Environment and Planning B: Planning and Design 2002, volume 29, pages 491 – 512

DOI:10.1068/b1287

Entity-based modeling of urban residential dynamics: the case of Yaffo, Tel Aviv

Itzhak Benenson, Itzhak Omer, Erez Hatna
Department of Geography and Human Environment, University of Tel Aviv, 69978, Tel Aviv, Ramat-Aviv, Israel; e-mail: bennya@post.tau.ac.il, omery@post.tau.ac.il, erezh51@post.tau.ac.il
Received 6 February 2001; in revised form 14 August 2001

Abstract. The dynamics of the ethnic residential distribution in the Yaffo area of Tel Aviv, which is jointly occupied by Arab and Jewish residents, is simulated by means of an entity-based (EB) model. EB models consider householders as separate entities, whose residential behavior is defined by the properties of the surrounding infrastructure and of other householders. The power of the EB approach lies in its ability to interpret directly different forms of decisionmaker behavior in the model's terms. Several scenarios of residential interactions between members of local ethnic groups are compared on the basis of detailed georeferenced data taken from Israel's 1995 Population Census. The model simulates very closely the residential dynamics during the period 1955 – 95; the importance of the qualitative aspects of residential choice, as captured by the EB approach, is demonstrated by this correspondence.

Introduction

Traditional urban modeling is based on differential or difference equations that describe the dynamics of the city when divided into administrative areas (Bertuglia et al, 1987; Hagget et al, 1977). These areas summon information on infrastructure (for example, fractions of land usage, types of dwellings, average prices) and population (for example, fractions of socioeconomic or cultural groups), and are motivated by urban statistics, usually supplied for these long-established administrative units.

The utility of such a modeling approach in urban research, planning, and management is limited (Klosterman, 1994), in light of the negative effect of the 'ecological fallacy'—that is, the making of inferences about individuals from area-unit findings. As much recent research confirms, there is no philosopher's stone for transmuting information about groups into conclusions about individuals (Wrigley et al, 1996). As a result, the structuration approach (Giddens, 1984), which considers local socio-spatial interactions as the driving forces of urban dynamics, came to dominate social geography during the last two decades (Omer, 1996). The structuration approach is supported by complex systems theory (Portugali, 1999; Weidlich, 1987) that clearly demonstrates that the fallacy results from ignorance of two basic factors. The first is local environmental heterogeneity (social and economic), which affects the behavior of urban actors (Green and Flowerdew, 1996; Openshaw and Rao, 1995; Steel and Holt, 1996) and the second is interactions between the actors when making decisions regarding relocation in the city. The study of these relationships has a long history in human geography and sociology and is rooted in the Chicago School publications of the 1920s and 1930s, especially of the group that gathered around Robert Park. Their publications established the concept of a *natural area*, "a geographical area characterized both by physical individuality and by the cultural characteristics of the people who live in it" (Ley, 1983, page 68). The natural area concept was later applied to other classifications of social areas in cities (Shevky and Bell, 1955). In parallel, notions of *sense of place* (Lynch, 1981; Relph, 1976; Tuan, 1977) and *home area* (Lee, 1973), which considered the local urban infrastructure and the human agents with their social relations as one unit, became important in the humanistic stream of geography.

Inspired by these views on the one hand and the computer revolution on the other, an alternative approach to urban modeling, aimed at overcoming the limitations of traditional regional modeling, has arisen during the last two decades. This new approach addresses the most elementary entities comprising urban infrastructure and is usually implemented within the cellular automata (CA) framework (Couclelis, 1985; Phipps, 1989). The CA framework requires that the city's infrastructure be represented by means of a rectangular, high-resolution grid of cells. Each cell can be in one of several states, which can change over time; urban dynamics are determined by the set of rules that define the state of each cell at the next time step, based on the state of a cell itself and the states of the neighboring cells. The CA approach is very promising with regard to urban dynamics modeling from both a theoretical and an applied point of view (Batty and Xie, 1997; Torrens, 2000). Conceptually, the CA model is, by definition, a bottom-up model. Thus it allows easy simulation of self-organization phenomena, including the emergence of novel patterns and bifurcations (Portugali, 1999; Torrens, 2000). Successful simulations of urban infrastructure dynamics for the cities of Cincinnati (White et al, 1997), Cardiff (Batty and Longley, 1994), Guangchou (Wu, 1996), and San Francisco (Clarke et al, 1997) have demonstrated the capability of CA for real-world applications.

The immobility of the cells is a prerequisite of CA models. As a result, these models do not allow explicit consideration of the urban human and social milieux, the latter consisting of innately mobile householders, businesses, public services, and so forth. To avoid this limitation we have extended the CA approach to what we call here entity-based (EB) modeling (Benenson, 1999; Portugali, 1999). The EB model considers the city as consisting of two interacting layers. The first represents immobile urban components and is described by a CA-type model, whose elementary units are infrastructure elements that can be treated as innately homogeneous: land parcels, houses, street segments. The form and size of such units vary in space; thus, the structure of the neighborhood also varies from unit to unit, although the core of the CA concept—dependence of the unit's next state on those of its neighbors—is preserved. The second layer of the EB model represents the instantaneous spatial distribution of mobile urban decisionmakers, the dynamics of which is described by means of an agent-based (AB) model. The AB model framework considers an urban population as a collection of independent interacting actors, whose behavioral rules are implemented as a part of the simulation software. The global urban population dynamics is, therefore, an outcome of agents' collective behavior. AB simulations have proved to be useful in physics, chemistry, ecology, and in the social sciences (Gilbert and Troitzsch, 1999). With regard to urban dynamics, an AB simulation approach began to emerge in the mid-1990s (Benati, 1997; Benenson, 1998; Dibble, 1996; Omer, 1999; Portugali, 1999; Portugali et al, 1997), but is still in its initial stage of development, especially with regard to real-world urban applications.

The immediate advantage of the separation between the infrastructure and population layers within an EB modeling framework is an ability to account directly for different rates of population and infrastructure changes. That means that for smooth stages of infrastructure development (Portugali, 1999) we can study detailed dynamics of the fast population component of the urban system on the basis of a very rough description of slow infrastructure dynamics. The degree of differences between these rates can be illustrated by the Tel Aviv example, where during the period 1970–98 new dwellings were completed at a rate of 1% or less annually, while the percentage of householders changing their location in the city was above 10% annually (figure 1).

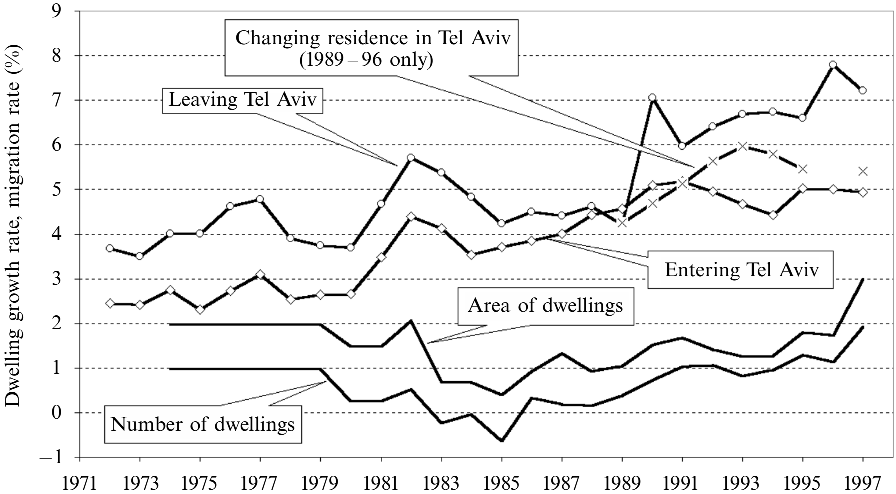


Figure 1. Dynamics of dwelling growth and migration rates, Tel Aviv, 1972 – 97 (based on Tel Aviv – Yaffo Municipality, 1999).

