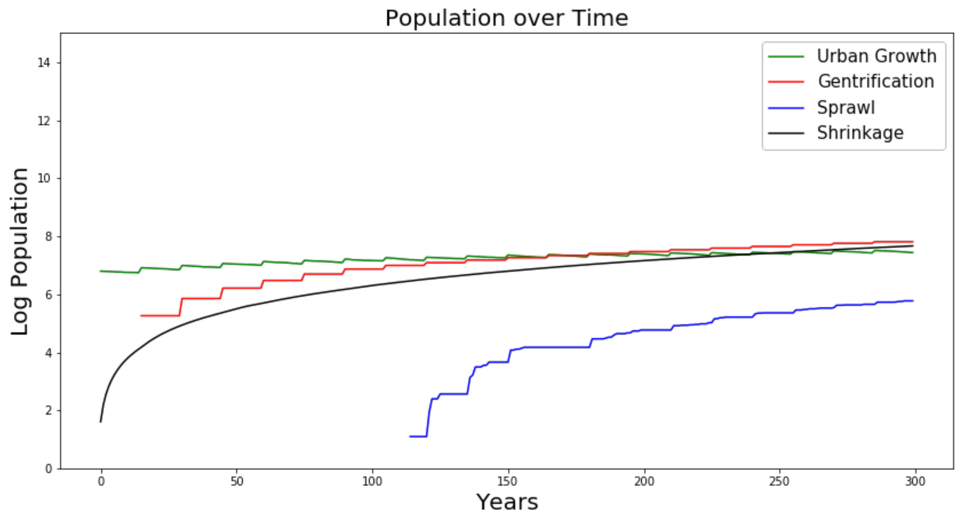

Figure 86. Gentrification by Supply: Scenario J

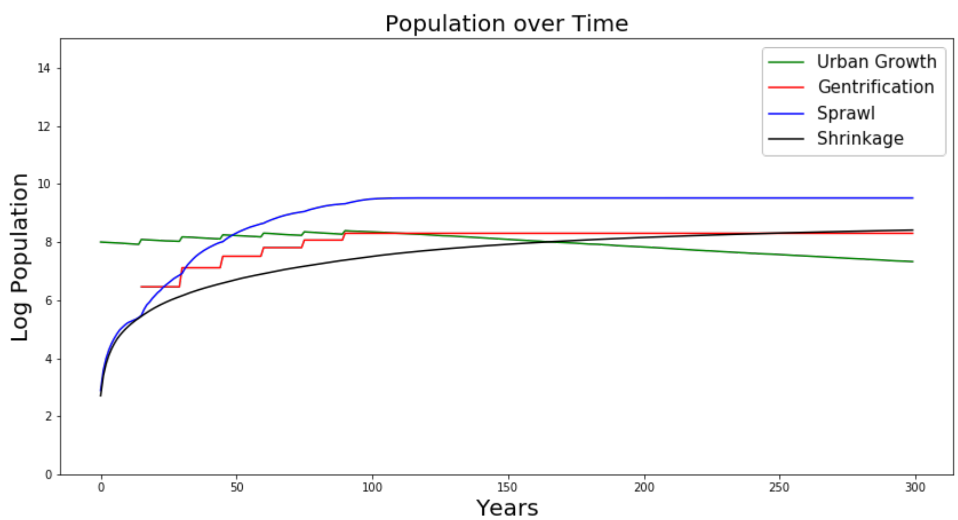

Figure 87. Gentrification by Supply: Scenario K

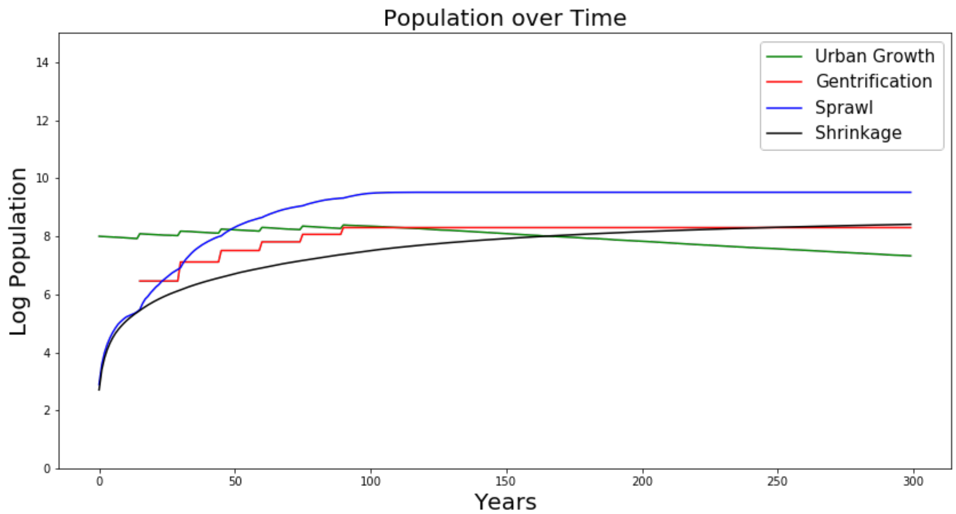

Figure 88. Gentrification by Supply: Scenario L

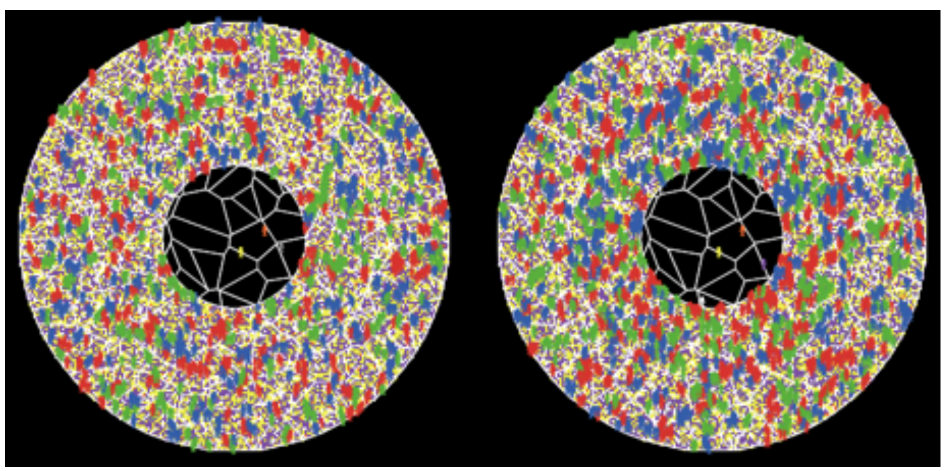

Figure 89. Representative Gentrification by Supply: Scenario K (left) and L (right)

4.3 Chapter Summary

The research question at the center of this thesis has been to see if I can generate a life cycle of a city by using an agent-based model and observe the unfolding of emergent behaviors. As the results show in this chapter, the model presents a platform for agents to interact with each other, their environment and the patterns emerging throughout the life cycle of the city. While chapter 2 provided the foundational work for this model, and chapter 3 covered the methods used to conduct the research, here I demonstrated the details of the model results. Section 4.2 showed the results for various experiments on the model with default settings, urban growth, shrinkage, sprawl, gentrification by demand and by supply. The results illustrated the intertwined underlying system of a city. The systems sensitivity to certain parameters such as, urban growth rate, initial population and gentrification rate were discovered. The findings will be discussed in detail in section 5.2.

As previously mentioned in chapters 1 and 3, this research is weaving the previous models in the field to discover their validity in an even more complex set of dynamics. While experimenting and gathering results can lead to interesting findings, further extensions to the question and model will allow the findings to be interpreted as they are and when applied to real urban systems. Section 5 will delve into the extensions.

5 Discussion and Conclusion

5.1 Introduction

As mentioned in the first chapter and observed throughout the thesis, cities are complex systems with interrelated subsystems. These subsystems interact with one another while their parts interact with each other as well. These interactions of self-organizing subsystems of cities result in a hierarchy that demonstrates the concept of near-decomposability (Simon, 1996). This understanding is important for modeling the life cycle of a city and its interdependent subsystems in an abstract space. This thesis has implemented the dynamics and rules within a city and observed the unfolding of emergent behaviors. The model was formed by utilizing previous models and theories in the field to discover their validity in an even more complex set of dynamics. The interactions of agents with each other and their environment on the micro-level and the urban dynamics with each other in a macro-level, create a unique representation of the life of a city.

