Capturing the Effects of Gentrification on Property Values: An Agent-Based Modeling Approach

Niloofar Bagheri-Jebelli, Andrew Crooks, and William G. Kennedy

Abstract Cities are complex systems that are constantly changing because of the interactions between the people and their environment. Such systems often go through several life cycles which are shaped by various processes. These may include urban growth, sprawl, shrinkage, and gentrification. These processes affect the urban land markets which in turn affect the formation of a city through feedback loops. Through models, we can explore such dynamics, populations, and the environments in which people inhabit. The model proposed in this paper intends to simulate the aforementioned dynamics to capture the effect of agents' choices and actions on the city structure. Specifically, this model explores the effect of gentrification on population density and housing values. The proposed model is significant in its integration of ideas from complex system theory which is operationalized within an agent-based model stylized on urban theories to study gentrification as a cause of an increase in land values. The model is stylized on urban theories and results from the model show that the agents move to and reside in properties within their income range, neighboring agents that have similar economic status. The model also shows the role of gentrification by capturing both the supply and demand aspects of this process in the displacement and immobilization of agents with lower incomes. This is one of the first models that combine several processes to explore the life cycle of a city through agent-based modeling.

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1 Introduction

All cities change over time, with periods of growth and development followed by shrinkage and demolition. They transform in size [3], form [4], density [20], and land values [1]. Over the last two decades, a modeling approach has emerged to simulate urban environments and their transformations through time focusing on individual interactions from the bottom up. This approach is that of Agent-Based Modeling (ABM) which has been utilized in various studies (e.g., [30, 41, 43, 46]). Such an approach provides a platform for spatial and agent-agent interactions for heterogeneous commodities to be traded and for studying the resulting non-equilibrium dynamics. As such, ABM is an approach suitable for modeling land markets [43]. To this point, agent-based models have often focused on examining one aspect of a city's life cycle; in this paper, we examine multiple aspects of urban dynamics.

To focus on the formation of micro-dynamics between agents, this model is designed in an artificial environment, from stylized facts [36, 44]. 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 so that they can be implemented in an ABM framework. Agent-based models are structured with different sections, including agents, agent attributes, assumptions, and rules, as the framework to study specific phenomena. To inform each of these sections, we review relevant literature and use the material to create the various pieces (sections) of the model. By using plots and monitors, the model allows us to follow the evolution of the city throughout the simulation process.

The agent-based model studied in this paper focuses on demonstrating the relationship between gentrification and housing value. To examine this relationship, fluctuations in the housing value are studied in every neighborhood in which agents reside and trade properties. Then, patterns of gentrification by demand and supply are searched to understand their effect on fluctuations in population density and housing value in a neighborhood. By observing the relationship between housing value and gentrification, we can gain a deeper understanding of invasion and succession in the environment that leads to the rise and fall of a neighborhood, shaping the city cycle. 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. In the remainder of this paper, we discuss the related works in Sect. 2, before introducing our model design in Sect. 3. We present our results in Sect. 4 and discuss them in Sect. 5. Finally, we draw some initial conclusions in Sect. 6.

2 Related Work

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 (e.g., [17, 23, 42, 46]). Previous models and theories have examined the various processes and subsystems of an urban environment, but as cities comprise a variety of interacting processes and subsystems, they show novel results when studied as a whole rather than in isolation [28]. As the focus of the model presented in this paper is on the life cycle of a city, its research requires multiple phases. All the phases rely on understanding urban land markets. The urban land market studies that are included in the literature review use existing cities as their case studies while similar to the work of other researchers [35, 43], this model will present a hypothetical city. The model will demonstrate urban growth based on flat land with concentric zones represented by multiple circular rings around the Central Business District (CBD) [9]. Residential land prices are inspired by Alonso [1]. The residential prices vary based on distance from the CBD which causes competition among agents who prefer to be in close proximity to the city center. One could consider the life cycle of a city comprise of processes such as urban growth, sprawl, shrinkage, and gentrification. 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 being occupied, while the compaction results from an increase in density or intensity. Urban growth has been a topic of interest among researchers developing descriptive and mathematical models dating back to the early twentieth century and through their most current computer simulations and models (e.g., [5, 9, 12, 29]). 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 [8].

Urban sprawl is based on population mobility and occurs in a process called suburbanization. It results from the demand for greater space and lower density [5] among car-dependent communities [23]. Based on the static model of cities, residents want to be closer to the CBD. This desire, along with the residents' preference to be as far from the congestion of city life as feasible, contributes to the formation of urban sprawl. Therefore, this growth in mobility is observed at the edge of the city. Urban sprawl has been modeled mainly in the past two decades [6, 48]. Urban sprawl happens simultaneously as a city grows or shrinks.