In this paper we apply an EB approach to simulate the dynamics of ethnic distribution in the Yaffo area of the city of Tel Aviv during the period 1955 – 95. Each householder is considered as a separate entity, whose residential behavior is defined by the properties of the surrounding infrastructure entities (that is, the physical environment) and other householders (the social environment). Estimates of the parameters and the model scenarios are based on a comprehensive experimental study of residential distribution in Yaffo carried out by Omer (1996). The simulation results are then compared with detailed georeferenced population data taken from the Israeli's 1995 Population Census, which is available for supervised analysis at the Israel Central Bureau of Statistics (ICBS).

Model description

We assume that a householder's residential decision is determined by the characteristics of the dwelling, the properties of the dwelling's neighborhood, and the neighborhood population (neighbors). Let us define the infrastructure units, the population units, and the relationships between them.

Infrastructure

The characteristics of the urban infrastructure are retrieved from the model GIS, which is constructed on the basis of the GIS of the 1995 Population Census conducted in Israel (ICBS, 2000). The model GIS data are organized into two layers (table 1).

Table 1. Layers of model GIS.

Database	Geographical features	Attributes employed in the model
Streets	polylines, representing street segments between junctions	width (m) type (main, secondary, internal, etc) street name
Buildings	polygons, representing building foundations	address type (dwelling, business, public, etc) architectural style number of floors

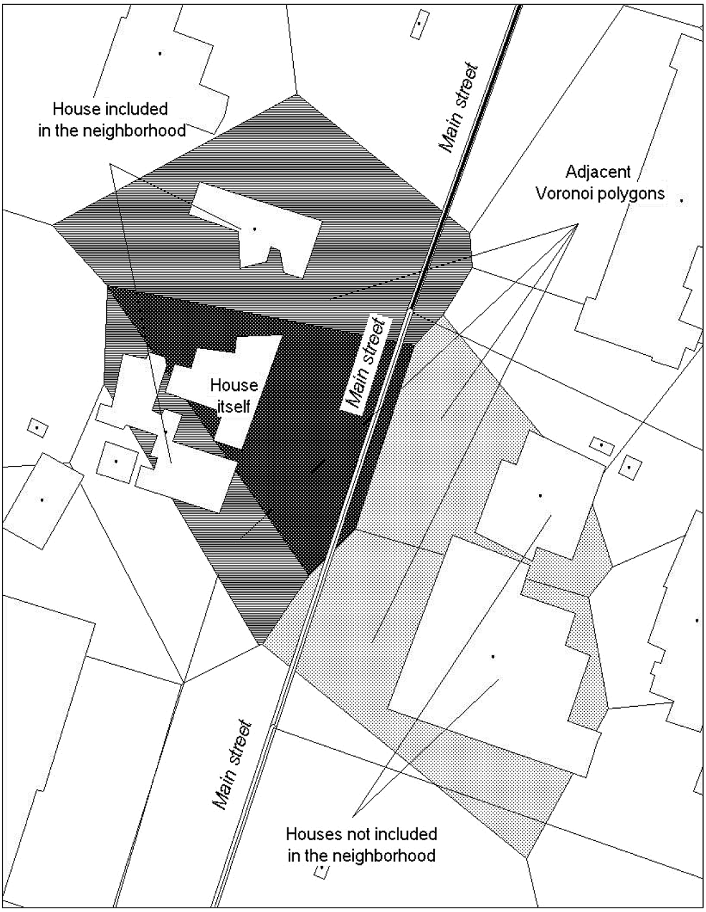


Figure 2. Definition of neighborhood by means of Voronoi polygons (only houses on the same side of the main street are included).

The rules of an EB-model are based on the definition of the neighborhoods of buildings. Our definition of a neighborhood is based on the adjacency of Voronoi polygons constructed around the centroids of the buildings and on the location of buildings relative to streets. We consider two Voronoi polygons as adjacent if they have a common edge, and define neighborhood $U(H)$ of house H as a set of houses G satisfying the following conditions (figure 2):

1. the Voronoi polygon of G is adjacent to the Voronoi polygon of H;
2. the distance between the centroids of G and H is less than a given threshold value;
3. G and H are on the same side of a street if the street is of either 'main' type or its width is over 15 m.

The neighborhood defined in this way consists mainly of the houses which are visible from the given house. Halls et al (2001) discussed this recently in detail.

Agents

The only population agents we consider are householders. The description of a householder in the model is multidimensional. It includes age, income, employment, origin, education, marital status, and religious affiliation for each member of a family, information available from the database constructed during Israel's 1995 Population Census (ICBS, 2000).

The census database contains the householder's address; thus, it allows one to locate each householder in the urban space and to estimate local relations between householders within a house and within the neighborhood of a house. Israeli law restricts the use of georeferenced census data on householders; therefore, the part of the research demanding access to these data was conducted under the supervision of ICBS staff. In this paper we account for only two householder characteristics—origin and religious affiliation.

Model rules

Household agents in-migrate to the city, occupy and change residential locations there, and out-migrate if they fail to find a suitable residence during the search. They estimate the state of the neighborhood and the neighbors, and behave in accordance with that information. The flowchart in figure 3 represents the stages of the model's dynamics during each time step. The rules of interactions between the model's units—householder agents and households—are based on the notion of residential dissonance (Portugali et al, 1997).

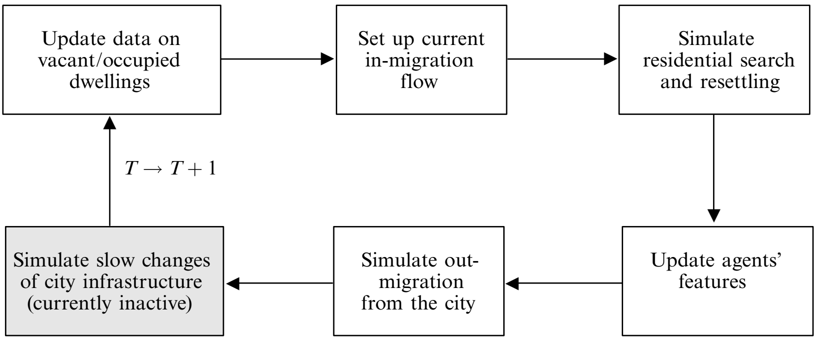


Figure 3. Model flow-chart.

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 et al (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, $D_f\big(A, U(H)\big)$, between agent A and neighborhood $U(H)$ of H given f. The only constraint we impose on $D_f\big(A, U(H)\big)$ is that its average value increases monotonically with an increase in the differences between A and $U(H)$ given f. Second, we combine values of the dissonance according to several factors, $f_1, f_2, \ldots$, and estimate the overall dissonance, $D\big(A, U(H)\big)$, between an agent and a neighborhood:

$$D\big(A, U(H)\big) = 1 - \prod_i \big[1 - \alpha_i D_{fi}\big(A, U(H)\big)\big] , \tag{1}$$

where $\alpha_i \in [0, 1]$ reflects the weight of f_i in the overall dissonance. The analytical form of equation (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 equation (1), to obtain a high overall dissonance value it is enough to obtain a large $D_{fi}\big(A, U(H)\big)$ for only one of the factors 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, $D\big(A, U(H)\big)$. The analytical form of the dependence, $P(D)$, that we use in this paper assumes that P grows linearly with D:

$$P(D) = P_0 + (1 - P_0)D\,, \tag{2}$$

where probability P_0 stands for the component of $P(D)$ that is independent of A's characteristics. $P(D)$, like P_0 and D, is a stochastic variable; its mean value varies within the interval $[P_0, 1]$ when D varies with [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 residence, it is included in a set, $\boldsymbol{M}$, of potential 'internal' migrants. In-migrating agents, involved into residential choice in the city for the first time, are also appended to $\boldsymbol{M}$.