Previous models and theories generally examined the processes and subsystems of an urban environment, but as cities comprise of a variety of interacting processes and subsystems, they show novel results when studied as a whole and not in isolation (Heppenstall et al., 2016). Here, I implemented urban growth, sprawl, shrinkage and gentrification by demand and supply, within a single ABM framework, to examine the effects of various parameters, settings and dynamics on the agent groups – developer, professionals and non-professionals – the environment – inner-city and suburbia – and the urban systems itself.

As reported in section 4.2, the main findings of the results show the importance of population size on the behavior pattern of the agent and the system. The model showed that while low population and urban growth rate lead to a more inclusive coexistence of professionals and non-professionals in the inner-city and suburbia, low population and shrinkage rate resulted in the dominance of professionals in the inner-city. A significant behavior in the model is the confirmation that urban growth generates and induces urban sprawl. The movement of the professionals with the lowest income from suburbia to the inner-city generated gentrification by demand while the new expensive properties constructed in the inner-city by the developers and bought by the professionals generated gentrification by supply. Section 5.2 expands on the implications of the aforementioned findings, while section 5.3 outlines areas of further work and section 5.4 notes final words for this thesis.

5.2 Implications of the Findings

The implications of the experiments on the urban dynamics at various settings were mainly explained in section 4.2. Many works have examined an isolated dynamic within urban markets. In this thesis, I have demonstrated emergence of patterns of complexity. The experiments captured the effects of certain urban dynamics on one another. The methods in section 3.6, by which previous models and theories mentioned in chapter 2 were applied, built the foundational rules and assumptions for the model. An example of this is the interplay between urban growth and gentrification reported in sections 4.2.2

and 4.2.5. The patterns arising from such experiments illustrate sub-system interaction which changes the macro-level formations and results of the system.

One of the findings shows the importance of population size on the behavior pattern of the agent and the system as a whole. The significance of initial population was observable throughout the experiments in section 4.2. While low population and urban growth rate lead to a more inclusive coexistence – per section 4.2.2 – of professionals and non-professionals in the inner-city and suburbia, increasing the population segregated the agents. In this instance, the population increase directly effects the demographics of the city based on randomly assigned economic capabilities. These results can imply that the model is applicable to mega-cities.

