Agent-Based Modeling of Residential Distribution

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The multi-agent approach is the most promising among the modeling techniques developed in recent decade and applicable to demography and social science. Its development has revived old and raised new questions regarding the dynamics of complex human systems. This paper considers these questions with respect to the dynamics of urban residential distribution. The discussion is illustrated by several model examples, ranging from Schelling-type abstract agent-based models to real-world simulations of the population dynamics of an urban region having a population of 30,000.

1. AGENT-BASED MODELING versus STATE EQUATIONS

The basic question that continues to be valid despite successive scientific journals (JASSS), conference series (Artificial Life, From Animals to Animates) and books (Epstein, Axtell, 1996, Adami, 1998, Gilbert, Troitzsch, 1999) on the subject is the relation of the agent-based to the traditional approach to population dynamics. In brief, the traditional approach is based on state equations, which can be characterized as follows:

STATE EQUATIONS: The population is portrayed by a set of 'state variables' representing fractions or numbers of individuals possessing certain demographic properties. System dynamics are described by the set of equations, which relate the (partial) derivatives of the state variables to their current values, the values of external factors, etc.

The agent-based or 'agency' approach can be formulated as:

AGENCY: A population of adapting individual decision-makers, bearing socio-economic traits, who interact and evolve in time is modeled by means of a computer program that simulates the behavior of each individual agent. The system dynamics are given by the 'collective behavior' of the agents in space and in time. State variables are obtained as population estimates.

In spite of widespread acceptance of the agent-based approach during last decade, researchers vary in their applications of the methodology. Two attitudes exist regarding implementation.

OPTIMISTIC (WYSWYG): Agents provide a convenient way of thinking about reality. The laws of agent behavior can be easily translated into a computer program. So, let us formulate certain real-world problem in terms of agents, develop the associated computer program, and investigate its output for various values of parameters.

SKEPTICAL (SYSTEM): We study the dynamics of complex system consisting of units that are themselves complex systems. It ***seems*** that the standard framework (i.e., equations) is insufficient to interpret the evolution of the units, the complexity of their relationships and, hence, to explain important effects observed in reality. Let us look for evidence of inefficiency in the state equations and, if appropriate, try the agent-based approach.

Each of us is located somewhere between these two positions. In this paper, we follow the more demanding approach and demonstrate that even a "skeptical" analyst cannot avoid the use of multi-agent simulations.

2. EMPIRICAL CONFIRMATIONS OF AGENT-BASED APPROACH

To approve agency, the analyst requires two kinds of evidence. First, we have to show him/her that

AGENCY IS NECESSARY TO EXPLAIN GLOBAL SYSTEM DYNAMICS: That is, we have to present examples of demographic phenomena that are inconvenient or even impossible to explain by means of state equations, but may be adequately represented if agency is introduced. This is not a simple task; I suggest we recall the complex dynamics of minimally non-linear diffusion equations or Ising model of phase transition.

Second, we have to demonstrate that

AGENCY IS SUFFICIENT TO EXPLAIN IMPORTANT LOCAL EVENTS: Here we need to present examples of demographic or behavioral traits of individuals that can be interpreted as the ability of a few agents to influence the further development of the entire system.

To illustrate the difficulties of finding supporting statements, let us recall the two most frequently used arguments in favor of agency. The first applies to the importance of local relationships (householders recognize their immediate neighborhood and neighbors and react to their traits); the second applies to changes occurring in the agents' own traits with age. Agency is unnecessary to model these phenomena.

It is difficult to find documented adequate evidence for the skeptical analysts; the naive approach, which accepts the idea of agency as self-evident, is clearly more convenient. The few examples we present refer to global properties of residential distributions that are based on data from the population census conducted in Israeli in 1995. This census is one of the first in the world that was based on a high-resolution GIS (ICBS, 2000). The census GIS contains layers of building contours and streets for the entire territory of Israel; the personal database contains the householder's address both in the standard form and as the identifier of the building polygon.

To confirm the necessity of agency, we consider the following global property of residential distributions:
Real-world population distributions are highly heterogeneous yet display patches of homogeneity. Members of certain population groups are segregated over portions of the area, but share the rest of the area with members of other groups. It is difficult to obtain this result when using state equations.

Regarding local population dynamics, the following characteristics of individuals and their behavior appear to demand agent-based approach:

1. Long-distance residential migrations within the city
2. Relationships between distant agents: Householders recognize the state of distant neighborhoods and neighbors, and change their traits accordingly
3. Habitats in specific areas attract individuals with certain characteristics. The numbers of these individuals grow there despite the higher availability of the similar habitats in other areas

Figures 1 - 3 demonstrate residential distributions, at the resolution of separate houses, which are simultaneously segregated and random. Diffusion equations are very inconvenient for obtaining distributions of this type. The example in Figure 1 presents the distribution of Russian-born and Israeli-born householders in the city of Ashdod (population: 100,000), while Figure 2 presents the distribution of Jewish and Arab householders in the city of Ramle (population: 30,000). The last example (Figure 3) displays the residential distribution in Tel-Aviv according to income from work.

