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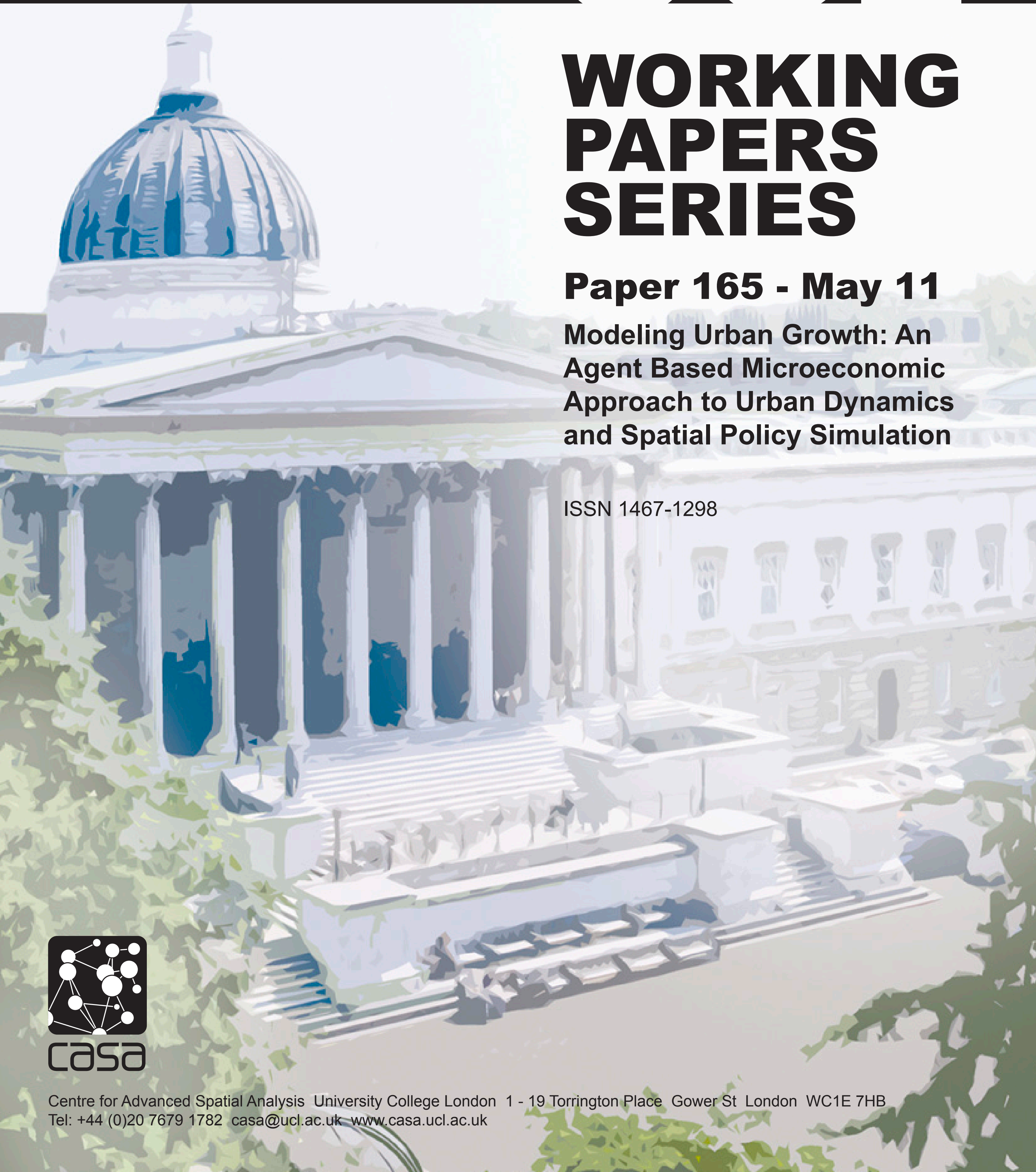

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Modeling Urban Growth: An Agent Based Microeconomic Approach to Urban Dynamics and Spatial Policy Simulation

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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 understanding complex urban systems and provides an arena for exploring the possible outcome states of various policy actions. Yet most research efforts of this sort adopt physical and heuristic approaches which tend to neglect socio-economic dynamics which is critical in shaping urban form and its transformation.