Testing the model with low population and shrinkage rate resulted in the dominance of professionals in the inner-city. This behavior is partially an outcome of agent income. As explained in section 3.4, agents start with random incomes which define their housing budgets. Upon residing in a property, they become indebted to the system because the property values are higher than their housing budgets and they have to build the money back by saving. This transaction causes the majority of agents to start their residence in the inner-city – as observed in the lower population results in section 4.2. As time passes and patches and neighborhoods become denser, little by little the agents move out of the inner-city and sprawl across the regions – verifying the dynamics established in section 3.6. The intensity and speed of sprawl is dependent on the sprawl density threshold and sprawl moving rate. This is why sprawl is not observed at low population size, shrinkage or growth rate – confirming the notion introduced in sections 2.4.1 and 2.4.2. In the meantime, the developers construct properties on land that has reached the rent gap

(Smith, 1979). Their development and the agents' residence in the new expensive properties generates gentrification by supply which is modeled based on the previous works introduced in section 2.4.4 and formed as a method in section 3.6. The results of this experiment – reported in section 4.2.6 – with every initial population (100, 300 and 1000) demonstrate that the gentrification rate is the key factor effecting this dynamic and that the cap rate only plays a small role in the ultimate pattern of the urban environment.

In conclusion, the model shows that the preferences of every agent group, introduced in section 3.4, lead its decision-making and movement. In satisfying their preferences to reach their state of happiness, the professional and non-professional agents are effected by the increase of development. The increase in development limits the property choices of professional and non-professional agents. This outcome shows a dynamic where the actions of one agent group effects the options and limits the actions of another agent group. The behavior of professional and non-professional agents creates a segregation pattern of decisions made based on economic status – demonstrated all through section 4.2. This pattern can suggest that, based on the methods explained in section 3.6, the developers who construct properties adjacent to a forming cluster have a higher chance of increasing their NOI than developers who construct properties away from agents and their forming clusters. A balance between the gentrification rate and the sprawl moving rate creates a more dynamic behavior across the city. The model landscape displays that the actions of every agent contributes to the global pattern and the global pattern defines the behavior of the agent group.

5.3 Further Work

The implications of the model discussed in section 5.2 reveal the opportunities for further work. The most important extension is calibration and validation. Validation helps the model reach a closer fit to the real-world (Axtell & Epstein, 1994). Once the model is validated, it builds a foundation for a more detailed and customized model on existing city structures. As noted in section 2.5, while the specificity in geographically detailed spatial representations allows for an accurate and extensive study of a given case, abstract spatial representations allows for a more general study that aims to exhibit the dynamics and interactions of a system and its subsystems. Both of these representations are practical and applicable depending on the subject of research. It is also important to improve the model logic for better interplay of dynamics. This could include redefining and introducing some of the rules, assumptions and parameters for more connectivity between the subsystems within the model. For example, the urban growth occurring every 15 time-steps in the model can be smoothed over the period of the examination to observe any changes in the emerging patterns.

Another extension is adding features to experiment with more cognitive aspects of decision-making is a possibility for further extension. The abstract nature of this model can be used as grounds for applying it to other models of urban structure such as the sectoral and the multi-nuclei models introduced in section 2.2. Some of the features yet to be examined include: transportation, costs for professional and non-professional agents (e.g. utilities), expenses for developers (e.g. cost of building material, feasibility analysis, construction and management), intermediary agents such as realtors (e.g. Gilbert et al., 2009), development regulations, etc. With the current setting, the model does not take into consideration where the purchase money of undeveloped properties that are bought by professional and non-professional agents goes. This can be further extended through defining a buyer and seller dynamic similar to Filatova et al., (2009). Running the model for multiple hundred time-steps, can reveal further behaviors of the system. For example, revealing if the city will have a rise and fall and what factors can accelerate or decelerate the process. The model could also be extended in reach, to capture the effects of urban growth, shrinkage and sprawl beyond the boundaries of the current city. Making such changes to the model can notably change the decision-making of the agents and its ultimate results. I intend to expand and extend the model to be more inclusive and answer more questions about the urban dynamics that shape the life cycle of a city.

5.4 Final Words

Studying land markets and urban dynamics as a connected system would be more beneficial than as isolated pieces of a larger whole. ABMs allow for the investigation of such notions at the micro and macro level. This thesis has connected and portrayed systems as a whole and unraveled some of the nuances that play key roles in the behavioral pattern of the system. The methods and results of this research can be utilized to further the study for even more compelling findings as briefly discussed in section 5.3.

This thesis has produced holistic results with regards to urban dynamics. The examination of urban land markets sheds light on the key factors that affect the behavior of the system as a whole. By employing further works, developers, policy makers and residents could make better market predictions and smarter housing decisions.