Figure 1

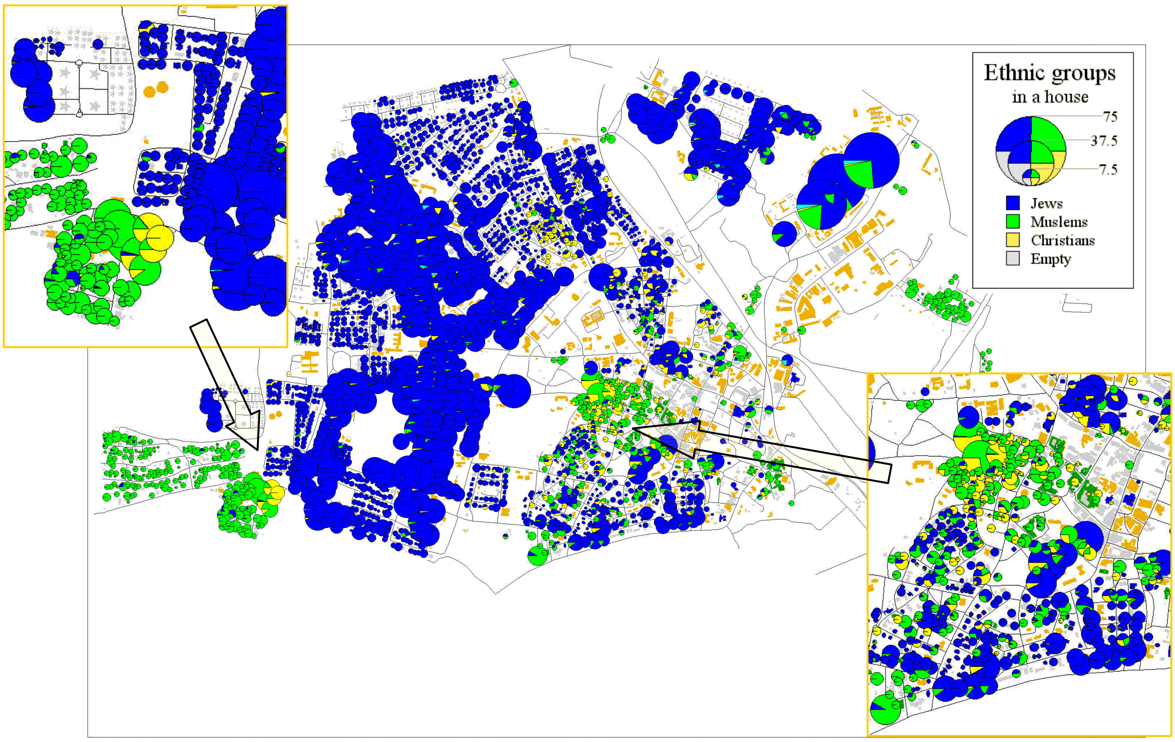


Figure 2

A critical investigation of the literature and our own examples have brought us to conclude that regarding local properties 1 – 3 above we have only one indirect proof of householders' adaptation to neighbors - the changing in time reaction of Jewish inhabitants living in Yaffo to their Arab neighbors (Figure 4). The breakthrough occurred during a conversation with our colleague, Prof. Itzhak Schnell, whose paper "Spatial segregation of labor migrants in Tel-Aviv" will appear in the forthcoming *Journal of Israeli Sociology,* 4(2). Schnell studied the residential distribution of illegal foreign workers in Tel-Aviv, whose numbers, according to different estimates, vary between 20,000 and 40,000. He demonstrates two important phenomena. First, one of the residential strategies adopted by illegal foreign workers in Tel-Aviv is to withdraw from the established region of low-status, segregated populations in the southern part of the city. Those who follow this strategy rent apartments in medium- and even high-status regions, thereby avoiding the police, who target areas having high concentrations of illegal workers. Second, he demonstrates that all the socio-cultural contacts of the individuals living far from the segregated population core remain within their core communities, structured according to country of origin, language, or religion. Interviews with neighbors indicate that local residents are aware of a decline in the region's property values consequent to the entry of illegal foreign workers, but no confirmation of this trend is yet available.

It should be stressed that in spite of several situations that appear to be similar to that of illegal foreign workers in Israel, such as the Ethiopian Jewish minority, we have been unable find arguments in favor of similar processes. The descriptions transmitted by real estate agents, for example, remain impressionistic. Hard data is still unavailable.

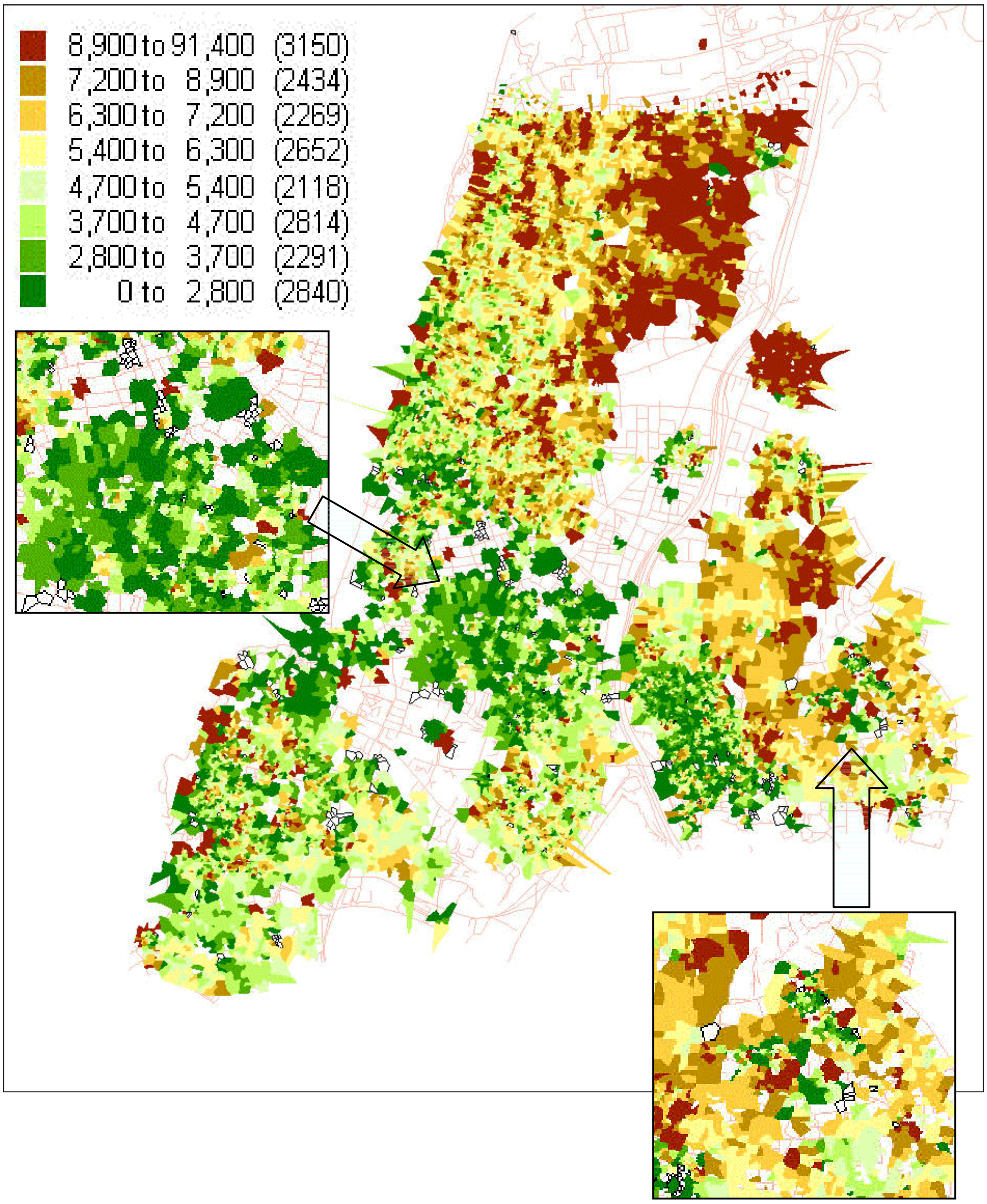


Figure 3

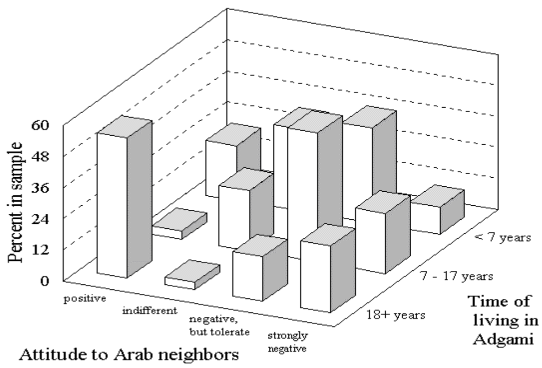


Figure 4

Examples of the type given above do not free the skeptical analyst from resolving one more dichotomy:

'SIMPLE' AGENTS versus 'COMPLICATED' AGENTS

COMPICATED AGENTS - The naive approach to agent-based modeling allows the researcher to assign as many properties and rules as he/she desires. At the next stage, the search for combinations of parameters that may provide interesting results begins.

