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Modeling Urban Growth: An Agent Based Microeconomic Approach to Urban Dynamics and Spatial Policy Simulation

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Abstract: Spatially explicit and dynamic urban growth models provide valuable simulations that encapsulate essential knowledge in planning and policy making such as how and where urban growth can occur and what the driving forces of such changes are. Agent Based Modeling (ABM) yields a useful framework for

functions, supply side behavior is only implicitly considered in this model. Land is assumed ready for residential use without any extra conversion costs. Absentee landlords accept the highest possible bid which is same as the maximum rent that a household can pay for. In short, there is no lag or disequilibrium in this market clearing process. Moreover reserved agricultural land rent is not defined in this model. If the reserved agricultural rent were to be set, then transportation cost determines the size of residential expansion in a general bid rent approach. If the reservation bid rent for agricultural land is omitted, the city grows as long as there is in-migration and land available for development. As a result, agricultural land is not ‘protected’ by a market mechanism in this case, and there is no optimal growth limit to the city. Instead the growth limit imposed by agricultural rent constrains total urban growth as a kind of exogenous variable in this model. In this way, the model links with macro level demand or with external forces affecting urban growth. Indeed, this kind of approach to urban growth has been developed and is well described by the constrained cellular automata urban land use models developed by Engelen et al. (1997) and White et al. (1997).

In summary, micro level local behavior is defined by short run utility maximizing location choice in a bid rent function. Urban growth is attained as a sequence of such decision-making in an agent based modeling framework. On the other hand, macro level global system behavior is not subject to endogenous market equilibrium conditions. It is collective agent behavior on one hand and the location and magnitude of spatial heterogeneity on the other hand that shape global system behavior and spatial configurations. Such spatial heterogeneity is assumed a priori, but here the government agency is also assumed to dictate spatial heterogeneity through zoning regulation or transportation development.

3. THE MICROECONOMIC MODEL

3.1 Basic Residential Location Choice

The basic behavior of household is a simple reproduction of conventional residential location choice. A household is assumed to use a standard Cobb-Douglas utility function for two types of goods and thus maximizes its utility subject to the budget constraint:

$$\mathrm{Max}U = g^{\alpha} h^{\beta}, \quad \alpha = 1 - \beta \tag{1}$$

$$y = g + hs + td \tag{2}$$

where g is the consumption of a non spatial composite good (or numeraire), h is rent for housing, s is the size of housing land/plot, and t represents the transportation cost which proportionally varies with distance to the CBD. α and β are the elasticity parameters.

The first rule in a utility maximization problem is to yield optimal solutions for the numeraire good g and housing size s, which are given by substituting the MRS (marginal rate of substitution) into budget constraint (2), that is

(3)

(4)

Substituting the optimal consumption bundle of g and s into the utility function (1) yields an indirect equilibrium utility function:

(5)

Then the location specific bid rent for a household at $location_{xy}$ can be written as:

(6)

In this standard monocentric model, a household faces a trade-off between transportation cost and land rent. Thus the bid rent always decreases as distance from CBD increases. The resulting spatial structure is based on concentric circles of differing land rent and hence land use around the CBD.

3.2 Extensions with Local Externalities

A notable extension of the standard monocentric model is achieved by considering location specific neighborhood characteristics and local externalities. The types of local externalities affecting residential location choice include natural environmental factors such as green space, population density and composition, and public goods. Such externality effects can be either positive or negative, and this model deals with both cases starting with the former.

The effect of a local externality and varying neighborhood characteristics are first incorporated as an argument into the residential location choice model. The residential utility function with the local externality E can thus be described as:

(7)

Solving the utility maximization problem with budget constraint (2) yields the location specific bid rent at $location_{xy}$ with local externality effect as follows:

(8)

To define the local externality function, we adopt and modify the local amenity function used by Wu and Plantinga (2003). The positive local externality level at a $location_{xy}$ in this context is defiiE6258.64 ( )102e57.-8(i)6(l)6(i26(i)ET)2(6(i)TdFigu(i)e3hT4d.(rei)69(y)47(

The above function gives a positive relationship between proximity to the local externality and the bid rent which increases as the distance to local externality decreases. The result raises land rent around the location of the positive externality and the polycentric residential agglomeration that results. Relevant spatial patterns will be presented in a two-dimensional physical simulation environment in the next section.

