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Editorial

Cellular automata and urban simulation: where do we go from here?

Introduction

> "He figured out that mathematicians, unlike carpenters, only needed to have one tool in their toolbox, if it were the right sort of tool. Turing realized that it should be possible to build a meta-machine that could be reconfigured in such a way that it would do any task you could conceivably do with information. It would be a protean device that could turn into any tool you could ever need. Like a pipe organ changing into a different instrument every time you hit a preset button."
>
> Stephenson (1999, page 197)

For some time now, cellular automata (CA) have been in popular use for urban simulation. Many of the most significant contributions to this new, emerging field have featured in *Environment and Planning B*, with a special issue devoted to the topic (Batty et al, 1997). The range of applications of cellular automata to urban studies is impressive. CA models have been employed in the exploration of a wide variety of urban phenomena, from traffic simulation and regional-scale urbanization to land-use dynamics, polycentricity, historical urbanization, and urban development. CA models of sprawl, sociospatial dynamics, segregation, and gentrification have been developed, as have simulations of urban form, growth, and location. CA have many advantages for modeling urban phenomena, including their decentralized approach, the link they provide to complexity theory, the connection of form with function and pattern with process, the relative ease with which model results can be visualized, their flexibility, their dynamic approach, and also their affinities with geographic information systems and remotely sensed data (Torrens, 2000). Perhaps, the most significant of their qualities, however, is their relative simplicity. By mimicking how macroscale urban structures may emerge from the myriad interactions of simple elements, CA offer a framework for the exploration of complex adaptive systems. However, with CA, this principal innovative feature is also one of its greatest weaknesses. CA models are constrained by their simplicity, and their ability to represent real-world phenomena is often diluted by their abstract characteristics. Unlike Stephenson's description of Turing machines in the above quote, as applied to urban systems, CA are not a one-tool solution for urban simulation ... the 'killer app' for urban simulation still eludes us.

Cellular automata and cellular urban models

At the most rudimentary level, a cellular automaton is an array or lattice of regular spaces or cells. At any given time, a particular cell is in one of a finite number of allowed states, and that state will change according to the states of neighboring cells in the lattice according to a uniformly applied set of transition rules. Cells alter their states iteratively and synchronously through the repeated application of these rules. A CA is thus composed of four principle elements: a lattice, a set of allowed states, neighborhoods defined by the lattice, and transition rules. In addition we might consider a fifth, temporal component.

Urban simulation models are abstract, simplified versions of real world objects and phenomena that may be used as laboratories for exploring ideas about how cities work and change over time. CA are no exception to this characterization. However, the basic CA formalism, as defined by Ulam, von Neumann, Conway, and Wolfram

(Wolfram, 1994) is not well suited to urban applications; the framework is too simplified and constrained to represent real cities. Indeed, radical modification is necessary before CA can approximate even a crude representation of an urban system. This often necessitates the introduction of additional components to add functionality to the basic CA framework.

Adaptation of, and experimentation with, urban CA has been both prolific and innovative and many of the results of that research have been published in the pages of this journal. The dimensions and structure of CA lattices have been modified and the range of cell states has been expanded. Additionally, neighborhoods have been varied considerably to accommodate action-at-a-distance above and beyond the simple Moore and von Neumann manifestations of formal CA. Transition rules have also been modified and expanded to include notions such as hierarchy, self-modification, probabilistic expressions, utility maximization, accessibility measures, exogenous links, inertia, and stochasticity. To a lesser extent the temporal behaviors of urban cellular models have also been modified. In fact, many—if not all—urban CA bear little resemblance to the formal CA model. Modification has been so extensive that it remains in doubt as to whether urban CA actually constitute CA at all, or are in fact simply *cellular* models of urban systems (O'Sullivan and Torrens, 2000).

