AN EMPIRICAL AGENT-BASED MODEL FOR RESIDENTIAL SEGREGATION, CASE STUDY: TEHRAN

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ABSTRACT:

Residential segregation as a known consequence of rapid urbanization in developing countries is a complicated socio-economic phenomenon. Quantified description, analysis, and prediction of urban dynamics as a complex system have always been challenging issues. The recent intensive developments of multi-agent simulations as a solution to these problems still lack enough real-world examples. Our purpose in this research is to develop a spatially explicit model of residential segregation in urban space which accounts for a specific city's infrastructure. The proposed agent-based simulation of the residential dynamics of Tehran over a 20-year period between 1996 and 2016 is based on the GIS datasets provided by Tehran Municipality and the Statistical Center of Iran.
This is the first effort at presenting an agent-based model for Tehran's residential segregation. We revised the "Schelling" segregation model in an attempt to customize it and arrive at an acceptable fit for Tehran. In addition to Schelling's parameters, which comprise purely social factors, we identified several important socio-economic and spatial-environmental criteria, in turn categorizing them based on the AHP method. A certain number of the parameters like "neighborhood prestige" specifically belong to Tehran and are suggested for the first time. The proposed expert-based model was implemented in Netlogo. Validation of the resulting pattern using the Kappa indicator showed that the model simulated Tehran's segregation pattern at a rate higher than 62%.

1. INTRODUCTION

Regarding the uneven distribution of facilities in urban areas (especially capital cities) of developing countries in recent decades, the rapid unsustainable growth of cities and its' negative consequences - such as residential segregation - have become important issues (Afrough, 2015) studied by many researchers. Residential segregation in Iran is a complex socio-spatial problem that is greatly influenced by misguided cultural policies and the city's socioeconomic/infrastructural situation. This is in turn one of the main causes of unequal physical development, which has resulted in urban polarization (Azadeh, 2003; Azhdari et al., 2018). Residential segregation is a multi-scale phenomenon as a result of different factors. Some of them such as where citizens choose to live occur at the micro level, while others, including societal and environmental changes, occur at the macro level. (Azadeh, 2003; Feitosa et al., 2011). Schelling defined segregation as a spatial pattern of different social classes which begins when one individual prioritizes living in a same-class neighborhood and then expands to having everyone in an entire city wanting to do the same (Schelling, 1971). People move into and out of areas meeting the heterogeneity of neighbors (Crooks, 2010).

While making an efficient model of a multi-scale phenomenon is not possible on a macro-scale, it is on a micro-scale (individual level) via a bottom-up approach (Heppenstall et al., 2016). Over the past three decades, agent-based models (ABMs) are often applied to urban issues given that their bottom-up approach provides spatiotemporal simulation of people's interactions at the micro-level and results in phenomena at the macro level (Mahdavi Ardestani et al., 2018). The unique ability of agents to learn, evolve, and make decisions adaptively in both space and time allows researchers to explore complex systems like cities defined by heterogeneity and all levels of interaction, from individuals to government policies (Heppenstall et al., 2016). However, the recent intensive development of ABMs as a solution for segregation simulation still lacks enough real-world examples. In Iran, almost all studies on segregation are strictly limited to social science methods, and studies like (Attar, 2019; Azhdari et al., 2018) that employ a spatial approach are rare.

Schelling's model is the most popular agent-based segregation model; he devised a model to demonstrate how individuals' relocation decisions entail global segregation. His theory is based on individuals' satisfaction with their residential areas in relation to two main factors: "neighbor's class", "neighborhood radius" (Crooks, 2010; Immorlica et al., 2017; Schelling, 1971). He concluded that it almost invariably reached a final, stable configuration with a distinctly segregated pattern (Immorlica et al., 2017). Hundreds of researchers have reaffirmed this observation through computer simulations of his model. See (Attar, 2019; Benenson et al., 2009; Feitosa et al., 2011; Mahdavi Ardestani et al., 2018). Some others have tried to improve on Schelling's model. For instance, in a model by Hatna & Benenson, agents are also interested, under specific condition, in integrating with neighbors of different classes (Hatna & Benenson, 2015). Silver D. et al. examined how the existence of physical venues, like churches and bar, affects the baseline patterns of Schelling's model. (Silver et al., 2021).

In this research, we used results of a limited number of Iranian social studies to identify factors that affect residential decisions. In addition to Schelling's parameters, we determined several socio-economic and environmental factors inspiring (Silver et al., 2021) about the role of POIs[1] in residential choices. We developed an expert-based model for residential dynamics,

[1] Urban's Places Of Interest

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while using AHP method to weigh the criteria. We benefited from real census/geometric data, to implement the simulation.

2. METHODOLOGY AND EXECUTIVE STEPS

2.1 Study Area

The proposed model was implemented using real data from an area of 18 km² in north-west Tehran which includes seven neighborhoods. Two famous highways (Yadegar and Niayesh) and two river valleys (Darakeh and Farahzad) are prominent natural features of the area. While a dramatic demographic heterogeneity can be seen in periodic census data, it has intensified due to recent worsening economic conditions. The growth rate of 4.5% in the study area (compared to an average rate of 3% in greater Tehran) represents the potential of the area to absorb new residents, causing in turn the socio-environmental changes seen for instance in the growing affluence of the "Kouyefaraz" neighborhood.