This research project has two main goals. First, it develops an agent based urban simulation model which has a more rigid theoretical explanation of agent behavior than most such models hitherto. To achieve this, the research integrates microeconomic theory into an agent based modeling framework. Utility maximizing residential location choices made by households are modeled as the main impetus for urban growth through agglomeration and sprawl. Then random utility theory is used to capture the stochastic nature of agent behavior. Second based on such urban dynamics, alternative planning policy options such as greenbelts and public transportation are modeled so that their impacts can be clarified. In this way, the model examines how planning policy alters the economic utility of households and redirects market-led urban development.

Keywords: agent based model, location choice, urban growth

1. INTRODUCTION

Complexity science based modeling frameworks such as cellular automata and multi agent systems have gained in popularity over past decade in the study urban systems, their spatial structure, and their temporal dynamics (Batty, 2005). This strength is firmly based on realistic representations of system behavior through the explicit manifesto of individual system entities and their interactions. Although complexity urban models provide a useful framework to understand the temporal dynamics of complex urban systems at a fine scale, their implicit representation of socio-economic factors reveals limitations in their use as decision support tools. The autonomy of available theory and heuristic approaches to simulating related model outcomes do produce rich system behaviors but this also results in limited explanatory power. In the past, these applications have been mainly centered on the study of self-organizing urban morphologies with a focus on generative knowledge discovery (Batty 2009, Crooks et al. 2008, Matthews et al. 2007, Manson and O'Sullivan 2006, Epstein 2007), and this has limited their applicability in real planning.

Recently a new approach to integrating urban economic theories into urban modeling frameworks has emerged through the study of land use change systems. The main benefit is not only stronger explanatory power from the perspective of agent based modeling but also a greater behavioral/spatial heterogeneity with respect to how the urban economy is modeled and represented. Combined together, these developments have the potential to offer a new type of dynamic and operational spatial policy support system to planning practice.

The bid rent theory and utility maximization principle which forms the core of urban economics forms the common ground in this approach. While pure urban economic models mainly focus on finding and describing general spatial equilibrium conditions where an assumption is made that all economic agents are homogeneous, these new integrated approaches have generally paid attention to the effects of heterogeneous agents on the formation of urban structure. Brown and Robinson(2006) have presented various urban sprawl patterns resulting from heterogeneous preferences in the utility maximizing location choice of households. Preference sets such as distance to local service centers, aesthetic quality, and social similarity selected from existing survey result on residential location choice, have been used Caruso et al. (2007) modeled the emergence of diverse urban fringe formations depending on the effect of neighborhood externalities and household preferences with respect to environmental or social amenities. Filatova et al.(2009) have implemented an agent based land market model with a focus on the interaction between buyers and sellers. Reproducing conventional concentric urban ring formations, the model shows that the magnitude of land rent distribution can vary according to the interaction between buyers and sellers as well as in terms of buyer preferences on proximity to the CBD or other local green amenity.

The main purpose of this paper is thus to present an agent based urban growth model which integrates with microeconomic residential location choice theory. Previous works in this tradition suggest that varying preferences among a specific agent preference set undoubtedly has a significant influence on the formation of urban structure. This study note this point but pays less attention to it for it rather focuses rather more on investigating the effect of spatial heterogeneity caused by local externalities and planning policies. It starts from the reproduction of conventional simple monocentric urban structure, and then presents the emergence and evolution of multiple urban agglomerations which arise from such spatial heterogeneity.

2. THEORETICAL BACKGROUND AND MODEL ASSUMPTIONS

The theory of urban residential location choice is fundamentally rooted in von Thünen's agricultural land use model but it is now more directly based on the work of the so-called new urban economists Alonso (1964), Mills (1967), and Muth (1969), who resurrected von Thunen and linked his work to more mainstream micro-economics. With a different focus on land and housing consumption, the Alonso-Mills-Muth models explain the behavior of urban land use formation under the common assumption of a monocentric spatial configuration which results from the assumption that the origin of urban activity is at the core of a city, at its market around which everything else revolves. The urban space in those models is featureless except the distance to a single employment center, the central business district (CBD). Households allocate their income on spatial goods (land or housing) and other non-spatial composite goods subject to income constraints. As the distance from CBD increases, the bid rent decreases due to increasing transportation cost. Although built on many simplifying, hence rather unrealistic assumptions, the models do yield important explanations for the formation of urban structure particularly in concentric rings around the core of the city based on the ability to pay rent for proximity to the CBD and the rest of the metropolis.