SIMPLE AGENTS - Followers of the skeptical approach to agent-based modeling recognize that most of the parameters associated with behavioral rules are barely available; thus, the effects of the parameters should be investigated during study of the model. The general theory of systems clearly demonstrates that very few parameters (say, 5) and the simplest non-linear (e.g., quadratic) relationships are sufficient to obtain **any** dynamic effect we are interested in. To understand whether the important system effects are indeed implied by the human properties of the model's agents, we must limit ourselves to a small number of agent traits and simplify as much as possible the description of the relationships between the agents. Only in this way can we confirm or reject the necessity of agency.

In the examples below we try to demonstrate that simple agents are sufficient for obtaining important and likely population effects. Before proceeding to the examples, we should note that agency ideally fits the paradigm of object-oriented programming, but the investigation of the AB-model demands a great deal of computation, including Monte Carlo repetitions aimed at estimating the variation of results. Many AB simulation environments are available (see, for example http://www.econ.iastate.edu/tesfatsi/acecode.htm and links there), SWARM being the most popular. Those few we have tried do not seem to be convenient and learning the environment demands too much time. The most likely explanation for this is the generality of the environments, as confirmed by the way successful commercial MAS environments are developing – they are aimed for implementation in specific domains, usually combat games.

3. ABSTRACT AGENT-BASED MODELS OF RESIDENTIAL DYNAMICS

The abstract agent-based models that can compete with state equations are based on the Schelling model (1974) and its generalizations (Portugali, Benenson, Omer, 1994, 1997; Epstein, Axtell, 1996; Benenson, 1999). The examples of population residential dynamics we present in the lecture rest on the following rules:

1. All free locations are available for migrating individual (long-distance migration)
2. The probability to leave/occupy a location depends on **local dissonance –** some estimate of the difference between the agent's traits and those of the neighbors (within 5x5 Moore neighborhoods).
3. If an agent stays in a strange neighborhood for a long period, then his/her traits evolve towards those of the neighbors (adaptation to local conditions)

The examples presented demonstrate the effects considered above as principles for accepting agency, namely, mixed segregated and random population distributions, bifurcation, and emergence of socio-spatial groups. No matter how persuasive they appear to be, the "ultimate weapon" used to convince the skeptical analyst must be an agent-based simulation of real-world residential distribution dynamics. (This also applies to population projections.) The remainder of the lecture is devoted to such an example, namely to

4. AGENT-BASED MODEL OF RESIDENTIAL DYNAMICS IN YAFFO AREA OF TEL-AVIV

Description of the Yaffo Region and the Available Data

General: Yaffo, a region lying in the southern reaches of Tel-Aviv (the city is officially called Tel-Aviv – Yaffo) is occupied by Arab and Jewish residents. Its area covers about 7 km^2. In 1995 the population of Yaffo was about 39,000, and composed of a Jewish majority (about 70%) and an Arab minority (the other 30%). Before Israel's War of Independence (1948), Yaffo was an independent Arab city of 70,000. After the War, only 3,000 of the original Arab inhabitants remained almost all of whom were concentrated within the small Adjami neighborhood; Jewish immigrants later entered Adjami and other parts of Yaffo (Portugali, 1991; Omer, 1996). During the period 1955-1995, the Arab population of Yaffo continuously grew and spread throughout the region, whereas the Jewish majority gradually left (Figure 5). Precise data are available for the period 1961-1995, when the size of the Arab population increased from 5,000 (8% of Yaffo's population in 1961) to 12,000 (30% in 1995). According to research conducted by Omer (1996), the ethnic composition of the neighborhood as well as the architectural style of the buildings are the major factors influencing the residential decisions made by the members of Yaffo's three cultural groups – Jews, Arab Muslims and Arab Christians.

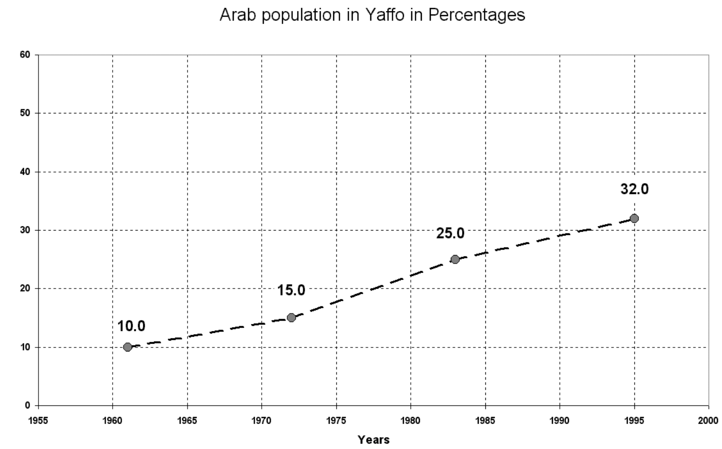


Figure 5

Yaffo's Dwellings: Although Yaffo existed before Tel-Aviv was founded, the majority of its present buildings were constructed during the early 1960s. For this reason, we use the layer of houses constructed in 1995 as a proxy for the entire period 1955-1995. As the street network remained stable during this period,we utilize the 1995 street layer for constructing the neighborhood for each of Yaffo's residential building according to the Voronoi-based algorithm defined above. The layers of houses and streets, as well as the detailed geo-referenced information on the population distribution in Yaffo in 1995, were made available to us by the ICBS. The architectural style of about 90% of buildings in Yaffo can be characterized as either "oriental" or "block", with the remaining 10% approaching one of these two styles (Figure 6). We take only residential buildings into account; the dwelling capacity of a building is estimated by the number of its floors and it's the area of its foundations, assuming that the average apartment area in Tel-Aviv equals 100 m^2.

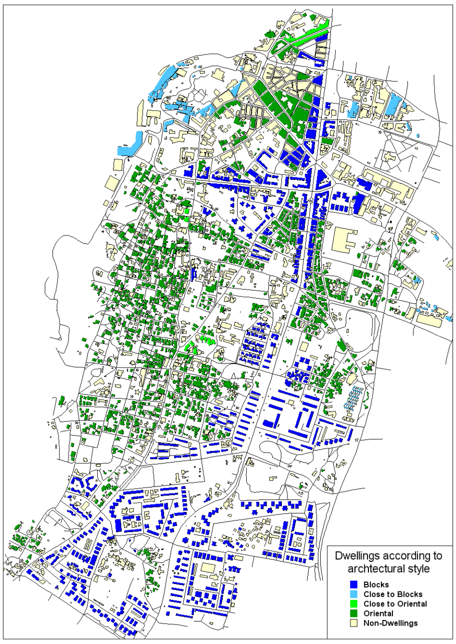


Figure 6

Yaffo's householders: To represent the cultural affiliation of Yaffo's householders, we combine two available parameters – origin and religion – into one parameter, agent identity. We denote a "Jewish" agent as $\mathbf{A_J}$, a "Muslim Arab" as $\mathbf{A_M}$ and a "Christian Arab" as $\mathbf{A_C}$. According to the 1995 population census, the fraction of families mixed according to origin and/or religion in Yaffo is below 1%. Thus, we construct Yaffo's 1995 population distribution on the basis of householder data only. The 1995 distributions of householders' salaried income of the three groups are similar and we do not include income as a feature of Yaffo's householder agents.