Stage 2: estimating the attractiveness of vacancies

At the second stage, for each agent A, $A \in \boldsymbol{M}$, several (usually 10) houses are randomly selected from the set of houses currently containing vacant dwellings. Below we denote this set as $\boldsymbol{H}_A$ and suppose that the vacancies in $\boldsymbol{H}_A$ alone are considered as currently accessible to A. The dissonance, D, between A and each vacant dwelling from $\boldsymbol{H}_A$ 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 complements 'repellence' (2):

$$Q(D) = 1 - P(D) = (1 - P_0)(1 - D)\ . \tag{3}$$

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

Stage 3: occupying vacant residences

At this stage, each potential migrant A, $A \in \boldsymbol{M}$, decides whether to occupy one of $\boldsymbol{H}_A$ vacancies. To do that, A examines the vacancies in $\boldsymbol{H}_A$ in order of their attractiveness. In order to simplify this procedure, the set $\boldsymbol{H}_A$ is ordered according to the attractiveness of its dwellings prior to the examination. First, A 'visits' the most attractive vacancy $H_{A,1}$ among $\boldsymbol{H}_A$. If $H_{A,1}$ is still free at the time of the visit, A decides to occupy it with a probability determined by $H_{A,1}$'s attractiveness, $Q(D) = D\big(A, U(H_{A,1})\big)$, as given in equation (3). If A occupies $H_{A,1}$, then A's address is changed and A is excluded from $\boldsymbol{M}$. A remains in $\boldsymbol{M}$ if vacancy $H_{A,1}$ 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 $\boldsymbol{M}$ are randomly selected to visit the best vacancies in their $\boldsymbol{H}_A$.

After all the members of $\boldsymbol{M}$ have explored 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 $\boldsymbol{M}$ are randomly selected for visits to resolve the situation when several agents list the same vacancy.

Members of $\boldsymbol{M}$ who are residents of the city, but fail to resettle during these trials, either remain at their current residence with probability $1 - L_A$, or leave the city with probability 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, L_A, that a resident agent A will leave the city when failing to find a vacant residence to resettle, as mentioned above.

Modeling Yaffo's ethnic distribution

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 3000 of the original Arab inhabitants remained, almost all of whom were concentrated within the small Adjami neighborhood [Tel Aviv – Yaffo statistical areas 721, 722, 723, color plate 2(b), page 504]; Jewish immigrants later entered Adjami and other parts of Yaffo (Omer, 1996; Portugali, 1991) and occupied dwellings left by the Arabs.

During the period 1955 – 95, the Arab population of Yaffo grew continuously and spread from Adjami throughout the region, whereas the Jewish majority gradually left (figure 4). Precise data are available for the period 1961 – 95, when the size of the Arab population increased from 5000 (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 and 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.

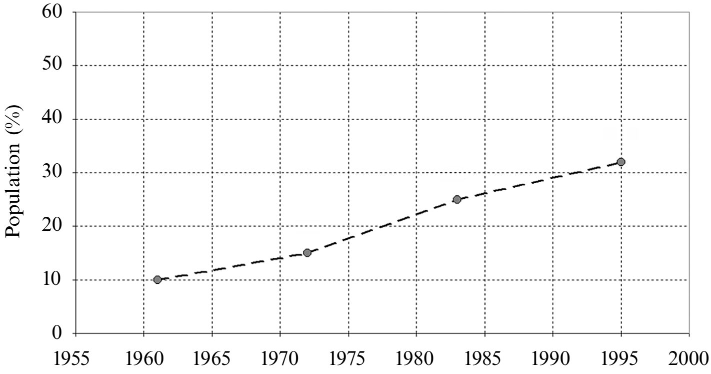


Figure 4. Arab population dynamics, Yaffo, 1961 – 95.

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 1955–95. 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 buildings according to the Voronoi-based algorithm defined above. The layers of houses and streets, as well as the detailed georeferenced 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 (color plate 1). We have no direct data on dwelling prices depending on architectural style of the building. The published data on dwelling purchasing, which are averaged by streets, do not display significant differences between the areas of oriental and block-style buildings. The only regular factor that influences prices of dwellings is sea visibility, but houses close to the shore constitute only a few percent of all dwellings. Therefore, we do not account for dwelling prices in the model. We take only residential buildings into account; the dwelling capacity of a building is estimated by the number of its floors and the area of its foundations, assuming that the average apartment area in Tel Aviv equals 100 m^2. The overall capacity of Yaffo buildings is about 10 000 dwellings according to this estimate.

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 A_J, a 'Muslim Arab' as A_M, and a 'Christian Arab' as 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 (in new Israeli shekels, NIS) are similar (table 2); hence, we currently do not include income as a feature of Yaffo's householder agents.

Table 2. The 1995 distribution of salaried income of Jewish, Arab Muslim and Arab Christian householders in Yaffo.

Group	Number	Mean monthly income (NIS)	Standard deviation (NIS)
Jewish	424	3100	2600
Moslem	245	2600	1900
Christian	149	3500	2300
Other	27	2900	1300

Schedule of model studies

In what follows, we detail the EB model in order to demonstrate its ability to explain the dynamics of ethnic residential distribution in Yaffo. We first simulate Yaffo's residential dynamics for the period 1955–95 and demonstrate that the two factors posited as potentially influencing residential choice in the area—house 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 with regard to changes in the quantitative expression of agents' relations; we also suggest an explanation of this phenomenon and discuss its consequences.

Calculation of residential dissonance

General approach

According to our understanding of the forces driving Yaffo's residential dynamics, we estimated the residential dissonance for two factors: one arising between an agent and a building and one arising between 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 Muslim Arabs. Then we extend the definitions for the heterogeneous cases of dwellings in buildings of arbitrary architectural style and mixed neighborhoods.

To mirror the relationships between Yaffo inhabitants we delineate six qualitatively different levels of dissonance and quantify them as shown in table 3. For example, the dissonance between a Christian Arab agent and purely Muslim neighborhood is assumed to be 'low', and between a Jewish agent and purely Muslim Arab neighborhood is assumed to be 'very high' (see tables 4 and 5 below). To reflect the 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 3, and standard deviation, SD, calculated as

$$\mathrm{SD} = \delta[D(1-D)]^{1/2} . \qquad (4)$$

In what follows we set $\delta = 0.05$. The third column of table 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.

Table 3. Quantitative values of dissonance levels.

Qualitative evaluation of the dissonance level	Representative value of the dissonance, D	95% confidence interval for the case of $\delta = 0.05$[a]
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)

[a] See equation (4).

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; a unit value denotes 'block'. The majority of the 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' ($S = 0.8$) (color plate 1). The model dissonance, 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 shown in table 4 (over). According to table 4, 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.

Table 4. Dissonance, D_h, between an agent and a house.

Agent's identity	House's architectural style	
	oriental ($S = 0$)	block ($S = 1$)
Jewish, A_J	intermediate	zero
Arab, A_M, A_C	zero	high

To extend the definition to the general case of an agent of identity A_i with regard to a choice of a dwelling in a house H of 'impure' style S, we define the dissonance, $D_h(A_i, H)$, as

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

where A_i is one of A_J, A_M, A_C; H_0 stands for a dwelling in a house of an oriental style and 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 shown in table 5. The estimates shown in table 5 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.

Table 5. Dissonance, D_p, between an agent and a homogeneous neighborhood.

Agent's identity	Neighborhood identity[a]		
	Jewish, $U(H)_\mathrm{J}$	Muslim, $U(H)_\mathrm{M}$	Christian, $U(H)_\mathrm{C}$
Jewish, A_J	zero	very high	high
Moslem, A_M	high	zero	very low
Christian, A_C	intermediate	low	zero

[a] $U(H)_\mathrm{J}$, $U(H)_\mathrm{M}$, and $U(H)_\mathrm{C}$ denote the common identity of the neighbors.