The shrinkage of an urban area is a product of population decline caused by deindustrialization and out-migration from the inner-city. Urban shrinkage can have two reasons: economic (i.e., long-term industrial transformation such as in the USA) or demographic (i.e., falling birth rates such as in Germany) [52]. The process of urban shrinkage results in an oversupply of housing and a decline in housing prices which then accelerates migration in the region and causes an increase in the housing prices of the areas where migration happened. Urban shrinkage has been studied and modeled using case studies of various cities across the globe [26, 52]. Schwarz and

Ernst [46] argued that analyzing the housing price oscillation resulting from urban growth and shrinkage mirrors the dynamics between supply and demand.

Gentrification, also affected by supply and demand, has been described as the "middle-class settlement in renovated or redeveloped properties in older, inner-city districts formerly occupied by a lower-income population" [25]. This urban process has been studied both from the supply and the demand aspects and modeled utilizing each aspect [30, 33, 47]. Gentrification happens either through a bottom-up process of people attracted to the neighborhoods located near the CBD, with low rent prices [17, 30, 33] or by developers who recognize the opportunity in the Potential Rent (PR) of the land [47]. Developers seize these opportunities that arise in the market [13, 21]. The developers' goal is to earn profit and increase their Net Operating Income (NOI) [39].

Smith's [47] Rent Gap Theory presents an understanding of the developers' decision-making process. The rent gap explains the supply side of the rise of the land value and developers' decision to revitalize. The theory suggested by Smith [47] states that every piece of land could have an improved value (capitalized rent) or unimproved 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, rehabilitating buildings, and investing in large-scale residential projects [17]. This chain of events leads to gentrification and changes the land market at the aggregate level by increasing the potential and capitalized rent of the neighborhood [47]. The developers owning higher capital than individual households find the rent gap a profitable opportunity. The process of demand leads to the changing of a neighborhood, resulting in an increase in its density and land value, which may lead to sprawl, in the sense that the supply process increases land value in a previously shrinked neighborhood, causing growth.

Models of the urban structure have also been studied to understand the aforementioned processes. The three classic models of urban growth and structure are the concentric zone model [9], the sector model [29], and the multiple nuclei model [27]. The zonal model considers the city to form in concentric circles with the central business district (CBD) as the core [9]. This model presents the process of urban expansion in terms of invasion and succession of one zone into the next outer zone, resulting in the physical expansion of the city [9, 25]. 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). These models are useful in providing a spatial base for modeling urban land markets.

Land markets form where land is traded or purchased monetarily or through services. Social, political, cultural, economic, legal, and environmental factors affect land markets, and land markets affect them in return [25]. Land use is the management and modification of the natural and artificial environment. The Alonso model [1] also known as the bid rent model is perhaps the most famous model of land use and forms the basis of urban land market theory. Alonso's [1] bid rent model is constructed in zones of different land uses 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 trade-off between three main parameters, travel cost, rent, and space needed by the household. Like the Burgess [9] model, this example focuses on the CBD as the agent's work destination. The model, grounded in location choice feedback loops, adaptation, and evolution, demonstrated a bidding and competing process between firms and firms, residents and residents, and firms and residents [15]. Alonso's [1] 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 [15]. Regardless of the model implemented, the spatial environment of that model will largely affect the narrative and results.

The neighborhood where an agent resides or is deciding to reside in paints a local picture that 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 allow for a more general study that aims to exhibit the dynamics and interactions of a system and its subsystems. The traditional cellular spaces define neighborhoods either in the Von Neumann style with an agent in the center cell and four neighboring cells covering each side or the Moore style with the center cell and eight neighboring cells covering each side and corner. To examine the effects of spatial structure on segregation, Flache and Hegselmann [19] applied Schelling's [45] model to irregular grids using a Voronoi tessellation. The neighbors in this model are defined as cells that share common borders with the main cell [19]. The results of the Flache and Hegselmann [19] model showed that the size and structure of a neighborhood does not affect the outcome of segregation. Table 1 demonstrates example applications of models of urban dynamic researched and selected to design the model presented in this paper. This model is inspired by the parameters, environments, and agent behaviors of the models presented in Table 1. The models noted in Table 1 employ mathematical and cognitive approaches for the decision-making of their agents [14, 31]. While the mathematical models use ad hoc direct and custom coding of behaviors, cognitive models implement cognitive frameworks to capture better human decision-making [14].