The relationships between model agents are expressed by means of the residential dissonance

Residential dissonance: Informally, we posit that householders prefer to reside among agents similar to themselves. Formally, we assume that the probability of leaving a residence increases, and the probability of occupying a vacant residence decreases, with the increase in difference between the properties of an agent and the properties of the neighbors and the neighborhood. Following Portugali, Benenson and Omer (1997), we call this difference residential dissonance. Dissonance is conceived of as a stochastic variable and varies among agents possessing identical characteristics. We estimate the residential dissonance of an agent **A** residing in house **H** given factor **f,** in the following way. First, we define a (simple) rule aimed at calculating the dissonance $\mathbf{D_f(A, U(H))}$ between agent **A** and neighborhood **U(H)** of **H** given **f**. The only constrain we impose on $\mathbf{D_f(A, U(H))}$ is that its average value increases monotonously with an increase in the differences between **A** and **U(H)** given **f**. Second, we combine values of the dissonance according to several factors $\mathbf{f_1}$, $\mathbf{f_2}$, … and estimate the overall dissonance **D(A, U(H))** between an agent and a neighborhood:

$$\mathbf{D(A, U(H)) = 1 - \Pi_i(1 - \alpha_i * D_{fi}(A, U(H)))} \qquad (1),$$

where $\alpha_i \in [0, 1]$ reflects the weight of $\mathbf{f_i}$ in the overall dissonance. The analytical form of (1) is aimed at implementing the "negativist" approach to residential choice. That is it considers a certain residence as generally "unsuitable" if it does not comply with some or even only one of the factors. According to (1), to obtain a high overall dissonance value it is enough to obtain a large $\mathbf{D_{fi}(A, U(H))}$ for only one of the factors $\mathbf{f_i}$.

The most important of the model's processes is that of residential choice, which we describe in detail.

Stage 1: Marking potential migrants. Each resident agent **A** decides whether "to change residence." Formally, the probability **P** of this decision is estimated on the basis of the dissonance **D(A, U(H))**. The analytical form of the dependence **P(D)** that we use in this paper assumes that **P** grows linearly with **D**:

$$\mathbf{P(D) = P_0 + (1 - P_0) * D} \qquad (2)$$

where probability $\mathbf{P_0}$ stands for the component of **P(D)** that is independent of **A**'s characteristics. **P(D)**, like $\mathbf{P_0}$ and **D**, is a stochastic variable; its mean value varies within the interval $\mathbf{[P_0, 1]}$ when **D** varies within **[0, 1]**.

At the end of the first stage each resident agent **A** either decides to remain at its current location with probability **1 – P(D)** or decides to change the residence with probability **P(D)**. If **A** decides to change the residence, it is included in a set ***M*** of potential "internal" migrants. In-migrating agents, involved into residential choice in the city for the first time, are also appended to ***M***.

Stage 2: Estimating the attractiveness of vacancies. At the second stage, for each agent $\mathbf{A} \in \boldsymbol{M}$ several (usually 10) houses are randomly selected from the set of houses currently containing vacant dwellings. Below we denote this set as $\boldsymbol{H}_\mathbf{A}$ and suppose that the vacancies in $\boldsymbol{H}_\mathbf{A}$ alone are considered as currently accessible to **A**. The dissonance **D** between **A** and each vacant dwelling from $\boldsymbol{H}_\mathbf{A}$ is estimated as is the probability **Q(D)** that an agent **A** will occupy the vacancy. We call **Q(D)** the attractiveness of **H** for **A** and assume that attractiveness compliments to "repellence" (2):

$$\mathbf{Q(D) = 1 - P(D) = (1 - P_0) * (1 - D)} \qquad (3)$$

As a result, the mean attractiveness **Q(D)** of a vacancy varies within the interval $\mathbf{[0, 1 - P_0]}$ when **D** varies within **[0, 1**].

Stage 3: Occupying vacant residences. At this stage, each potential migrant $\mathbf{A} \in \boldsymbol{M}$ decides whether to occupy one of $\boldsymbol{H}_\mathbf{A}$ vacancies. To do that, **A** examines the vacancies in $\boldsymbol{H}_\mathbf{A}$ in order of their attractiveness. In order to simplify this procedure, the set $\boldsymbol{H}_\mathbf{A}$ is ordered according to the attractiveness of its dwellings prior to the examination. First, **A** "visits" the most attractive vacancy $\mathbf{H_{A,1}}$ among $\boldsymbol{H}_\mathbf{A}$. If $\mathbf{H_{A,1}}$ is still free at the time of the visit, **A** decides to occupy it with a probability determined by $\mathbf{H_{A,1}}$'s attractiveness $\mathbf{Q(D) = D(A, U(H_{A,1}))}$, as given in (3). If **A** occupies $\mathbf{H_{A,1}}$, then **A**'s address is changed and **A** is excluded from ***M***. **A** remains in ***M*** if vacancy $\mathbf{H_{A,1}}$ is already occupied or is not sufficiently attractive. To avoid the bias arising when the same vacancy is the most attractive for several potential migrants, the members of ***M*** are randomly selected to visit the best vacancies in their $\boldsymbol{H}_\mathbf{A}$.

After all the members of ***M*** explore their most attractive vacancy, the visiting procedure is repeated for the second attractive vacancy, and so on, until each potential migrant tests all the accessible vacancies and either moves into one of them or fails to occupy any. At each round of choice, members of ***M*** are randomly selected for visits to resolve the situation when several agents list the same vacancy. Members of ***M*** who are residents of the city, but fail to resettle during these trials, either remain at their current residence with probability $\mathbf{1 - L_A}$, or leave the city with probability $\mathbf{L_A}$. Out-migrants, who failed to find a residence, decide to leave the city forever.

In-migration: The numbers and the characteristics of agents trying to enter the city for the first time depend on the scenario. The in-migrants are "fabricated" in the model, added to the set $\boldsymbol{M}$ of potential in-migrants and participate in the residential choice.

Out-migration: The only model parameter responsible for out-migration is a probability $\mathbf{L_A}$, that a resident agent **A** will leave the city when failing to find a vacant residence to resettle, as mentioned above.

Calculation of Residential Dissonance in Yaffo

General approach: According to our understanding of the forces driving Yaffo's residential dynamics, we estimated the residential dissonance for two factors arising – between an agent and a building and an agent and the neighboring agents. We first define the dissonance for the homogeneous cases, for example, the dissonance between an agent of Jewish identity and a dwelling of oriental style, or the dissonance between a Christian Arab agent and a neighborhood where all the other agents are Muslims Arabs. Then we extend the definitions for the heterogeneous cases of dwelling in the building of arbitrary architectural style and mixed neighborhood. To mirror the relationships between Yaffo inhabitants we delineate six qualitatively different levels of dissonance and quantify them as follows (Table 1, Columns 1, 2):

Table 1

Qualitative evaluation of the dissonance level	Representative value of the dissonance **D**	95% Confidence interval for the case of δ = 0.05 - see formula (1)
Zero	0.00	-
Very low	0.05	(0.029, 0.071)
Low	0.20	(0.161, 0.239)
Intermediate	0.50	(0.402, 0.598)
High	0.80	(0.761, 0.839)
Very high	0.95	(0.929, 0.971)

To reflect stochasticity of the agent's reaction to a neighborhood we consider the dissonance **D** as a normal random variable, truncated on [0, 1], with the mean given in Table 1, Column 2, and STD calculated as:

$$\mathrm{STD} = \delta * \sqrt{(\mathbf{D} * (1 - \mathbf{D}))} \qquad (4).$$

Below we set δ = 0.05. Table 1, Column 3, presents a 95% confidence interval for the basic dissonance values.