Following Alonso-Mills-Muth, many extensions and applications has been developed to explain urban growth and sprawl under varying conditions. Some selected works are relevant to this study. Solow (1973) introduced the indirect utility function to explain residential land rent and suggested the possibility of polycentric urban structure with multiple local employment centers, also discussing an extension to embrace residential segregation derived form different income groups. Anas (1978) suggested a residential urban growth model in which the city grows as a sequence of short run residential equilibria. Fujita (1989) has also synthesized theories to describe equilibrium patterns of residential land use and urban structure. Starting from the basic monocentric model, he suggests extended models dealing with the effect of economic externalities such as traffic congestion and local public goods which further explain more diverse causes and results of urban form. Wu and Plantinga (2003) have developed a model to explain the influence of local scale environmental amenity in residential location choice where equilibrium land rent is not only a function of distance to the CBD but also that of environmental local amenities. As in many theoretical economic models, these models are also static and focus on deriving long run stationary equilibrium conditions while the effects of spatial heterogeneity are often ignored.

The basic spatial and behavioral configuration of the model to be developed here conforms to the fundamental assumptions of the Alonso-Mills-Muth framework. The space is an open city where in and out migration is possible without extra cost. The city generates a monocentric structure in the first instance, and homogeneous households commute to a single CBD. Total transportation cost for commuting is incremental to the distance from residential location to the CBD whilst households allocate their income on land rent for housing, transportation, and all other composite goods in order to maximize their utility. However, this study introduces additional features and releases certain constraints. Firstly, the model deals with diverse spatial heterogeneities which result in polycentric and non-concentric urban growth patterns. Two main factors are investigated in this regard: local externalities that change location specific amenities and urban development that changes transportation costs. Although space is functionally still monocentric (based on a single CBD), the introduction of such spatial heterogeneities amends the utility function of households and eventually results in polycentric spatial structures.

Secondly, neither general market equilibrium conditions for land supply and demand nor partial spatial equilibrium conditions for the residential and agricultural use are considered. While demand side behavior is explicitly defined by residential bid rent 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:

$$Max U = g^{\alpha} h^{\beta}, \ \alpha + \beta = 1 \quad (1)$$

$$y = g + hs + td \quad (2)$$

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

$$g^* = (\alpha / \alpha + \beta)(y - td) \quad (3)$$

$$s^* = (\beta / \alpha + \beta)(y - td) / h \quad (4)$$

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

$$U^* = \alpha^{\partial} \beta^{\beta} (y - td) / (\alpha + \beta)^{(\alpha+\beta)} h^{\beta} \quad (5)$$

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

$$\psi_{xy} = [\alpha^{\partial} \beta^{\beta} (y - td) / (\alpha + \beta)^{(\alpha+\beta)} v]^{1/\beta} \quad (6)$$

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:

$$Max U = g^{\alpha} h^{\beta} E^{\gamma}, \ \alpha + \beta = 1, \ \gamma > 0 \quad (7)$$

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

$$\psi_{E_{xy}} = [\alpha^{\partial} \beta^{\beta} E^{\gamma} (y - td) / (\alpha + \beta)^{(\alpha+\beta)} v]^{1/\beta} \quad (8)$$

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 defined as:

$$E_{p_{xy}} = 1 + e^{-\theta d_{E_{p(i,j)}}} \quad (9)$$

where d_E is distance to the local externality at *(i, j)*, and θ is a distance decay parameter.

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]:

$$E_{N_{xy}} = 1 + e^{-\varsigma / d_{E_{n(i,j)}}} \tag{10}$$

Now the negative local externality returns a decreasing land rent as the distance to it increases. The result is lower rent around the location of the negative externality and a concave spatial pattern towards it. The spatial pattern for this case will be also examined in the next main section.

