Itzhak Benenson, 2004, Chapter 4. Agent-Based Modeling: From Individual Residential Choice to Urban Residential Dynamics, In M. F. Goodchild, D. G. Janelle (eds.) *Spatially Integrated Social Science: Examples in Best Practice*, Oxford University Press, 67-95

Agent-Based Modeling:
From Individual Residential Choice to
Urban Residential Dynamics

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Introduction

Householder residential choice and residential mobility are among the touchstones of theoretical and applied studies of urban systems. Sociology and human geography focus on these individual processes, which are inherently spatial and locally determined. Urban residential dynamics are an outcome of all the householders' simultaneous choices; hence, no programs ranging from neighborhood rehabilitation to prevention of epidemics, can be planned without the ability to understand and foresee the global urban consequences of those individual decisions in the short and long term.

When confronting this challenge, conceptual as well as methodological issues have arisen that focus on the perspective we should adopt when analyzing residential choice, mobility, and their consequences. First, let us look at the problem in its simplest terms. When faced with the responsibility of changing residence, individuals are pitted against an often confusing if not threatening entity called the "city". A city's dwelling market is always in flux; transportation problems abound; the variety of social, economic, and cultural arrangements, neighborhoods, and so forth make finding a home a behaviorally complex endeavor. Based on their own partial and distorted image of the city (Golledge and Timmermans, 1990), and driven by changing conditions and tastes, householders nevertheless do relocate. In the process, they determine the characteristics of the urban population, and the spatial patterns found in neighborhoods, boroughs, regions, and the entire city.

It is veritably impossible to anticipate the effects of the relationships derived from and in turn inducing mobility among large numbers of residents – whether in individual neighborhoods or the city as a whole - without *dynamic models*: analytical, simulation or mixed. During the last half-century, scholars' belief in modeling as the proper means to grasp the unexpected and sometimes counter-intuitive behavior of urban systems spread together with the perception of the city as a complex, open system and with the notion of self-organization (Haken and Portugali, 1995; Portugali, 2000). Despite the general acceptance of this view, just how to develop a model of the urban residential dynamics resulting from householders' residential choices remained and still remains an open question. In this chapter, we will offer contemporary response to this question.

Approaches to modeling urban residential dynamics

There are two main approaches to modeling urban processes in general and residential dynamics in particular.

Regional Approach

The traditional regional approach, originating in economics, dates from the 1960s and 1970s (Anselin and Madden, 1990; Bertuglia et al, 1994). This approach focuses on flows of assets, including jobs, information, and population between urban (usually municipal) regions; these comprise the elementary units of the model. Averaging over regions depends on the scale of the regional partition; however, research of the 'Modifiable Areal Unit Problem' has undeniably demonstrated that the conclusions reached on the basis of aggregate datasets can change significantly when the same data are considered at different scales (Openshaw, 1983).

Regional models are also data-consuming. For a city divided into 20-30 regions each described by 10 state variables, the equations that describe flows between all possible pairs of regions have to account for astronomical number of parameters. To overcome this problem, regional modelers unify inter-regional flows in various ways (White and Engelen, 2000); nonetheless, the dimension of parameter space required remains very high. We will consider regional models of residential dynamics in some detail below (van Wissen and Rima, 1988, Batty and Longley, 1994).

Averaging characteristics over units containing thousands of elementary independent decision-makers – householders – makes regional models insensitive to the behavior of particular individuals. Although such outcomes may be appropriate in the physical realm, researchers of social processes have always been aware of the conceptual inappropriateness of applying the regional approach to the behavior exhibited by the human constituents of the city, elements that exhibit “free will.” This is not meant to be overly critical; rather, such limitations have driven researchers to search for another approach, one that takes the “human” nature of residential dynamics into account.

Agent-Based Approach

Formulated in early 1970s, the major alternative to the regional approach (Schelling, 1971, 1974; Sakoda, 1971) is seemingly simple. It requires that we populate computer memory with many explicitly located, distinct decision-makers, each of whom assesses the urban social and physical reality and makes residential decisions according to her own rules. Despite its inherent attractiveness for social research, this idea – Agent-Based (AB) modeling – remained somewhat buried in the methodological repertoire for years. Only in the last decade has it become a hotbed of social and urban modeling (Epstein and Axtell, 1996; Gilbert and Conte, 1995; Gilbert and Troitzsch, 1999; Portugali, 2000). The ‘agents’ in social AB model represent humans; they interact with other human agents as well as with the objects comprising the physical environment. Regarding residential dynamics, individual householder agents behave – choose and resettle in the new dwellings – and influence other agents accordingly. As a result, they affect urban infrastructure. From the perspective of an AB model, regional or global urban dynamics are the outcomes of agent behavior yet influence individual agents’ characteristics and behavior in turn. The emergence and persistence of ecological patchiness, traffic flows, and economic structures all are examples of processes for which AB models have recently been applied (Sichman, Conte and Gilbert, 1998; Moss and Davidson, 2000, Ligtenberg, Bregt and van Lammeren, 2001). The general theory of AB-systems (Ferber, 1999) concentrates on agent behavior per se. The focus on *space* and *spatial interactions* clarifies our understanding of agent behavior; the resulting spatial models integrate various sources of information, allowing experts from various disciplines to coordinate their knowledge and propose social policy options.

The conceptual advantages of the AB approach extend beyond straightforward reflection of individual behavior. One can argue that quantitative and qualitative changes in urban systems can also be better understood within its framework because they are dependent on actors who strongly and directly influence their immediate environment (Maes 1995; Portugali, 2000). In contrast, aggregation by preset geographic partitions demands two-way 'translation', of real-world events into parameters of inter-regional flows and of averaged regional dynamics into consequences at the individual level. The relationships between aggregate and individual characteristics always remain of uncertain validity – a problem known in geography as the 'ecological fallacy' (Openshaw and Rao, 1995; Wrigley et al., 1996).

The self-evident authenticity of AB approach in the representation of social phenomena neither endows it with superiority over the regional approach nor automatically implies meaningful results, which are still scarce in coming. This chapter presents recent advances in AB modeling of residential choice and migration in addition to the effects of these processes on urban residential dynamics. As an introduction, I begin with a short description of current views on urban location processes and their experimental support. I then consider abstract AB models of residential behavior; these provide the foundations for understanding the system effects of feedback from neighborhood structure on individual residential behavior. Several examples of aggregate residential models are also presented. The last section presents real-world simulations of residential dynamics, including details of the AB simulation of the residential dynamics for an urban region having a population of 30,000.

How residential agents make choices – ideas and experiments

The Agent-Based model is, by definition, based on rules of agent (or individual) behavior. To make the model work, we must specify, at each time moment and for each agent, what she "knows" about the city and how she reacts (if at all) to a perceived situation. The natural way to establish these rules for residential models is to mirror the behavior of the householders revealed in experiments on the residential choice. These experiments are themselves rooted in theoretical perspectives on individual residential behavior that follow two main arguments.

Agents optimizes their state

The view that reigned during the 1970s and 1980s assumed that residential choice belongs to the broader spectrum of individual economic behavior. *Homo economicus* (Sonis, 1992) tends to optimize her state in various respects. Regarding residential choice, she maximizes the net sum of three components: benefits at the current location, costs of moving (or mobility) and benefits obtainable at the potential location; each can be calculated in different ways (Goodman, 1981; DaVanzo, 1981). A typical example is the trade-off between housing and commuting costs (Alonso, 1964): the closer the residential location to work (i.e., the lower the commuting costs), the higher the probability that the agents will choose this location for residence.

Theoretically, the optimization hypothesis is consistent with the regional approach to modeling mainly because it adjusts residential distributions to the distribution of jobs, dwellings, commerce and transport networks over regions (Alonso, 1964, Mills and Hamilton, 1989). However, it has failed to survive empirical tests. For instance, the trade-off between housing and commuting costs is either not true at all, or is so weak that it can be ascertained only after the effects of housing and neighborhood characteristics are eliminated (Herrin and Kern 1992, van Ommeren, Rietveld and Nijkamp, 1996). Other analyses have demonstrated weak uni-directional dependence, with job location dependent on residence location (Deitz 1998) or vice-versa (Clark and Withers, 1999)

The failure of the optimization hypothesis does not exclude economic factors from scholarly consideration; instead, it forces us to extend the framework to include other factors — social, cultural, and historical — as directly influencing residential choice.