We generalize the definition of the dissonance for the case of a heterogeneous neighborhood in the same way as in equation (5). The dissonance, $D_p\big(A_i, U(H)\big)$, between an agent of identity A_i and mixed neighborhood $U(H)$ is calculated as an average of the values shown in table 5 weighted by the fractions of the agents of a given identity residing in the neighborhood:

$$D_p\big(A_i, U(H)\big) = D_p\big(A_i, U(H)_\mathrm{J}\big)F_\mathrm{J} + D_p\big(A_i, U(H)_\mathrm{M}\big)F_\mathrm{M} + D_p\big(A_i, U(H)_\mathrm{C}\big)F_\mathrm{C}, \tag{6}$$

where A_i is one of A_J, A_M, or A_C and F_i is the fraction of the agents of identity i within $U(H)$. For example, a dissonance between a Jewish agent and a neighborhood consisting of 10% Jews, 70% Muslims, and 20% Christians is calculated as $(0.0 \times 0.1) + (0.95 \times 0.7) + (0.8 \times 0.2) = 0.825$. The dissonance between an agent and an unpopulated neighborhood is assumed to be zero.

Overall dissonance

According to equation (3), the dissonance between an agent of identity A_i located in a house H of a style S within a mixed neighborhood $U(H)$ is calculated as

$$1 - \big[1 - \alpha_h D_h(A_i, H)\big]\big[1 - \alpha_p D_p\big(A_i, U(H)\big)\big], \tag{7}$$

where $D_h(A_i, H)$ is given by equation (5), $D_p\big(A_i, U(H)\big)$ is given by equation (6), 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 or occupy a dwelling
The above rules are sufficient to compute the probability that an agent A_i of identity i will leave or occupy a dwelling in a house 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 or her other neighbors are assigned for homogeneous cases according to tables 4 and 5. Second, these values are weighted according to equations (5)–(6). Third, overall dissonance is calculated according to equation (7) and the probability to leave [equation (2)] or to occupy [equation (3)] a dwelling is calculated last. The probability, P_0, of occasional leaving or occupying in equations (2) and (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 the period 1955–95, 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, 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, Arab householders having 10 times fewer options for resettlement compared with Jewish ones.

Initial population distribution
According to Omer (1996) in 1955, 3000 Arab inhabitants of Yaffo were concentrated in three statistical areas [color plate 2(b)]; one third of them were Christians, the rest Muslims. Translating these numbers into the numbers of householders (table 6), we built an initial model residential distribution by randomly distributing 450 Muslim and 300 Christian householders among dwellings in the houses within the three areas above for 1955 [color plate 2(a)]. 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.

Table 6. Mean size of Jewish, Arab Muslim, and Arab Christian households in Yaffo in 1995.

Agent identity	Jew	Christian	Muslim
Mean family size	2.25	3.05	4.31

Examination of the model
Stochastic nature of the model
To estimate the variation of the model results arising from 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 attractive 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, α_h and α_p, and comparing the model results with the Yaffo data according to three global characteristics of the Yaffo residential distribution. First, we compare the model fraction of the Arab population with the real Yaffo data available for 1961, 1972, 1983, and 1995 (figure 4). 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 the model and in reality by means of Moran's index, I, of spatial autocorrelation (Anselin, 1995) between the fraction of Arab agents in a building and in a building's neighborhood. The value of I was found to be 0.646 ($p < 0.001$) for the 1995 distribution. The noncorrespondence of the population with the architectural style of the buildings is characterized by the fractions of agents occupying less attractive houses in 1995. With regard to 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%. Most of the real data relate to the individuals, whereas the model agents represent householders. To transform the data on householders to absolute population numbers we use the estimates of family size, obtained from 1995 data for Yaffo (table 6).

Establishing α_h and α_p

To establish the values of α_h and α_p, we run the model for 25 possible pairs (α_h, α_p), where α_h, α_p = 0.0, 0.05, 0.1, 0.5, and 1.0. The trajectories of the model fraction of Arab agents and of I during the period 1955–95, are presented in figure 5. When human neighbors and house style do not influence residential choice ($\alpha_h = 0$, $\alpha_p = 0$), the fraction of the Arab population reaches 21% in 1995 [the lowest group of curves in figures 5(a)], much below the true value. Too low a rate of growth of the fraction of Arab agents is characteristic for all runs where the neighbors alone influence the residential behavior of agents, that is, for $\alpha_h = 0$ and $\alpha_p > 0$ [the lowest group of curves in figure 5(a)].

If building style alone influences residential choice ($\alpha_h > 0$, $\alpha_p = 0$), then all the dwellings in the houses of oriental style are identical for purposes of in-migration and occasional resettlement of Arab agents; the same holding true for Jewish agents and buildings in the block style. The residential dynamics in this case are characterized by rapid redistribution of Arab agents over the dwellings in the buildings of oriental style during the first five to ten years of the simulation. Further increase of the proportion of Arab agents over this area is uniform [figure 5(b)]. As a result, until Jewish agents leave most of the dwellings in the buildings of oriental style (the first fifteen years of the simulation), we observe a highly unrealistic situation: Arab agents residing in the same building as Jewish agents. This contradicts Omer's (1996) findings regarding Yaffo's residential distribution, where the number of houses of oriental style mutually occupied by Jews and Arabs always remained below 15%. In addition,

