Urban Modeling

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Glossary

Agent-Based Models (ABMs) A class of models developed since the 1980s which are based on representing objects and populations at an elemental or individualistic level which reflects behaviors of those objects through space and time. These models operate from the bottom up and sometimes generate emergent spatial and temporal patterns at more aggregate levels.

Calibration The process of dimensioning a model in terms of finding a set of parameter values that enable the model to reproduce characteristics of the data in the most appropriate way. Calibration is not the same as validation which seeks to optimize a model's goodness of fit to data, but often, these processes are equivalent.

Cellular Automata (CA) A class of spatially disaggregate models, often pictured as being formed on a two-dimensional lattice of cells, where each cell represents a land use and embodying processes of change in the cellular state are determined in the local neighborhood of any and every cell. Such models can be seen as simplifications of agent-based models where the focus is on emergent spatial patterns through time.

Complex Systems Systems that show surprising and unanticipated or 'emergent' behaviors as shown in patterns that arise at the aggregate level from the operation of system processes at the micro or agent level. Such systems are intrinsically unpredictable in an overall sense but can be fashioned in such a way that makes knowledge of them useful and certain. Cities are the archetypical example, but so too is the economy.

Discrete Choice A development of computable microeconomic theory in which individuals maximize a utility, subject to constraints on their choices which can be tailored to reflect how decisions are made in complicated situations. Such models have been applied extensively in transportation modeling and have strong links to more aggregate maximization models as derived from spatial interaction and social physics.

Land-Use Transport (LUT) Models A class of models that focus primarily on the way populations and employments locate in urban space consistent with the spatial interactions between different locations of these activities. These models usually simulate the city at a cross section in time and as such, bundle urban dynamics into equilibrium behaviors.

Social Physics The application of ideas from classical 'Newtonian' physics to social systems usually in the form of analogies with Newton's laws of motion as reflected in the concepts of potential energy and gravitational force. This lies at the heart of spatial interaction modeling but more recently such physics has been extended to embrace notions of complexity as reflected in scaling, self-organization, and the dynamics of far-from-equilibrium systems.

Spatial Interaction Movements of goods, people, and information between different spatial locations, often referred to as origins and destinations, theorized and simulated using analogies with gravitational laws in physics. Such models form the basis of standard methods for describing and modeling interactions ranging from trip making in cities to long-range migration between cities.

Urban Dynamics Representations of changes in urban spatial structure through time which embody a myriad of processes at work in cities on different, but often interlocking, time scales ranging from life cycle effects in buildings and populations to movements over space and time as reflected in spatial interactions.

Urban Economics The development of microeconomic theory at the urban scale, following the tradition of the von Thunen model in which location and land rent are hypothesized as a function of distance or travel costs from some market center. The development of these ideas in the 1960s led to this branch of economics being called the New Urban Economics and more recently it has been extended using growth and trade theory.

Urban Modeling The process of identifying appropriate theory, translating this into a mathematical or formal model, developing relevant computer programs, and then confronting the model with data so that it might be calibrated, validated, and verified prior to its use in prediction.

Urban Models Representations of functions and processes which generate urban spatial structure in terms of land use, population, employment, and transportation, usually embodied in computer programs that enable location theories to be tested against data and predictions of future locational patterns to be generated.

Online Resources

There are many online resources that can be used to extend the material of this article. Land-use transportation (LUT) models tend to be large and uniquely tuned

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to particular applications and although software might be downloaded, there are few, if any, online demonstrations. However the state of the art is represented by the UrbanSim class of models which are now being fashioned into the Open Platform for Urban Simulation (OPUS) which is located at http://www.urbansim.org/. Cellular automata (CA) models are more manageable and software is available to download to generate simple examples. The Dynamic Urban Evolutionary Model (DUEM) developed in London and Michigan can be accessed at http://www.casa.ucl.ac.uk/software/duem.asp and used to develop simple demonstrations of cellular growth. More complex models developed for simulating urban growth in North America have been developed by United States Geological Survey (USGS) as part of their project Gigalopolis and these SLEUTH models can be downloaded and viewed at http://www.ncgia.ucsb.edu/projects/gig/. Extensive and up-to-date information about agent-based models (ABMs) is available at http://gisagents.blogspot.com/. Simple demonstrations of such models are available at http://www.genesis.ucl.ac.uk/ and at http://www.complexcity.info/.