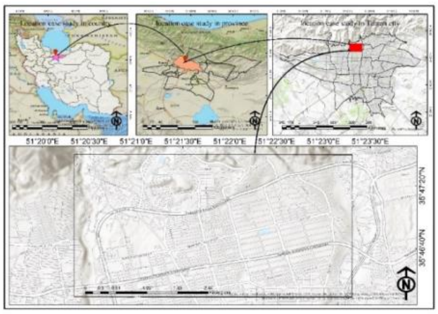

Figure1: Case study area and its location in the city, the province, and the country

2.2 Proposed Model – Parameters and Components

2.2.1 Parameters: The physical characteristics of a neighborhood are affected by various socio-economic and environmental factors with different impact scales (Azadeh, 2003). In this research, the effective factors of residential segregation were sorted in a hierarchal structure as presented in figure 2. This structure was designed so that the top level reflected estate prices (economic factors exert a huge influence on people's decisions). Environmental and social criteria have also been presented on other levels. Considering several socioeconomic parameters, such as job, education and salary, households were classified into 4 classes. The first and second classes contain wealthy and middle classes, respectively. The third class addresses the labor class, and the fourth comprises households with similar/worse conditions to the third class; however, due to certain similarities (in terms of ethnicity, etc.), they have a relative tendency to create social ghettoes.

Usually, a social class does not reside everywhere in the environment; residential areas of each class are limited based on people's purchasing power and/or willingness to buy real estate (Gkartzios & Ziebarth, 2016). So, the function of "suitability of price" was defined for every socio-economic class. It reveals the fact that each class is more willing to reside in an area with a specific price range. While there is no willingness to settle in those parts containing inferior classes, people cannot choose a neighborhood with superior classes due to their purchasing power. Therefore, the function in its simplest format was considered as a discrete linear function (Eq.1). Its ranges were determined for each class through consulting with estate experts and residents. It is worth noting that the selection of each agent affects neighborhood's characteristics (especially price and prestige). This may in turn attract or repel other people from choosing this neighborhood, since the features which provoke the upper classes into competing for housing, cause further price inflation (Gkartzios & Ziebarth, 2016). It is an advantage of the proposed model compared to previous works.

$$f(x) = \begin{cases} f1, & x \leq a \\ f2, & a < x < b \\ f3, & x \geq b \end{cases} \tag{1}$$

Where: x = the real price of estate
a, b = the price range in which each class has respectively no willingness and purchasing power to buy real estate
f1, f2 and f3= first-degree linear functions of x

Environmental factors address an area's suitability[2], dependency[3] and incompatibility[4] for residence (Azadeh, 2003). Social factors refer to mental, and cultural characteristics of society by which urban growth has been affected.

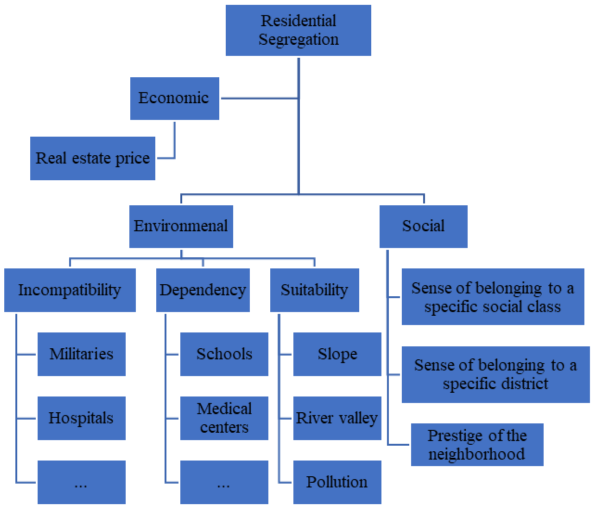

Figure 2: The hierarchy of effective factors in segregation

The environmental criterion was divided into three sub-criteria of "suitability", "dependency", and "inconsistency", which have their own indices. The suitability sub-criterion includes a set of geographical factors determine the suitability of an estate for residential land use. "Slope", "distance from river valleys", "noise, and air pollution" were selected as its factors. "Dependency" addresses the concept of access to those urban facilities that play an important role in selecting an estate for residence. This sub-criterion includes 14 main POIs. The "inconsistency" refers to the incompatibility between residential land use and other land uses. It consists of 10 main POIs make estate conditions unsuitable. The impact of these indicators was considered negative. The radial distance to the POIs was defined as the indicator. Some POIs have a dual role.
Three sub-criteria were considered for the social criterion. One of them is "sense of belonging to a neighborhood" which defined by Sik Hong et al. as a feeling of belonging to a

[2] Suitability: suitability of neighbourhood for residential land use

[3] Dependency: being convenient and reach to urban utilities which affect quality of life

[4] Incompatibility: presence of some land uses such as military bases and hospitals, both of which can cause problems for residents of the neighbourhood.

specific place and can be differentiated from social, racial, gender, and religious affiliations (Dezfooly, 2013). This feeling makes people consider "proximity to the current neighborhood" as a positive parameter in their choice. A "sense of belonging to a certain social group" is another sub-criterion which defined in most of the existing models as the percentage of same-class neighbors. However, in the proposed model and when adopting a strict approach, the presence of hetero-type neighbors has an adverse impact on selecting an alternative place by the upper-classes. This parameter is called "dissonance". So, the indicator of latter sub-criterion was defined as "homogeneity degree in a specified neighborhood radius" called "similarity", explained in Eq. 2 and Eq. 3. The third social sub-criterion is "prestige". There are some neighborhood that have always been of great interest to buyers despite having several problems like heavy traffic, poor public transportation and so on. While in a theoretical model, these problems make prices decrease, in the real world these neighborhoods are expensive. On the other hand, the high price can cause a loss of purchasing power in the model. Therefore, to justify people's increased willingness to buy properties in a higher-priced neighborhood, we defined a parameter called "neighborhood prestige". The higher degree of prestige for a property, the more willingness to be selected.