We next set the levels of dissonance for all possible homogeneous situations and extend the definition of dissonance to the case of heterogeneous neighborhoods.

Dissonance between householders and dwelling: The buildings in Yaffo differ in their architectural style (**S**), which we consider as a continuous variable whose values range from 0 to 1. A zero value denotes an "oriental" style; unit value denotes "block". The majority of dwellings in Yaffo belong to one of these two polar styles, although the style of some of the buildings can be defined as "close to oriental" (**S** = 0.2) or "close to block" (**S** = 0.8) (Figure 6). The model dissonance $\mathbf{D_h}$ between an agent and a dwelling in a house of an oriental or a block style depends on whether an agent's identity is Jewish or Arab and is set (Omer, 1996) as follows (Table 2):

Table 2

Dissonance $\mathbf{D_h}$ between an agent and a house

	House's architectural style	
Agent's identity	Oriental (**S** = 0)	Block (**S** = 1)
Jewish – $\mathbf{A_J}$	Intermediate	Zero
Arab – $\mathbf{A_M}$, $\mathbf{A_C}$	Zero	High

According to Table 3, the Arab agents strongly avoid "blocks" and prefer houses of "oriental" architectural style, whereas Jewish agents prefer newly built "blocks". The dissonance between Jewish agents and dwellings in oriental houses is assumed to be intermediate.

To extend the definition to the general case of an agent of identity $\mathbf{A_i}$ regarding choice of a dwelling in a house **H** of "impure" style **S**, we define the dissonance $\mathbf{D_h(A_i, H)}$ as:

$$\mathbf{D_h(A_i, H) = D_h(A_i, H_0) * (1 - S) + D_h(A_i, H_1) * S} \qquad (5)$$

where $\mathbf{A_i}$ is one of $\mathbf{A_J}$, $\mathbf{A_M}$, $\mathbf{A_C}$; $\mathbf{H_0}$ stands for a dwelling in a house of an oriental style and $\mathbf{H_1}$ for a dwelling in a house of a block style.

Dissonance between householder and neighbors: According to Omer's (1996) qualitative estimates, the dissonance between an agent **A** and his or her neighbors, that is, inhabitants of the houses within **U(H)**, when all of the neighbors belong to one of three possible identities, is as follows:

Table 3

Dissonance $\mathbf{D_p}$ between an agent and a homogeneous neighborhood

Agents' Identity	Neighborhood identity		
	Jewish – $\mathbf{U(H)_J}$	Muslim – $\mathbf{U(H)_M}$	Christian - $\mathbf{U(H)_C}$
Jewish – $\mathbf{A_J}$	Zero	Very High	High
Moslem – $\mathbf{A_M}$	High	Zero	Very Low
Christian – $\mathbf{A_C}$	Intermediate	Low	Zero

where $\mathbf{U(H)_J}$, $\mathbf{U(H)_M}$ and $\mathbf{U(H)_C}$ denote the common identity of the neighbors.

The estimates shown in Table 3 express, for example, very strong dissonance between Jewish agents and Muslim neighbors, and strong dissonance between Muslim agents and Jewish neighbors, while relations between Muslims and Christians are positive though slightly asymmetric.

We generalize the definition of the dissonance for the case of a heterogeneous neighborhood in the same way as in (2). Namely, the dissonance $\mathbf{D_p(A_i, U(H))}$ between an agent of identity $\mathbf{A_i}$ and mixed neighborhood $\mathbf{U(H)}$ is calculated as an average of the values shown in Table 3 weighted by the fractions of the agents of a given identity residing in the neighborhood:

$$\mathbf{D_p(A_i, U(H)) = D_p(A_i, U(H)_J)*F_J + D_p(A_i, U(H)_M)*F_M + D_p(A_i, U(H)_C)*F_C} \qquad (6)$$

where $\mathbf{A_i}$ is one of $\mathbf{A_J}$, $\mathbf{A_M}$, or $\mathbf{A_C}$, and $\mathbf{F_i}$ is a fraction of the agents of identity $\mathbf{i}$ within $\mathbf{U(H)}$.

Overall dissonance: According to (2) – (3), the dissonance between an agent of identity $\mathbf{A_i}$ located in a house $\mathbf{H}$ of a style $\mathbf{S}$ within a mixed neighborhood $\mathbf{U(H)}$ is calculated as

$$\mathbf{1 - (1 - \alpha_h * D_h(A_i, H)) * (1 - \alpha_p * D_p(A_i, U(H)))} \qquad (7)$$

where $\mathbf{D_h(A_i, H)}$ is given by (2), $\mathbf{D_p(A_i, U(H))}$ is given by (3) and α_h and α_p denote the weights of the “style” and “population” factors. We vary α_h and α_p in the subsequent model runs.

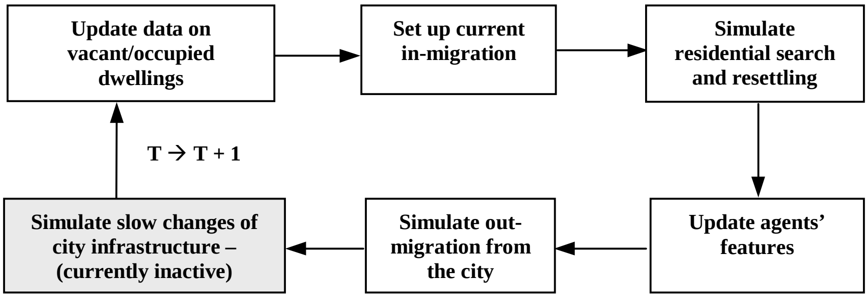
Computation of the probability to leave/occupy a dwelling: The above rules are sufficient to compute the probability that an agent $\mathbf{A_i}$ of identity $\mathbf{i}$ will leave/occupy a dwelling in a house $\mathbf{H}$ of a given style within the neighborhood of given population structure. First, depending on the agent’s identity, the values of the dissonance between an agent and a dwelling in a house and an agent and his other neighbors are assigned for homogeneous cases according to Tables 2 and 3. Second, these values are weighted according to (2) – (3). Third, overall dissonance is calculated according to (4) and the probability to leave (2) or to occupy (3) a dwelling is calculated last. The probability $\mathbf{P_0}$ of occasional leaving/occupying in (2) - (3) is set equal to 0.05.

In-migration and Out-migration

In-migration: We have no data on variations in in-migration to Yaffo during 1955-1995, and assume that the flow does not vary throughout the whole period of the simulations. Based on partial data obtained by Omer (1996), we set the annual potential in-migration into Yaffo as 300 householders, with the ratio of Arabs to Jews equal to 1:2, and the ratio of Christians to Moslems among the Arab in-migrants also equal to 1:2. In all model scenarios we find that the percentage of in-migrants successfully settling in Yaffo never exceeds 50-60% of potential in-flow.