While the effect of a local externality is usually examined in the above positive sense, this study further modifies the externality function and suggests a function of negative externality[1]

(10

for train, and t_{cn} denotes the total cost for combined use of car and train. In a similar vein, d_c is the distance to the CBD and d_{cn} represents combined distance to a transit station and the CBD. The commuting cost for train can be treated either as lump sum or unit cost per distance, but it is treated as the former in this paper.

This function can also return physically polycentric urban forms even in its functionally monocentric configuration. If the commuting cost with train is cheaper than that with the automobile, then the bid rent price near transit station is higher and the transit capitalization effect occurs. However, the magnitude and size depend on the actual transportation cost and its elasticity. If nothing else is considered, cheaper train costs tend to result in a larger local agglomeration effect around the transit station.

4. SIMULATION IN AN ABM FRAMEWORK

4.1 The Theoretical Simulation

Now consider a Euclidean grid space f^2 with a horizontal dimension X = 50 and vertical dimension Y = 50 from the origin (0, 0). Suppose that a von Thünen style single point CBD is located at ½* X and 4/5*Y. Space is featureless except for the local externalities where the location of each externality will be given in each simulation.

In these theoretical simulations, only one agent enters the space to find housing location at each time step and the agent makes a location choice based on the functions defined in the previous section. The lot size is fixed to a single cell. Thus the cell is a spatial unit for urban conversion at each time step. The consecutive entrance of an agent and the cumulative settlement thus represent dynamic urban residential growth.

The location choice in a two dimensional space with an agent based modeling framework requires additional configurations regarding the initial location of agent and its search/movement range (in terms of its neighborhood configuration). The initial location of an agent may or may not have an influence on the simulation result, depending on the neighborhood configuration. If an agent has scope for an unlimited search, i.e. the neighborhood configuration is as big as the size of entire space, the initial location does not affect the simulation result. In this case, an agent can search for ‘the best location’ in the entire space at one time step. However, if an agent has a limited neighborhood configuration, it can find the best location only within its search scope. In fact, we use a concentric neighborhood configuration with a radius of 8 cells – a total 64 cells from the location of agent. The neighborhood size is thus adjustable as a model parameter, but this is subject to the compute power available for the simulation and in very big cellular systems this might impose some limits. This point will be discussed in more detail later.

Parameter values used in the theoretical simulation are described in Table 1. As mentioned before, different preference values result in different spatial configurations. Defining such values is an empirical question, and possible variations with regard to the parameters are not explored in this work. It rather focuses on the effects of spatial heterogeneity with neutral parameter values.

Table 1: The Value of Parameters

Parameter	Value
.	0.5
	0.5
	0.5
,	1
y	1000
t_a	2
t_t	10

Simple Monocentric

The first simulation presents a standard monocentric growth without any local externality effect. In this well-known condition, urban form is always concentric with respect to the CBD. Urban structure keeps the same form with different volumes of development over time (t=500, t=1000, t=2000).

t = 0 t = 500 t = 1000 t = 2000

Figure 1 Monotonic Urban Growth

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Figure 2 Leapfrog and Assimilation

Negative Local Externality

Instead of previous positive externality, a negative local externality is introduced at the same point ½*X and Þ*Y In this case the bid rent decreases as the distance to the externality increases. As a result, the existence of

Multiple Transportation

This simulation investigates the effect of a new transit station which implies the notion of transit oriented development (TOD). Consider a station that is introduced at the point of ½*X and Þ*Y. As discussed before, this diversifies the number of transportation modes and changes the location specific transportation cost. At the beginning of the simulation, the city grows from its immediate surroundings in the CBD as typical in a monocentric configuration. However, as the city expands, polycentric urban structures emerge (t=500), with physical patterns similar to that of the positive externality case. But the driving force here is reduced transportation cost around the station and transit capitalization benefits. Thus this simulation reveals a different urban growth path. Unlike the local externality effect, two urban agglomerations evolve together (t=1000). With no global equilibrium mechanism and threshold for agricultural rent, these are eventually merged together but retain their own form (t=2000). Thus it can be inferred that this type of urban development can lead self-sustaining urban forms. The relative size of the two urban agglomerations depends on the difference between transportation cost for automobiles and public transit. This effect of transit development can also be combined with various types of positive and negative externalities, and it can explain why proximity to transportation nodes does not always return the higher land price in those cases.