The stress-resistance approach

Even before firm empirical rejections of the optimization approach began to appear, social scientists felt profound discomfort with its view of residential behavior. This aversion was strongly supported by psychological research, where the *satisficing* hypothesis of human choice behavior, popular since the mid 1950s (Simon, 1956, 1982, Gigerenzer and Goldstein, 1996), was proposed as an alternative to optimization. The sociological models developed in the 1960s and established as theoretical mainstays in the 1970s liberated householders from the need to solve optimization problems. These models "allowed" householders to resettle to avoid unpleasant or negative conditions at their current locations and to search for better conditions at a new one. The new scenario thus maintained that an individual is influenced by local factors - state of the house, the ethnic and socio-economic structure of the neighborhood, distance to shops and transportation, among other things - but not by the average (or general) characteristics of the urban region in which her house is located.

To optimize a decision outcome, the householder should deal with all stages of residential choice simultaneously; if optimization is eliminated, we can break the process down into sequences of behavioral steps, each taking place in *time*. A typical choice process thus begins with assessment of one's residential situation, followed by the decision to attempt to leave; available alternatives are then investigated, their utility estimated and compared to that of the current location. All these result in the decision to resettle or to stay.

The *stress-resistance* approach (Wolpert, 1965, Brown and Moore, 1970, Spear, 1974, Phipps and Carter, 1984) formalized this view. In its standard application, householders take two basic steps, the first relates to the decision to leave the current location, the second to the decision to reside in the new location. At the first step, residents estimate the "stress" to move by comparing the current to the desired residential situation; if the stress is sufficiently high, they decide to move. At the second, those prepared to move estimate the "resistance" to moving by comparing available alternatives to their current location and then deciding either to relocate to one of the alternatives or to stay where they are. To avoid unnecessary associations with psychological stress, different authors have suggested the notions of dissatisfaction (Speare, 1974), utility (Veldhuisen and Timmermans, 1984), and *residential dissonance* (Portugali, Benenson and Omer, 1994). I adopt the latter in my description of the householder's situation.

The stress-resistance hypothesis had also compelled modelers to shift from the aggregate to the individual, that is, to the Agent-Based approach. Because householder stress, resistance, and choice-decisions are perceived as locally determined, images of the urban space must be sufficiently resolute to distinguish separate habitats. The ability to capture variation in householder and household characteristics likewise becomes crucial.

To verify the stress-resistance hypothesis, the economic and social factors that determine the householder's decision at each step of the choice process need to be identified. Speare proposed a natural classification of the factors that can determine the selection of a specific residence by a given householder (Speare, 1974, Speare, Goldstein and Frey, 1975). His categories have been incorporated as a basis for experimental research and consistently used since their formulation.

Speare, Goldstein and Frey (1975) assign decision factors to one of four categories: (1) individual, (2) household, (3) housing, and (4) neighborhood. This classification naturally fits the Agent-Based modeling scheme and can be extended if we wish to isolate factors related to higher levels of the urban hierarchy, such as time of trip to work, walking distance to the nearest commercial center, and so on.

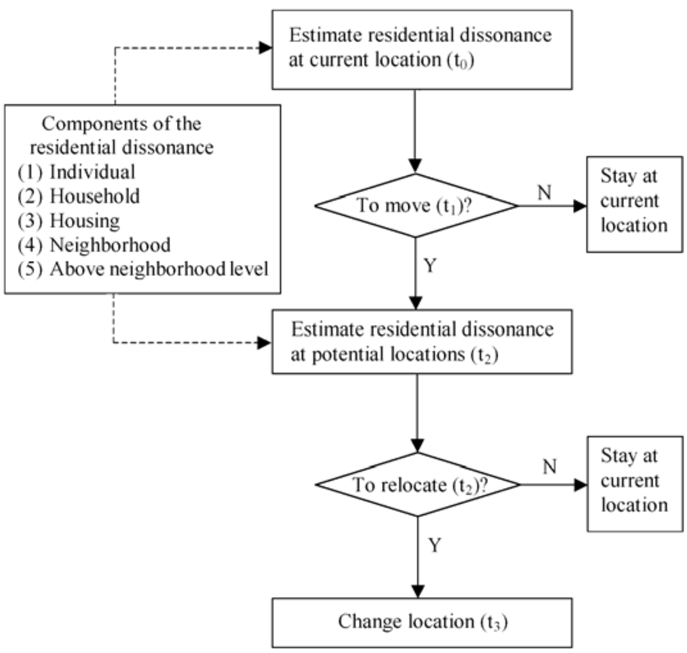

Figure 1 represents the stress-resistance hypothesis schematically; $t_0 < t_1 < t_2 < t_3$ denote consecutive moments of the *individual's time* sequence related to residential choice.

Figure 1. Stress-resistance hypothesis

Experimental studies of personal residential preferences

Two main approaches are used in experimental studies of residential choice. The *revealed preferences* approach utilizes real-world data on the outcomes of residential choice, while the *stated preferences* approach uses controlled experiments, where householders evaluate potential residences according to stated combinations of characteristics (Timmermans and Golledge, 1990; van De Vyvere, 1994). Revealed preferences tell us about real-world choices but can be biased by external constraints to making choices, such as lack of information about the dwelling. Alternatively, stated preferences reveal intentions; however, these may not necessarily be realized. Regarding model construction, the results obtained by the stated preferences approach help establish behavioral rules and their parameterization, while the revealed preferences approach helps verify the model.

The majority of studies published report experiments conducted within the stated preferences framework (van de Vyvere, 1994); there are fewer studies of revealed preferences, mostly due to difficulties in obtaining data (Timmermans and Golledge, 1990). Because the results of residential choice are qualitative in the main, the multinomial logit model is used as a basic tool for relating factors with choice outcomes; general statistical models are employed to account for factor hierarchies, latent variables, and so forth (Timmernams and van Noortwijk, 1995). The research demonstrates that many factors, all belonging to the categories in Speare’s taxonomy, are likely to significantly influence residential decisions (Phipps and Carter, 1984, van de Vyvere, Oppenwal and Timmermans, 1998: van Ommeren, Rietveld and Nijkamp, 1996; Fokkema and van Wissen, 1997; Molin, Oppenwal and Timmermans, 1999; Schellekens and Timmermans, 1997, Tu and Goldfinch, 1996):

- Householder: Age, Number of persons in a family, Economic status/Income, Ethnicity;
- Household: Size, Number of rooms, Floor, Costs of maintenance, Tenure;
- Housing: Type of house, Age of house;
- Neighborhood: Housing structure, Demographic structure, Ethnic structure;

- Above-neighborhood level: Distance to city center, Frequency of public transport, Travel time to work, Travel time to school.

For different groups of householders, specific characteristics may be important, such as loneliness and need for home care among persons aged 55+ (Fokkema and Van Wissen, 1997) or neighbors' ethnicity for minorities (Sermons, 2000)

Among the factors investigated, characteristics of housing and of the social structure and housing options in the householder's vicinity are usually somewhat more important than factors such as location of the house relative to other infrastructure elements or distance to shopping or public transport (Louviere and Timmermans 1990). Nevertheless, no factor is, a priori, more salient than the others (van de Vyvere, Oppewal and Timmermans, 1998); pairwise correlations usually remain within an interval (-0.2, 0.2), reaching ±0.4 in some cases. Taken together, the investigated factors explain, according to R^2, about 20 – 30 percent of the variance in residential choice.

The low level of overall fitness exhibited in choice experiments has dimmed the optimism inspired by statistically significant relationships although they continue to be intensively discussed. It is difficult to believe that salient factors have been overlooked in so many experiments. Are weak correlations sufficient to explain the observed urban residential distributions? Can we agree that essential components of a person's residential choice heuristics are irrational or that each type of stimulus induces a different type of response? Agent-Based models can help to answer these questions by direct interpreting qualitative assumptions and experimentally discovered stated preferences in terms of agents' behavioral rules.