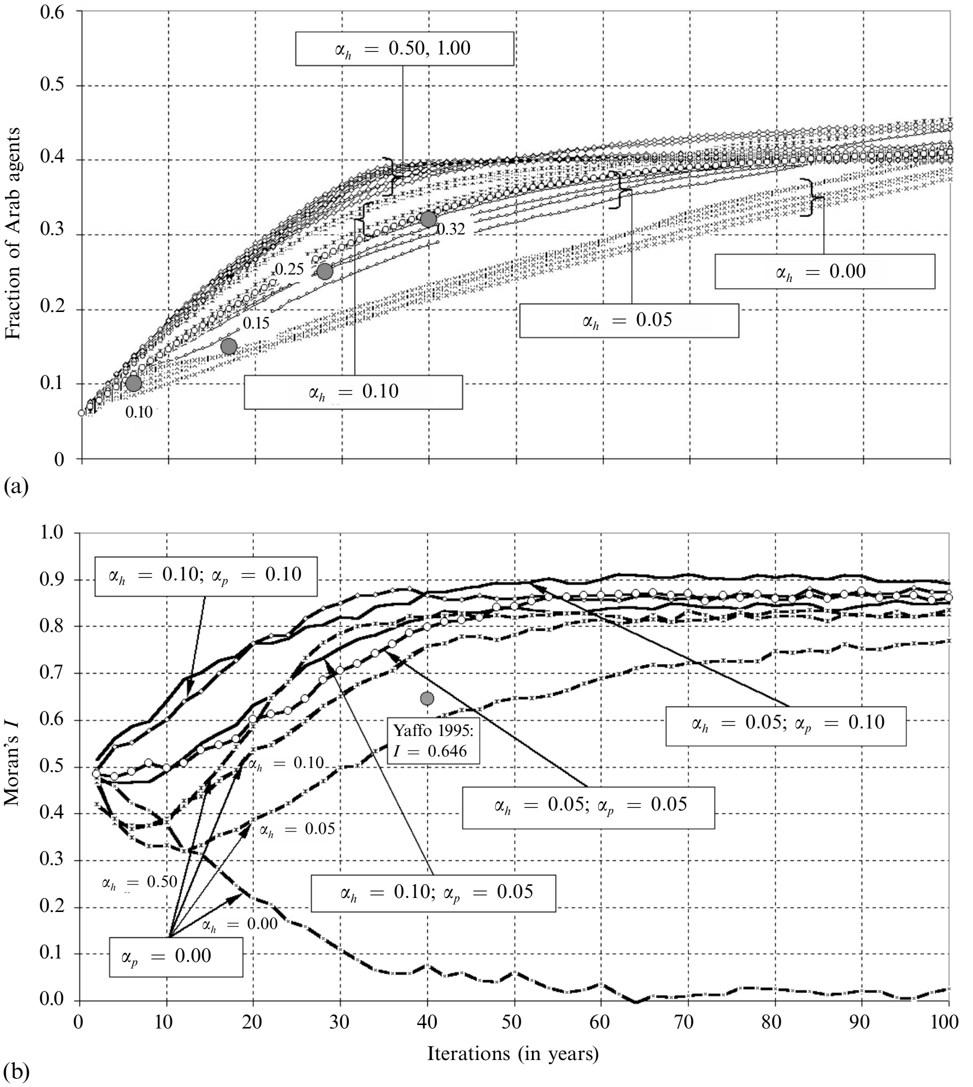
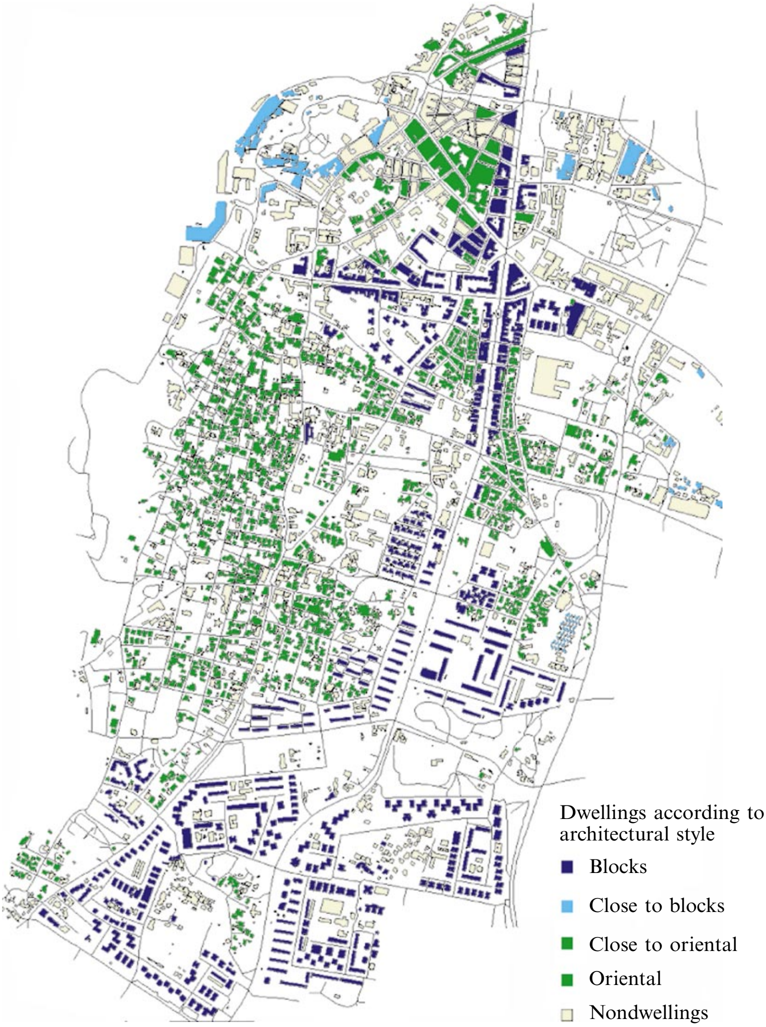


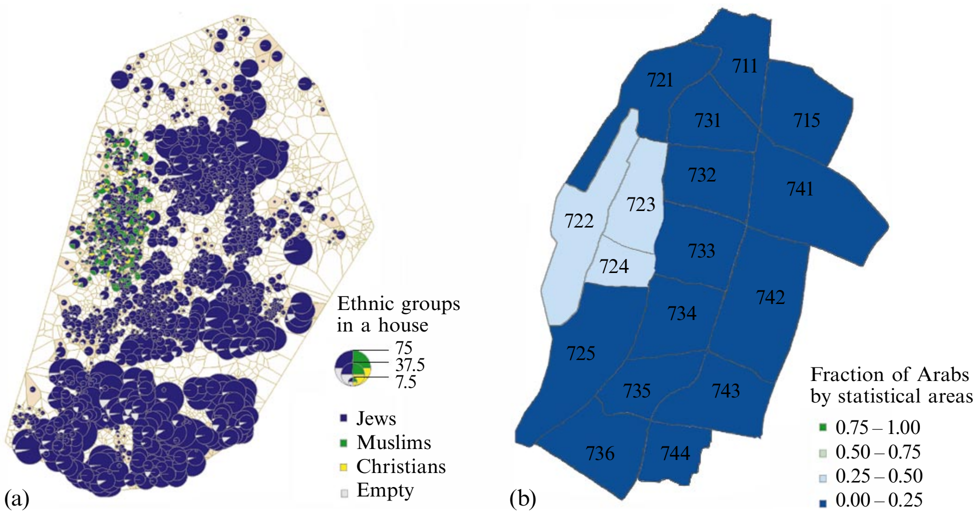
Figure 5. Yaffo: model dynamics projected for 100 years and the real data (gray points). (a) Fraction of Arab agents; each group of trajectories represents specified values of α_h and all possible values of α_p—0, 0.05, 0.1, 0.5, and 1.0. (b) Dynamics of the Moran's index I for $\alpha_p = 0$, and $\alpha_h = 0, 0.05, 0.1, 0.5$, and 1.0 (architectural style alone influences residential choice) and for four runs with $\alpha_h, \alpha_p = 0.05, 0.1$, when the I-values most closely approximate that obtained for Yaffo in 1995.

the simulation dynamics driven by house style alone constrict Arab agents' penetration into houses of block style. The model fraction of Arab agents occupying houses of block and close to block style in 1995 remains below 1% for any α_h, compared with the true value of 18.5%.

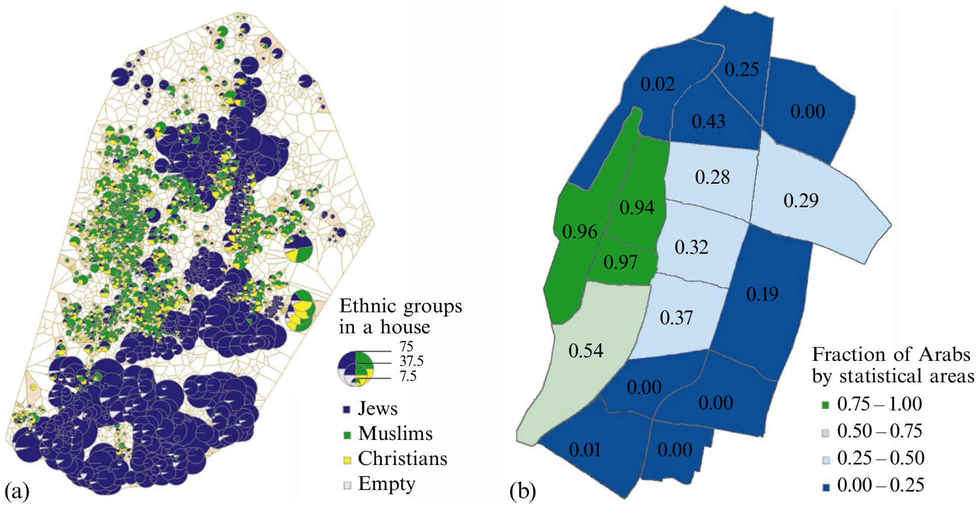
This analysis leads us to conclude that no one factor is sufficient for explicating Yaffo's residential dynamics, that is, $\alpha_h > 0$ and $\alpha_p > 0$. The 25 comparison runs clearly demonstrate that the higher the values of α_h and α_p, the lower the correspondence between the model and the true dynamics. According to figure 5(a), higher values of α_h entail too fast a growth of the Arab population, whereas according to figure 5(b), higher values of α_p result in oversegregation of the population. For nonzero values of