3 Model Design

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 the previous section, this NetLogo model intends to simulate the

Table 1 Example applications of models of urban dynamics

Author	Application	Entity	Behavior	Spatial scale	Temporal scale
Benenson [7]	City dynamics	Individual	Cognitive and mathematical	Neighborhood and city	Years
Crooks [15]	Residential segregation	Individual	Mathematical	Neighborhood and city	Years
Devisch et al. [16]	Residential choice	Individual	Cognitive and mathematical	Neighborhood	Years
Landis [32]	Urban growth	City	Mathematical	City	Years
Schelling [45]	Segregation	Individual	Mathematical	Neighborhood	Not specified
Haase et al. [26]	Urban shrinkage	Household	Mathematical	Neighborhood and city	Years
Batty and Xie [5]	Urban growth and sprawl and decline	City	Mathematical	Neighborhood and city and regions	Years
Clarke et al. [12]	Urban growth and sprawl	Individual	Mathematical	Neighborhood	Years

effect of gentrification by supply and demand on density fluctuation through urban growth, sprawl, and shrinkage, and its effect on property value. While the model includes calculations for all of the dynamics, in this paper, we explain those relevant to gentrification and land value. For interested readers, the model and data to run the model are available at https://github.com/niloofar-jebelli/UrbanDynamics.

3.1 Data

The data used in the model is stylized on the real-world data of Washington, D.C. Stylized data provides the flexibility to explore a model for the purpose of understanding its dynamics, rather than extracting exact outcomes. The data concerning income, budget, housing, and land rent prices are extracted from the websites of the United States Census Bureau (USCB) [49], Mayor Muriel Bowser Office of Planning (MMBOP) [37], the Economic Policy Institute (EPI) [18] and the Urban Land Institute (ULI) [50]. This data is focused on Washington, D.C. with its 131 neighborhoods for modeling with realistic amounts. According to the Census Bureau [49] between 2010 and 2014, from the 306,184 housing units in the District, 37.6% were single-family units while 62.4% were multifamily 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. The average household size was 2.2 persons. The median value of an owner-occupied unit was $486,900. The 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 a great effect on the validity of the process and output. Table 2 demonstrates 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 is initiated at the beginning of every simulation.

3.2 Environment

The environment is modeled with the bottom layer of patches as houses in a Moore neighborhood definition of 3×3 cell configuration to generate an abstract spatial representation. The middle layer holds Voronoi tessellations representing a region in the city (e.g., a neighborhood). To form the abstract urban structure, the top layer is formed according to the zonal model by Burgess [9]. The zones are designed (from the center out) with the CBD in the core, then the inner-city, and then the suburbia. The CBD and suburbia are considered to be more expensive zones, while the inner-city is less expensive as is often the case in many cities [9, 27, 29].

3.3 Agent Classes

Inspired by various studies, the agents are designed to be in three categories: professionals, non-professionals (e.g., [30, 35]), and developers (e.g., [17, 22]). Agents make decisions and move in a temporal scale expressed as time-steps. Each time-step of this model is notional but could be considered to represent one year because all the rules and assumptions are set to adjust in that manner to accommodate the rates (e.g., shrinkage rate). Similar to Schelling's [45] model, time is purely notional in this abstract model but can be considered in yearly intervals [44]. The model is also run for 300+ time-steps to represent enough time in the life cycle of a city.

3.3.1 Professionals and Non-professionals

Professional and non-professional agent groups have incomes, budgets, and preferences. Professional agents have a higher income than non-professional agents. 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 with a random income and a budget then move around based on their preferences until they are satisfied. The agents' initial state is unhappy to ensure their movement across the landscape to reach a happy state when their preferences are met. 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 [1], with at least 20% of its neighbors being of the same class, inspired by Schelling [45], or the same color, and choose a housing type with travel cost

Table 2 Input parameters of the urban life cycle model

Parameter	Value	Default	Reference
Developer	Normal distribution (mean, standard deviation): $N(\mu, \sigma)$		
State	Happy/unhappy	Happy	Benenson [7], Schelling [45]
Income	N(5,000,000, 4,000,000)		Miles et al. [39]
Budget	69% of annual income		Miles et al. [39]
Saving	Income–budget		Miles et al. [39]
NOI	≥ 0	0	Miles et al. [39]
Professional			
State	Happy/unhappy	Unhappy	Benenson [7], Schelling [45]
Income	N(137,814, 20,728)		EPI [18], MMBOP [37], ULI [50], USCB [49]
Budget	69% of annual Income		EPI [18], MMBOP [37], ULI [50], USCB [49]
Saving	Income–budget		EPI [18], MMBOP [37], ULI [50], USCB [49]
Housing	28% of budget		EPI [18], MMBOP [37], ULI [50], USCB [49]
Non-professional			
State	Happy/unhappy	Unhappy	Benenson [7], Schelling [45]
Income	N(42,814, 10,938)		EPI [18], MMBOP [37], ULI [50], USCB [49]
Budget	69% of annual Income		EPI [18], MMBOP [37], ULI [50], USCB [49]
Saving	Income–budget		EPI [18], MMBOP [37], ULI [50], USCB [49]
Housing	28% of budget		EPI [18], MMBOP [37], ULI [50], USCB [49]
Properties			
State	Occupied/vacant	Vacant	Author's estimation
Zone	Inner-city/suburban		Burgess et al. [9]
Type	C: Condo/S: single family house		MRIS [38]
Size	C: N(926.96,31.26), S: N(1650.40,504.14)		MRIS [38]
Price	C: N(492,867,14,715.43), S: N(769,387,201,379.80)		MRIS [38]