From modeling of single choice to modeling of residential dynamics

Processes and factors beyond the standard framework of residential choice studies become important when we consider the population of householders and proceed to long-term modeling. Householders themselves change and make residential decisions again and again in evolving local and global circumstances. The stress-resistance approach ignores the recurrent character of residential behavior as well as the change in information available, initiated by changes in residential patterns, in- and out-migration, real estate markets, and other environmental conditions. The scheme displayed in Figure 1 is therefore incomplete in this respect and should be revised. Figure 2 demonstrates one way of doing so.

In this scheme, T represents time in an urban system; ΔT is a time interval between two consecutive observations of its state. In this paper, I do not discuss the meaning of “system state” and “system time” in relation to urban systems and base my arguments on an intuitive grasp of these notions (for an in-depth discussion see Nicolis and Prigogine, 1977; Allen and Sanglier, 1981, Haken and Portugali, 1995). In what follows, it is convenient to consider ΔT to be in the order of several months and to assume that $\Delta T >> t_3 - t_0$ that is, an individual makes decisions at a pace faster than she observes the urban system.

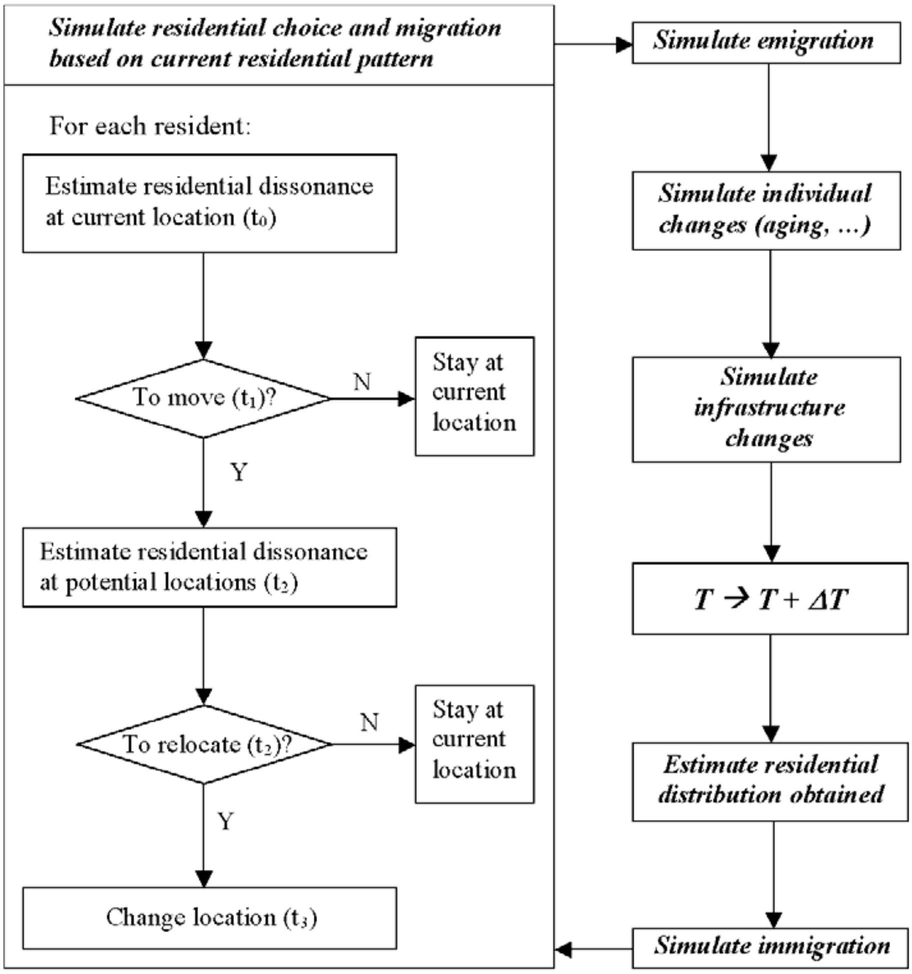

Figure 2. Agent-based description of urban residential dynamics based on stress-resistance hypothesis

Each component added to the residential dynamics scheme in Figure 2 could be elaborated into finer details. As our goal is to understand the long-term outcomes of residential choice rules, we can begin with the simplest demographic and infrastructure models or even set them as constant. Yet, from a systemic point of view, the outcome of a model can be complex because of limited capacity of an urban space. For example, the inherently competitive character of householder interactions entails *non-linear* reactions of the system as a whole; one can easily imagine these effects when the numbers of householders looking for dwellings within an attractive area is beyond the area's capacity to respond. For open and non-linear systems, self-organizing effects are to be expected, such as "sudden" increases in dwelling prices, emergence of fashionable areas, formation and dissolution of segregated residential patterns, all motivated by no clearly identifiable forces. Apparently, relatively simple urban systems exhibit this same kind of behavior (Benenson, 1999; Portugali, 2000).

Agent-Based modeling offers several conceptual advantages over regional modeling when implementing the scheme shown in Figure 2. First, its convenience for representing rules of residential behavior naturally extends to the representation of individual changes as well as in- and out-migrations. Second, the urban physical environment consists of separate spatial (but immobile) objects, just as populations consist of agents. The most popular high-resolution tool for modeling infrastructure dynamics is the Cellular Automata, which can be easily combined with Agent-Based models of individual behavior (Portugali, Benenson and Omer, 1997, Benenson, 1999, Portugali, 2000, Torrens, 2000).

In what follows, we use the simplest possible description of demographic and infrastructure processes and concentrate on the outcomes of repeated acts of residential choice.

The urban consequences of individual residential behavior

The factors in Speare's scheme are classified according to the level of urban hierarchy at which they operate. To analyze urban residential dynamics, it is important to distinguish between factors that influence residential choice but are not directly influenced by choice outcomes, and those that change together with the residential distribution. The characteristics of householders, houses, infrastructure, and in-migration do not directly follow changes in residential distributions and can be considered as *external* to residential distribution. Factors related to neighborhood structure act differently: A neighborhood's population directly reflects the residential behavior of the householders and should be considered as *internal* to residential distributions. Stated differently, a direct *feedback relationship* exists between neighborhood structure and urban residential distribution.

Examples of abstract models aimed at understanding the consequences of basic internal feedback relationships that entail the emergence and self-organization of urban segregation are presented first; models based on external factors are illustrated afterwards.

Agent-Based modeling of urban segregation as self-organizing phenomena

Residential distributions in cities populated by agents of two non-friendly types tend to display segregation. Two researchers, Thomas Schelling and James Sakoda independently published this basic result in the early 1970s (Schelling, 1971, 1974; Sakoda, 1971). They had no computers and played "urban games" on a chessboard, used to question the long-term consequences of individual tendencies to locate within friendly neighborhoods and to relocate when residential dissonance increases. Their models' assumptions and rules of agent behavior were intentionally primitive, namely, the chessboard was populated with constant numbers of agents of two types, say Black (B) and White (W), whose overall number was much below the number of cells. The cells themselves were set as designating location only. The residential behavior of the model agent was determined by the residential dissonance between the agent and her neighbors within the 3x3 square neighborhood around the agent's location. Schelling and Sakoda differed in the way they calculated local residential dissonance and formulated rules of agent reaction to dissonance. Sakoda (1971) defines the attitude - attraction (1), neutrality (0), or avoidance (–1) - of an agent to agents of her own and the other type; the agent reacts to the sum of attitudes to neighbors. Two versions of the model are considered: agents in both avoid representatives of the unfamiliar group; however, in the first they are attracted to the agents of their own type (Table 1.a) while in the second they are neutral regarding these agents (Table 1.b). Schelling's (1971) agents react to the fraction of familiar agents within the neighborhood, and also can be formulated in terms of attitude: agents are attracted by agents of their own type and neutral to agents of the other type (Table 1.c).