Somewhere in the transition from an abstract mathematical formalism to an urban simulation tool, CA have evolved into a class of model that bear only passing resemblance to their cousins in physics, mathematics, and computer science. This begs the simple question, So what? Is it really a matter for concern if urban CA models have been altered beyond their early specifications? The answer here is not as straightforward as the question. The matter of modification has long been a source of disquiet in CA modeling. The concern has been that model developers may focus their attention on the intricacies of model construction with less attention paid to the reasons why models were developed in the first place. Certainly, urban simulation is as much an exercise in simulation as it is in urban studies, but it is important to consider that urban simulation is an applied science. Balancing the need for new functionality while keeping an eye on deviations from a reasonably well understood class of formal models is a difficult, but necessary task.

A taxonomy of cellular urban models

The modification of the basic CA framework in urban studies with expanded functionality is clearly influenced by the intended use of the models. Cellular models of urban systems are generally developed for three (not mutually exclusive) purposes: to explore spatial complexity, to test theories and ideas about cities in an abstract manner, and as operational urban planning support systems. CA models of spatial complexity are used to advance understanding of *general complex adaptive systems* (of which urban systems are an example) alongside similar models in the natural sciences. A more specifically *urban theoretic* or *urban geographical* research direction may also be identified, wherein urban CA and related models are used to explore ideas in urban economics, urban geography, and urban sociology. A third strand of research is potentially more demanding of urban CA and entails modifying the models beyond their formal specifications so that they can be put to use as practical planning and policy tools.

Each of these application domains is quite different, with varying demands placed on the capabilities of models and consequently on the appropriate model structure. Models used to explore the principles that govern urban spatial emergence in dynamic contexts, for example, require little development of the simple CA formalism. With a few limited adjustments, the basic CA is adequate for these purposes. In many cases, the addition of extra components to lend the model a particular relevance to urban studies may be counterproductive for the tasks at hand. At the other extreme, however, CA models designed for use in practice, in urban planning, urban management, and policy formulation, must often be drastically altered before they become even vaguely realistic representations of urban systems. Here, modification is essential and likely to be extensive. Nevertheless, even for practical applications, this modification must be approached with care. CA exist, as it were, on the edge of chaos. Launching enthusiastically into dramatic modification of models, without a full appreciation of the system dynamic implications, may produce simulations that we do not fully understand. Such elaborated models may have little operational value, since our lack of understanding of how they work may mean that only negligible value can be attached to their predictions and the resulting recommendations.

Given these considerations, where are cellular automata and urban simulation likely to go from here? Aside from technical modifications and further tweaks to models, there are several key areas on which those working with urban CA might focus future efforts and build upon existing success: explorations in spatial complexity, infusing urban CA with theory, exercises in education and outreach, the development of hybrid model structures, and new strategies for validating cellular urban models.

Explorations in spatial complexity

Cities are fine examples of complex emergent systems. From local-scale interactions such as individual movement habits, the geomarketing strategies of retail establishments, social biases, and residential and lifestyle choices, large-scale and at least partially ordered patterns emerge in the aggregate. Peak-hour congestion, specialist retail areas, social segregation, and distinctive neighborhoods may all be regarded as patterns in this sense. These aggregate patterns often emerge apparently independently of the dynamics driving the individual components of the system. Urban systems also display many traits common to complex systems in the biological, physical, and chemical worlds.

The idea behind using urban CA models to study complexity is to look at the simple ingredients of complexity that we find in cities, and to examine how these findings compare with elements of complexity in other fields. CA models have been used to explore the self-organizing properties of urban systems and experiments with fractal geometry and feedback mechanisms in urban CA have been performed. However, there remains room for connecting that work with studies in other disciplines. Indeed, many aspects of complexity studies remain relatively unexplored by urban CA. Areas such as path dependence, bifurcation, and phase transition have been explored in a general sense for cities, but the opportunity to use CA as a formal framework for facilitating that work remains.