2.2.2 Agent: We developed a model in which residential decisions are made by *agents* that *interact* based on *environment*'s conditions. The model result is a segregation pattern based on individuals' choices, who have a tendency to choose areas that offer better living conditions, often moving because they're dissatisfied with their current place. We have created 4 classes of agents according to social classes. These agents are active types that react against other agents and understanding of environmental conditions. As shown in table 1, the agents share four characteristics: The "age" is assigned to each agent randomly when entered into the model and increased by one unit per each period of model running. This characteristic can limit agents' movements and presence in the environment; While "group" shows the agent's class, "Fail factor" is a positive integer that indicates whether the agent has been able to find its desired residence or not. In case of success, the value will remain zero; otherwise, one unit is added to this value after every failure. The last factor, "happiness", shows the agent's level of satisfaction or dissatisfaction with their current residence. Agents have the ability for mutational movement by which it can displace from its pixel to every other pixel throughout the model.

Attribute	Range of value
age	1-50
group	1-4
Fail factor	>= 0
happiness	Satisfaction or dissatisfaction

Table 1: Attributes of agents

2.2.3 Environment: Regarding an area's residential capacity and population, the environment was supposed to be a raster form with resolution of 25 m. Each pixel was modeled as a passive agent whose characteristics remain constant except for some limited changes over time reflecting the presence of other agents around that pixel. The characteristics are as follows:
- Land use: addresses occupation of the target pixel by social classes 1, 2, 3 or 4.
- Forbidden: addresses if a pixel is allowed for residence or not. 0 means the pixel is residential, while 1 means non-residential or forbidden (for example, it may be a military).
- Value: the total value of all environmental criteria indicators
- Prestige: the quantitative value of prestige indicators
- Price: the quantitative value of real estate prices
- Capacity: the number of floors in each estate
- Utility: the suitability degree of each pixel for occupation by each of the agent quad classes. This degree derived from contributing all social and environmental parameters.

A brief description of environmental attributes is listed in table 2. The environment, in terms of price is divided into five categories: *expensive, middle, inexpensive, upper middle and lower middle*. However, being inspired by (Hatna & Benenson, 2015) and in order to move closer to a better model, *the upper middle* and *lower middle* categories were considered "growing areas" that are shared between first and second, as well as second and third groups, respectively. Accordingly, if a higher-class agent settles in a pixel of these areas, both price (Gkartzios, M. & A. Ziebarth, 2016) and prestige of that pixel and its neighbors will rise. Over time, the tendency of a higher social group is to increase as the quality of life and prices grow there. It is worth noting that one improvement in the proposed model is the capacity of the environment's pixels. The capacity in previous works has usually been defined as one agent at a time. To move closer to the real world, the number of floors for each parcel was considered as pixel capacity, making it possible for a couple of agents to settle in a same pixel simultaneously.

attribute	Range of value
Land use	1-4
Forbidden	0 or 1
Value	0-1
Prestige	0.1-1
Price	2000000-5000000
Capacity	1-20
Utility	0-1

Table 2: Attributes of environment

2.2.4 Interaction: Interactions include either those that take place among agents or between agents and the environment (Crooks, 2010). In this model, the term agent interaction refers to reflection of the agent to neighborhood's homogeneity. As mentioned, one of the social parameters for each agent is its neighborhood's degree of similarity. In other words, each agent prefers agents of its same class to live in the neighborhood. They particularly experience dissonance with neighbors of other groups, including people from inferior classes. Eq. 2 and Eq. 3 show the main interactions between agents:

$$\text{dissonance}(j) = \sum f_i * w_i^j \tag{2}$$

Where: f_i = number of neighbors of ith type
w_i^j (Ranges between the values 0 and 1) = the dissonance degree of an agent of j type with a neighbor of i type
dissonance(j) = the dissonance degree in a certain neighborhood radius from an agent of j type

$$\text{similarity}(j) = n - \text{dissonance}(j) \tag{3}$$

Where: n = the number of neighbors in a certain neighborhood radius for an agent of j type.
similarity(j) = the degree of homogeneity in the neighborhood.

It is mentioned that dissonance among various groups was determined based upon a field survey and consultation with experts in a qualitative range which converted to quantitative one based on Satti table. Accordingly, each agent, except for the fourth class, experiences no dissonance with higher class.