Defining Models

Models are simplifications of reality – theoretical abstractions that represent systems in such a way that essential features crucial to the theory and its application are identified and highlighted. In this role, models act as a vehicle to enable experimentation with theory in a predictive sense, and to enhance understanding which may be prior to predictions of situations as yet unrealized, for example, in the future. This role of experimentation is usually through an environment somewhat different from the laboratory sciences where manipulation of the phenomena in question is direct and controlled. Models in the context here, are invariably implemented in computer environments which act as a surrogate for the laboratory where this use of the term 'model' has gained considerable currency over the last 50 years with the rise of computing in the social sciences. Urban models are thus essentially computer simulations of the way cities function which translate theory into a form that is testable and applicable without experimentation on the real thing. Computers act as the laboratory for experimentation on phenomena which is represented digitally, with its manipulation being virtual. Urban modeling, the subject of this article, is the activity of defining, building, and applying such digital models for specific purposes which, traditionally, have been in physical planning. These applications increasingly extend to other social and human geographies built around location theory and spatial analysis in commercial as well as public decision contexts.

In this article, we first define an urban model, and then chart the process of building such a model from the assembly of data through calibration to validation and prediction and thence into forecasting, design, and planning. Over the last 50 years since computer models were first developed in the urban domain, several distinct types have emerged, and we will classify these in such a way that the various techniques and modeling styles associated with them are clarified. In particular, we will identify distinct generations of model, beginning with static and aggregate LUT models which had their heyday in the 1960s, dynamic variants of these same models, more recent bottom-up styles of model which are called agent-based and are dynamic and disaggregate, and urban models which focus on the temporal dynamics of aggregate populations. All these types still exist today as the field continues to develop and proliferate.

Urban Theory, Models, and the Scientific Method

Science begins with theory that is translated into a form that enables it to be compared with reality through the process of making predictions. If the predictions are good, the theory has withstood the test and confidence is gained in its relevance. As our abilities to model different and more richer realities are enhanced, it becomes increasingly unlikely that our theory can be tested in the controlled conditions of the laboratory, and this is where the computer plays an essential role. Theories are thus translated into a form that enables them to be represented as mathematical or logical models, with the computer acting as the laboratory in which simulation of the reality takes place.

In terms of cities, the kinds of urban theory that are basic to the development of computer models are those that are traditionally called location theories: theories that propose mechanisms that enable industries, services, and households to locate in space within economic constraints of income and profitability. In turn, these economies are conditioned primarily by distance (often as a proxy for travel cost) between land uses associated with these activities which depend upon a range of market conditions essentially underpinned by trade. Thus, distance and movement are central to such theory which by the mid-twentieth century had more or less resolved itself into three styles: an aggregate theory in which space was differentiated according to principles of social physics which loosely revolved around energy and potential, an aggregate theory of macroeconomic relationships between various types of production and consumption, and a more disaggregate theory based on the microeconomics of competing land uses in which transport cost, land rent, and spatial profit dominated location.

Alonso, in 1964, was perhaps the first to fashion a formal statement of urban economic theory which came to be called the 'new urban economics', although it was Isard *et al.* who presented a catalog of more practical methods based on spatial interaction ideas from social physics and macroeconomic models such as input–output analysis. The first generation of urban models were based on applying such techniques by treating the urban system as a static entity whose land uses and activities were to be simulated at a cross section in time and whose dynamics were largely regarded as self-equilibrating. Thus, the early models were in the tradition of comparative statics. Movement at a cross section in time either as long-term migration and/or as routine, diurnal transportation through trip making was central to these models developed in analogy to gravitational and potential theory where flows were simulated in inverse proportion to travel cost or distance between 'origin' and 'destination' places. Much of the theory that passed muster in those early days is still with us although the influence of movement has lessened; other factors, particularly economic, governing housing choice have come onto the agenda, and the strong macroeconomic focus through input–output and economic-base theory has weakened.

The link from theory to model as a vehicle to test hypotheses has also fractured somewhat as traditional models have loosened their link to theory. In essence, theories of the city system were found wanting in that they did not reflect the diversity and heterogeneity that was very evident in modern cities, nor did they reflect the comparative volatility of urban dynamics suggesting that this dynamics could be absorbed within a wider equilibrium. During the 1970s and 1980s, the aggregate static approach to theory and modeling began to switch around to more bottom-up decentralized dynamics. As these styles of modeling gained ground, their data requirements exploded to the point where it became impossible to even calibrate, never mind validate, such models in their entirety. This of course reflected the move to relativism, postmodernism, and a style of social science that was diametrically opposed to the traditions of urban economics and social physics. No longer are models vehicles for testing hypotheses. Urban models are more likely to be frameworks for assembling relevant information, frameworks for formal and informal dialogs where they are essential tools in much more consensual and participative processes of decision support.