It is also notable that urban CA have, for the most part, adopted a two-dimensional perspective on systems dynamics, with very few applications of urban CA to multidimensional examples (however, see Semboloni, 2000). Also, there is a strong need for measured experimentation with the construction of transition rules within a relatively formal CA structure and the patterns that those rules generate. However, in order to converse with other disciplines, from biology and physics to chemistry, it may be necessary that the form of urban CA preserve as many features of strict and formal CA models as possible. Perhaps there is also some justification for an exhaustive exploration into urban spatial complexity along the lines of Wolfram's research into the landscape of possibilities that can be derived from simple, formally specified classic CA (Wolfram, 1994). Indeed, by adopting a limited, well-defined *family* of CA modifications, with origins in urban spatial complexity, other researchers may be encouraged to experiment with CA model structures derived from urban settings (O'Sullivan and Torrens, 2000).

Infusing urban CA with theory

One of the drawbacks of urban CA models is that in some cases they have done relatively little to inform theory. Claims are made that models explore various hypothetical ideas about the city, but the reported results are often more concerned with the fine details of model construction, at the expense of the theories that they set out to explore. Research in urban CA modeling is just that: research in modeling, and not research on urban dynamics and theory. Researchers are explaining *how* to build urban CA without really exploring *why*. This is often the case with new techniques in quantitative geography, where initial enthusiasm for analysis techniques dominates the early research agenda. As CA move towards relative maturity as an academic exercise, however, calls for advances in this area may strengthen—a case of 'what have urban CA done for me, lately?'

The key to developing closer links between CA and urban theory is to be found in the formulation of transition rules and a more direct link between rules and theory. Some innovative advances have been made in the formulation of transition rules derived from theory. Batty and colleagues have built several models for exploring general spatial processes in urban environments and Webster and Wu have developed several influential urban economic models. Other groups have also made important inroads in the field (see Batty et al, 1997). These efforts can be extended to embrace other areas of urban theory—as well as other urban theories—such as social justice, location theory, urban design, political economy, environmental studies, urban sociology, and urban ecology. This would have the advantage of strengthening the theoretical basis of urban CA. Additionally, it offers the opportunity for moving urban modeling away from an overarching allegiance to that old crutch (!), urban economics, and towards an expanded interdisciplinary focus.

One of the manifold potential uses of CA in urban theoretical research is the generation of novel city-like phenomena from theoretically informed components. Because the technology is still at a developmental phase, urban CA models have focused on replicating well-documented urban phenomena, such as growth, multinucleation, and land-use transition; a sort of proving ground for the models. The opportunity to generate new organic urban forms with these models has not yet been capitalized upon. Potentially, urban CA models allow us preemptively to explore urban futures, simulating the next edge city, technopole, or megalopolis phenomenon. Of course, such research may prove rather difficult; how would we recognize new urban forms if we did actually observe them in models? But, the possibilities that these models offer are too rich for the opportunity to be missed.

Education and outreach

Urban models of various types have always been employed as educational tools. Conceptual models such as those developed by von Thunen, Hotelling, Burgess, and Losch, have contributed greatly to our understanding of the city, even with their limiting assumptions and limited description of the city. CA offer plentiful opportunities to follow in this tradition. Indeed, the chance to use CA models in the classroom as a dynamic, visual, and interactive educational tool for urban geography is beginning to be seized upon, especially as software specifically catering for education and freely accessible in the public domain becomes available (Epistemology and Learning Group, 2000; Freiwald and Weimar, 2000).

CA also hold potential for improving the interface between models and users in planning, policy, and elsewhere. The CA approach emphasizes simplicity in model formulation and affirms dynamic visualization as a means of presentation. These properties grant CA the possibility of engaging model users in an interactive manner.

With these techniques, operational urban models have a chance to become more intelligible, accessible, user-friendly, and ultimately *useful*. The use of urban CA for education and outreach is another area where existing efforts might be extended and their appeal broadened.