t = 0 t = 500 t = 1000 t = 2000

Figure 5 Leapfrog and Conurbation

Zoning Regulation

The greenbelt, sometimes called the growth boundary, is one of the most powerful planning regulations on urban development. The effect of course varies by shape, thickness, and location of greenbelts (Brown et al. 2004, Wu and Plantinga 2003). However, this simulation argues that its effect also depends on what is outside the greenbelt. It captures the effect of greenbelts under different spatial arrangements at the same time stage (t=1000). In a monocentric setting, (a) the greenbelt blocks expansion of city to a certain extent. The blocked urban growth expands to its left and right sides. In case of a positive externality, (b) the greenbelt allows leapfrogging development from an early stage. It shows that the greenbelt may protect open space within the designated area, but it cannot stop the sprawl if a positive externality exists outside the belt. If a negative externality exists, (c) the city does not reach the boundary of the greenbelt at the same time steps. In this case, the greenbelt has no particular effect on stopping the growth but protecting its own open space. If the greenbelt is placed between two self-sustaining urban agglomerations, (d) it can create a buffer zone and prevent the emergence of a conurbation. It is also worth noting that the total demand and quantity of urban development is not reduced by the introduction of a greenbelt. As a result, development occurs elsewhere to compensate for non-development of the greenbelt area and this changes urban form.

These model outcomes represent rather well what has happened with the growth of Seoul, the capital city of South Korea. The greenbelt was introduced in the 1970's when Seoul itself was the only urban agglomeration in the capital region, and it successfully stopped the expansion of Seoul at a certain time point. However, growth eventually penetrated the belt and then leapfrogged the greenbelt. The rise and growth of new towns also touched the greenbelt from outside, and all these factors have meant that the effects of greenbelt have changed in the time and due to their surrounding conditions.

t=1000

(a) (b) (c) (d)

Figure 6 Varying Effects of Greenbelt

4.2 Empirical Integration

The theoretical models introduced above are applied to a case study which enables us to investigate model implications for real world urban systems. The study area is a southern fringe of Seoul, where the CBD is located at the north end of study area. Figure 7 shows the extent of the area. It is based on a 25km by 25 km grid space south10(3 >

Figure 7 Study Area

It is assumed that urban growth occurs at the cost of agricultural land where agricultural land is the only developable land here. Thus the location decision of households converts agricultural lands into urban. Initially 1000 agents are placed in the space. Each agent searches for its utility maximizing location and then moves to that spot. Once the agent finds its own residential location, it is removed from the simulation and a new agent enters into the space. The total amount of urban conversion is constrained by the exogenous global demand, and the simulation stops once the system reaches that threshold. Apart from utility maximizing location choice principles, no other behavioral rules such as proximity to road network are taken into account.

The simulation results show that the release of greenbelt undoubtedly allows the development in area of agricultural land. New developments however are likely to occur in the closers location to Seoul city in both cases. However, while both scenarios show small scale sprawling settlements due to the spatial heterogeneity and households' bounded rationality, the main difference in the results is the emergence of local agglomerations.

The proposed location of transit stations plays a key role in the future urban transformation in these scenarios. The case with transit oriented development shows much more focused urban development compared to the other. Deregulation of greenbelt land is not likely to attract spontaneous development into specific areas, allowing sprawling urban development as we show in Figure 8(a). One the other hand, the development of new transit station is likely to pull urban development into the vicinities of the stations as in Figure 8(b).

The simulations use hypothetical data values and thus are explorative. However these experiments reveal how location specific zoning regulations and urban development can affect the spatial decision making of individuals and alter the resulting urban formation. This has important implications for urban planning policy:

reciprocal interactions of self-motivated individual actors and public policy.

(a) (b)

Figure 8 Comparison of Scenario

5. CONCLUSION AND FUTURE STUDY

In this paper, we have presented agent based residential urban growth models integrated with urban economic theory. The models proposed introduce explorations of various effects of spatial heterogeneity with a focus on location specific local externalities and transit oriented urban development. The simulations show how concise economic models can produce complex urban structures if they are combined in a dynamic agent based modeling framework. The simulations also suggest that urban growth structures subject to constant growth can reveal different evolving forms over the time.

The approach proposed here brings not only new research opportunities but also research challenges. Less reliance on heuristic algorithms, the agent based model become more operational, providing an opportunity for spatial policy analysis with stronger explanatory power and incorporating richer system behavior. However, for policy support, this study identifies two research challenges.

Firstly, empirical analysis of model parameters is necessary with regard to the explanations of household location decision Making. Indirect solutions to this can be developed using existing survey data. Brown and Robinson (2006) analyze data in the Detroit Area Study to define residential preferences. More direct solutions include conducting dedicated econometric estimations using random utility theory (McFadden 1973). Specification of the deterministic parts of such models can be configured by indirect utility functions from bid-rent theory. The stochastic part can be
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