Model Principles, Types, and Styles

There are a limited but fundamental set of principles for building computer models which are generally accepted by those involved in the field. In essence, modeling is a process of simplification where paraphrasing Einstein's famous dictum, models "…should be as simple as possible but not simpler." This reflects the difficulties in abstraction where there is always a tension between how much to leave in and how much to leave out of any theory and its model. We will divide this discussion into approaches to abstraction and implementation, dealing with these in turn.

Scientific Abstractions

The first issue involves simplifying the spatial system in terms of articulating spatial structure at a cross section in time – in 'equilibrium' – or as a dynamic sequence of change. From one perspective, cities can be seen as largely unchanging in terms of their land uses and transport structures with marginal change far less important to that which exists in totality. This might almost be a matter of taste for there is another view that sees structure as being continually transformed even though it remains in place and, in this sense, any model should be dynamic reflecting such processes of ceaseless transformation. 'Statics' versus 'dynamics' is thus a central and often contentious issue.

This issue of time also relates to 'aggregation' and 'scale'. In general, the finer the spatial scale and the shorter the time period, the greater the dynamic in that as we aggregate activities from their elemental form, we tend to average, thus reducing 'heterogeneity'. Again, the degree to which the model should reflect heterogeneous activity depends on what is being modeled at what scale with this trade-off part of the process of simplification. In some models, there are consistent schemes for illustrating what actually happens when data and model elements are aggregated but, in general, the process is *ad hoc* and distinct differences of theory and style exist between the aggregate and disaggregate, between 'macro' and 'micro': models based on economic theory are the classic example.

'Representation' of the key elements of urban structure whether they be as individuals comprising various populations or aggregates thereof involves key problems of definition and classification. In the models considered here, spatial representation is critical for the scale in terms of size of the areal unit as well as its configuration directly relating to the way the system's elements are defined. Individuals exist at point locations but many models simplify these by aggregating basic units into groups which are associated with distinct areal units, often called zones or regions. This issue involves the previous two: temporal dynamics and heterogeneity, and clearly the greater the degree of aggregation, the simpler the model. When urban models were first developed in the 1960s, almost all were highly aggregated in terms of their representation, whereas now a new class of individual or ABMs have appeared which seek to represent the urban system in much more disaggregate and heterogeneous terms. In terms of the actual spatial units defined, there is a recurrent argument as to whether densities or counts should be the way of representing elements – densities implying a regular spatial system of 'cells' on a lattice in contrast to variable vector reporting units usually based on 'administrative units' or 'zones'. All these issues involve trade-offs involving scale which in turn are determined by more pragmatic concerns, such as available resources of data and computation.

Mathematical Implementations

To introduce the various styles of mathematics used to construct urban models, we define population as P and employment as E, location by subscripts i and/or j, and time as t. We will present six kinds of model which reflect the main types used to date: urban economic-base models, social physics models that distribute activity according to gravitational hypotheses and are widely referred to as spatial interaction models, and rent and population density models based on microeconomic theory which trades off the demand for space against cost or distance traveled usually to workplaces. These are all static spatial models which are in stark contrast to models that deal with time. Dynamic models can be at an aggregate level, such as those based on population dynamics, or more micro in terms of mobility, and there are various models that deal with long-term dynamics that reflect discontinuous change in the urban system. The last class of models deals with the supply of land and reflects developer dynamics and decision making. We will now sketch these types to give some sense of how urban models are constructed.