Developing hybrid models

Traditionally, operational land-use and transport models have been developed in the spatial interaction framework. Advances on that approach have been formulated and forays into spatial choice simulation have been made. Operational urban models have typically turned to rule-based formulations based on logit models and decision theory. Also, in transport modeling, activity-based simulations have been gaining ground, and microsimulation with operational models has long been underway. It does not take a quantum leap to fuse those approaches with CA, which essentially add a *dynamic* and *spatial* spin to these existing techniques. However, the current stock of models in operational use remain largely centralized, aggregate, relatively static, and top down in their treatment of urban activity (with a few exceptions). The complexity approach has put decentralization, detail, dynamics, and bottom up approaches in the simulation spotlight. There is considerable justification for carrying those ideas through to urban simulation. Many urban systems do exhibit signs of emerging from microscale dynamics up to macrolevel manifestations, and these systems may well be better modeled with CA. However, as suitable to the simulation of urban systems as CA models are, there are some things that they do not model well, most notably constraints such as planning restrictions that are applied to urban systems from the top down and global level phenomena that strongly influence urban systems, but do not necessarily emerge from local components. In light of these considerations, there is a convincing argument for developing *hybrid* operational urban models.

One potential framework for a hybrid model would combine the best elements of CA, traditional land-use and transport and regional science techniques, and models based on intelligent spatially mobile agents. A hybrid model would simulate the aggregate and global level (top down) dynamics of the urban system in the conventional manner by using techniques widely employed in practice—spatial interaction, spatial choice, input–output models, demographic forecasting techniques, and so on—but could delegate microscale (bottom up) dynamics to CA and agent models. Essentially, the macrolevel models would feed the CA-agent models with a set of known zonal level conditions (these can serve as constraints on state values). The microlevel models would then distribute these values at the local level by using theoretically informed dynamic engines. Ideally the connection between the two sets of models would be tightly integrated and seamless, but a hybrid approach could also constitute a suite of models, each with a unique perspective on the problem at hand. Advances in this area have already been made (Benenson, 1999; White and Engelen, 2000), and modular simulation architectures are paving the way for these hybrids. However, there are a number of obstacles that need to be overcome before future progress towards these objectives can be made.

The nature of process directionality in dynamic and intricately codependent urban systems demands serious attention, to improve our understanding of which feedback loops exist and where connections should be made. Once again, the issue of modification comes to the fore. With each additional component added to the model, the realism of the simulation grows; however, the simulation often becomes more difficult to manage. Perhaps, even more importantly, the need for stronger calibration techniques for registering model results with real world data is currently looming as a limiting factor for the development of hybrid planning models using CA.

Validating cellular urban models

The issue of model validation is key to the development of all urban CA models, but particularly those applied in operational contexts. The emphasis thus far in urban CA modeling has been on pattern based validation techniques: pattern recognition, and measures of match such as the chi-squared and kappa-statistics. The weaknesses of these approaches have been well documented and much intellectual energy is being expended on advancing our ability to calibrate urban CA models. Some significant advances have been made in using GIS to analyze the patterns that CA generate, including some 'fuzzy' recognition techniques. However, much of this effort is still bogged down in pattern-based approaches. This ignores the fact that CA comprise pattern and process, form and function. Future research may therefore have to look to new process-related validation measures such as Monte Carlo averaging, spatial information statistics (Wolfram, 1994), and measures of complexity.

Closing thoughts

At a recent meeting at University College London's Centre for Advanced Spatial Analysis, a one-day symposium of researchers in the field was held (details of the symposium can be found at http://www.casa.ucl.ac.uk/workshop.htm). The purpose of this gathering was to assess the state of the art in CA modeling of urban systems: to share past successes, brainstorm present difficulties, and ponder future challenges. Many of the issues we have aired in this editorial were raised. There seemed to be general consensus that now is a good time to pause and take stock of where research in this field has been, where it is now, and where it might or ought to head in future. There was also wide agreement that much remains to be done, and that some very difficult challenges remain in truly realizing the potential of CA and related modeling approaches. Hopefully, researchers in the field will feel encouraged to report future developments in these areas in the pages of *Environment and Planning B: Planning and Design*.

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