Agent-environment interactions include two steps: first, the agent's understanding of the environment, second, the agent's response. In this model, in initial phase, a certain number of agents is randomly placed in the environment. Then, the next agents are entered into the model one-by-one in each period of the model; number of those agents is based on the population growth rate and share of each group in total population. These agents examine the environment in a restricted fashion; some pixels that meet the requirements of Equations 4 and 5 are randomly chosen and examined by each agent.

$$forbiden^{j} > 1 \tag{4}$$

Where: j = the pixel number

$$density^{j} > n \tag{5}$$

Where: j = the pixel number
n = the number of agents located in a pixel

While the term "forbidden" refers to the pixel character "forbidden", Eq. 4 reveals the fact that the selected pixel should not be in the forbidden area. Considering the number of floors to be the "capacity" of each pixel, Eq. 5 examines whether the chosen pixel has any vacant place for a new agent.

Two concepts have been defined and applied for selecting the suitable alternative pixels. The first concept is utility, which refers to the utility degree of the pixel to be selected by the agent. In this model, we considered two types of utility: preliminary utility and complete utility, which are explained by Eq. 6 and Eq. 8 respectively. The second concept is satisfaction, which addresses the satisfaction level of an agent in each group having a residence place. In other words, a pixel will not be settled by an agent if satisfaction levels decline below a certain range. (This level is often different for each socio-economic class in the real world.) In this model, once an agent is entered into the model for the first time, it evaluates the alternative places one by one considering its own group and the environmental conditions found at that place. Once the preliminary utility of an option is higher than agent's expected satisfaction level, it will be chosen to settle. The preliminary utility level of a pixel is calculated using Eq. 6.

$$u^{j}(i)= W_{i}es*(W_{i}en*env^{j}_{i} + W_{i}s*Pres^{j}_{i}) + W_{i}ec*bp^{j}_{i} \tag{6}$$

Where: i = group of agents
j= pixel's number
$W_{i}es$ = weight of non-economic criteria for an agent of i^{th} group
$W_{i}ec$ = weight of economic criterion for an agent of i^{th} group
$W_{i}en$ = weight of environmental criterion
$W_{i}s$ = the weight of social criterion
env^{j}_{i} = a function of environmental parameters in the j^{th} pixel
$Pres^{j}_{i}$ = the prestige factor in j^{th} pixel
bp^{j}_{i} = a function of real estate price as mentioned in Eq. 1. It represents the purchasing power related to an agent of group i and the pixel j.
$u^{j}(i)$ = the preliminary utility level of j^{th} pixel for an agent from i^{th} group.

It means, among all available alternatives, the agent selects the first option validated in Eq. 7 to reside in.

$$utility^{j}_{i} > satisfaction^{j}_{i} \tag{7}$$

Where: $utility^{j}_{i}$ = the utility level of the pixel j for the agent i
$Satisfaction^{j}_{i}$ = the level of satisfaction related to agents of the group i and pixel number j

Utility is computed through either Eq. 6 or Eq. 8 depending on whether the agent enters for the first time (Eq. 6), or it is the end of each model's period (Eq. 8). It is worth mentioning that satisfaction can be determined and set interactively by the model's user at run time; this capability makes the proposed model more flexible compared to that of the previous work. Eq. 7 means that the agent would be happy in the pixel where utility level is greater than the agent's satisfaction level. So, at the end of each period, Eq 7 is examined for all agents, and unhappy agents decide to move. A random number of pixels which fit in Equations 4 and5 are selected as alternatives. This time, the agents examine conditions of each alternative based upon Equations 7 and 8. Among the alternatives validated in Eq. 7 the one with a higher utility is selected to relocate.

$$U^{j}(i)= W_{i}es*(W_{i}en*env^{j}_{i} + W_{i}s*Socio^{j}_{i}) + W_{i}ec*bp^{j}_{i} \tag{8}$$

Where: $Socio^{j}_{i}$ = a function of social parameters for agents of group i in pixel j
$U^{j}(i)$ = the complete utility level of the pixel j for an agent of group i.

The only difference between Equations 6 and 8 is the replacement of "Pres" with "Socio" in Equation 8. At its initial entry into the model, the agent considers basic economic and non-economic parameters. But at the end of each period, when all the agents have been settled, agents consider all the social parameters before selecting a new place to move. It should be mentioned that env^{j}_{i} and $Socio^{j}_{i}$ are calculated from Eq. 9.

$$cr = \sum w_{k} * f_{k} \tag{9}$$

Where: f_k = k^{th} indicator of the criterion *cr*,
w = weight of k^{th} indicator

There is a restricted interaction related to the environment. Some of the pixels' characteristics change due to the presence of agents. In this model, pixel's "land use" is altered based on the class of the majority group of agents residing in the pixel. In addition, due to the presence of agents belonging to higher groups surrounding a pixel, the prestige and price values will increase for that pixel.

2.3 Data Preparation in GIS and Calculating Co-Efficient

Given the limitations in data availability, a collection of geo-statistical data related to an area of 18 km² in northwest Tehran has been collected to reconstruct the model environment as well as calibrate the model. The geo-database has been produced by TMICTO (Information and Communication Technology Organization of Tehran Municipality) in 2016, and is composed of several geo-datasets, including urban parcels, road networks, POIs, and DEM. In addition, the governmental census data of Tehran gathered in 1996 and 2016 was utilized to model the population pattern of the study area at the start and end of the simulation period. Given the wide range of available raster-based functions for spatial analysis and compatibility of indicators with this data-model, we utilized ArcMap to generate the maps for the factors based on related indicators. We calculated proper weights for all factors and criteria with AHP method based on "Satti" tables via Super Decision software.