Urban economic-base models divide aggregate employment E into basic employment B which drives demand for nonbasic or service employment S through the multiplier effect where $E = B + S$. We relate demand for services to total employment as $S = \beta E$ from which it is easy to demonstrate that $E = B(1-\beta)^{-1}$, where $(1-\beta)^{-1}$ is the multiplier. If we then consider that population can be generated by applying an activity rate α to employment as $P = \alpha E$, we have the rudiments of a generative sequence that has been widely used in input–output modeling on the one hand and in cross-sectional urban modeling on the other. If we now consider that employment and population are related spatially through movements or interactions called T_{ij} between work i and home j, we can articulate these as

$$T_{ij} = E_i \frac{R_j d_{ij}^{-\lambda}}{\sum_k R_k d_{ik}^{-\lambda}} \text{ where } P_j = \alpha \sum_i T_{ij} \qquad [1]$$

where d_{ij} is the distance or travel cost from zone i to j, λ is a friction of distance parameter, and R_j is some measure of attraction at residential location j. If we were also to relate the location of services to population through another gravitational model of the same form as eqn [1], we would have a scheme tying population and employment together through the economic-base relation at the spatially aggregate level and through gravitational hypotheses at the spatially disaggregate level. In fact, this is the model first developed by Lowry, in 1964, which is still the most widely applied of all operational urban models and which has been elaborated in various ways, particularly in relation to the transportation sector.

This kind of modeling does not take account of the supply of land or other infrastructures and thus there is no market clearing. Consequently, prices for land are not determined. It is quite easy, however, to embed theories of the urban economy into these structures using theories of land rent first extended to the urban housing market by Alonso in 1964. This clearly demonstrates that rent ρ_j at location j is an inverse function of distance (or travel cost) from some central location $i = 0$ which can be simulated as $\rho_j = K d_{0j}^{-\gamma}$ where K and γ are parameters of the function. This theoretical result emerges from utility maximization subject to constraints on travel costs and other goods which are realized through an income constraint set for a typical individual. The focus on budgets enables the model to be integrated into gravitational models through various kinds of utility/entropy maximization associated with constraints on travel and housing costs.

Dynamic models have usually focused on longer-term temporal dynamics which involve demographic change and mobility through migration. Standard population accounting methods composed of births, deaths, and migration components are typically used to forecast future aggregate change in the urban system with spatial disaggregation often accomplished using the spatial model types noted above. Constrained population growth reflecting both exponential change and capacity which, in turn, reflect densities and congestion are simulated using various kinds of logistic growth. For example, aggregate population change from time $t-1$ to t defined as $\Delta P(t)$ can be modeled as

$$\Delta P(t) = \eta P(t)[P_{\max} - P(t)] \qquad [2]$$

where η is a composite growth/change rate and $P_{\max}$ is the maximum population that the system can take. If we examine eqn [2], when population $P(t)$ is small, then the term $[P_{\max} - P(t)]$ makes little difference and the system grows exponentially at an increasing rate with positive feedback. When population $P(t)$ is large relative to capacity, the growth is dampened by negative feedback, with total population increasing at a decreasing rate as capacity is reached when the change is zero. This is classic logistic growth that appears to occur in constrained systems which mirror human populations in contrast to Malthusian exponential growth. Extended urban models of this kind have been applied to city systems beginning with Forrester, in 1969, and have been developed to deal with more complicated dynamics where singularities and catastrophes can occur as distinct breaks in continuous growth. Wider systems of coupled equations extend the nonlinearities in such systems enabling cycling of various kinds to take place as well as bifurcations that generate novelty and surprise in growth and change. Models of this kind have been developed by Allen, in 1997, and Wilson, in 2000, among others and map surprisingly well onto recent developments in complexity theory where systems with multiple positive and negative feedbacks generate emergent structure.

There are many mathematical developments but we have sketched those of most importance with the exception of a rather different style of modeling that has recently become popular. More aggregate modeling has slowly given way to models which are articulated from the bottom up, rather than the top down, reflecting the increasingly popular paradigm of decentralization which appears to offer much better explanations of the way human systems function. This also reflects the move to dynamics from statics and to process rather than product. Models in which agents or actors (individuals or groups) are central, are now being widely developed. These models focus on various dynamics in the urban system embodying fast to slow processes, from local movement, such as travel, to migration over different time scales through to changes in individual life styles and cycles in the built form itself. These models may include more classical simulation techniques, such as those already sketched, but they are usually focused on decision rules in which agents behave in response to their environment and in response to each other. In this sense, the models simulate emergent phenomena and are capable, at least in principle, of embodying novelty, surprise, and innovation in the system.

