PERGAMON

Computers, Environment and Urban Systems
28 (2004) 1–8

Computers,
Environment and
Urban Systems

www.elsevier.com/locate/compenvurbsys

Editorial

Geosimulation: object-based modeling of urban phenomena

1. Introduction

Urban simulation has undergone somewhat of a transformation in recent years. The field has emerged from an "evolutionary" phase, which has spanned the last two decades. A "new wave" of urban models have begun to take center stage, influenced by technologies such as cellular automata (CA) and multi-agent systems (MAS) (Batty, Couclelis, & Eichen, 1997; O'Sullivan & Torrens, 2000; Torrens, 2000, 2002). The familiar regional models detailing the exchange of population, goods, and jobs between coarsely represented divisions of geographical space have gradually been substituted by simulations of urban systems as collectives of numerous elements acting in the city. These "new wave" urban models are more likely to be formulated based on individual-scale urban objects—homeowners, renters, pedestrians, commuters—and detailed descriptions of the rules governing their "real-time" behavior in space, across scales from the "microscopic" through to the regional (Benenson, 1998, 1999; Benenson, Omer, & Hatna, 2002).

The introduction of these models can, perhaps, be considered in the broader context of a paradigm shift in living systems modeling. In tandem with geography and urban studies, the new wave of simulation flowed over ecology, economics, and social science (Balzter, Braun, & Koehler, 1998; Berec, 2002; Berger, 2001; Cetin, Nagel, Raney, & Voellmy, 2001; Epstein & Axtell, 1996; Gilbert & Conte, 1995; Gimblett, 2002; Grimm, 1999; Kohler & Gumerman, 2001; Luna & Stefansson, 2000; Schenfisch, 2001; Schreckenberg, Neubert, & Wahle 2001; Sun, 2001; Tesfatsion, 1997, 2002). The motivations behind the move to individual-scale simulation is clear: in all these fields of study, knowledge about systems' microstructures and the role and behavior of individual elements has progressed dramatically, while simulation technology has advanced beyond the "black box" format popularized by cybernetics in the 1960s and 1970s (Wiener, 1961) to entity-level representations.

Nowadays, our knowledge of systems and simulation has reached a point where object-based behaviors can be directly translated into computable rules and used to generate living systems in silico, in simulated computer settings composed of realistic artificial environments and avatars. In the context of these developments, many

doi:10.1016/S0198-9715(02)00067-4

researchers are beginning to move away from the aggregate compartmental framework of traditional modeling, where the questions that can be explored are necessarily related to "average" individual elements, and are now favoring the flexibility of new approaches, presenting almost limitless possibilities of *directly* interpreting individual behavior.

The opportunities for geographers to contribute to the development of these new tools and the debate about real-world systems that they foster are considerable, particularly given the need for careful consideration of spatial structure and spatial behaviors in object-based models (Torrens & O'Sullivan, 2001). There is, perhaps, justification for a spatially explicit branch of study—which we designate *geosimulation*—in this emerging field of modeling. The remainder of this editorial will discuss various ways in which a research agenda for geosimulation might be formulated. The next section introduces the geosimulation approach. Following sections examine the influence of recent developments in the field and introduce the papers in the special issue.

2. Geosimulation as object-based modeling

At the most fundamental level, the geosimulation approach can be distinguished from other simulation methodologies by its explicit attention to space and geography (hence the "geo"). This is illustrated particularly well by objects' depiction in simulations, specification of their behavior, and delineation of objects' dynamics.

2.1. Object representation

Geosimulation models are noteworthy in their depiction of simulated entities. More traditional approaches, particularly those used in large-scale land-use and transport models, often represent urban space in an aggregate fashion whereby spatial units are described at coarse resolutions as modifiable units (e.g. the traffic analysis zone—TAZ), which can be united into bigger units or partitioned into any number of smaller ones. Spatial aggregation dictates amalgamation of urban objects such as people, vehicles, and buildings and the drawbacks of this so-called "modifiable areal unit" approach, and associated issues of ecological fallacy, have been well-documented (Openshaw, 1983). Geosimulation models are more judicious in their translation of urban geography into artificial schemes as they facilitate spatial resolution necessary to distinguish between the urban objects participating in the study. Geosimulation, thus, considers urban systems as collectives of spatially non-modifiable elements, or objects, at "atomic" resolutions: individual people, households, vehicles, buildings, land parcels, etc.

2.2. Object behavior

Representation of entity behavior is another innovative feature of geosimulation models. Geosimulation models generally represent autonomous objects, and focus on their interactive behavior in a systems setting. Distinct entities of geosimulation models, physically separate from other objects in a simulated system, can also be designed with autonomy of behavior, for example, a household can be represented with preferences for residential location choice depending on their individual properties as well as properties of their neighbors and neighborhoods (Benenson, 1998; Benenson et al., 2002; Torrens, 2001). Borrowing from ideas in complex adaptive systems research (Holland, 1995, 1998), geosimulation models concentrate on the collective outcomes of interactive behavior, treating observed patterns and phenomena at above-individual levels of urban hierarchy as emergent.

2.3. Object timing

Traditionally, time in urban models has been inherently continuous, and outcomes were considered indifferently with respect to the choice of time units and the discretization of time. In contrast, geosimulation models are based on time units corresponding to the "internal clocks" of interacting objects. Because objects of different kinds may retain differing internal clocks, geosimulation tends toward event-driven rather than time-driven implementations, and therefore to asynchronous updating of object attributes in simulated systems.