The prepared maps were then reclassified, normalized, and overlaid based on related weights; they were finally retrieved as raster layers in Netlogo. Note that the weighing process was done separately for each of the quad groups. tables 3 and 4 show these weights for indicators of the "incompatibility" sub-criterion. Two instances of GIS maps are presented in figures 3 and 4; include respectively the distance to military places as an indicator of "incompatibility", and the "dependency" sub-criterion for class 1.

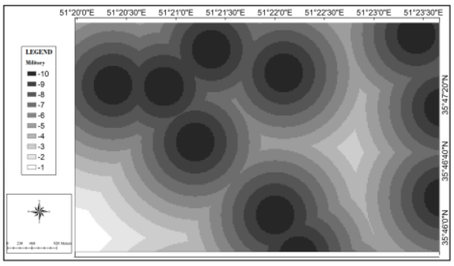

Figure 3: Distance to military bases for group 1

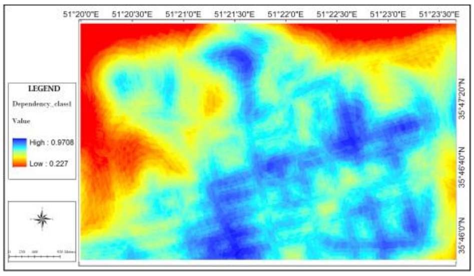

Figure 4: Dependency sub-criterion for group 1

	School	Factory	Military	Hospital	Gas station	Fire station	Mall	Big governmental, business, or administrative center	prison
School	1	2	4	2	2	2	4	2	4
Factory		1	2	1/3	1	1	2	1/3	2
Military			1	1/3	1/3	1	4	1/3	2
Hospital				1	1	2	4	1	2
Gas station					1	1	1	1/3	1
Fire station						1	2	1/3	4
Mall							1	1/3	2
Big governmental, business, or administrative center								1	2
prison									1

Table 3: Qualitative weights of incompatibility indicators for groups 1 and 2

Indicator	Groups 1 & 2	Groups 3 & 4
School	0.0442	0.0422
Factory	0.1558	0.1555
Military	0.1691	0.19
Hospital	0.083	0.083
Gas station	0.1036	0.1028
Fire station	0.0817	0.0777
Shopping Mall	0.1003	0.0915
Large governmental, business/administrative centre	0.0748	0.0698
prison	0.1875	0.1875

Table 4: Quantitative weights of incompatibility indicators for all groups

To model price and prestige patterns, we collected prices of real estate properties from 50 sample points across the area. We also assigned them a prestige value in a range of [0.1 1], considering different factors like a neighborhood's appearance and facilities as well as its overall socio-economic conditions. The relevant maps were generated using Kriging interpolation methods. The co-efficients in price suitability (Eq. 1) were also calculated separately for each social class.

2.4 Model Implementation

All components of the model were scripted in a certain module in Netlogo. Since the considered period for the simulation is 20 years, each model's runtime includes 20 steps called ticks. In the proposed model, each tick is regarded as one year, and each agent is considered as 2 households. In order to differentiate the agents of different groups, the agents of the first to fourth groups were demonstrated in red, green, blue and black, respectively. Further, for the purpose of making the model flexible and applicable for the whole city, and to make it possible to generate and examine different scenarios as well, a couple of parameters were implemented by the *slider* tool that can be customized by the user. These parameters include number of agents, neighborhood radius, share of each agent group in total population, population growth rate, and the satisfaction leveble 3l of each group.

3. RESULTS AND DISCUSSIONS

3.1 Resulted Segregation Pattern

The output of the model is a raster map which shows residential segregation pattern in the study area. Figures 5 to 7 illustrate three rounds of running the calibrated model. The initial tick is shown in figure 5, where all the initial agents have entered the environment; next, pixels of the environment have obtained their primary values based on resident agents and the utility concept proposed by the model. Starting with the tick 1, new agents enter the environment examining alternative pixels to find the desired one based on Equations 6, 7 and 8. The 6th and the last ticks are presented respectively in figures 6 and 7.

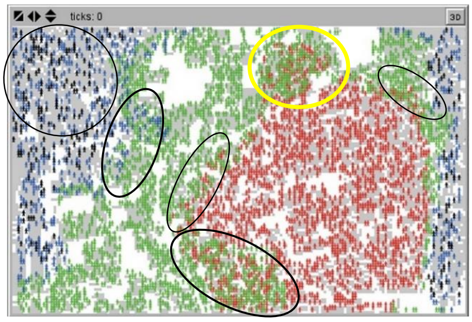

Figure 5: Initial phase of the model

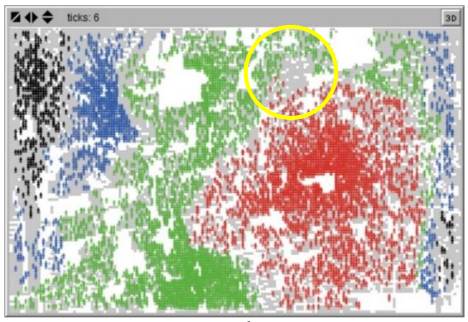

Figure 6: Tick 6th of the model

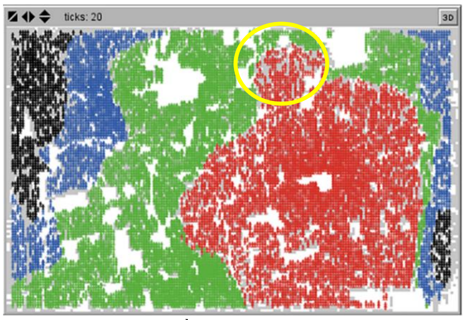

Figure 7: Tick 20th (the last tick) of the model

At the beginning of the simulation period, initial agents settle in the environment rather randomly. There is just a minor limitation in terms of the price. So, some combinations can be seen between different groups' areas, especially in the "growing areas" and around the edges of territories (like the ones marked with black circles). Figure 6 depicts that in the next ticks, while new agents enter the environment, all the agents may move around looking for a better location according to Eq. 7. That is why the growing areas disappear gradually and agents seem to be gathered within sensible boundaries.