(continued)

Table 2 (continued)

Parameter	Value	Default	Reference
Age	[0–100]		Author's estimation
Potential rent	>0		Diappi et al. [17], Smith [47], Author's estimation
Capitalized rent	>0		Diappi et al. [17], Smith [47], Author's estimation
Environment			
Cap rate	[4.75–7.75]	7.50	CBRE [34]
Urban growth rate	[0–1]	0.17	CBRE [34]
Initial population	[100–1000]	1000	CBRE [34]
Gentrification rate	[0–1]	0.26	CBRE [34]
Sprawl density threshold	[0–1]	0.2	CBRE [34], Author's estimation
Sprawl moving rate	[0–1]	0.1	CBRE [34]
Shrinkage rate	[0–1]	0.0050	CBRE [34]

in relation to their budget. The parameters of travel cost, rent, and space that play central roles in Alonso's [1] bid rent theory are used as inspirations for the preference setting of the professional and non-professional agents. The developers are driven by the profitability of the land. They check their available savings, 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 the previous section, and search for the rent gap using a rent gap threshold [17, 47]. The movements arising from the interaction of the agents with each other and their environment shape the state (growing, sprawling, shrinking, or gentrifying) of the city modeled.

3.3.2 Developers

The developers are fixed agents because their movement is not essential to the model, and it is only their decision-making and developments that affect 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 on the income generated by the property. Based on the 2014 Coldwell Banker Richard Ellis (CBRE) cap rate survey report [34], 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 are in the CBD symbolizing working in the city center. The developers also have randomly assigned budgets and preferences. Although the agents are limited by their incomes and budgets, their decision-making process determines a large portion of their movements. 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. Developers buy vacant properties if the rent gap [47] is high and the property age is 60 or higher. By doing so, inspired by Gilbert et al. [22] model of the English housing market, they change the properties' ages to zero which makes them great options for agents to buy. The developers also acquire properties when unhappy professionals or non-professionals sell their property to the developer with the most development in their neighborhood if the source of their unhappiness is an increase in population that does not match their preferences. 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 [17] method, neighborhood IDs were used to count the patches within them and 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.

3.3.3 Properties

According to the Metropolitan Regional Information System (MRIS), the average sold price of a two-or-less bedroom detached property in 2015 was $553,782, while an attached property was $512,290 [38]. The same market analysis showed that the 2015 average sold price per square feet for all property types averaged $491 and ranged from $453 to $509. The properties in this model are divided into single-family houses developing in the outer circle and condominiums developing throughout the three zones. Each property has a spatial location, occupancy, a CR, and PR and a state of decay. Properties have ages, types based on their zones, sizes based on their types, and 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, while properties in the suburban zone are attached and detached single-family houses.

3.4 Gentrification Calculation

Focusing on the central question of this paper, while there are underlying mechanisms for all the urban dynamics introduced, we will present those causing and affecting gentrification by supply and demand. From the prices determining total value, rental prices were achieved using United States Census Data on the 32.02 price-to-rent ratio [51] in Washington, D.C. As mentioned by Smith [47], the property capitalized and potential rents are equal. In time, the capitalized rent declines and creates 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 [17] method. Governing analysis from the American Community Survey and Longitudinal Tract Database [24] 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 potential rent is calculated as presented in Eq. 1:

$$PR = \frac{p}{r \times 12} \tag{1}$$

where *p* is the property price and *r* is the price-to-rent ratio. As presented in Eq. 2, we estimate the *PR* using the *CR* and a decaying function over the age of the property:

$$CR = PR \times e^{-\lambda \times a} \tag{2}$$

where λ is the decaying parameter and *a* is the age of property. We use $\lambda = 0.04$ throughout the experiment since it provides a more realistic value for the *CR*. As demonstrated in Eq. 3, we use the *PR* and the *CR* to calculate the rent gap:

$$\mathrm{Re}ntGap = \frac{PR - CR}{PR} \tag{3}$$

Due to its effect on land value and urban dynamics, 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 in Eq. 4 as follows:

$$\text{density} = \frac{n}{np} \tag{4}$$

Density is a significant parameter for gentrification and urban sprawl [10, 33], and therefore needs to be accounted for as we do in Eq. 5; as the density increases, the property prices increase as follows:

$$p = e^{1+\text{density}} \times (CR \times r \times 12) \tag{5}$$

The direct relationship between density and housing price is demonstrated in their corresponding plots in Figs. 3 and 4. While gentrification by supply is modeled by setting the preferences of the developers, gentrification by demand is modeled by setting the preferences of the professional and non-professional agents. Then, 30% of the agent population is randomly selected to have an interest to pay low rent, while everyone has the interest to be near CBD. Gentrification by demand is represented by calculating the number of non-professional and professional agents who prefer to be near CBD and pay low rents. Gentrification by demand is considered to have taken place if the professional agents who can afford to live in suburbia decide to live in the inner-city due to the aforementioned preference, and by doing so cause displacement to the non-professionals. 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 1 demonstrates

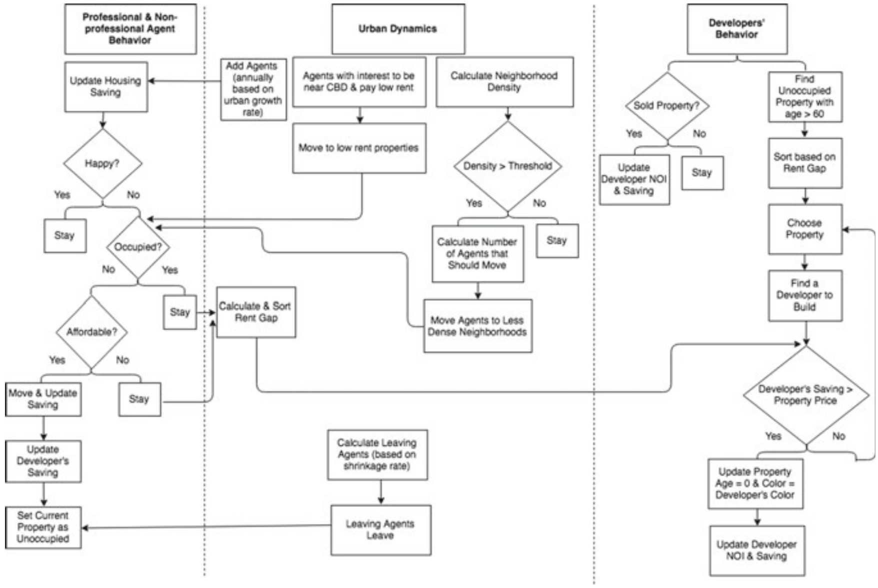

Fig. 1 Model logic and interactions between entities during a simulation

this interconnectivity from the initiation of the model for the course of a simulation.

3.5 Verification

As the purpose of this model is to capture the qualitative agreement with emerging patterns of macro-structures forming a city cycle, it is validated as a level one type according to Axtell and Epstein's [2] validation levels. Therefore, the mode was examined in accordance with its level type. An essential part of building an agent-based model is verifying the model for correct performance [11]. To implement the model, various verification procedures have taken place. We walked through the code to ensure the matching of the model inputs with the background data. Then, we performed testing measures such as printing the outputs of each section of the code for debugging. Once we gathered the output data and results, we 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, we traced the model's dynamics to detect emergent behavior. Since this model is demonstrating an abstract city to focus on the urban processes, its inner validity has been examined by comparing the implemented model with its design [40, 44]. Our examination of the model's inner validity showed that it was behaving as expected.

4 Results

To test the methodology and data, an environment with agents was simulated in NetLogo. To examine various aspects and dynamics, the model was tested for 300+ time-steps. The environment of the model is demonstrated as zones that represent the CBD (central circle with the zID = 30), inner-city (middle ring with the zID = 60), and suburbia (outer ring with the zID = 90), and the polygons represent regions that form the neighborhoods (referred to by nIDs). As explained in the Model Design section, 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.

The cap rate, urban growth rate, gentrification rate, shrinkage rate, sprawl moving rate, sprawl density threshold, and initial population ranges appear as sliders to support sensitivity analysis. The developed properties are demonstrated on a monitor. There are six plots on the geographical user interface that display various information such as developers' average savings, developers' NOI, and professional and non-professional agents in the inner-city and in suburbia and their savings. These details are illustrated in Fig. 2.