3.3 Extension with Multiple Transport Modes

We now propose an extension for the case of multiple transportation modes. A standard monocentric model with extensions to deal with local externalities assumes only one type of implicit transportation, which is usually attributed to the private automobile. Previous sections showed that a possible polycentric urban structure could occur even in monocentric configuration if there are effects of local externalities. In this extension, it is assumed that a household faces a set of transportation modes for commuting and chooses the cheapest option to maximize its utility.

Consider the standard monocentric model once again. However, now suppose that a high speed rail station which implies a transit oriented development (TOD) is introduced by a government agent/agency. In such conditions, three types of commuting exist: by car only, by train only, and by a combination of the two. What to choose depends on the total cost of each alternative. A household minimizes its transportation cost to maximize its utility, while commuting time and personal preference are not considered.

From the standard function under the monocentric condition (6), the bid rent with a varying transportation costs can be rewritten as:

$$\psi_{T_{xy}} = [\alpha^{\partial} \beta^{\beta} (y - T_{\min}) / (\alpha + \beta)^{(\alpha+\beta)} v]^{1/\beta}, \; T_{\min} \in \{t_a d_c, t_t d_c, t_{cn} d_{cn}\} \tag{11}$$

If this is combined with the local externality effect:

$$\psi_{T_{xy}} = [\alpha^{\partial} \beta^{\beta} E^{\gamma} (y - T_{\min}) / (\alpha + \beta)^{(\alpha+\beta)} v]^{1/\beta}, \; T_{\min} \in \{t_a d_c, t_t d_c, t_{cn} d_{cn}\} \tag{12}$$

where t_a represents the unit transportation for automobile, t_t is the transportation cost

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[1] Common examples include urban facilities like airport, landfills, and power plant that provoke 'NIMBYism'.

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 $\Re^2$ 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.

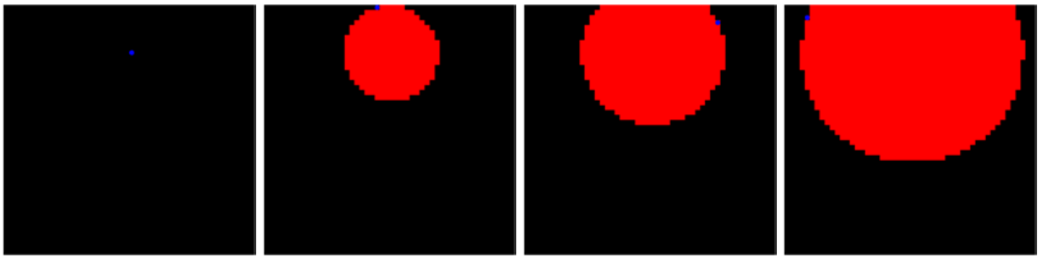
Parameter values used in the theoretical simulation are described in Table 1. As mentioned before, different preference values result in different spatial configurations. Defining such values is an empirical question, and possible variations with regard to the parameters are not explored in this work.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

Table 1: The Value of Parameters

Parameter	Value
α	0.5
β	0.5
γ	0.5
θ,ς	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

Positive Local Externality

Now a positive local externality is introduced at the location ½*X and ⅖*Y. The introduction of such a local externality increases the amenity value radically around this location. Thus leapfrog development takes place due to the modified land rent distribution, and a polycentric urban form emerges (t=500). It is noteworthy that the urban expansion from the CBD is smaller than that of simple monocentric growth at this same time step because the development occurs around the local externality. As the city continuously grows, agglomeration into conurbation eventually occurs (t=1000). In the longer run (t=2000), the leapfrogged local agglomeration is absorbed into the main urban area, and the resulting spatial configuration becomes virtually identical to that of the simple monocentric one.

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

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 ⅖*Y. In this case the bid rent decreases as the distance to the externality increases. As a result, the existence of this negative externality greatly changes the urban growth pattern from a very early stage. It takes a flat ellipse form because of the avoidance of the negative externality (t=500). The urban space further expands to the left and right edge rather than to the downward (t=1000). Although the distance to the CBD is greater on the edge, urban growth keeps moving to the left and right. Then it goes reduces from there while still avoiding the areas where the negative externality exists (t=2000).