Appendix 1

Causes of urban growth	Compact growth	Sprawled growth
Population growth	•	•
Independence of decision		•
Economic growth	•	•
Industrialisation	•	•
Speculation		•
Expectations of land appreciation		•
Land hunger attitude		•
Legal disputes		•
Physical geography		•
Development and property tax		•
Living and property cost		•
Lack of affordable housing		•
Demand of more living space	•	•
Public regulation		•
Transportation	•	•
Road width		•
Single-family home		•
Nucleus family	•	•
Credit and capital market		•
Government developmental policies		•
Lack of proper planning policies		•
Failure to enforce planning policies		•
Country-living desire		•
Housing investment		•
Large lot size		•

Figure 90. Table Demonstrating Causes of Urban Growth [Source: Bhatta, 2010]

Appendix 2

Model	Main purpose	Main variables and functional relationships
System dynamics (SD)		
SD_1 urban dynamics	Modelling urban system in general, explicitly including urban decline. Examples focus on a specific topic, for example, rapid population growth, demolition et cetera and therefore require specific models.	Original model by Forrester (1969): three subsystems: business, housing, population.
SD_2	Integrated land-use and transportation model for estimating scenarios regarding transport policies.	Seven sub-models: (1) population, (2) migration, (3) household, (4) job growth, employment and commercial land development, (5) housing development, (6) travel demand, (7) congestion.
SD_3	Assessing the impact of urban sprawl on wetland biodiversity and social welfare.	Population growth within city → higher population density and greater demand for agricultural land → expansionists attempt to buy surrounding area → wetland area changes to urban area and more agriculture decreasing wetland biodiversity → conservationists' valuation of remaining biodiversity increases → conservationists buy wetland area for nature protection.
SD_4	Redefining Forrester's (1969) model of urban dynamics, including: (1) spatial dimension (16 squares) and (2) disaggregation: different types of housing, industry, and people in zones.	Bidirectional causal loops between: population, housing availability, houses, land availability, business structures, and job availability (linked with population). Two markets: labour market and housing market compete for land (no transport).
SD_5 SCOPE	Simulation model to provide scenarios for future land use in Santa Barbara, for example, with restrictions on urban growth.	Five sectors: housing, population, business, quality of life, land use.
SD_6	Assessing the impact of future policy interventions on the social housing market (specific: rate of building new dwellings).	Four stocks: (1) commercial housing stock, (2) social housing stock, (3) waiting families, (4) supply of available social houses, Processes involved: migration, demolition, construction.
SD_7	To simulate medium-term and long-term effects of urban transport policies with reference to sustainable travel.	Seven major blocks: urbanisation, internal travel demand (trips within system), car ownership, external travel demand (in-flowing, out-flowing and through traffic), transportation (comparing supply and demand), and evaluation (socioeconomic and environmental appraisals).

Figure 91. Tables Demonstrating Land use Models [Source: Schwarz et al., 2010]

Transport – urban models (TU)		
TU_1 MUSSA	To represent the urban real-estate market and its implications for transport.	Consumers' behaviour within the market, developers, transport system, governmental regulations. Interaction with another transport model is possible.
TU_2 IRPUD	To simulate intraregional location and mobility choices in an urban region.	Submodels: transport, ageing, public programmes, private construction, labour market, housing market. Interaction on five markets: labour, commercial buildings, housing, construction and real estate, transport.
TU_3 MEPLAN	To simulate spatial economies for cities or regions with a focus on interactions between land-use changes and transport.	Two markets interact: land and transport with land prices and transport prices, respectively. Determined by land or floor space plus activity location, mediating variable between markets: accessibility.
TU_4 TRANUS	To evaluate regional transportation and land-use policies using a market-based urban model.	Economic demand → employment in zones of the region → residents follow work. Travel follows from land uses (flows of goods, workers, shoppers) → prices for transportation → rearrangement of employment ... until the equilibrium is reached for both the land and travel market.
Cellular automata (CA)		
CA_1 CLUE-s	Tool for understanding land-use patterns; possible future scenarios for given demand.	Input: predefined change in demand for land by different sectors for whole simulation area → CLUE-s assigns new land uses per grid. Each cell: most preferred land use based on suitability of location and competitive advantage of different land-use types (demand). Check: is land-use change allowed? If no: next most preferred land use is chosen.
CA_2 CUF-2	Simulating urban growth; scenarios for future development.	Top-down approach: future trends of population, households, jobs are assigned to grid cells. Econometric models predict future population, households, employment (at 10-year intervals). LUC-model: estimates probabilities for land-use change from historical data, and simulation engine assigns probabilities to cells. Probability of land-use change (multinomial logit models) for a cell from i to $j = \mathrm{f}$ (initial site use, site characteristics, site accessibility, community characteristics, policy factors, relationships to neighbouring sites) → probabilities are interpreted as bids for (re)development → population and jobs are assigned to cells by bids. Seven urban land-use categories: undeveloped, single-family residential, multifamily residential, commercial, industrial, transportation, public.

Figure 91. Continued Tables

Model	Main purpose	Main variables and functional relationships
Cellular automata (CA) (continued)		
CA_3 CURBA (California Urban and Biodiversity Analysis)	Development of policy scenarios of urban growth; impact on habitat change and biodiversity.	Two components: (1) urban growth model and (2) policy simulation and evaluation model. Urban growth model is based upon CUF-2. Policy simulation and evaluation: several growth scenarios → impact on habitat change and habitat fragmentation.
CA_4 MOLAND	To monitor developments of urban areas and identify trends at the European scale; focus is on growth scenarios.	Growth of economy and population (global level) → growth in competing regions (regional level), sets boundaries for all cells in a region → rules for land-use change at the grid level: physical suitability, institutional suitability (for example, planning documents), accessibility (via transport network), dynamics at the local level (land-use functions attracting or repelling each other). Feedback from grid level to regional level: spatial distribution leads to quality and availability of space for different activities, which influences the attractiveness of a region when compared with others.
CA_5 SLEUTH	Modelling urban growth; scenarios for future development of an urban region.	Two components (use depends on available data): (1) urban growth: cells have one of two states: urban or nonurban, (2) urban land-use change with different land-use types. Four types of growth behaviour: spontaneous, diffusive (with new growth centres), organic (into surroundings), and road-influenced. Five main coefficients: diffusion, breed, spread, slope, and road coefficient (need to be calibrated for each case study). Self-modification rules: for example, concerning the kind of exponential of S-curve growth; denser road network → road gravity factor increases; land availability decreases → slope resistance factor is decreased (more hilly areas); spread factor increases over time.