Out-migration: We assume that the probability $\mathbf{L_A}$ that a resident agent **A** will leave the city if he or she cannot find a vacant residence to resettle is 0.1 per month for Jews and ten times lower for Arabs, that is, 0.01 per month. The factor of 10 is set according to the ratio of the areas available for resettlement of Jewish and Arab householders in Tel-Aviv, the latter having 10 times fewer options for resettlement compared to the former.

The model flow-chart is as following:



In what follows, we first simulate Yaffo's residential dynamics for the period of 1955–1995 and demonstrate that the two factors posited as potentially influencing residential choice in the area - houses' style and interactions with neighbors – are indeed necessary for simulating likely dynamics. The fairly good approximation of Yaffo's residential dynamics during that period permits us to experiment with Jewish-Arab relationships in Yaffo and to study the consequences of these experiments. We show that the model's dynamics are robust regarding changes in the quantitative expression of agents' relations and suggest an explanation of this phenomenon.

Initial population distribution

According to Omer (1996) data, in 1955, 3000 Arab inhabitants of Yaffo were concentrated in three statistical areas – 723, 723 and 724 (Figure 7); one-third of them were Christians, the rest Muslims. The Jewish householders populated the rest of the dwellings in the mixed statistical areas and all the dwellings over the rest of Yaffo's territory.

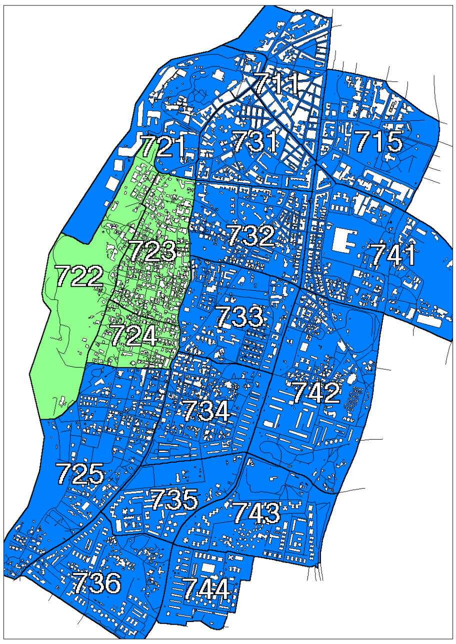


Figure 7

Examination of the model

Stochastic nature of the model

To estimate the variation of the model results due to the stochastic variation of parameter values, we repeated each simulation run 100 times. For all the investigated scenarios, the variation in the three global model characteristics (fraction of Arab agents, Moran index of spatial autocorrelation, and fraction of agents occupying dwellings in less attracting houses) is very low. For example, the coefficient of variation (CV) of the fraction of Arab agents always remains below 0.02. The local properties of the residential distribution, for example, the fraction of agents of given identity in a building, may vary significantly, although this variation substantially decreases when larger spatial units, say, statistical areas, are considered. In this paper, we are interested in "typical" model behavior; thus, we consider model outcomes for "modal" runs whose characteristics approach values averaged over 100 repetitions. We then compare the model results and the real data according to global characteristics only, and delay the discussion of the spatial variability in results to future papers.

Model calibration

We calibrate the model by varying the weight coefficients $\alpha_{\mathbf{h}}$ and $\alpha_{\mathbf{p}}$ and comparing the model results with the Yaffo data according to three global characteristics of Yaffo residential distribution. First, we compare the model fraction of Arab population with the real Yaffo data available for 1961, 1972, 1983 and 1995 (Figure 5). Two other comparisons are based on detailed data on Yaffo's residential distribution available for 1995. We compare the levels of segregation of population groups in model and in reality by means of Moran index **I** of spatial autocorrelation (Anselin, 1995) between the fraction of Arab agents in a building and in building's neighborhood. The value of **I** was found to be 0.646 ($p < 0.001$) for the 1995 distribution. The non-correspondence of the population with the architectural style of the buildings is characterized by the fractions of agents occupying less attractive houses in 1995. Concerning Yaffo's residential distribution the fraction of Arab agents occupying dwellings in houses of block or close to block style was found to be 18.5%, and the fraction of Jewish agents occupying houses of oriental or close to oriental style was found to be 28.1%.

To establish the values of $\alpha_{\mathbf{h}}$ and $\alpha_{\mathbf{p}}$, we run the model for 25 possible pairs ($\alpha_{\mathbf{h}}$, $\alpha_{\mathbf{p}}$), where $\alpha_{\mathbf{h}}$, $\alpha_{\mathbf{p}}$ = 0.0, 0.05, 0.1, 0.5 and 1.0. Omitting the details, the pair of smallest non-zero values tested, $\alpha_{\mathbf{h}} = 0.05$ and $\alpha_{\mathbf{p}} = 0.05$, provide the best possible correspondence between the model and the true fraction of the Arab population during 1955-1995. The segregation of Arab individuals (Moran **I**) in 1995 for these values of $\alpha_{\mathbf{h}}$, $\alpha_{\mathbf{p}}$ remains at the level 0.79, surpassing the true value of 0.646. We still lack correspondence to the fraction of Arabs in block and close to block houses - below 1% in the model versus the true value of 18.5% - and the fraction of Jews in the houses of oriental or close to oriental style - 11% versus the true value of 28.1%.

The experiments with dissonance

The correspondence between the model dynamics of the fraction of Arab agents and the level of their segregation (given by Moran I), and the true Yaffo data is achieved after 13 (!) estimates of the dissonance values in Tables 2 and 3, based on qualitative assumptions only. This is quite surprising, and to understand the reasons for this correspondence we test the sensitivity of the model results to changes in the dissonance. We use values $\alpha_{\mathbf{h}}$, $\alpha_{\mathbf{p}}$ = 0.05 for these experiments and entitle the model run that utilizes $\alpha_{\mathbf{h}}$, $\alpha_{\mathbf{p}}$ = 0.05 and the values of dissonance given in Tables 2 and 3 as the "Basic Scenario". We examine the sensitivity of the model outcomes to changes in dissonance values along the qualitative approach and consider scenarios in which the dissonance values are increased or decreased by one or two grades according to those indicated in Table 1. Table 4 displays five scenarios that we compare (α_h, α_p = 0.05 throughout):

Table 4: Model scenarios

	Change in dissonance versus basic scenario			
Scenario	Arab agent – block house	Jewish agent – oriental house	Arab agent – Jewish neighborhood	Jewish agent – Arab neighborhood
Co-Assimilation 1	One grade less	One grade less	One grade less	One grade less
Co-Assimilation 2	Two grades less	Two grades less	Two grades less	Two grades less
Arab Assimilation 2	Two grades less	Unchanged	Two grades less	Unchanged
Jewish Assimilation 2	Unchanged	Two grades less	Unchanged	Two grades less
Co-Competition 1	One grade more	One grade more	One grade more	One grade more

For example, in the "Co-Assimilation 1" scenario, the changes of dissonance values between agents and neighbors are as follows (marked in gray in tables 5).