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

Figure 3 Pressed Growth

Multiple Local Externalities

A combination of the positive externality at ¼*X and ½*Y and the negative externality at ¾*X and ½*Y reveals the following results. Urban growth around the CBD is skewed toward the source of the positive local externality from an early stage, and eventually leapfrogging development occurs (t=500). Then the evolution of the conurbation can be observed as the urban expansion from the CBD further approaches it (t=1000). Overall urban growth tends towards the location of the positive externality, and the area affected by the negative externality is largely left behind (t=2000).

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

Figure 4 Skewness and Dissymmetry

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 ⅖*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

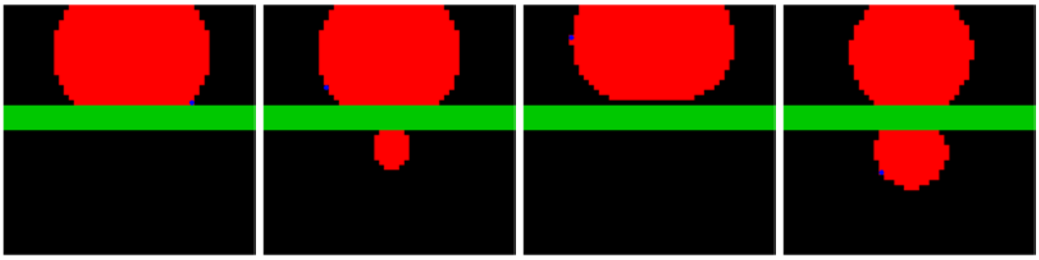
Figure 5 Leapfrog and Conurbation

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 with a cell size of 50m (giving a total of 250,000 cells). Most open space in this area, including agricultural land, has been protected by the greenbelt over the past decades. However, the government is now considering a partial release of greenbelt area in order to accommodate new development. In addition, there is an ongoing development plan for a new high speed rail system in the area. Although the main purpose of the new transit system is to facilitate commuting travel to the main business districts in Seoul, it is clear that the introduction of such new transportation systems would affect the future urban growth of the region. Two scenarios are thus tested. A baseline scenario releases greenbelt without further investment in public transportation. An alternative scenario considers the deregulation of greenbelt as well as the introduction of a new transit station.