Figure 91. Continued Tables

Agent-based model (ABM)		
ABM_1 ILUMASS	Dynamic simulation model with a focus on urban traffic flows, including activity behaviour, changes in land use, and effects on the environment.	Five modules (+ integration module): (1) changes in land use, (2) activity patterns and travel demand, (3) traffic flows, (4) goods transport, (5) environmental impacts of transport and land use. Land use → demand for spatial interaction (work, shopping trips) → traffic → environmental impacts. Feedback: (a) transport → accessibility of locations → location decisions of households, firms, developers; (b) environmental factors → location decision (for example, clean air, traffic noise). Land-use module: moving households, location of firms, investment from developers, new industrial area.
ABM_2 ILUTE	Evolution of an entire urban region with emphasis on transport.	Land development → location choice → activity schedule → activity patterns → back to land development and all other variables in the chain. Transportation network → automobile ownership → travel demand → network flows → back to transportation network and all other variables in the chain. Influences.
ABM_3 PUMA	Predicting urbanisation with behavioural agents.	Demographic change → decisions of individuals → land-use change. Not yet implemented: developers, authorities and firms or institutions (so far exogenous). (Impact of household's decision on land use not described.)
ABM_4	Development of built-up area in periurban region, driven by households and entrepreneurs; urban growth with different growth rates.	Initialisation: increase of household and workplace numbers is defined as: (1) municipality choice depending on regional attractiveness criteria (numbers of people, households, and workplaces in the starting year, average travel time to district centres and capital city, average share of attractive land-use classes in the municipality (open space, forest areas) → households growth and workplace growth per municipality → transformation of absolute values into relative search frequencies → agents choose municipality via discrete choice, (2) local target-area search: start with random cell, choosing most attractive cell, (3) land-use change (new built-up area, higher density) → influencing local attractiveness.
ABM_5 UrbanSim	Link between transport and land use; impact of different planning strategies.	Exogenous: (1) macroeconomics (population, employment) and (2) travel demand (travel conditions). Six models: (1) accessibility (output: access to workplaces and shops for each cell), (2) transition (output: number of new jobs and new households per year), (3) mobility [output: number of moving (existing) jobs or households], (4) location (output: location of new or moving jobs–households), (5) real-estate development (output: land-use change), (6) land price (output: land prices).

Figure 91. Continued Tables

References

Adams, D., & Tiesdell, S. (2012). *Shaping places: Urban planning, design and development* (1st ed.). Abingdon, UK: Routledge.

Allen, E., & Iano, J. (2011). *Fundamentals of building construction: Materials and methods* (4th ed.). Hoboken, NJ: John Wiley & Sons.

Alonso, W. (1964). *Location and land use: Toward a general theory of land rent*. Cambridge, MA: Harvard University Press.

Andersen, H. S. (2003). *Urban Sores: On the interaction between segregation, urban decay and deprived neighbourhoods*. Farnham, UK: Ashgate Publishing.

Axtell, R. L., & Epstein, J. M. (1994). Agent-based modeling: Understanding our creations. *The Bulletin of the Santa Fe Institute*, *9*(2), 28–32.

Batty, M. (2006). Rank clocks. *Nature*, *444*(7119), 592–596.

Batty, M. (2008). The size, scale, and shape of cities. *Science*, *319*(5864), 769–771.

Batty, M., & Longley, P. A. (1994). *Fractal cities: A geometry of form and function*. Cambridge, MA: Academic press.

Batty, M., & Xie, Y. (2005). Urban growth using cellular automata models. In D. J. Maguire, M. Batty, & M. F. Goodchild (Eds.), *GIS, spatial analysis, and modelling* (pp. 151–172). Redlands, CA: ESRI Press.

Batty, M., Xie, Y., & Sun, Z. (1999a). Dynamics of urban sprawl. In *Centre for Advanced Spatial Analysis (University College London): Working Papers 15*. London.

Batty, M., Xie, Y., & Sun, Z. (1999b). Modeling urban dynamics through GIS-based cellular automata. *Computers, Environment and Urban Systems*, *23*(3), 205–233.

Benenson, I. (1998). Multi-agent simulations of residential dynamics in the city. *Computers, Environment and Urban Systems*, *22*(1), 25–42.

Bhatta, B. (2010). Causes and consequences of urban growth and sprawl. In *Analysis of urban growth and sprawl from remote sensing data* (1st ed., pp. 17–36). Heidelberg, Berlin: Springer-Verlag.

Burgess, E. (1925). *The city*. Chicago, IL: University of Chicago Press.