The name "Kouyefaraz", which marked with a yellow circle, is one of the neighborhoods of Tehran that has changed a lot over the past 3 decades. Due to its environmental potential, it has been gradually occupied by the wealthy class and altered to an affluent neighborhood. Figures 5 to 7 illustrate this conversion.

3.2 Model Validation

From three methods of ABM validation, include comparing its output with 1) real phenomenon, 2) mathematical model results, 3) other simulation method results (Pullum & Cui, 2012), we applied the first one. Figure 8 shows the model output. Figure 9 generated by converting the vector dataset of Tehran's parcels to a raster form, while class number of the majority group of residents was assigned to each urban block.

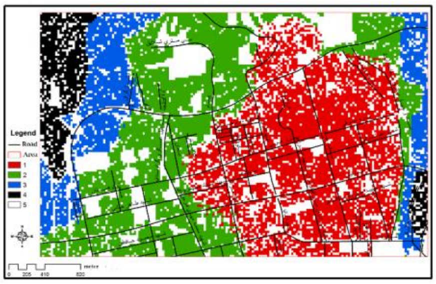

Figure 8: Segregation pattern- model output

Figure 9: Segregation pattern- real world

To create comparable raster maps, the colour of the majority group of agents in each pixel was assigned to it. It is noted that the white pixels refer to forbidden parcels in the real world, which is mentioned in 2.2.3. While a visual comparison of these figures indicates that the model's output corresponds well to the real world, we used the Kapa indicator to compare them statistically since it is a standard measurement method that is widely used for determining accuracy, especially in LUC[5] analysis (Mas et al., 2022). Results of computing confusion matrices and the Kappa in ArcMap indicated that the model accuracy was 62.5%.

3.3 Model Verification

Internal validation is a popular verification techniques for ABMs (Ormerod & Rosewell, 2009; Zhang & Vorobeychik, 2019) by which model's behaviour is examined through parameter variability. In this case, we studied the behaviour of our model while changing values of "neighborhood radius" and "satisfaction degree" as the basic parameters of the majority of the segregation models.

3.3.1 Change in Neigborhood Radius: The scope of social parameters, for example "sense of belonging to a particular group", is the neighborhood itself. Thus, making significant changes to the neighborhood radius is supposed to influence agents' decisions and the final segregation pattern. In two parts of figure 10, the segregation pattern is comparable at the satisfaction level of 70% for neighborhood radiuses of 2 and 10. As shown, in case of a smaller radius, several agents of each group could reach expected satisfaction levels in just a small colony (some samples are marked in black circles); however, larger radiuses join larger colonies around them. Comparing these figures illustrates the sharper and more specific segregated parts in figure 10-2 rather than 10-1. In addition, as expected, by increasing the neighborhood radius, the number of segregated parts decreases; as a result, their structure is more coherent. Further, the distance among segregated parts is also greater in figure 10-2 due to social screening and neighbors' impact within a wider radius.

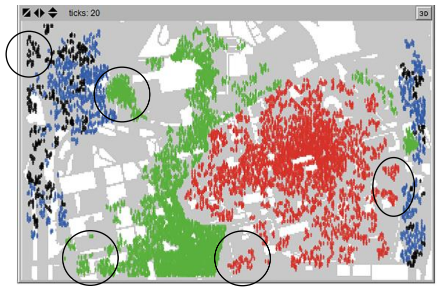

Figure 10-1: Segregation pattern at a satisfaction level of 70% and radius 2 pixel

Figure 10-2: Segregation pattern at a satisfaction level of 70% and radius 10 pixel

5 Land use cover

3.3.2 Change in Satisfaction Level: The three parts of figure 11 illustrate segregation pattern resulted by different satisfaction levels. In most of the previous models, percentage of same-class neighbors is the factor for agent decision-making. Due to role of different socio-environmental parameters in our mode, agent’s general satisfaction with utility of its place is the basis of deciding for residence or relocation. Figure 11 shows that model’s behaviour is as expected; with higher degree of satisfaction, the agents’ choices in each group will be limited to high-graded territory of that group, and their gathering in these areas will increase as well. While separation boundaries between groups will be more detectable due to intensified segregation, considering a low satisfaction level make them distributed over the environment and increase the groups mixture at borders. This phenomenon that had been demonstrated before by (Hatna & Benenson, 2015) is approved by our model results showed in figure 11.