Table 5: Dissonance between an agent and the neighbors for "Co-Assimilation 1" scenario

Agents' Identity	Neighborhood Identity		
	Jewish	Muslim	Christian
Jewish	Zero (Unchanged)	High (Instead of Very High)	Intermediate (Instead of High)
Moslem	Intermediate (Instead of High)	Zero (Unchanged)	Very Low (Unchanged)
Christian	Low (Instead of Intermediate)	Low (Unchanged)	Zero (Unchanged)

The resulting curves of the dynamics of Arab fraction and Moran **I** are presented in Figure 8a-b. According to Figure 8a, the growth curves of the fraction of Arab agents in Yaffo behave realistically during 1955–1995 for "Co-Competition 1," "Arab Assimilation 2," and, to a lesser extent, for "Co-Assimilation 1." The symmetric increase in agents' tolerance to dissimilar neighbors and to houses of less attractive style results in a decrease in the model fraction of Arab agents, whereas the unilateral increase in Jewish tolerance results in a significant decrease in this fraction (Figure 8a). The trajectories of the Moran **I** index (Figure 8b) appear reasonable for four of the five scenarios, with the exception of "Co-Assimilation 2" (see discussion of "Random testing of vacancies" below). Moreover, for two scenarios – "Co-Assimilation 1" and "Arab Assimilation 2" - the value of Moran **I** in 1995 equals 0.66, equivalent to the reality.

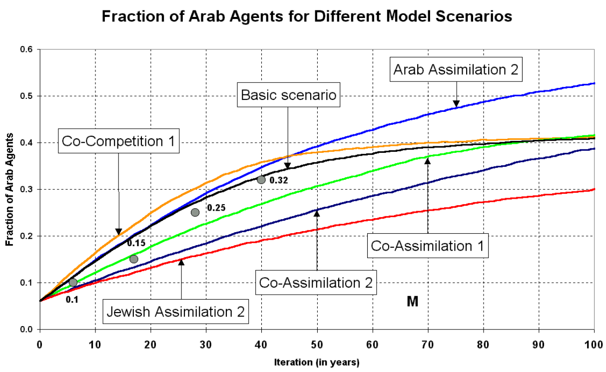


Figure 8a

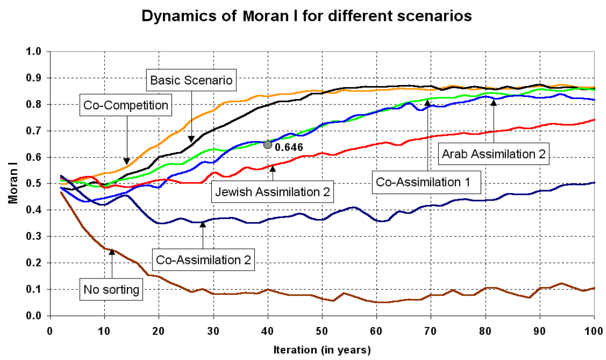


Table 6 summarizes the results of the comparison between the 1995 data and the model for two most likely scenarios. These scenarios differ according to the fraction of the population group occupying dwellings in less attractive houses. As we can see, the “Co-Assimilation 1” and “Arab Assimilation 2” scenarios fit the Yaffo data well and vary from that data to a similar degree. We can say, therefore, that compared to the level of competition assumed initially, much weaker competition for space between Yaffo population groups is sufficient to explain the residential distribution found.

Table 6: Characteristics of Yaffo’s population distribution in 1995 vs. outcomes of three most likely scenarios in model year 40

Scenario	% of Arab agents in houses of block or close to block style	% of Jew agents in houses of oriental or close to oriental style	Overall % of Arabs agents	Moran index **I** of segregation for Arab agents
Yaffo data	**18.5**	**28.1**	**32.2**	**0.65**
Co-Assimilation 1	3.0	26.5	27.0	0.66
Arab Assimilation 2	8.0	15.0	34.8	0.66
Co-Competition 1	1.2	5.6	35.9	0.83

The results reflect reality more closely when both Jewish and Arab agents are more tolerant of each other and of "strange" houses (i.e., buildings in architectural styles that go against the ethnic norm), or when Arab agents alone become more tolerant and choose to or continue to occupy dwellings in houses of block style and/or in partially Jewish neighborhoods. The last finding coincides with our earlier theoretical results (Portugali, Benenson, Omer, 1994) and contradicts "common sense" views of the advantages of competitive behavior. The residential