Table 1. Attitudes of agents to their neighbors

a. Sakoda I				b. Sakoda II				c. Schelling		
Agent type	Neighbor type			Agent type	Neighbor type			Agent type	Neighbor type	
	B	W			B	W			B	W
B	1	-1		B	0	-1		B	1	0
W	-1	1		W	-1	0		W	0	1

In Schelling's (1971) experiments, agents located in cells where less than half of their neighbors are of their own type migrates to the closest free cell, where the fraction of agents of their own type is above 50 percent. Sakoda (1971) assumes that an agent tries to optimize her state and repeatedly estimates her potential dissonance at each empty cell within a 3x3 square neighborhood. If vacancies better than the current one are found, an agent migrates to best of those options. Initially, agents are randomly distributed on the chessboard in each model; they make decisions in sequence, according to a preliminary order established in advance.

The main result of both papers is independent of the attitude scheme: B- and W-agents segregate after a number of migration loops and the residential patterns obtained does not change qualitatively in subsequent time periods. Thus, both models show that socially determined local residential preferences do result in full segregation in the long run.

Schelling's and Sakoda's basic result has been extended and generalized during the last decade, with computers replacing the chessboard. Hegselmann and Flache (1999) have applied the predecessors' choice rules on much larger grids. They reveal two additional effects after varying the number of urban agents and the agents' sensitivity threshold to their neighbors. First, they reveal qualitative differences in outcomes of the Sakoda I and Sakoda II models. In the case of mutual distrust (Sakoda I), agents of each type create many clusters (Figure 3a), while attitudes of avoidance only (Sakoda II) result in full separation of the two groups (Figure 3b); that is, uni-directional influences can induce sharper segregation than do bi-directional influences[1]. First, they demonstrate that the 50 percent threshold of familiar agents in the Schelling's model can be decreased: B- and W-agents segregate when an agent needs 30 percent or higher level of familiar neighbors, to initiate a search for housing (Figure 3c).

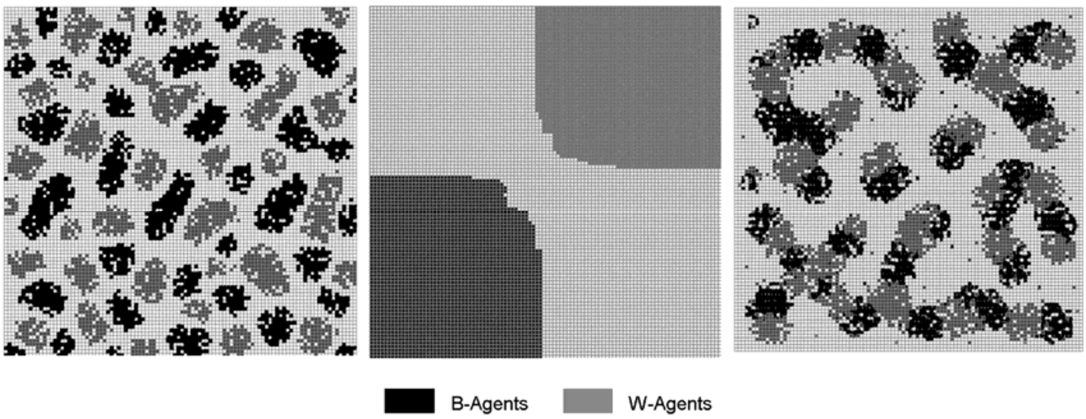

Figure 3. Typical stable spatial distribution of agents in Sakoda and Schelling models
a. Sakoda I model
b. Sakoda II model
c. Schelling model, 40 percent threshold

Portugali, Benenson and Omer (1994) extended Schelling's and Sakoda's models to cover more "human" agent behavior and more realistic city dynamics. First, they introduce the simplest forms of in- and out-migration; in doing so, they partially implement the scheme shown in Figure 2 (infrastructure and agent properties remaining constant). Second, they eliminate the deterministic view of householder behavior and assume residential choice to be a stochastic process. Formally, they introduced the probability to leave (P) or to occupy (Q) a residence H as a function of

[1] The ideas captured by the Schelling and Sakoda models are very rich and can be easily implemented. When preparing Figure 3, few experiments were sufficient to realize that the outcomes strongly depend on many factors ignored by the basic model - e.g., population density, behavior of an agent located

the agent's local dissonance D(H) at H, that is P = P(D(H)) and Q = Q(D(H)). The rule for calculating residential dissonance D(H) in their model is complimentary to Schelling's and Sakoda', that is, D(H) depends on fractions of familiar and unfamiliar agents within a 5x5 square neighborhood. Regarding dependencies P(D) and Q(D) on D, they assume that the probability to leave a location P(D) increases and the probability to occupy a location Q(D) decreases monotonically with an increase in D.

To make their computer agents closer resemble humans more closely, Portugali, Benenson, and Omer (1994) assume that the information on vacant residences available to an agent deciding to move is not limited to the agent's neighborhood. On the contrary, all residences in the city are potentially available to a migrating agent and she can reside at any distance from her current location. At the same time, access to this information is limited to a finite number (usually 10) of vacancies that an agent can consider during a unit of system time ΔT. At the occupation stage of residential choice, the probability of occupying each new vacancy is set inversely proportional to the agent's dissonance at each vacancy. One more humanizing assumption is that agents of the same type behave differently: Some agents of both B- and W-types avoid the agents of the other type (Sakoda II scheme), while the rest are neutral towards those same strangers and are attracted by the agents of their own type (the Schelling scheme).

The above generalization of the model strengthens the basic result of Sakoda (1971): to cause and maintain stable residential segregation, uni-directional avoidance is sufficient. Segregation is maintained if a substantial portion of agents of both types are neutral regarding strangers: two-thirds of the agents, whose behavior is aimed at avoiding agents of the other type, are sufficient to obtain segregation between B- and W-agents (Figure 4a). The stochastic nature of the residential decision embodies a new, important feature of the segregated residential distribution modeled: At the boundaries between segregated groups, agents are always in flux (Figure 4b).

within a fully occupied neighborhood, distance at which agents can relocate – all of which have to be investigated in depth.

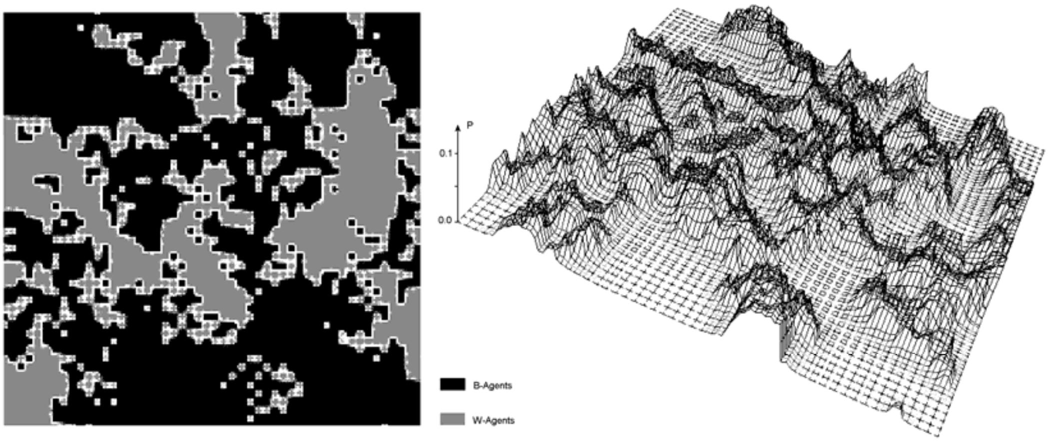

Figure 4. Typical stable spatial distribution of agents in the Portugali, Benenson and Omer (1994) model:

a. Distribution of agents
b. Probability that one agent can be substituted at the next iteration by an agent of the other type

Portugali, Benenson and Omer (1994) conclude that boundary areas are especially important if the agents themselves (like the humans they represent) change: agents with new properties enter the unstable areas first. The agents can enter the city from the outside, but they can also be residents who have altered their residential behavior. To further investigate the latter possibility, Portugali and Benenson (1997), Portugali, Benenson and Omer (1997) and Benenson (1998) assume that agents can adapt their residential behavior to local and global urban environments. They consider the situation where the information on the local and global environment available to an agent is in conflict with the incentives available for agent adaptation. Specifically, they assume that the longer a scarcity of vacant habitats (i.e., migration options) forces an agent to remain within a neighborhood occupied by unfamiliar neighbors, the higher the probability that the agent will change her attitude toward these neighbors from avoidance to neutrality. In opposite, the higher the average level of segregation of individuals of the agent's type over the entire city space (not necessarily proximate to the agent's location), the higher the probability that the agent's avoidance of unfamiliar neighbors will persist.