The model was tested by multiple runs and with various settings for sensitivity analysis. Due to the focus of the paper on the effect of gentrification on density and property value, relevant parameters such as initial population were changed to find the most interesting cases worth describing in the paper. The model demonstrated the most dynamic results when tested with a population of 1000 agents and 20% similarity in the happiness preference setting of professional and non-professional agents which created a segregated environment based on income and color. Setting 30% of the population to randomly prefer to be near CBD increased the number of professionals in the inner-city while displacing the non-professionals and causing a

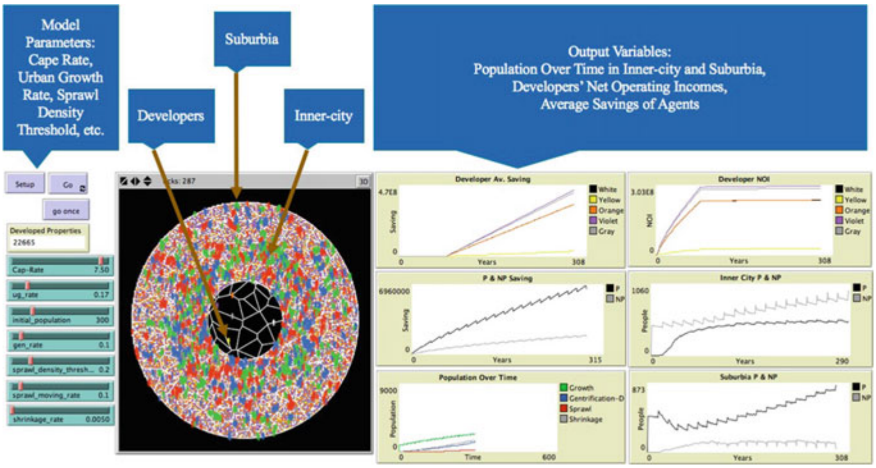

Fig. 2 Model graphical user interface at default settings

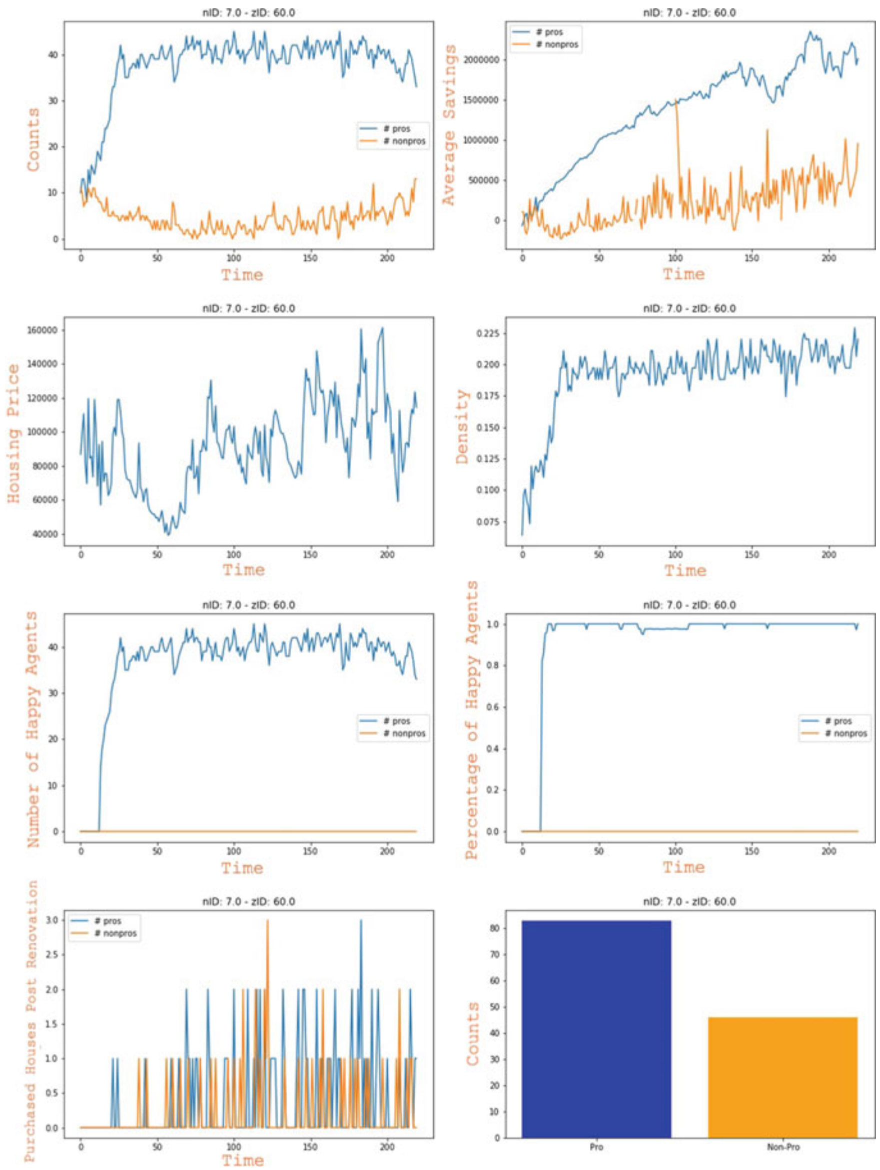

Fig. 3 Gentrification by supply in the 7th neighborhood of the inner-city