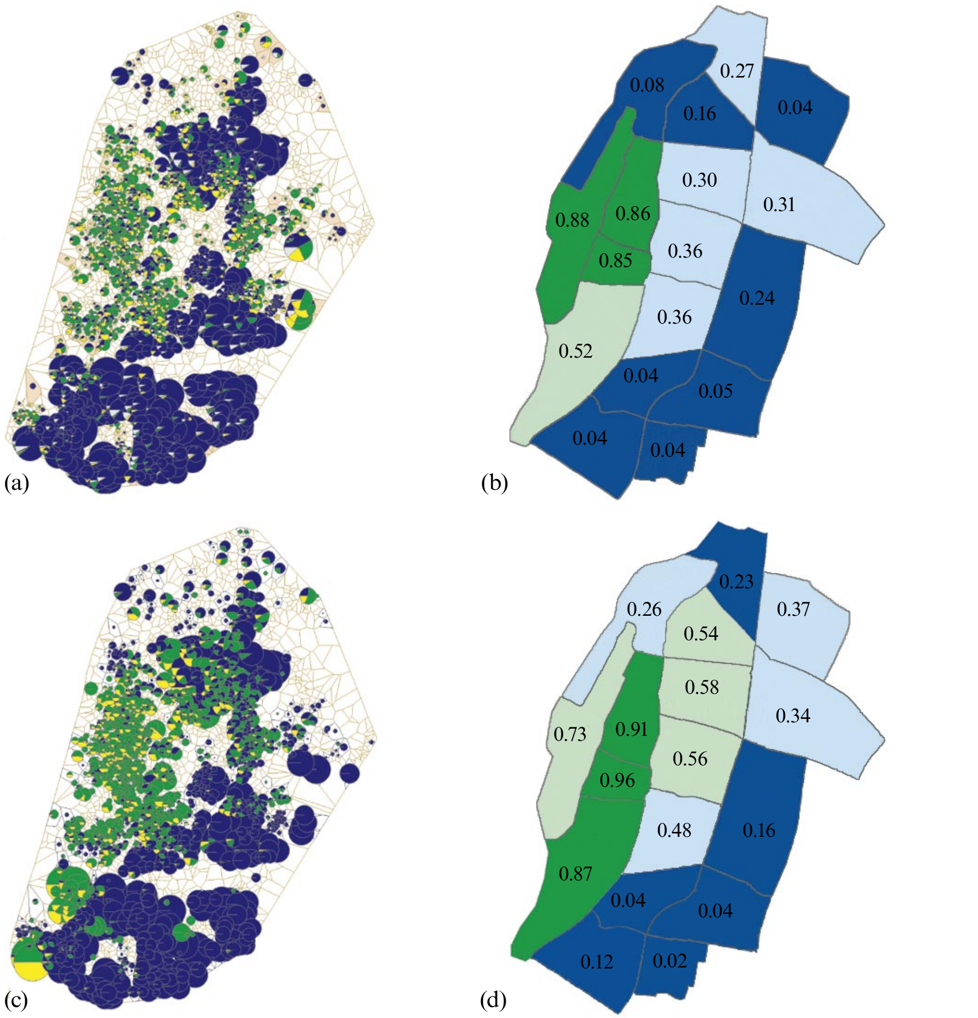
Color plate 1. Distribution of houses in Yaffo by architectural style, 1995.



Color plate 2. (a) Initial model residential distribution in 1955 by houses. (b) Yaffo residential distribution in 1955 (available by statistical areas only).



Color plate 3. Model residential distribution at year 40 (1995) for $\alpha_h = 0.05$, $\alpha_p = 0.05$: (a) by houses, (b) fraction of Arab population by statistical areas.



Color plate 4. Residential distribution at model year 40 (1995) for the Arab assimilation 2 scenario [(a), (b)] and the real-world residential distribution, Yaffo, 1995 [(c), (d)], α_h, $\alpha_p = 0.05$: (a), (c) by houses, (b), (d) fraction of Arab population by statistical areas. For key see plate 3.

α_h and α_p, the higher the values, the weaker the dependence of the model outcomes on those values. The pair of smallest nonzero values tested, $\alpha_h = 0.05$ and $\alpha_p = 0.05$, provide very good quantitative correspondence between the model and the true fraction of the Arab population during the period 1955–95. The segregation of Arab individuals (Moran's I) in 1995 for these values of α_h, α_p remains at the level of 0.79, while surpassing the true value of 0.646 [figure 5(b)]. 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%. Color plate 3 presents the model residential distribution at the level of separate houses and at the level of statistical areas for the case of α_h, $\alpha_p = 0.05$.

The Christian agents are located along the boundaries and somewhat within the domain occupied mostly by Arab agents for all the scenarios where α_h, $\alpha_p > 0$. In this paper we concentrate on Jewish–Arab relations and do not discuss Christian residential dynamics.

The correspondence between the model dynamics of the fraction of Arab agents and the level of their segregation (given by I), and the true Yaffo data is achieved after 13 (!) estimates of the dissonance values in tables 4 and 5, 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 α_h, $\alpha_p = 0.05$ for these experiments and call the model run that utilizes α_h, $\alpha_p = 0.05$ and the values of dissonance given in tables 4 and 5 the 'basic scenario'.

The experiments with dissonance

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 in tables 4 and 5 are increased or decreased by one or two grades according to those indicated in table 3. Table 7 displays five scenarios that we compare (α_h, $\alpha_p = 0.05$ throughout). For example, in the co-assimilation 1 scenario, the changes of dissonance values between agents and neighbors and agent and building are as shown in tables 8 and 9 (marked in gray).

Table 7. Investigated scenarios versus the basic one.

Scenario	Change in dissonance versus basic scenario			
	Arab agent–block house	Jewish agent–oriental house	Arab agent–Jewish neighborhood	Jewish agent–Arab neighborhood
Co-assimilation 1	1 grade less	1 grade less	1 grade less	1 grade less
Co-assimilation 2	2 grades less	2 grades less	2 grades less	2 grades less
Arab assimilation 2	2 grades less	unchanged	2 grades less	unchanged
Jewish assimilation 2	unchanged	2 grades less	unchanged	2 grades less
Co-competition 1	1 grade more	1 grade more	1 grade more	1 grade more

The resulting curves of the dynamics of Arab fraction and Moran's I are presented in figure 6 (see over). According to figure 6(a), the growth curves of the fraction of Arab agents in Yaffo behave realistically during the period 1955–95 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 6(a)]. The trajectories of I [figure 6(b)] appear reasonable for four of the five

Table 8. Changes in dissonance values between agents and 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)
Muslim	intermediate (instead of high)	zero (unchanged)	very low (unchanged)
Christian	low (instead of intermediate)	low (unchanged)	zero (unchanged)

Table 9. Changes in dissonance values between agents and building for co-assimilation 1 scenario.