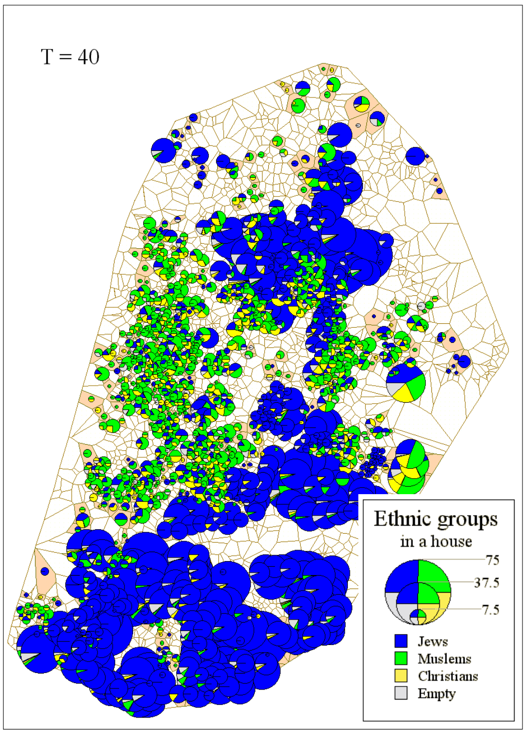


Figure 9a

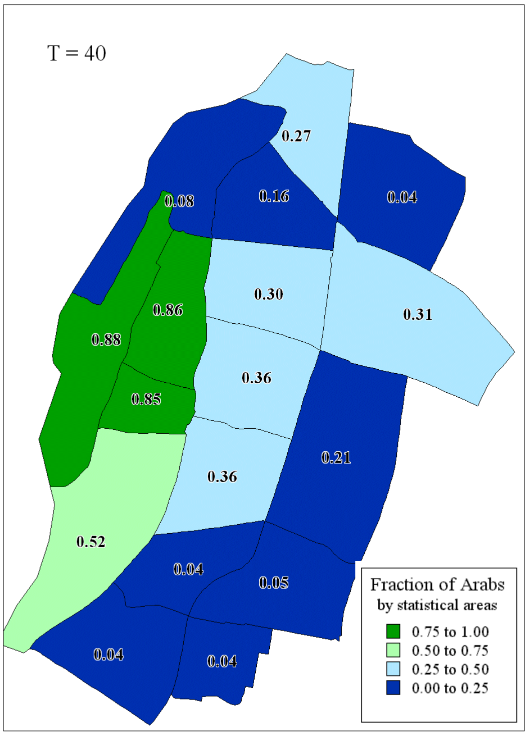


Figure 9b

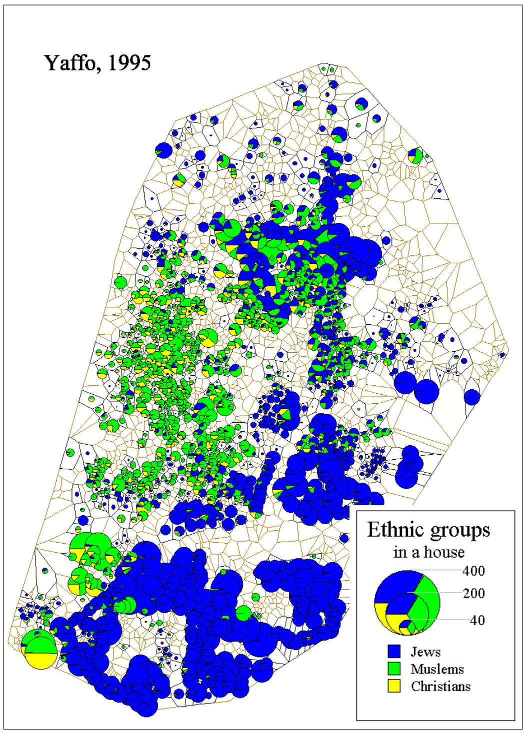


Figure 9c

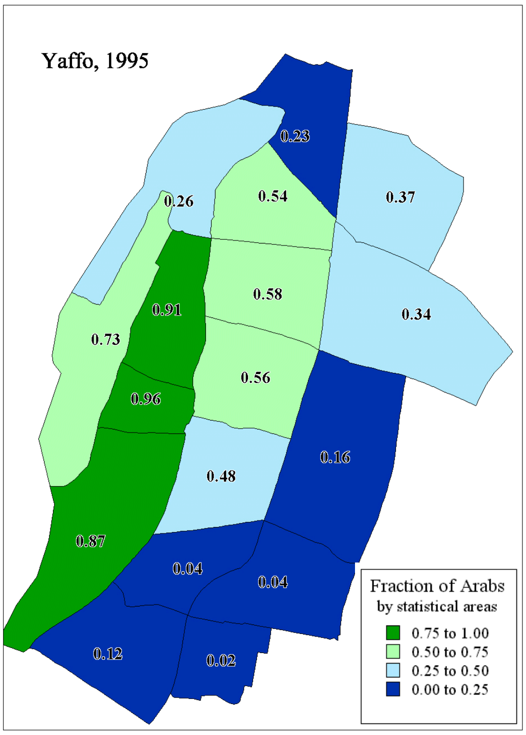


Figure 9d

distributions for the "Arab Assimilation 2" scenario and the actual Yaffo residential distribution in 1995 are presented in Figure 9.

Structural stability of the model results

Till now we have investigated the conditions that provide the maximum possible *quantitative* correspondence between the Yaffo and the model data. With respect to the *qualitative* correspondence, for "reasonable" values of the parameters, the model runs mirror important characteristics of the Yaffo dynamics for most of the variants considered in the two previous sections. That is, for non-zero values of α_h and α_p and for a wide spectrum of variation in the dissonance values, the ethnic residential segregation persists in the model: Jewish and Arab agents maintain relatively high levels of segregation, and the total fraction of the Arab population steadily grows. In short, for broad ranges of parameter values, the model reasonably reproduces the gradual expansion of the Arab population from the initial core into the areas occupied by Jews. This qualitative and quantitative correspondence is not self-evident; we did not anticipate such correspondence at the outset the research. The question becomes then, even if we occasionally selected the "right" parameter values, why did the variations we present above not influence the qualitative output? One may suspect in this situation that the model has some implicit feature(s) that determines its robustness.

Our model does contain such an implicit feature and we demonstrate it here in brief. Let us concentrate on the agents' behavior at stage three of residential choice, namely the testing of vacancies according to their estimated attractiveness. This stage crucially restricts the sensitivity of the model results to parameter changes. Namely, let us suppose that for a given set of parameters that the vacancy in house $\mathbf{H_1}$ is more attractive for agent **A** than the vacancy in house $\mathbf{H_2}$. If the model parameters change and, consequently, the numerical values of the dissonance between an agent and vacancies in $\mathbf{H_1}$ and $\mathbf{H_2}$ change as well, this does not necessarily change the order of the two dissonance values considered; the habitat in $\mathbf{H_1}$ may remain more attractive than $\mathbf{H_2}$. If so, the agent begins stage three of residential choice by testing the same habitat in $\mathbf{H_1}$ as it would with the first set of model parameters; thus, the quantitative changes in parameters have only partial influence on the model outcomes.

According to this logic, different sets of parameters can cause qualitatively different results if they entail changes in the order of dissonance estimates of significant numbers of habitats for many agents. This surely cannot be achieved with slight changes in parameters $\alpha_\mathbf{h}$, $\alpha_\mathbf{p}$, and explains why the model results change so drastically when $\alpha_\mathbf{h}$ and/or $\alpha_\mathbf{p}$ are non-zero. Moreover, it also makes clear why we cannot reach an even better quantitative correspondence between the model and reality - the qualitative component of the model scenarios regarding relationships between agents, physical environment, and neighbors are so strong that we cannot alter the outcome by quantitatively changing parameters. None of the changes, for example, made the dwellings in the houses of oriental style more attractive for Jewish agents when compared to Arab agents.

A deeper discussion of the structural stability of the model is beyond the framework of this paper. Just to illustrate the importance of the vacancies testing according to a priory estimated attractiveness, let us presents the model results given $\alpha_\mathbf{h}$, $\alpha_\mathbf{p}$ = 0.05, provided that each agent tests vacant habitats from $\boldsymbol{H}_\mathbf{A}$ in a random order (Figure 8b, lowest curve). As we can see, the residential distribution is not segregated at all in this case.

To conclude, we have succeeded in very closely simulating the residential dynamics that occur in reality. Moreover, the AB model of Yaffo's residential dynamics clearly demonstrates which features of agent (householder) behavior are of principal importance for understanding the dynamics of the residential distribution there. We would argue that these are the qualitative aspects of residential choice that, therefore, demand further experimental and conceptual investigation. The principles of non-spatial human choice behavior are intensively discussed in the psychological literature (see review of Gigerenzer, Goldstein, 1996), and serious experimental and analytic arguments in favor of the "bounded rationality" (Simon, 1956) have been provided. In the Yaffo model an agent behaves according to this principle. It chooses a new location among several randomly selected vacancies, estimates their attractiveness while ignoring available information regarding future neighbors, to say nothing about economic state of householders, real estate prices and global urban parameters. As we have demonstrated, the most important feature of agents' behavior is the choice made on the basis of the attractiveness of the vacancies, a process where an agent attempts to occupy the vacant dwellings having the highest expected attractiveness, followed by the next in order if the previous attempt fails, and so on. This feature resembles "satisficing" (Simon, 1982), where an agent accepts the first object that comes close to satisfying its demands. Hence, we can argue that the assumption of satisficing *spatial* behavior by Yaffo agents both enables likely simulation of the real-world population dynamics and makes the model results ***robust***. The advantage of robustness is evident: It allows us to adequately describe the urban system dynamics (as we do in this paper) in spite of perpetually limited knowledge of the characteristics of individual behaviors and environments. We consider robustness to be a primary feature of a successful explanatory/descriptive model. Following this approach, we will explore in depth the geographic consequences of the "bounded rationality" of residential choice in a future paper, where we apply our AB model to larger areas and account for a greater number of variables characterizing household agents and households.

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