Long-term residential dynamics in such a model evidently depend on the relative strength of the two opposing inclinations. If the tendency to adapt to local conditions is much stronger, then all agents become neutral to one another and the residential distribution of agents according to initial B- and W-types becomes random. If the reaction to global situation (of segregation) is stronger, initial behavior is preserved and complete segregation of B- and W-agents is obtained in the long run. The most interesting case occurs when both tendencies are strong: a sufficient number of agents become *neutral* towards members of the types initially present, segregate and remain within the urban context (Portugali and Benenson 1995, 1997, Portugali, Benenson and Omer, 1997). If agents' adaptation is regarded according to *several traits* simultaneously, then the groups of agents bearing new properties will *recurrently* emerge and vanish (Benenson, 1998, 1999).

Abstract AB models elicit important qualitative conclusions regarding the internal factors motivating residential preferences and migration: first, permanent preferences to locate in friendly neighborhoods and/or avoid strangers are sufficient for urban residential patterns to (self-) organize; second, adaptation to the global state of the city entails emergence, persistence and segregation of agents possessing novel properties. Before we proceed to the model that combines internal and external factors in a real-world situation, the relative influence of the latter on rules of agent behavior should be verified.

Agent-Based modeling of residential reaction to the physical environment

To model the influence of the physical environment, data on the housing market should be incorporated into the model. Schellekens and Timmermans (1997) developed an Agent-Based simulation of residential choice aimed at comparing different rent subsidy policies. Model implementation differs for four different housing markets in Holland: four of the country's largest cities, other Dutch cities containing more than 100,000 residents, new towns, and other municipalities. Householders in the model are characterized by economic status, which does not change in time; residential decisions are based on household characteristics only and markets are set as static. The model is limited to global external factors and ignores the spatial distributions of the habitats and the residents. For each market considered, it reveals likely and significant differences in the fraction of migrants and buyers, mean price of apartment, fraction of subsidized persons, amount of subsidy, and monthly rent in a subsidized versus a non-subsidized situation.

The agents in Schellekens and Timmermans (1997) model are purely mechanistic in their perception of the spatial situation as averaged over the entire city; their “human” characteristics are reflected by the rule, according to which they select one specific habitat from the several options available. In the abstract models previously noted, choice is *parallel* and wholly rational – agents are cognizant of all the options before they decide which to select; the probability that a habitat will be chosen, is set inversely proportional to dissonance between the agent and that habitat. Schellekens and Timmermans (1997), however, follow another – less rational and more human – *sequential* choice heuristic. The householders in their model examine available vacancies when they become available; if the first available vacancy is accepted, the choice procedure is cancelled; otherwise, the second vacancy is examined, and so forth. Sequential choice reflects the satisficing hypothesis of human choice behavior (Gigerenzer and Goldstein, 1996) and, as Benenson, Omer and Hatna (2002) demonstrate, essentially increases robustness of the system dynamics to changes in numerical values of the model parameters. It is applied in the real-world model of residential dynamics in Yaffo below.

The rule of selection is unimportant for classical regional models, where the number of newcomers of different types into a region is determined by the capacity to develop dwelling infrastructure. If physical environment strongly governs the social structure, a regional model can provide good approximations and predictions of urban residential dynamics. This seems to be the case in the van Wissen and Rima (1988) model, which represents Amsterdam by means of 20 dwelling zones. In each zone, 11 dwelling types and 24 types of households of four different sizes are distinguished. The intensity of migration and the residential choice of each family are dependent upon the age of the head of household (according to five-year age categories) and on the number of family members (seven categories). Immigration, emigration, births, and deaths are included. The model’s parameters were estimated on the database for 1971 – 1984. The resulting approximation of population and household dynamics was very good: for thirteen zones, the R^2 statistics of correspondence between actual data on population structure and model results are higher than 0.9; for the remaining zones, excluding one, it is not less than 0.5. Based on these correspondences, two scenarios of Amsterdam population and household dynamics for 1985 – 2000 are compared. The first reflects central government plans to build new dwellings in Amsterdam, while the second reflects local government measures to decrease construction quotas in the expanding suburbs, which diverge at the level of 10 percent or less during the period studied.

The van Wissen and Rima model (1988) still remains an outstanding example of exceptionally good approximation. The Batty and Longley model (1994) exhibits a common level of approximation for population dynamics in Greater London. In the model, the city is divided into 32 zones, each described by percentages of dwellings of four types. The probabilities of occupying dwellings of each type are considered as functions of the distance between the CBD and the zone, and the mean age of the zone's dwellings. The overall percentage of the model's correct predictions, 0.432, is essentially lower than in the Amsterdam model. Spatially, prediction is much better for zones close to the CBD and for the outermost suburbs than for the intermediate zones.

To conduct a full study of the consequences of residential choice and migration for urban systems, we have to combine internal and external factors, which require high-resolution data on demography and infrastructure. The latter was unavailable until the 1990s; recent developments in GIS and census databases have corrected this situation. The remainder of the chapter is devoted therefore to a recently developed Agent-Based model of residential migration in the Yaffo area of Tel-Aviv, where we account for the influence of one internal and one external factor on residential choice. The detailed analysis of this model is presented in Benenson, Omer and Hatna (2002); here it is used to illustrate the implementation of the AB modeling approach in a real-world situation.

A Real-World Agent-Based Model of Residential Choice and Migration

The model presented here simulates the residential dynamics (1955-1995) of Yaffo, an area lying in the southern reaches of Tel-Aviv and populated by Arab and Jewish householders. The model scheme resembles that shown in Figure 2; for the present purposes, the model components that do not directly relate to residential choice and migration are severely simplified (see description below).

Why Yaffo?

The selection of Yaffo for construction of a real-world model of residential dynamics is not random. First, one can assume that ethnicity induces the residential behavior of Yaffo agents, and that the relationships between the agents, representing Arab and Jewish householders are similar to the theoretical attraction-avoidance relations explored above. Second, quite a lot is known about Yaffo's infrastructure: during the Israeli Census of Population and Housing of 1995, high-resolution GIS coverage of streets and houses was constructed and released for all Israeli cities, including Tel-Aviv (ICBS, 2000). Hence, individuals in the ICBS database are precisely geo-referenced: personal and family records of each person indicate the house where the person lives. The individual census record contains age, education, origin, ethnicity, marital status, salaried income, and many other characteristics of the individual effective for 1995. The family record contains data on the house and the residence – the householder's estimate of the year the house was built, number of rooms in the apartment, home appliances, travel time to work, and so forth. The individual data are available for supervised study in the Israeli Central Bureau of Statistics (ICBS) offices; furthermore, the model is calibrated, based on characteristics of Yaffo's residential distribution calculated from these data.

Yaffo's infrastructure

Yaffo covers about 7 km^2; its infrastructure was set in the early 1960s, when the majority of Yaffo's buildings were constructed. The GIS layers of houses and streets, constructed in 1995, are used as proxies for the entire 1955-1995 period, further proliferation of the infrastructure dynamics is avoided. Figure 5 presents the GIS view of Yaffo; houses are marked according to their architectural style, which enables use of this characteristic in the model. The architectural style of about 90 percent of Yaffo's buildings can be characterized as either "oriental" or "block", with the remaining 10 percent approaching one of these two styles; architectural style of a building (S) is defined as a continuous variable whose values range from 0 (oriental) to 1 (block). Only residential buildings are taken into account; the dwelling capacity of a building is estimated by the number of floors and the foundation area, assuming that average apartment area in Tel-Aviv covers 100 m^2.