Chin, N. (2002). Unearthing the roots of urban sprawl: A critical analysis of form, function and methodology. In *Centre for Advanced Spatial Analysis (University College London): Working Papers 47*. London.

Cioffi-Revilla, C. (2017). *Introduction to computational social science* (2nd ed.). London: Springer-Verlag.

Clark, W. A. (1991). Residential preferences and neighborhood racial segregation: A test of the Schelling segregation model. *Demography*, *28*(1), 1–19. https://doi.org/https://doi.org/10.2307/2061333

Clarke, K. C., Gazulis, N., Dietzel, C., & Goldstein, N. C. (2007). A decade of SLEUTHing: Lessons learned from applications of a cellular automaton land use change model. *Classics in IJGIS: Twenty Years of the International Journal of Geographical Information Science and Systems*, 413–427.

Clarke, K. C., Hoppen, S., & Gaydos, L. (1997). A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B: Planning and Design*, *24*(2), 247–261.

Coiacetto, E. J. (2000). Places shape place shapers? Real estate developers' outlooks concerning community, planning and development differ between places. *Planning Practice and Research*, *15*(4), 353–374.

Crooks, A. (2006). Exploring cities using agent-based models and GIS. In *Centre for Advanced Spatial Analysis (University College London): Working Papers 109*. London.

Crooks, A. (2008). Constructing and implementing an agent-based model of residential segregation through vector GIS. *International Journal of Geographical Information Science*, *24*(5), 661–675.

Devisch, O. T., Timmermans, H. J., Arentze, T. A., & Borger, A. W. (2009). An agent-based model of residential choice dynamics in nonstationary housing markets. *Environment and Planning A*, *41*(8), 1997–2013.

Diappi, L., & Bolchi, P. (2008). Smith's rent gap theory and local real estate dynamics: A multi-agent model. *Computers, Environment and Urban Systems*, *32*(1), 6–18.

District of Columbia Office of Planning. (2016). *District of Columbia Office of Planning Population Trends* (Presentation) (pp. 1–26). Washington, DC. Retrieved from https://dme.dc.gov/sites/default/files/dc/sites/dme/publication/attachments/Office%20of%20Planning%20Presentation%20for%20CSCTF%204%2026%2016.pdf

Duany, A., Speck, J., Lydon, M., & Goffman, E. (2011). The smart growth manual.

Economic Policy Institute. (2015, August 26). Family budget. Retrieved November 10, 2017, from http://www.epi.org/resources/budget/

Engelen, G., Lavalle, C., Barredo, J., Van der Meulen, M., & White, R. (2007). The MOLAND modelling framework for urban and regional land-use dynamics. In E.

Koomen, J. Stillwell, A. Bakema, & H. J. Scholten (Eds.), *Modelling land-use change* (pp. 297–320). Dordrecht: Springer.

Epstein, J. M., & Axtell, R. (1996). *Growing artificial societies: social science from the bottom up*. Brookings Institution Press.

Filatova, T., Parker, D., & Van der Veen, A. (2009). Agent-based urban land markets: Agent's pricing behavior, land prices and urban land use change. *Journal of Artificial Societies and Social Simulation*, *12*(1). Retrieved from <http://jasss.soc.surrey.ac.uk/12/1/3.html>

Flache, A., & Hegselmann, R. (2001). Do irregular grids make a difference? Relaxing the spatial regularity assumption in cellular models of social dynamics. *Journal of Artificial Societies and Social Simulation*, *4*(4). Retrieved from <http://jasss.soc.surrey.ac.uk/4/4/6.html>

Forrester, J. (1969). *Urban dynamics* (Vol. 11). Cambridge, MA: MIT press.

Fujita, M. (1989). *Urban economic theory: Land use and city size*. Cambridge, UK: Cambridge University Press.

Fujita, M., & Krugman, P. (1995). When is the economy monocentric? Von Thünen and Chamberlin unified. *Regional Science and Urban Economics*, *25*(4), 505–528.

Gardner, M. (1970). Mathematical games: The fantastic combinations of John Conway's new solitaire game "life." *Scientific American*, *223*(4), 120–123.

Geltner, D., Miller, N. G., Clayton, J., & Eichholtz, P. (2001). *Commercial real estate analysis and investments* (Vol. 1). Cincinnati, OH: South-western.

Gilbert, N., Hawksworth, J. C., & Swinney, P. A. (2009). An agent-based model of the English housing market (pp. 30–35). Presented at the AAAI Spring Symposium: Technosocial Predictive Analytics, Stanford University, CA.

Glaeser, E. L., & Kahn, M. E. (2004). Sprawl and urban growth. *Handbook of Regional and Urban Economics*, *4*, 2481–2527.

Governing. (2016, January 16). Washington D.C. gentrification maps and data. Retrieved October 21, 2017, from http://www.governing.com/gov-data/washington-dc-gentrification-maps-demographic-data.html

Gregory, D., Johnston, R., Pratt, G., Watts, M., & Whatmore, S. (2011). *The dictionary of human geography*. Hoboken, NJ: Wiley-Blackwell.

Haase, D., Haase, A., Kabisch, N., Kabisch, S., & Rink, D. (2012). Actors and factors in land-use simulation: The challenge of urban shrinkage. *Environmental Modelling & Software*, *35*, 92–103.