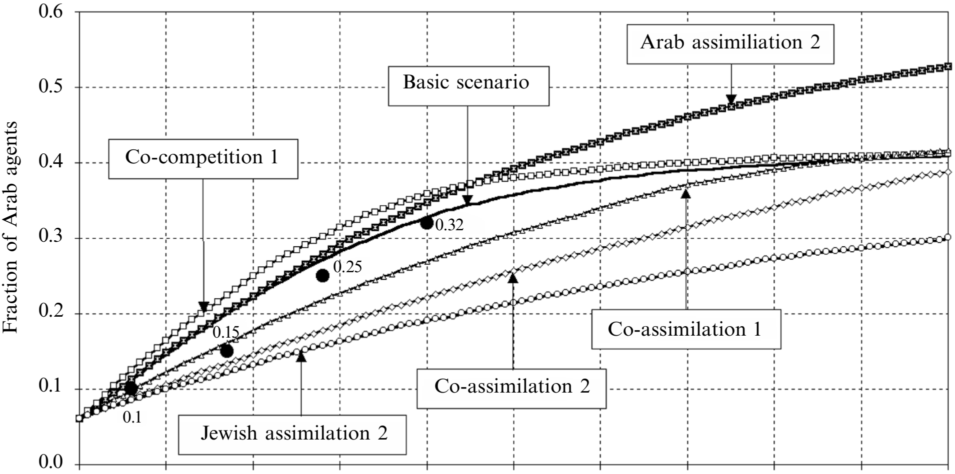
Agent's identity	Architectural style of a building	
	oriental	block
Jewish	low (instead of intermediate)	zero (unchanged)
Arab	zero (unchanged)	intermediate (instead of high)

Table 10. Model results for two most likely scenarios versus estimates obtained from 1995 census data.

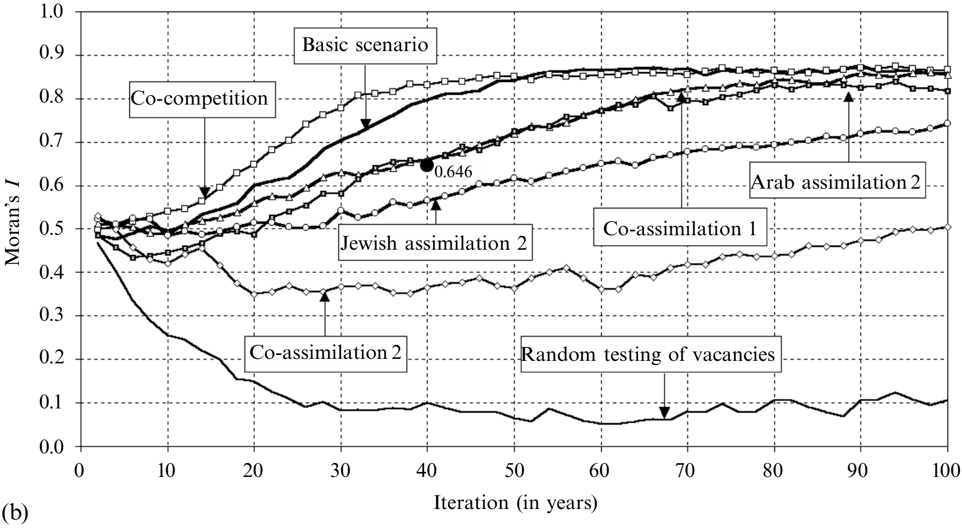
Scenario	Percentage of Arab agents in houses of block or close to block style	Percentage of Jewish agents in houses of oriental or close to oriental style	Overall percentage of Arab agents	Moran's index, I, of segregation for Arab agents
Yaffo data	18.5	28.1	32.2	0.65
Co-assimilation 1	3.0	26.5	27.0	0.66
Arab assimilation 2	15.0	8.0	34.8	0.66
Co-competition 1	1.2	5.6	35.9	0.83

scenarios, with the exception of co-assimilation 2 (see discussion of "Random testing of vacancies" case below). Moreover, for two scenarios—co-assimilation 1 and Arab assimilation 2—the value of I in 1995 equals 0.66, equivalent to the real value.

Table 10 summarizes the results of the comparison between the 1995 data and the model for three most likely scenarios according to population fraction and level of segregation. These scenarios differ according to the third characteristic—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 those data to a similar degree. The outcome of the co-competition scenario is oversegregated relative to the true Yaffo data. We can say, therefore, that compared with the level of competition assumed initially, much weaker competition for space between Yaffo population groups is sufficient to explain the residential distribution found. The results reflect reality more closely when Jewish and Arab agents are more tolerant of each other and of 'strange' houses (that is, buildings in architectural styles



(a)



(b)

Figure 6. Model dynamics for different scenarios, dissonance matrices varied (α_h, α_p = 0.05): (a) fraction of Arab agents, (b) Moran's index I (the lowest curve represents the dynamics of I for the case when agents test vacant habitats in random order).

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 et al, 1994) and contradicts 'commonsense' views of the advantages of competitive behavior. The residential distributions for the Arab assimilation 2 scenario and the actual Yaffo residential distribution in 1995 are presented in color plate 4.

Structural stability of the model results

Until 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 mirrors important characteristics of the Yaffo dynamics for most of the variants considered in the two previous sections. That is, for nonzero 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 grows steadily. In short, for broad ranges of parameter values, the model reproduces reasonably well 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 of 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 features that determine 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 3 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. Let us suppose that, for a given set of parameters, the vacancy in house H_1 is more attractive for agent A than the vacancy in house H_2. If the model parameters change and, consequently, the numerical values of the dissonance between an agent and vacancies in H_1 and H_2 change as well, this does not necessarily change the order of the two dissonance values considered; the habitat in H_1 may remain more attractive than that in H_2. If so, the agent begins stage 3 of residential choice by testing the same habitat in H_1 as it would with the first set of model parameters; thus, the quantitative changes in parameters have only a 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 α_h and α_p, and explains why the model results change so drastically when α_h and/or α_p are nonzero. 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 with 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 previously estimated attractiveness, we present the model results given α_h, $\alpha_p = 0.05$, provided that each agent tests vacant habitats from $\boldsymbol{H}_A$ in a random order [figure 6(b), lowest curve]. As we can see, the residential distribution is not segregated at all in this case.

Discussion

The clearest rationale for the necessity of a new, fine-scale urban geography was recently formulated by Batty (2000, page 483):

> "Until now, urban geography has been dominated either by aggregate theories of pattern description or by more idiosyncratic case studies of individual behaviour in an urban setting. ... [S]mall-scale studies of individual locations and individuals within urban locations ... [have] never been able to develop theory of sufficient generality to illustrate how local decisions and actions are consistent with and determine large-scale urban structures. All this is changing. Quite suddenly so it appears, a new kind of fine-scale geography is beginning to emerge from data which are sufficiently *intensive* to detect detailed patterns and morphologies but also sufficiently *extensive* to enable these patterns to be generalized to entire metropolitan areas."

Entity-based modeling is a tool to be used in this new geography. It incorporates de facto human – environment relations, operating at fine scale, within the repertoire of mechanisms for analyzing urban system dynamics.

We apply EB simulations to study residential segregation, an area where views on the principal role of the microscale spatial structure were formulated during the 1960s and 1970s (Morrill, 1965; Rose, 1970; Woods, 1981) in a series of intensive field studies. Just to mention a few, Boal (1982) demonstrated that the residential segregation between Protestants and Roman Catholics in Belfast depends on housing category and personal economic status; Peach (1998) showed that in Britain, house types influence ethnic spatial patterns; similarly, Ben Artzi (1980) illustrated how the architectural style of houses influences Arab dispersion into mostly Jewish residential areas in Haifa, Israel.

These and other studies (see, for example, Knox, 1982, pages 167 – 172; Raju et al, 1998) have detected the correspondence between the degree of residential segregation and characteristics of the physical or human environment. However, it is not enough to claim that segregation *can be determined* by these factors. The power of the EB approach lies in its ability *to test hypotheses* of this kind. We have done so with regard to the factors determining Yaffo's ethnic residential dynamics and have succeeded in simulating very closely the residential dynamics that occur in reality. Moreover, the EB model of Yaffo's residential dynamics clearly demonstrates which features of agent (householder) behavior are of principal importance for understanding the phenomenon of the residential segregation found there. We would argue that these are the qualitative aspects of residential choice that, therefore, demand further experimental and conceptual investigation. The principles of nonspatial human choice behavior are intensively discussed in the psychological literature (see Gigerenzer and 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 about future neighbors, to say nothing about the economic state of the 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 whereby an agent attempts to occupy the vacant dwelling with the highest expected attractiveness, followed by the next most attractive if the first 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 describe adequately 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 or 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 EB model to larger areas and account for a greater number of variables characterizing household agents and households.