longer and more fluctuated movement for them across the landscape. This caused a fluctuation in the population density which affected the property values. The parameters affecting the rent gap along with the developers, attempt to buy, renovate, and sell the properties, creating a fluctuation in the property values and thus the population density. Figures 3 and 4 are representative of the plots gathered to analyze the effect of gentrification on density and property value.

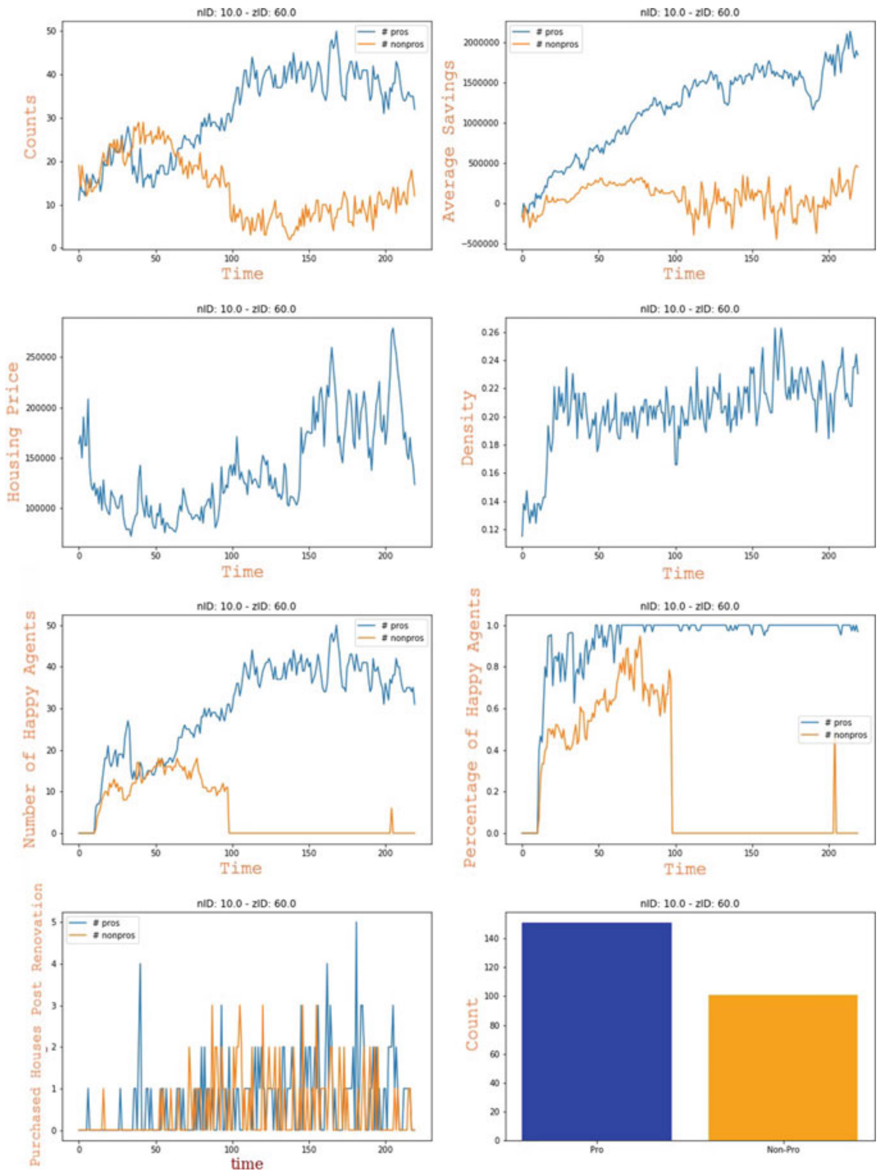

Fig. 4 Gentrification by demand in the 10th neighborhood of the inner-city

4.1 Gentrification by Supply

Figure 3 represents an example of gentrification by supply. The plots in this figure show the results of neighborhood number 7 in the inner-city. The plots demonstrate the continuous and dominant presence of the professionals with rising savings in this neighborhood. There is a considerable happiness gap among the professional and non-professional agents. Most important, it seems that more professionals bought properties after renovation and remained in the neighborhood. The presence of the professionals is correlated to the population density and the housing price.