Haase, D., Lautenbach, S., & Seppelt, R. (2010). Modeling and simulating residential mobility in a shrinking city using an agent-based approach. *Environmental Modelling & Software*, *25*(10), 1225–1240.

Han, J., Hayashi, Y., Cao, X., & Imura, H. (2009). Application of an integrated system dynamics and cellular automata model for urban growth assessment: A case study of Shanghai, China. *Landscape and Urban Planning*, *91*(3), 133–141.

Harris, C. D., & Ullman, E. L. (1945). The nature of cities. *The Annals of the American Academy of Political and Social Science*, *242*(1), 7–17.

Heppenstall, A., Crooks, A., See, L., & Batty, M. (2012). *Agent-based models of geographical systems* (1st ed.). Dordrecht: Springer.

Heppenstall, A., Malleson, N., & Crooks, A. (2016). “Space, the final frontier”: How good are agent-based models at simulating individuals and space in cities? *Systems*, *4*(1), 9.

Hoyt, H. (1939). The structure and growth of residential neighborhoods in American cities. *U.S. Government Printing Office, Washington D.C.*

Intergovernmental Panel on Climate Change. (1998). *Land Use, Land-Use Change and Forestry*. Geneva. Retrieved from http://www.grida.no/climate/ipcc/land_use/045.htm

Jackson, J., Forest, B., & Sengupta, R. (2008). Agent-Based simulation of urban residential dynamics and land rent change in a gentrifying area of boston. *Transactions in GIS*, *12*(4), 475–491.

James, P., Holden, M., Lewin, M., Neilson, L., Oakley, C., Truter, A., & Wilmoth, D. (2013). Managing metropolises by negotiating urban growth. In H. Mieg & K. Topfer (Eds.), *Institutional and Social Innovation for Sustainable Urban Development* (pp. 217–232). London: Routledge.

Kaldor, N. (1957). A model of economic growth. *The Economic Journal*, *67*(268), 591–624.

Knights, S. (2008). Bid rent [Online image]. Retrieved November 10, 2017, from https://commons.wikimedia.org/wiki/File:Bid_rent1.png

Landis, J. D. (1994). The California urban futures model: A new generation of metropolitan simulation models. *Environment and Planning B: Planning and Design*, *21*(4), 399–420.

Laurie, A. J., & Jaggi, N. K. (2003). Role of'vision'in neighbourhood racial segregation: A variant of the Schelling segregation model. *Urban Studies*, *40*(13), 2687–2704.

Lees, L., Slater, T., & Wyly, E. (2013). *Gentrification*. London: Routledge.

Ley, D. (1996). *The new middle class and the remaking of the central city* (1st ed.). Oxford: Oxford University Press.

Ludeman, C., Stoffers, B., Mcdonnell, T., Levy, S., Havsy, J., & Rice, J. (2014). *CBRE cap rate survey* (p. 50). Los Angeles, CA: CBRE. Retrieved from https://www.cbre.us/Research-and-Reports/US-Research

Magliocca, N. R. (2012). Exploring coupled housing and land market interactions through an economic agent-based model (CHALMS). In A. Crooks, M. Batty, L. See, & A. Heppenstall (Eds.), *Agent-based models of geographical systems* (pp. 543–568). Dordrecht: Springer.

Malik, A., Crooks, A., Root, H., & Swartz, M. (2015). Exploring creativity and urban development with agent-based modeling. *Journal of Artificial Societies and Social Simulation*, *18*(2). Retrieved from <http://jasss.soc.surrey.ac.uk/18/2/12.html>

Mayor Muriel Bowser Office of Planning. (2015, January 16). DC quickfacts. Retrieved November 10, 2017, from https://planning.dc.gov/publication/dc-quick-facts

Metropolitan Regional Information System. (2016, January 15). Housing market data for Washington D.C. Retrieved September 20, 2016, from http://www.getsmartcharts.com/mls/signup

Miles, M. E., Netherton, L. M., & Schmitz, A. (2015). *Real estate development: Principles and process* (5th ed.). Washington, DC: Urban Land Institute.

Nelson, A. C. (2014). *Foundations of real estate development financing: A guide to public-private partnerships*. Washington, DC: Island Press.

Niazi, M., & Hussain, A. (2011). Agent-based computing from multi-agent systems to agent-based models: A visual survey. *Scientometrics*, *89*(2), 479–499.

Norton, G. W., Alwang, J., & Masters, W. A. (2014). *Economics of agricultural development: World food systems and resource use*. Abingdon, UK: Routledge.

O'Sullivan, D. (2002). Toward micro-scale spatial modeling of gentrification. *Journal of Geographical Systems*, *4*(3), 251–274.

O'Sullivan, D., MacGill, J., & Yu, C. (2003). Agent-based residential segregation: A hierarchically structured spatial model (pp. 493–507). Presented at the Proceedings of agent 2003 conference on challenges in social simulation, The University of Chicago, Chicago, IL.

Otter, H. S., van der Veen, A., & de Vriend, H. J. (2001). ABLOoM: Location behaviour, spatial patterns, and agent-based modelling. *Journal of Artificial Societies and Social Simulation*, *4*(4). Retrieved from <http://jasss.soc.surrey.ac.uk/4/4/2.htm>

Parker, D., & Filatova, T. (2008). A conceptual design for a bilateral agent-based land market with heterogeneous economic agents. *Computers, Environment and Urban Systems*, *32*(6), 454–463.