Typical urban models in this style have so far focused on rather simple mathematics of bottom-up processes, such as CA. The system is partitioned into physical zones or cells which are small enough to reflect individual characteristics, such as distinct land uses. Cells change their state – their land use – dependent upon what happens in their neighborhood which essentially embodies the decision rules as to what land uses are compatible with one another at various spatial distances between them. These CA models can be articulated as rules of the following kind:

$$\text{if } C_j = \text{empty, and if } N_j^{\ell} = C_k^{\ell},\ \forall k \in \Omega_j, j \neq k, \\ \text{then } C_j^{\ell} = \text{developed } as\ \ell \qquad [3]$$

Essentially eqn [3] mirrors the decision process. A cell at location j is converted to development – to land use ℓ –; if there is a certain number # of cells N_j^{ℓ} with land use ℓ within a neighborhood of j called Ω_j. This is usually restricted to a few cells around the location in question. If the neighborhood is restricted in this way, then local rules lead to global emergence as in classic CA models, such as the Game of Life. Imagine this kind of system being extended to all zones with many different extents of neighborhood and many land uses with multiple counting, majority, and physical decision rules and this gives an idea of the sort of urban CA models that have been developed. If one adds individual actors to this environment, then one has urban models which are agent-based. Many CA but few ABMs of this kind have been developed to date. The advantage of this style of modeling is that it is dynamic and behavioral and can easily extend to both demand and supply sides of the development process. Its disadvantage is that it has enormous data requirements, and does not fit easily into more top-down processes that drive the urban system. Because heterogeneity in agents is often introduced by local randomness, it does not generate the sorts of deterministic prediction that are usually needed in operational urban modeling.

The Model-Building Process

When computer models were first developed, they were seen as embodiments of theory translated into compatible media that enabled their testing against data. This process of testing in its purest sense is one where hypotheses as theories are matched against 'the facts' and as such, represents the process whereby theory is falsified or confirmed. This is the process of validation which is distinct from calibration and verification. That a model be validated – that it pass various tests which ensure that it replicates the phenomena of interest in an acceptable way – is necessary before such a model can be used for making predictions which are then acted on in some way, for example, by professional or political decision makers.

This process is dominated by deduction in which models enable outcomes in the form of patterns and processes to be derived from theory and tested under experimental conditions setup as computer laboratories. In fact, the scientific processes of developing theory which makes good predictions, even laws, revolves around a sequence of induction and deduction through historical time and in practice; it takes a stretch of imagination to see a particular model-building process as mirroring this wider activity. In fact, most models are first calibrated or fine-tuned to data which simply ensures that they meet certain dimensional constraints on the system of interest. Calibration provides values for unknown parameters. Sometimes these are also chosen to optimize some goodness-of-fit criterion, such as how close predictions are to observed data, and in this sense calibration merges into validation, with the line between the two being blurred. Even if calibration is considered a separate process, validation takes place immediately after, the difference being that parameter values are often chosen using criteria different from those used to validate the model.

This rudimentary sketch is one that most applications loosely ascribe to. It is paralleled by the process of verification which accords to testing the model for internal consistency and is often separate from testing how good the model's predictions are. A key issue is to ascertain under what conditions the model is judged acceptable for further use; in short, what the conditions are for accepting the model as confirming the various theoretical constructs which it embodies. A strict test is to validate the model in an empirical situation different from that for which its parameters are calibrated but this is rarely done literally. Other prior applications of the model which have withstood this process are often assumed to be sufficient. However, the degree and strength of confirmatory evidence is difficult to ascertain. There are very few models that exist that can be tested on all their dimensions and the newer class of ABMs, which are much richer in terms of the hypotheses they frame and the data required to calibrate and validate them, will never meet all basic scientific criteria. This suggests that the rules for testing theory in this domain are changing and that the role of models is no longer entirely for this purpose: models are being developed as much for their exploratory and discursive value in a wider participatory process of developing robust but contingent knowledge than for their ability to generate good theory.

Urban Models and Their Applications

We have already introduced various modeling styles and, together with problem applications, these serve to define three main classes. These classes can be further subdivided into those which mainly have theoretical import and are not focused on empirical applications or policymaking in contrast to those that are, with the later subclass being considerably more pragmatic in structure than their theoretical equivalents.

Land-UseTransportation Models

This first class is built around the aggregate static models of economic and spatial interaction. Their theoretical pedigree is rooted largely in regional economics, location theory, and the new urban economics which represent the spatial equivalents of classical macro- and microeconomics, and perhaps in social physics insofar as this can be said to embody social theory. The most coherent recent statement in this vein is based on applications of trade theory to the urban economy as reflected in the work of Fujita, Krugman, and Venables in 1999 but there is a long heritage of empirical models in the Lowry tradition of 1964 which continues to be built. These models now incorporate the four-stage transportation modeling process of trip generation, distribution, modal split, and assignment explicitly and they are consistent with discrete choice methods based on utility maximizing specifically in their simulation of trip making.