Yaffo's demography

According to ICBS data, Yaffo's population in 1995 was about 40,000, composed of a Jewish majority (about 70 percent) and an Arab minority (the remaining 30 percent). After Israel's War of Independence (1948), only 3,000 of the original Arab inhabitants remained in Yaffo, almost all of whom were concentrated within the small neighborhood known as Adjami (Portugali, 1991; Omer, 1996). Beginning in 1948, the Arab population of Yaffo grew and spread throughout the area, whereas the Jewish majority declined by gradual out-migration. Precise percentages of the Arab population in Yaffo are available: 1961 – 10 percent, 1974 – 15 percent, 1985 – 25 percent and 1995 – 32 percent.

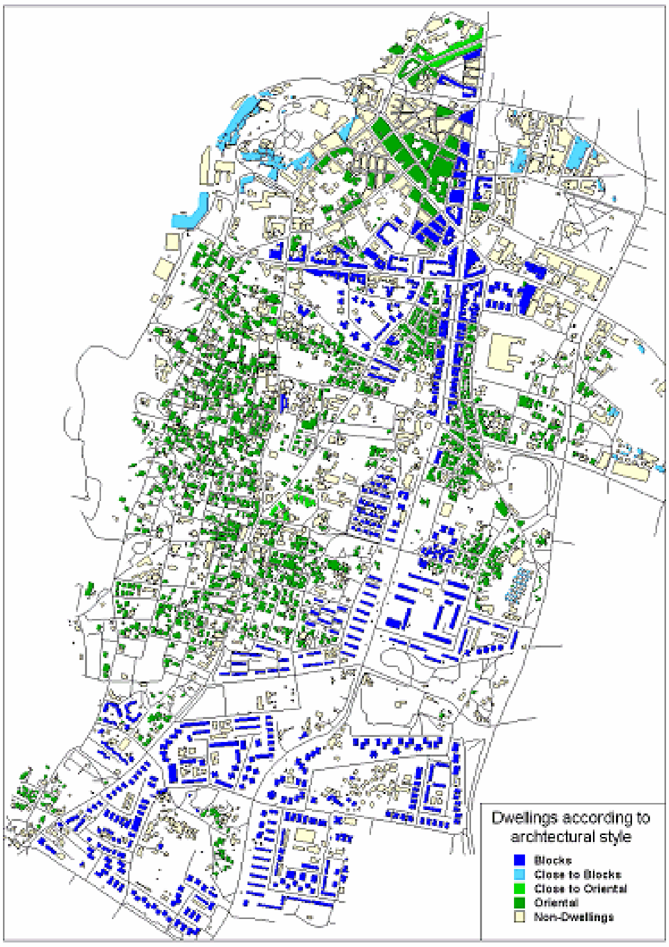

Figure 5. Yaffo at the resolution of separate houses, levels of gray indicate architectural type

The fraction of ethnically mixed families in Yaffo is below 1 percent (ICBS, 2000). The Arab population of Yaffo is divided into two major cultural groups – Muslims and Christians; the differences in their residential behavior are inconsequential for present purposes, and are thus ignored.

Factors determining residential choice in Yaffo

Direct data on the residential preferences of Yaffo inhabitants are not available. According to indirect evidence (Omer, 1996; Omer and Benenson, 2002), two factors, namely the Jewish/Arab ratio within the neighborhood and the architectural style of the buildings, can be considered as influencing the residential decisions made by Jewish and Arab agents in Yaffo. The 1995 distributions of salaried income for Yaffo's Jews and Arabs are similar (Benenson, Omer and Hatna, 2002); hence, the two factors of householder income and housing price are dispensed with here.

Neighborhoods

To determine the dissonance between an agent and her neighbors, "neighborhood" must be defined. The neighborhood for Yaffo's residential buildings is constructed according to a Voronoi tessellation[2] of the built area on the basis of house centroids (Benenson, Omer and Hatna, 2002, Halls et al, 2001); two buildings are considered as neighboring if their Voronoi polygons have a common boundary and they are on the same side of the main road (Figure 6).

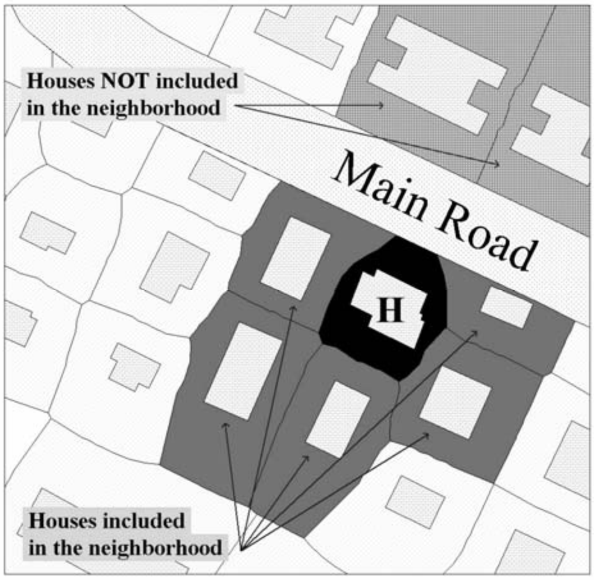

Figure 6. Definition of the neighborhood of the house H via Voronoi polygons

Quantification of residential dissonance

Based on qualitative estimates of Omer (1996), six different levels of residential dissonance are defined qualitatively for unmixed situations of the relationship between an agent and her local environment. These levels are then quantified as a stochastic variable; Table 2 presents average D_i, its standard deviation calculated as

[2] An algorithm of Voronoi tessellation divides a plain into polygons, one for each building. A Voronoi polygon of a given building contains it and all points for which the building is the closest one (Halls et al, 2001). Voronoi tessellation is popular in geodesy and can be constructed by add-ins supplied with most desktop GIS. Usually, the algorithm's implementations account for constraints: open spaces can be excluded from Voronoi coverage; streets can be made boundaries of the Voronoi polygons, and so on.

$STD_i = 0.05 * \sqrt{(D_i * (1 - D_i))}$, and 95 percent confidence intervals for each level i. Let us assume, for example, that the dissonance between an Arab agent located within purely Jewish neighborhood and her neighbors is "high". Her decision to leave will then be based on a dissonance value selected from the normal distribution with mean 0.8 and standard deviation 0.02.

Table 2. Residential dissonance estimates

Dissonance level	Zero	Very low	Low	Intermediate	High	Very High
Average value	0.00	0.05	0.20	0.50	0.80	0.95
Standard deviation	0.000	0.011	0.020	0.025	0.020	0.011
95% confidence interval	(0.000, 0.000)	(0.029, 0.071)	(0.161, 0.239)	(0.451, 0.549)	(0.761, 0.839)	(0.929, 0.971)

Dissonance between an agent and a household and between an agent and her neighbors

As shown in Table 3, for unmixed situations it is assumed that:

- Arab agents strongly avoid houses that are block and prefer houses of oriental architectural style; Jewish agents prefer the newly built block houses, although they accept oriental houses
- Arab and Jewish agents strongly avoid homogeneous neighborhoods populated by agents of the other type; avoidance of Arab agents by Jewish is maximal

Table 3. Initial estimate of the dissonance between an agent and a house (D_h) and between an agent and a homogeneous neighborhood (D_p). Values in italics stand for changes applied in "Arab Assimilation II" scenario.

	$D_h = D_h(A, H)$		$D_p = D_p(A, U(H))$	
Agent's identity	House's architectural style		Neighbors common identity	
	Oriental (S = 0)	Block (S = 1)	Arab – $U(H)_R$	Jewish – $U(H)_J$
Arab - A_R	Zero	High (*Low*)	Zero	High (*Low*)
Jewish - A_J	Intermediate	Zero	Very High	Zero

Residential dissonance for mixed situations is linearly interpolated based on estimates set up for the unmixed ones. The dissonance $D_h(A_E, H_s)$ of an agent of identity A_E regarding dwelling in a house H of style S is calculated as

$$D_h(A_E, H_s) = D_h(A_E, H_0) * (1 – S) + D_h(A_E, H_1) * S \qquad (1),$$

where A_E is either A_J or A_R; H_0 stands for a house of oriental and H_1 of block style.