Parker, D., Manson, S. M., Janssen, M. A., Hoffmann, M. J., & Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers*, *93*(2), 314–337.

Patel, A., Crooks, A., & Koizumi, N. (2012). Slumulation: An agent-based modeling approach to slum formations. *Journal of Artificial Societies and Social Simulation*, *15*(4). Retrieved from <http://jasss.soc.surrey.ac.uk/15/4/2.html>

Pearson Education, Inc. (2014). Von Thunen modeling [Online image]. Retrieved November 10, 2017, from http://moodle.jesuitcp.org/mod/page/view.php?id=77425

Pearson Prentice Hall, Inc. (2005). Burgess zonal model [Online image]. Retrieved November 10, 2017, from https://planningtank.com/settlement-geography

Pearson Prentice Hall, Inc. (2008). Hoyt sectoral model [Online image]. Retrieved November 10, 2017, from https://planningtank.com/settlement-geography

Pearson Prentice Hall, Inc. (2008). Multiple nuclei model [Online image]. Retrieved November 10, 2017, from https://planningtank.com/settlement-geography

Qineti, A., Rajcaniova, M., Braha, K., Ciaian, P., & Demaj, J. (2014). Land market imperfections and reform rigidities: A case study from rural Albania. In *European Association of Agricultural Economists: 142nd Seminar* (pp. 29–30). Budapest, Hungary.

Schelling, T. C. (1971). Dynamic models of segregation. *Journal of Mathematical Sociology*, *1*(2), 143–186.

Schwarz, N., & Ernst, A. (2009). Agent-based modeling of the diffusion of environmental innovations—an empirical approach. *Technological Forecasting and Social Change*, *76*(4), 497–511.

Schwarz, N., Haase, D., & Seppelt, R. (2010). Omnipresent sprawl? A review of urban simulation models with respect to urban shrinkage. *Environment and Planning B: Planning and Design*, *37*(2), 265–283.

Simon, H. A. (1996). *The sciences of the artificial* (3rd ed.). Cambridge, MA: MIT press.

Smith, N. (1979). Toward a theory of gentrification a back to the city movement by capital, not people. *Journal of the American Planning Association*, *45*(4), 538–548.

Toffoli, T., & Margolus, N. (1987). *Cellular automata machines: A new environment for modeling*. Cambridge, MA: MIT press.

Torrens, P. M. (2006). Simulating sprawl. *Annals of the Association of American Geographers*, *96*(2), 248–275.

Torrens, P. M., & Nara, A. (2007). Modeling gentrification dynamics: A hybrid approach. *Computers, Environment and Urban Systems*, *31*(3), 337–361.

United Nations Economic and Social Commission for Asia and the Pacific. (1998). *Urban Land Policies for the Uninitiated*. Bangkok. Retrieved from http://www.unescap.org/huset/land_policies/

United States Census Bureau. (2016a, February 29). District of Columbia income. Retrieved November 10, 2017, from https://www.census.gov/topics/income-poverty/income.html

United States Census Bureau. (2016b, July 1). District of Columbia quickfacts. Retrieved November 10, 2017, from https://www.census.gov/quickfacts/fact/table/DC/PST045216

Urban Land Institute. (2012, June 18). Professional real estate development: Developer's tool kit. Retrieved November 10, 2017, from https://americas.uli.org/book/professional-real-estate-development-developers-tool-kit/

Von Thünen, J. H. (1966). *Isolated state*. Oxford: Pergamon Press.

Wallace, N. (2016, February 29). Where to buy: Price-to-rent ratio in 76 US cities. Retrieved November 10, 2017, from https://smartasset.com/mortgage/price-to-rent-ratio-in-us-cities

Walzer, N., & Hamm, G. F. (2012). *Community visioning programs: Processes and outcomes*. Abingdon, UK: Routledge.

Wegener, M. (1982). Modeling urban decline: A multilevel economic-demographic model for the Dortmund region. *International Regional Science Review*, *7*(2), 217–241.

Wiechmann, T., & Pallagst, K. M. (2012). Urban shrinkage in Germany and the USA: a comparison of transformation patterns and local strategies. *International Journal of Urban and Regional Research*, *36*(2), 261–280.

Wikipedia. (2015, April 22). List of shrinking cities in the United States. In *Wikiperia*. Retrieved from https://en.wikipedia.org/wiki/List_of_shrinking_cities_in_the_United_States

Wilensky, U. (1997). NetLogo: Segregation model. *Center for Connected Learning and Computer-Based Modeling. Disponible En:< Disponible En: Http://Ccl. Northwestern. Edu/Netlogo/Models/Segregation>[Consultado El 5 de Abril de 2015].[Links]*.

Wurster, C. B. (1963). The form and structure of the future urban complex. In L. Wingo (Ed.), *Cities and Space* (pp. 73–102). Baltimore: Johns Hopkins University Press.

Zhou, Y. (2015, November 18). Segregation model and calculation of Moran's I. Retrieved November 10, 2017, from http://geospatialcss.blogspot.com/2015/11/segregation-model-and-calculation-of.html

Biography

Niloofar Bagheri Jebelli graduated from Narjes High School, Tehran, Iran, in 2009. She received her Bachelor of Arts in Anthropology and Middle East Studies from University of Maryland, College Park in 2013.