These models have slowly been adapted to simulate dynamic change although they still tend to generate the entire activity pattern of the city. They remain parsimonious in that the assumption is that all the outcomes from the model can be obtained in terms of their goodness of fit. They have also become more disaggregate and now there are links to physical land use although they still remain at the level of activity allocation despite their nomenclature as LUTs. In short, this class of models is the most operational in that newer styles tend to be less comprehensive in their treatment of urban activities and transportation. Probably the most highly developed of these models currently is the UrbanSim model, although the MEPLAN, TRANUS, and IRPUD models best seen in the EU PROPOLIS (2004) project also represent the state of the art.

Urban Dynamics Models

Very few aggregate dynamically temporal urban models have been applied empirically. After Forrester's early attempt in 1969, the focus has been on theoretical developments of nonlinear growth and change which generate discontinuities through coupled nonlinearities, threshold effects, or random perturbations. Allen, in 1997, was the first to show how bifurcations could be generated through random perturbations of nonlinear structures at the micro-level. Wilson, in 2000, did much the same except that he formally embedded spatial interaction models into the nonlinear dynamics of their independent variables. Various attempts have been made to link such models to ecological dynamics, building on Lotka–Volterra models of predator and prey, while attempts have also been made at fusing the chaos of the logistic and other maps into spatial dynamics. But in one sense, all these forays into dynamics were rather aggregate and consequently less applicable to the kinds of urban processes that are characteristic of cities. As such they were simply the path to more micromodels and have been eclipsed somewhat by spatial simulations of dynamic processes whose scale is at a much more individualistic level, as embodied in ABM.

Cellular Automata (CA), Agent-Based Models (ABMs), and Microsimulation

The last class which is attracting the greatest attention at present involves models built around representing the actions and behavior of individual agents located in space. As might be expected, there have been various predecessor models in this vein; for example, Chapin and Weiss's work in 1968 in North Carolina and Ingram, Kain, and Ginn's housing market models in 1972 were constructed around individuals, market processes, and developer decisions which are the meat of the new generation of ABMs. In fact, the most popular type of model which has been applied empirically but has not been used much for policymaking is that based on CA where agents are, in fact, cells which change their land-use cell state. There have been a substantial number of applications but few have been used to test urban policies in that transportation is handled rather crudely or even excluded in such models. The main focus, of course, is on urban growth, which in a contemporary manifestation is sprawled with these models tending to be indicative rather than predictive. The other issue in such models is that they are primarily physicalist in scope and as such, largely ignore features of the spatial economy such as house prices, wage rates, and transport costs.

There are some ABMs at the land-use or activities level which enable predictions of future urban patterns but the main focus is at the very micro-level where local movements in terms of traffic are being simulated. Several models that approach the agent-based ideal originate from other areas. TRANSIMS is a hybrid in that its roots are in agent-based simulation of vehicles but it has been scaled to embrace urban activities and even UrbanSim has been interpreted through the agent paradigm. A parallel but significant approach to individualistic modeling is based on microsimulation which essentially samples individual behavior from more aggregate distributions and constructs synthetic ABMs linked to spatial location.

Applications: Using Models in Urban Policymaking

To conclude, it is worth noting that urban models span both theory and practice and that their rationale depends on developing new theory as well as their use in policymaking and planning. This tends to confuse and conflate their development as the same class of model is often used for both. Traditional LUT models are the most applied and the most parsimonious and are still the dominant model used in practice. This is largely because they attempt to be comprehensive in simulating location and interaction, land use, and transport. But in this they sacrifice detail and process. They are largely nondynamic and in a world where change is to the fore, this limits their applicability. The rise of more microdynamic CA models and ABMs clearly attempts to meet this challenge and insofar as these models are being applied, they tend to concern more particular processes in cities, such as segregation, housing market policies, pedestrian movement, and related behaviors. What has happened, however, is a broadening of styles and model types. It is worth noting too that, at the edge of this domain, there are many computer methods, in GIS, for example, that in some circumstances might be considered as 'models' which blur into the model types reviewed here.

See also: Choice Modeling; Location Theory; Scientific Method; Simulation.

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