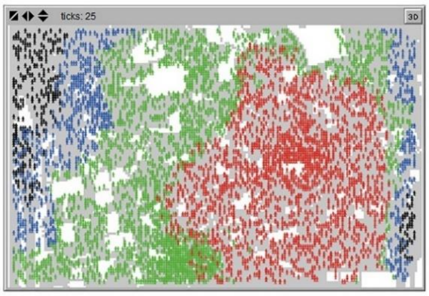

Figure 11-1: Segregation pattern resulting from satisfaction level of 20% in neighborhood radius 2

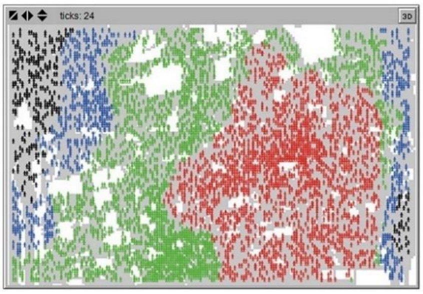

Figure 11-2: Segregation pattern resulting from satisfaction level of 50% in neighborhood radius 2

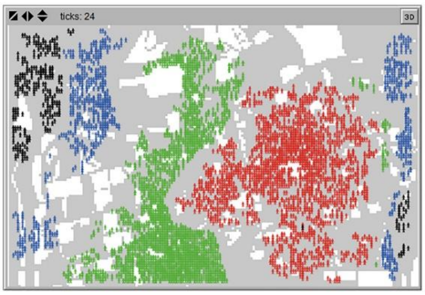

Figure 11-3: Segregation pattern resulting from satisfaction level of 80% in neighborhood radius 2

3.4 Model Calibration

To be able to rely on model results, it is necessary to apply real-world conditions to the parameters so that the model gets as close to reality as possible(Crooks, 2010). For model calibration, we adopted a strategy called “pattern-oriented modelling” (Zhang & Vorobeychik, 2019), which refines the model’s parameters by matching simulation runs with multiple patterns observed from empirical data. After making changes to some model parameters and studying their pattern of changes while using real data, we detected the appropriate value of each parameter that leads to the best simulation. Calibration procedure in this study includes an analysis of neighborhood radius, degree of satisfaction, number of agents, pixel size, price function extremes, dissonance among different groups, and rate of increase in price and prestige. The number of agents, rate of new agents in each period, and ratio of each group were derived from census data of the base and destination years. The pixel size for the environment was determined based upon: 1- mode of the parcel size, 2- number of parcel floors, which indicates the area’s residential capacity, and 3- the impact of pixel size on the calculation volume. To select the best neighborhood radius, the model outputs for radiuses of 2, 10, 20 and 25 pixels were compared with the real residence pattern. The results led to choosing the 20-pixel radius, which is approximately equivalent to 500m surrounding a parcel and corresponds to a subjective definition of neighborhood (Dezfooly, 2013). The same approach was adopted for satisfaction level, considering the number of dissatisfied agents removed from the model. Results showed that model accuracy decreased where the satisfaction level was higher than 70% and lower than 40%. Consequently, the satisfaction levels of 66%, 62% and 54% were selected for groups 1, 2, 3 and 4, respectively. It is worth noting that the closeness of the model accuracies related to satisfaction levels in the range of 50% to 70% indicated that all society classes generally act based on a moderate satisfaction level.

3.5 Model Application

Using models for better decision making is a main objective of every simulation. By forecasting the future, models can help managers gain a reliable perspective of upcoming situations. Figure 13 illustrates a predicted segregation pattern in Tehran in 2030 with an accuracy level of 62.5%.

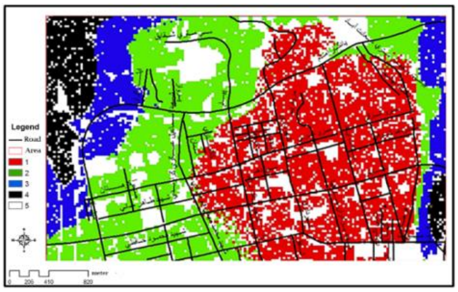

figure 12: Predicted pattern of segregation in 2030

Comparing figures 13 and 9 highlights that most changes will occur along class borders. In other words, the *upper middle* parts in the right side (and especially in the left side) of the wealthy’s territory will be gradually merged with it. Other borders do not show sensible differences with current patterns unless the left edge of the border between classes 2 and 3 moves slightly to the west. In other words, the households in group 2 will occupy vacant parcels in the western edge of their territory, ones which were mostly unoccupied in 2016. This means that these parts of the area could be developed in a way that could be attractive to group 2. This pattern corresponds to the observations of current (2022) urban growth in the northwest of Tehran where there is a great deal of development of major highways, malls, green belts, and recreational facilities. There is also less pollution and attractive scenic locations in this region; make it experience a rapid growth and a high level of conversion to affluent neighborhoods.

4. CONCLUSION

In this research, we proposed an integrated model to stimulate residential segregation patterns using GIS and agent-based method. We determined parameters that affect Tehran's segregation patterns considering a certain number of socio-economic and environmental sub-criteria. We determined parameters' weights through AHP method. By overlaying raster maps generated in ArcGIS, we presented influential patterns of each criterion with regard to the study area. The model was developed in Netlogo. Model tuning by internal validation revealed that its behaviour is in accordance with subjective expectations. The model was calibrated by factual data gathered in 1996 and 2016 from an area in northwest Tehran. The Kapp evaluated the model's accuracy rate to be 62.5%. Model results indicated that all members of society generally feel only a moderate level of satisfaction. They showed that although residential segregation is inherently a complex and multifaceted phenomenon, it could be pragmatically simulated by considering a limited number of socio-economic and environmental criteria. However, the results would have certainly been more tangible if it had been possible to incorporate dynamic changes in environmental parameters, satisfaction degree and price over time, which were ignored here to simplify the model. We consider these particular dynamics in modelling as well as the study of theorical scenarios (such as the impacts of prestige moderating and dissonance moderating on segregation patterns), to be worthwhile topics for future study.