4.2 Gentrification by Demand

An example of gentrification by demand is demonstrated in Fig. 4. The plots in this figure show results of neighborhood number 10 in the inner-city. These plots show a fluctuation in dominance between the agent classes, with the professionals succeeding in dominance over the neighborhood. Population density and housing prices correlate with their rising presence. The fluctuation in dominance seems to positively correlate with the happiness of the agents. Professionals also show a higher number of purchases of renovated properties.

5 Discussion and Further Works

5.1 Main Results

The overall findings of the model indicate the dominance of the professional agents in the majority of neighborhoods. While for the purpose of the study, the neighborhood is defined as the tessellation in which an agent resides, similar to Flache et al. [19], the structure and size of the neighborhood does not affect the urban dynamics occurring within it. After 300+ time-steps, the segregation caused by the happiness preference of agents is quite visible. The pattern of segregation by income and color follows notions from Schelling's [45] model.

5.1.1 Gentrification by Supply

The results of Fig. 3 prove the top-down nature of gentrification by supply explained in the Background section. The developers find opportunities during times that the neighborhood is undergoing shrinkage and is left with vacant properties to buy. They renovate and sell these houses, increasing the property value to its potential rent and its age to zero. This act affects the population density depending on the agent class most dominant in the area. Neighborhoods with high housing prices and a large population of professionals tend to thrive in such dynamics with more professionals moving to them. While this increases the density and may result in urban sprawl, it also causes a sense of unhappiness among non-professionals, leaving them displaced and unable to purchase properties in the neighborhoods to which they formerly belonged. Neighborhoods with high housing prices and a large population of non-professionals tend to cause a locked-in state for this agent class due to having inadequate savings to move. Other non-professionals who are attracted to the neighborhood are mostly unable to purchase a property there. This state results in more professional agents moving into the neighborhoods and buying the recently renovated properties. Renovations in neighborhoods follow a trend of displacement or immobilization for non-professionals while providing a high-quality residential opportunity for professionals.

5.1.2 Gentrification by Demand

Results in Fig. 4 demonstrate an example of the bottom-up structure of gentrification by demand. The preference of the 30% of the agents to not only live near CBD, but pay lower rents, is at the core of this dynamic. Figure 4 shows a neighborhood that is considered affordable to non-professionals but preferred to professionals since the non-professionals residing there mostly have no other option but the professionals who chose to live there can most likely afford a higher-priced property. It is this choice that ultimately results in the increase in population density and thus property value, causing a sense of unhappiness among non-professionals and their displacement to other neighborhoods. While their displacement may result in a temporary shrinkage, the neighborhood will eventually be populated by professionals with the savings to acquire the recently renovated and higher-priced properties. The choice of agents to reside in neighborhoods that are the only option of some others is followed by the displacement of the non-professionals.

One of the utilities of agent-based models is to test existing theories; however, when it comes to urban processes, there are very few theories that encapsulate a large number of such processes. Therefore, we have chosen those which are prototypical to the model. The purpose of this explanatory model is to combine various urban processes and demonstrate the life cycle of a city while focusing on the effect of gentrification on property value. To this point, the model is not constructed to recommend policy solutions, but rather to utilize empirical data in developing urban processes and demonstrating the outcome of their interactions. However, the model can be extended to possibly prevent gentrification or decrease the high rate of unhappiness among agents by performing sensitivity analysis to find the right threshold for various population levels. Further extension of the model focused on other theories and urban processes is left to future researchers to explore.

6 Conclusion

While many models have been developed to explore a single urban process, our model examined multiple processes, namely, urban growth, sprawl, shrinkage, and gentrification to portray their effect on the life cycle of a city. The model focused on the agent–agent and agent–environment interactions that play a role in population density and property value. For the purpose of this paper, we narrowed the analysis down to observing the role of gentrification by supply and demand. We observed in the results that the immobilization and displacement of the lower-income agents caused by developers revitalizing a neighborhood for profit and also by higher-income agents choosing to live near CBD and pay lower rents. The actions of the developers and professionals in the model directly affected the options that non-professionals are left with through the rise of population density and housing prices. Our model demonstrates patterns of increased segregation as a result of the preferences, rules, and interactions occurring between agents. Finally, the model supports the previous research revealing the disabling nature of gentrification for the unprivileged population residing in or native to a neighborhood undergoing development.

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