Acknowledgements. We thank Nina Reshef, Public Policy Program, Tel Aviv University and Paul Torrens, Center for Advanced Spatial Analysis, University College London, for helpful review and important comments.

References

Anselin L, 1995, "Local indicators of spatial association—LISA" *Geographical Analysis* **27**(2) 93 – 115
Batty M, 2000, "The new urban geography of the third dimension" *Environment and Planning B: Planning and Design* **27** 483 – 484
Batty M, Longley P, 1994 *Fractal Cities: A Geometry of Form and Function* (Academic Press, London)
Batty M, Xie Y, 1997, "Possible urban automata" *Environment and Planning B: Planning and Design* **24** 175 – 192
Ben Artzi Y, 1980, "The creation of the residential pattern and residential mobility characteristics of the Arab in Haifa", Jewish-Arab Center, Haifa University, Haifa (in Hebrew)
Benati S, 1997, "A cellular automaton for the simulation of competitive location" *Environment and Planning B: Planning and Design* **24** 205 – 218
Benenson I, 1998, "Multi-agent simulations of residential dynamics in the city" *Computers, Environment and Urban Systems* **22** 25 – 42
Benenson I, 1999, "Modeling population dynamics in the city: from a regional to a multi-agent approach" *Discrete Dynamics in Nature and Society* **3** 149 – 170
Bertuglia C S, Occelli S, Rabino G A, Tadei R, Wilson A G (Eds), 1987 *Urban Systems: Contemporary Approaches to Modeling* (Croom Helm, London)
Boal F W, 1982, "Segregation and mixing: space and residence in Belfast", in *Integration and Division* Eds F W Boal, J N H Douglas (Academic Press, London) pp 249 – 280
Clarke K C, Hoppen S, Gaydos L, 1997, "A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area" *Environment and Planning B: Planning and Design* **24** 247 – 261
Couclelis H, 1985, "Cellular worlds: a framework for modeling micro – macro dynamics" *Environment and Planning A* **17** 585 – 596
Dibble C, 1996, "Theory in a complex world: agent-based simulations of geographic systems", paper presented at GeoComputation 96, 1st International Conference on GeoComputation, University of Leeds, Leeds; copy available from the author, Department of Geography, Univerity of California, Santa Barbara, CA
Giddens A, 1984 *The Constitution of Society: Outline of the Theory of Structuration* (University of California Press, Berkeley, CA)
Gigerenzer G, Goldstein D G, 1996, "Reasoning the fast and frugal way: models of bounded rationality" *Psychological Review* **103** 650 – 669
Gilbert N S, Troitzsch K G, 1999 *Simulation for the Social Scientist* (Open University Press, Buckingham)
Green M, Flowerdew R, 1996, "New evidence on the modifiable areal unit problem", in *Spatial Analysis: Modeling in a GIS Environment* Eds P Longley, M Batty (Geoinformation International, Cambridge) pp 41 – 54
Hagget P, Cliff A D, Freey A E, 1977 *Locational Analysis in Human Geography* (Edward Arnold, London)
Halls P J, Bulling M, White P C L, Garland L, Harris S, 2001, "Dirichlet neighbors: revisiting Dirichlet tessellation for neighborhood analysis" *Computers, Environment and Urban Systems* **25** 105 – 117
ICBS, 2000, "Socio-economic characteristics of population and households in localities and statistical areas", publication 8 in the 1995 Census of Population and Housing series (State of Israel, Central Bureau of Statistics Publications, Jerusalem)
Klosterman R E, 1994, "Large scale urban models: retrospect and prospect" *Journal of the American Planning Association* **60** 3 – 7
Knox P, 1982 *Urban Social Geography* (Longman, Harlow, Essex)
Lee T R, 1973, "Psychology and living space", in *The Image of the Environment* Eds R Downs, D Stea (Aldine Publishing, Chicago, IL) pp 87 – 108
Ley D, 1983 *A Social Geography of the City* (Harper and Row, New York)
Lynch K, 1981 *Good City Form* (MIT Press, Cambridge, MA)
Morrill R L, 1965, "The negro ghetto: problems and alternatives" *Geographical Review* **55** 339 – 369
Omer I, 1996 *Ethnic Residential Segregation as a Structuration Process* (in Hebrew) unpublished PhD thesis, Department of Geography and Human Environment, Tel-Aviv University, Tel-Aviv
Omer I, 1999, "Ethnic residential segregation and demographic processes" *Discrete Dynamics in Nature and Society* **3** 171 – 184

Openshaw S, Rao L, 1995, "Algorithms for reengineering 1991 Census geography" *Environment and Planning A* **27** 425 – 446

Peach C, 1998, "South Asian and Caribbean ethnic minority housing choice in Britain" *Urban Studies* **35** 1657 – 1680

Phipps M, 1989, "Dynamical behavior of cellular automata under the constraint of neighborhood coherence" *Geographical Analysis* **21** 197 – 215

Portugali J, 1991, "An Arab segregated neighborhood in Tel-Aviv: the case of Adjami" *Geography Research Forum* **11** 37 – 50

Portugali J, 1999 *Self-organization and the City* (Springer, Berlin)

Portugali J, Benenson I, Omer I, 1994, "Socio-spatial residential dynamics: stability and instability within a self-organized city" *Geographical Analysis* **26** 321 – 340

Portugali J, Benenson I, Omer I, 1997, "Spatial cognitive dissonance and sociospatial emergence in a self-organizing city" *Environment and Planning B: Planning and Design* **24** 263 – 285

Raju K A, Sikdar P K, Dhingra S L, 1998, "Micro-simulation of residential location choice and its variation" *Computers, Environment and Urban Systems* **22** 203 – 218

Relph E, 1976 *Place and Placelessness* (Pion, London)

Rose H M, 1970, "The development of an urban sub-system: the case of the negro ghetto" *Annals of the Association of American Geographers* **60** 1 – 17

Shevky E, Bell W, 1955 *Social Area Analysis* (Stanford University Press, Stanford, CA)

Simon H A, 1956, "Rational choice and the structure of the environment" *Psychological Review* **63** 129 – 138

Simon H A, 1982 *Models of Bounded Rationality* (MIT Press, Cambridge, MA)

Steel D G, Holt D, 1996, "Rules for random aggregation" *Environment and Planning A* **28** 957 – 978

Tel Aviv – Yaffo Municipality, 1999 *Statistical Yearbook number 39* Tel Aviv – Yaffo Municipality, Center for Economic and Social Research, Tel Aviv

Torrens P M, 2000, "How cellular models of urban systems work", WP 28, CASA, http://www.casa.ucl.ac.uk/working_papers.htm

Tuan Y F, 1977 *Space and Place: The Perspectives of Experience* (University of Minnesota Press, Minnapolis, MN)

Weidlich W, 1987, "Synergetics and social science", in *Lasers and Synergetics* Eds R Graham, A Wunderlin (Springer, Berlin) pp 238 – 256

White R, Engelen G, Uljee I, 1997, "The use of constrained cellular automata for high-resolution modelling of urban land-use dynamics" *Environment and Planning B: Planning and Design* **24** 323 – 343

Woods R I, 1981, "Spatiotemporal models of ethnic segregation and their implications for housing policy" *Environment and Planning A* **13** 1415 – 1433

Wrigley N, Holt T, Steel D, Tranmer M, 1996, "Analyzing, modeling, and resolving the ecological fallacy", in *Spatial Analysis: Modeling in a GIS Environment* Eds P Longley, M Batty (Geoinformation International, Cambridge) pp 25 – 40

Wu F, 1996, "A linguistic cellular automata simulation approach for sustainable land development in a fast growing region" *Computers, Environment and Urban Systems* **20** 367 – 387