REFERENCES

Afrough, E. (2015). *space & social inequalities* (T. E. press, Ed. 2- in Persian ed.). https://doi.org/307.1216

Attar, M. A. (2019). Simulation of urban segregation by Agent-Based Modeling Case study: Shiraz Metropolis. *Geographical Planning of Space Quarterly Journal*, *9*(32), 121-136 https://doi.org/10.30488/gps.2019.93934

Azadeh, M. A. (2003). Residential segregation in Tehran. *JOURNAL OF HUMANITIES*, *1213*(4445), 25-50. https://www.sid.ir/paper/13903/en

Azhdari, A., Sasani, M. A., & Soltani, A. (2018). Exploring the relationship between spatial driving forces of urban expansion and socioeconomic segregation: The case of Shiraz. *Habitat International*, *81*, 33-44. https://doi.org/https://doi.org/10.1016/j.habitatint.2018.09.001

Benenson, I., Hatna, E., & Or, E. (2009). From Schelling to Spatially Explicit Modeling of Urban Ethnic and Economic Residential Dynamics. *Sociological Methods & Research*, *37*(4), 463-497. https://doi.org/10.1177/0049124109334792

Crooks, A. (2010). Constructing and implementing an agent-based model of residential segregation through vector GIS. *International Journal of Geographical Information Science*, *24*(5), 661-675. https://doi.org/10.1080/13658810903569572

Dezfooly, R. G. (2013). Sustainable Criteria Evaluation of Neighbourhoods Through Residents' Perceived Needs. *International Journal of Architecture and Urban Development*, *3*(2), 39-48. https://doi.org/https://ijaud.srbiau.ac.ir/?_action=articleInfo&article=595

Feitosa, F. F., Le, Q. B., & Vlek, P. L. G. (2011). Multi-agent simulator for urban segregation (MASUS): A tool to explore alternatives for promoting inclusive cities. *Computers, Environment and Urban Systems*, *35*(2), 104-115. https://doi.org/https://doi.org/10.1016/j.compenvurbsys.2010.06.001

Gkartzios, M., & Ziebarth, A. C. (2016). Housing: A Lens to Rural Inequalities. In *Routledge International Handbook of Rural Studies* (pp. 495-508). Routledge. https://doi.org/https://doi.org/10.4324/9781315753041

Hatna, E., & Benenson, I. (2015). Combining Segregation and Integration: Schelling Model Dynamics for Heterogeneous Population. *Journal of Artificial Societies & Social Simulation*, *18*(4). https://doi.org/10.18564/jasss.2824

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. https://www.mdpi.com/2079-8954/4/1/9

Immorlica, N., Kleinbergt, R., Lucier, B., & Zadomighaddam, M. (2017). Exponential Segregation in a Two-Dimensional Schelling Model with Tolerant Individuals. In *Proceedings of the 2017 Annual ACM-SIAM Symposium on Discrete Algorithms (SODA)* (pp. 984-993). https://doi.org/10.1137/1.9781611974782.62

Mahdavi Ardestani, B., O'Sullivan, D., & Davis, P. (2018). A multi-scaled agent-based model of residential segregation applied to a real metropolitan area. *Computers, Environment and Urban Systems*, *69*, 1-16. https://doi.org/https://doi.org/10.1016/j.compenvurbsys.2017.11.002

Mas, J.-F., García-Álvarez, D., Paegelow, M., Domínguez-Vera, R., & Castillo-Santiago, M. Á. (2022). Metrics Based on a Cross-Tabulation Matrix to Validate Land Use Cover Maps. In *Land Use Cover Datasets and Validation Tools: Validation Practices with QGIS* (pp. 127-151). https://doi.org/10.1007/978-3-030-90998-7_8

Ormerod, P., & Rosewell, B. (2009). Validation and Verification of Agent-Based Models in the Social Sciences. International Workshop on Epistemological Aspects of Computer Simulation in the Social Sciences, Berlin, Heidelberg.

Pullum, L. L., & Cui, X. (2012). *Techniques and Issues in Agent-Based Modeling Validation*. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States) Retrieved from https://www.osti.gov/biblio/1047028

Schelling, T. C. (1971). Dynamic models of segregation. *The Journal of Mathematical Sociology*, *1*(2), 143-186. https://doi.org/10.1080/0022250X.1971.9989794

Silver, D., Byrne, U., & Adler, P. (2021). Venues and segregation: A revised Schelling model. *PLoS ONE*, *13*(1). https://doi.org/https://doi.org/10.1371/journal.pone.0242611

Zhang, H., & Vorobeychik, Y. (2019). Empirically grounded agent-based models of innovation diffusion: a critical review. *Artificial Intelligence Review*, *52*(1), 707-741. https://doi.org/https://doi.org/10.1007/s10462-017-9577-z