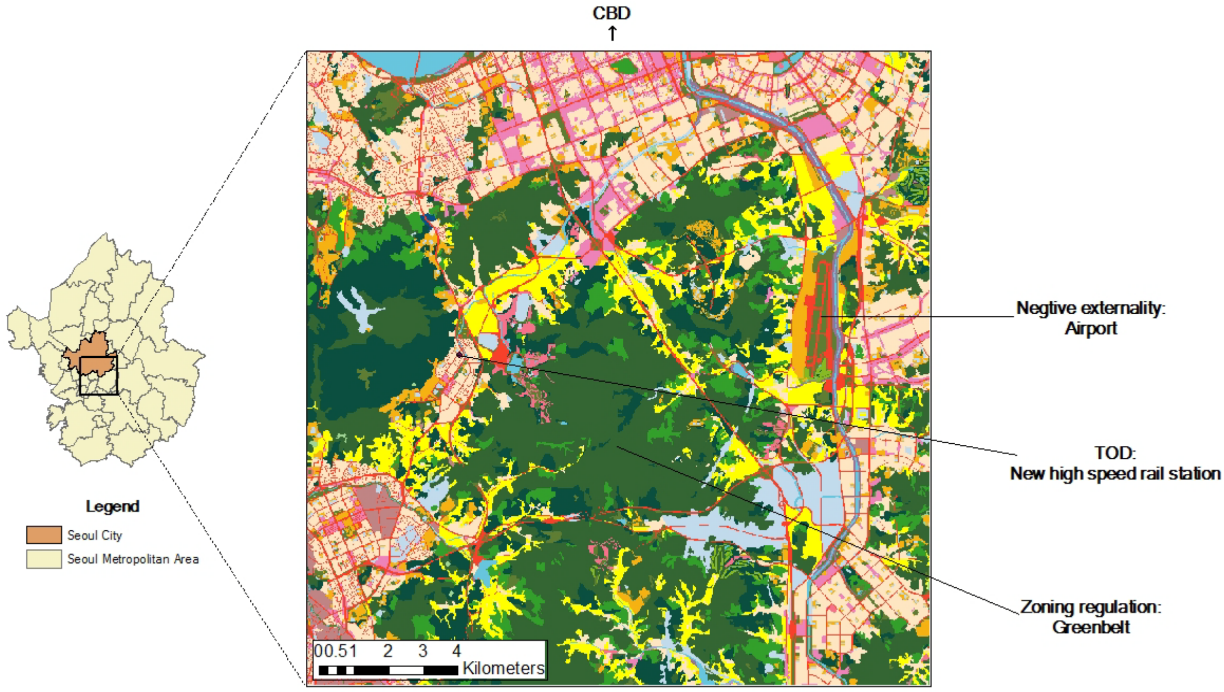


Figure 7 Study Area

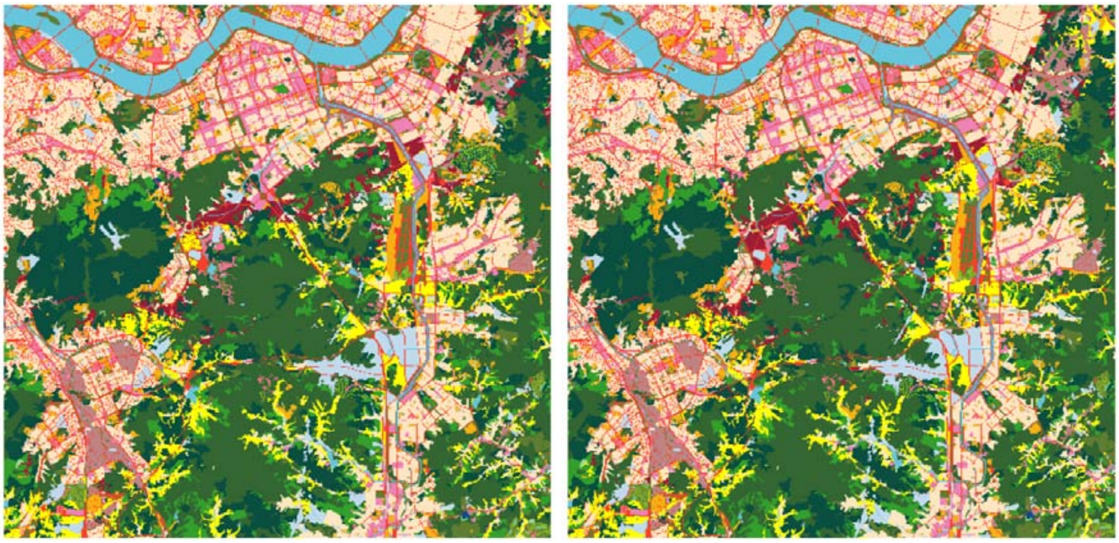
It is assumed that urban growth occurs at the cost of agricultural land where agricultural land is the only developable land here. Thus the location decision of households converts agricultural lands into urban. Initially 1000 agents are placed in the space. Each agent searches for its utility maximizing 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 modeled and estimated by logit or probit models. This also suggests that the integration of heterogeneous styles of models and analyses is inevitable as part of an enhanced agenda to better understand urban systems. Yet such efforts are not yet well coupled with the agent based models and this represents a key challenge.

Secondly, from the perspective of an agent based modeling framework, it can be concluded that this new style of disaggregate model still poses challenges for computing power although contemporary computers are much more powerful and efficient than those in early days of urban modeling. Spatial resolution and neighborhood configurations are directly subject to such computing issues. For instance, the limited search/movement space that we suggest here may have an analogy with bounded rationality and/or path dependency which in turn brings out unexpected system behavior at global scale. However, in terms of operational modeling for policy support, this has important implications for practical development and use of such models.

The above research challenges ay recall the critiques of Lee (1973). This modeling approach is still bounded by empirical data and computing resource issues. However, it is not a re-encounter of the same problems but an opening up of a new frontier on the way towards a better understanding of contemporary complex urban systems.

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