For a mixed neighborhood $U(H)_r$ with fraction r of Arab agents (and 1 - r of Jewish agents), the dissonance regarding neighbors is calculated as:

$$D_p(A_E, U(H)_r) = D_p(A_E, U(H)_J) * (1 - r) + D_p(A_E, U(H)_R) * r \qquad (2),$$

where $U(H)_J$, $U(H)_R$ stand for homogeneous Jewish and Arab neighborhoods respectively.

The overall dissonance $D(A_E, H_s, U(H)_r)$ between an agent of identity A_E located in house H_s of style S within a neighborhood $U(H)_r$ having a fraction of Arab agents r is assumed to be high if it is high according to any one of its components:

$$D(A_E, H_s, U(H)_r) = 1 - (1 - \alpha_h * D_h(A_E, H_s)) * (1 - \alpha_p * D_p(A_E, U(H)_r)) \qquad (3),$$

where α_h, $\alpha_p \in [0, 1]$ denote the influence of house style and ethnic factors.

Rules of residential choice and migration

An agent's residential choice and decision to migrate do not depend on distance but on residential dissonance only. A three-step algorithm represents residential choice and migration of the Yaffo model agents.

Step 1: Decide to migrate. The probability P that an agent A will decide to move linearly depends on overall residential dissonance D at the agent's location:

$$P(D) = P_0 + (1 - P_0) * D \qquad (4),$$

where $P_0 = 0.05$ is probability of sporadic departure. If the decision is to move, A is marked as a potential migrant; otherwise, agent A remains at her current location (with probability 1 – P(D)) and is ignored till the next step in time.

Step 2: Scan residence. Each potential migrant A randomly selects 10 houses H_v, $v = 1 \div 10$, from the set of houses currently containing vacant residences. The probability

$Q_v(D)$ (attractiveness) that agent A will decide to occupy vacancy v is calculated for each selected residence H_v as complementary to the probability to leave (4):

$$Q_v(D) = 1 – P_v(D) = (1 - P_0) * (1 – D_v) \qquad (5).$$

where D_v is dissonance at potential location H_v.

Step 3: Occupy one of the scanned dwellings. An agent A sorts information about all vacancies H_v according to their attractiveness $Q_v(D)$. After the sorted list of opportunities is constructed, A attempts to occupy the most attractive vacancy H_{best} with probability $Q_{best}(D)$; if A fails to occupy this vacancy, she turns to the second-best option, and so on.

Migration into and out of the city

Jewish or Arab potential migrants failing to resettle either leave the city with probability L_J (for Jewish agents) or L_R (for Arab agents) or remain at their current residence with probability 1 - L_J or 1 - L_R. We assume that L_J = 0.1 per month and L_R = 0.01 per month, that is, L_R is ten times lower than L_J. The factor 10 represents the ratio of areas available for resettlement of Jewish and Arab householders in Tel-Aviv, the latter having about 10 times fewer options for resettlement than the former.

Based on partial data obtained by Omer (1996), the number of individuals who attempt to settle in Yaffo for the first time is set at 300 householders (natural increase and in-migration combined), with the ratio of Arabs to Jews equal to 1:2. The actual number of new householders remains below 150 per year in all model scenarios studied. Agents who failed to enter Yaffo do not repeat the attempt.

Initial population distribution

According to Omer’s (1996) data for 1955, Yaffo’s 3,000 Arab residents were located in Adjami neighborhood. In that year, full capacity of Adjami was three times higher and Jewish householders populated the balance of the dwellings in Adjami as well as the remainder of Yaffo’s territory (Figure 7).

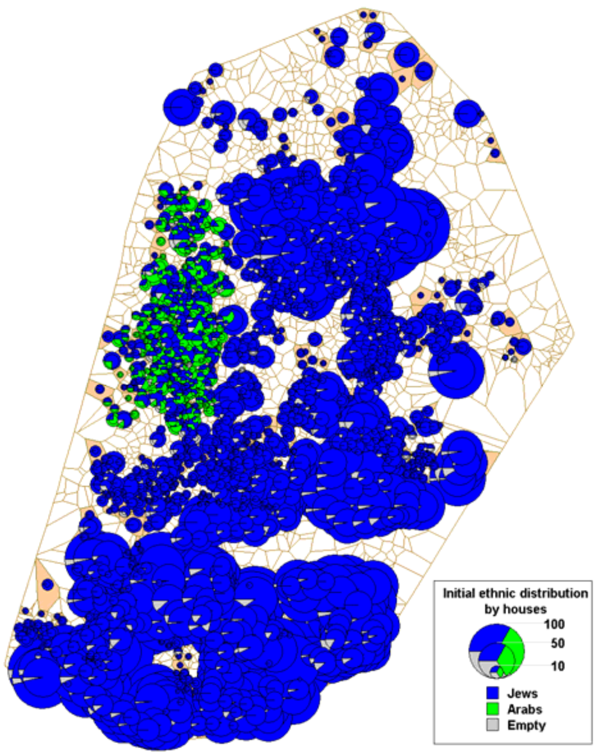

Figure 7. Initial (1955) distribution of Arab and Jewish agents in Yaffo model

Evaluation of the model

The Yaffo model is calibrated by changing coefficients α_h, α_p in (3) and by varying the attitude of agents from each ethnic group toward houses of an unfamiliar type or an unfamiliar neighborhood; the initial values are shown in Table 3. The model results are then compared with the reality in Yaffo according to four characteristics:

1. The fraction of Arab population, present in 1961, 1974, 1985, and 1995.
2. The level of segregation of Arab and Jewish agents as estimated by means of Moran index I of spatial autocorrelation (Anselin, 1995) at the resolution of buildings.
3. The non-correspondence of the population with the architectural style of the buildings.
4. The annual fraction of householders leaving a residence within Yaffo's boundaries.

The best correspondence is achieved with a scenario of low influence exerted by both factors explored (α_h = 0.05 and α_p = 0.05) and the tolerance of Arab agents adjusted two levels higher than initially suggested. In this "Arab Assimilation II" scenario, the dissonance between Arab agents and purely Jewish neighborhoods and "block" houses is set "Low" instead of "High", as marked by italics in Table 3. Table 4 and Figure 8 present the correspondence between real data and this scenario for 1995 and during the entire period of simulation. Confidence intervals of model characteristics are estimated based on 100 model runs under identical conditions.

Table 4. Characteristics of Yaffo's population distribution in 1995 versus the most likely scenario of "Arab Assimilation II" in model year 40

	Yaffo data	Model mean*	Model 95 percent confidence interval*
Overall percentage of Arabs agents	32.2	34.8	(34.4, 35.2)
Moran index I of segregation for Arab agents	0.65	0.66	(0.63. 0.69)
Percentage of Arab agents in block houses	18.5	15.0	(12.8, 17.2)
Percentage of Jewish agents in oriental houses	28.1	8.0	(6.7, 9.3)
Annual percentage of migrants	3.5	3.7	(3.5, 3.9)

*Based on 100 runs

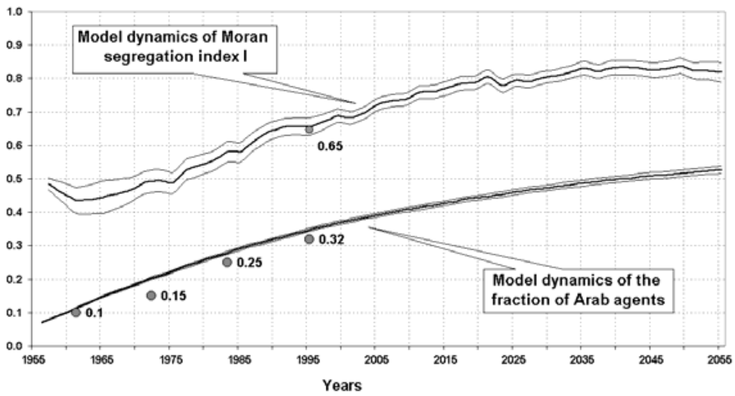

Figure 8. "Arab Assimilation II" scenario: Model dynamics of the fraction of Arab agents and of the Moran index I for the Arab population

The good correspondence between reality and the model in the case where Jews only experience dissonance within Arab neighborhoods coincides with the results of the theoretical models. Both in theoretical and the Yaffo models, if members of one group only either avoid strangers, or prefer members of their own group as neighbors, then residential segregation occurs. The "common sense" view that two-sided competition is necessary for segregation to take place is shown to be irrelevant.

Spatial determinism of Yaffo's residential dynamics

Table 4 and Figure 8 demonstrate global correspondence between the model and Yaffo reality. The Agent-Based approach makes it possible to investigate the finer properties of the residential distribution. The stochasticity of the model is extremely important in this analysis as represents the uncontrolled variation of the local factors to which the agents react. To test the 'inevitability' of the residential distribution observed in Yaffo, maps representing the probability that the fraction of Arab or Jewish agents in a house is above a given threshold F = 0.9 are constructed based on 100 runs of "Arab Assimilation II" scenario (Figure 9).

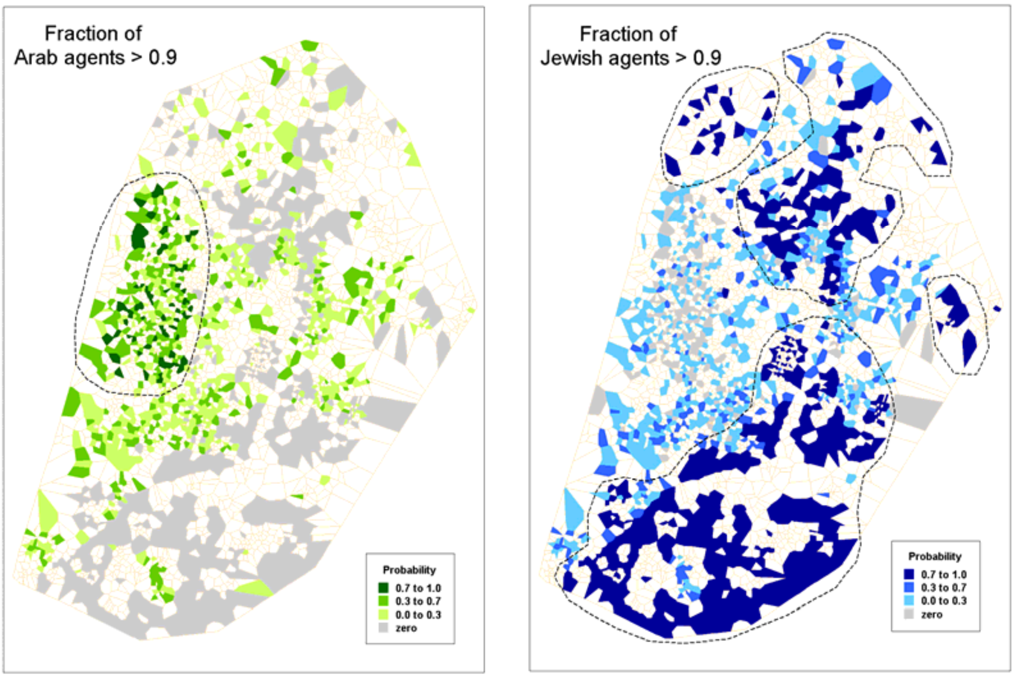

Figure 9. "Arab Assimilation II" scenario: probability maps for F = 0.9. Contours mark areas where the sensitivity of the results to local effects is low.

a. Probability that the fraction of Arab agents in a house is above 0.9
b. Probability that the fraction of Jewish agents in a house is above 0.9

These maps clearly indicate the areas where the variation in local processes have weakly influenced residential dynamics between 1955 and 1995; these areas contain about 80 percent of Yaffo's populated houses. The variation in the fraction of Arab agents in each house in the 'Arab' part of Yaffo area is higher, both relatively and absolutely, that in the Jewish part. That is, the Arab area is more responsive to factors that the model does not account for. The ethnic structure within the houses over the remaining fifth of Yaffo's area is very sensitive to its agent's residential behavior; hence, it could be strongly influenced by other factors external to the model. The specific behavior of the human agents in these local areas – for instance, exaggerated reactions to the strangers and housing constructed for one specific population group - may have significantly influenced residential choice and resulted in Yaffo's unique residential distribution.

Discussion

Despite the limited number of implementations, I believe it appropriate to pose the basic question regarding the Agent-Based approach: Is it a step forward, one that provides social science with a truly adequate modeling tool, or is it merely a product of fashion? With respect to the modeling of residential behavior, I would argue that the former is true:

The concept of agent makes it possible for the model to directly reflect human behavior.

AB models naturally reflect human capacities to perceive and react to information on different levels of the urban spatial hierarchy, to assess opportunities (vacant dwellings) before making a decision, to sort opportunities before exploring them on site, and so forth. All these cannot be directly projected onto the aggregate level; the concept of agent thus allows us to avoid problems related to the scale at which we observe social processes.

Agent-Based models do not demand comprehensive knowledge of the phenomena studied.

Changing the rules of residential behavior does not demand changing relationships between AB model components. This flexibility is a crucial asset for investigating different versions of the choice mechanism; we can begin with the simplest rules of agent behavior and increase their complexity while preserving the model's structure. For example, to study the economic aspects of residential choice in Yaffo, we can add prices to characterize dwellings, economic status to characterize agents, and revise the estimate of the residential dissonance to account for these characteristics; the other components of the rules of residential choice and migration will demand neither modification nor updating.

Formalization of behavioral rules reveals gaps in our knowledge of social processes. The ability to vary formal representation of agent behavior will reveal gaps in our knowledge. As the residential models reveal, further research on choice heuristics - and not one more study of residential preferences - will make a more significant contribution to our understanding of urban residential dynamics.

Self-organizing consequences of human behavior can be investigated directly.
Many urban phenomena are outcomes of local disturbances whose significance is recognized only long after the event. In the AB model framework, information regarding local changes in residential variables is made available to agents and collective urban phenomena can be investigated directly through the study of the spatial outcomes of the model. The AB model's ability to reflect local indeterminacy opens the door to investigating urban self-organization and emergence at different spatial and temporal resolutions. Urban space itself integrates various sources of knowledge about social processes on the one hand and physical environment on the other. The maps of residential trends in Yaffo illustrate this point.

These conclusions are to be considered within the framework of rising standards of population census taking that make available the high-resolution geo-referenced urban data necessary for constructing Agent-Based models. The Israeli Census of Population and Housing of 1995 (ICBS, 2000) demonstrates this trend. AB modeling makes possible *dynamic description* of the situations described by the census. It therefore enables explicit assessment of social and economic trends as well as the consequences of proposed planning decisions.

One final question should be asked: Does Agent-Based modeling invalidate the traditional regional paradigm? The response: Surely not! It remains an open question to what extent specific regional and AB model can be related *formally* whether by disintegrating the parameters and interpreting the equations as if they were behavioral rules applicable to human agents and infrastructure objects, or visa versa, by integrating parameters and individual behavioral rules. It is clear, however, that the need to do so will eventually be salient, once we have formulated explicit ideas regarding the part played in urban dynamics by human factors — local interactions, short- or long-term expectations, processing of distant and incomplete information and of information pertaining to higher levels of the urban hierarchy, to name but a few. My prognosis is that in the future, students of urban dynamics will use Agent-Based and regional models *simultaneously* (see van Dyke Parunak, Savit and Riolo, 1998 and Wilson, 1998 as initial examples of this trend). The outcomes of the regional and AB models developed for the same situation should be compared; the differences will indicate when, where and how human factors are important for the system.

Acknowledgements

The results presented in this chapter were obtained in part during the work performed in common with my colleagues, Prof. Juval Portugali, Dr. Itzhak Omer, and Mr. Erez Hatna; I am grateful for their assistance and fruitful comments. Thanks to Ms. Nina Reshef for valuable comments and language editing. Mr. Erez Hatna helped in preparing Figures 8 and 9. Development of Agent-Based model of Yaffo residential dynamics was supported by a research grant provided by Israeli's Ministry of Science.

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