3. The intellectual foundations of geosimulation

As a field of study, geosimulation draws influence from a wide variety of fields, and the papers in this special issue are illustrative of that point. Specifically, complex systems theory, Geographic Information Science, and object-oriented programming have been particularly influential in catalyzing the geosimulation approach, particularly as regards the aforementioned depiction of objects, their behavior, and representations of time. Indeed, while originally borrowing heavily from these fields, geosimulation is starting to infuse a *spatial* element back into the areas from which it drew inspiration.

3.1. Complex systems theory and geosimulation

In complex systems theory, systems are understood to be *emergent*, i.e. a small number of rules, applied at a local level and among many entities, are capable of generating counterintuitive complex phenomena, behaviors, and patterns at above-individual levels. Often, these are manifested in such a way that the actions of the parts do not simply sum to the activity of the whole.

The idea of emergent properties has obvious implementations in the simulation of urban and environmental systems. The geosimulation approach generally treats such systems as open and hierarchical; often, model objects are also considered as complex adaptive systems themselves (Portugali, Benenson, & Omer, 1997). Complex systems theory provides a framework for investigating the laws of object behavior and interactions as entailing non-linear and often discontinuous qualitative phenomena of self-organization, phase transition, and bifurcations, which occur across multiple spatial scales and levels of system hierarchy (Batty & Longley, 1994; White & Engelen, 1993).

3.2. Geographic Information Science and geosimulation

Advances in Geographic Information Science in the management analysis and visualization of spatially referenced data have supported the geosimulation approach. Large and refined Geographic Information Systems of high-resolution information now exist for initializing, calibrating, and validating geosimulation-based models. These databases provide an extraordinary background for geosimulation, because the information that they contain relates to "atomic" urban objects: land parcels, road segments, houses, parks, institutions, etc. GIS enables the encoding of spatial objects and information on their attributes into simulation models and provides methods for relating objects based on their proximity, intersection, adjacency, or visibility.

3.3. Object-oriented programming and geosimulation

Object-oriented programming (OOP) paradigms have also made a significant impact on geosimulation by providing an intuitive framework for representing real-world objects in computational terms and by offering new languages for developing simulations.

OOP focuses on representing objects and objects' behaviors regarding other objects (interfaces) (Hortsmann & Cornell, 2001, 2002). It provides a context for assembling geographical systems as collectives of object classes and for using them interactively to accomplish tasks. The OOP paradigm introduces a framework for encapsulating characteristics and behaviors of real-world entities within computer objects, as well as supporting the autonomy of objects. Through the concept of *inheritance*, objects that are more complex can be constructed on the base of simpler ones; object *polymorphism* enables substitution of objects of different types while leaving the rest of the system unchanged. Recent developments in object-oriented languages (Schumacher, 2001) and modeling environments provide a wide spectrum of possibilities for the effective implementation of geosimulation models and their investigation (Brookings Institution, 2001; Gulyás, Kozsik, & Corliss, 1999; Swarm Development Group, 2001; University of Chicago, 2001).

4. Advancing the research agenda for geosimulation

Geosimulation remains very much in its infancy as an avenue of research inquiry. As a tool, geosimulation is almost limitless in its flexibility and much opportunity remains for research into new techniques and methodologies for building geosimulation models, particularly as regards the representation of space (Torrens & O'Sullivan, 2001). As an applied field, geosimulation also offers much promise for further research: the investigation of geographic systems through the direct representation of elements' properties and behavior, the development of new generations of urban planning games, providing explicit operational planning support tools, and so on. The papers in this special issue advance geosimulation research in several aspects, touching on each of the themes mentioned above and contributing in important ways to the research agenda.

The paper by Miller, Hunt, Abraham, and Salvini presents a comprehensive object-based environment for applied urban modeling. It aims at application to real-world urban systems in Toronto and other Canadian cities but seems applicable for Western cities in general. The environment is a result of several years of development; it includes urban objects of many basic kinds and represents an important step toward establishing applied object-based geosimulation environments.

The paper by Semboloni, Assfalg, Armeni, Gianassi, and Marsoni describes the specification of an artificial urban society CityDev, which includes basic urban objects acting on the top of land-use CA. The approach differs from the comprehensive environment of Miller et al.: the behavior of each object in CityDev can be controlled by the user. The model, thus, becomes a kind of community game, and the user can play one or more roles via the Internet. CityDev is really a multi-agent game, comparable to SimCity (Maxis, 2002), where the user is a mayor who experiments with different urban policies. CityDev provides a better reflection of reality, where the user develops its plans by means of agents she controls.

Two papers deal with real-world geosimulation applications. The scrupulous statistical analysis of urban land-use data in the Tokyo metropolitan area, made by Arai and Akiyama, provides important empirical confirmation that the states of neighboring land cells do influence those of central cells. Also, Arai and Akiyama provide empirically justified numerical estimates of these dependencies. They propose simple, but hitherto unexploited, analytical forms of a stochastic transition function, where the probability that a cell state will change linearly depends on fractions of cells in *each* of several possible states in the neighborhood, rather than the neighborhood's average characteristics. The proposed model provides a good description of land-use dynamics in the investigated part of the Tokyo metropolitan area.

Ducrot, Le Page, Bommel, and Kuper simulate the outcomes of competition for water among farmers on the urban periphery. Their simulations are aimed at modeling the development of São Paolo. The combined use of cellular automata, specialized passive entities representing land parcels and communicating agents representing farmers, and water suppliers articulates connections between hydrological processes, land-use changes, and urbanization. This well-documented model approaches the applied stage and is developing as a tool for operational planning and management.

Three other papers provide important advances in geosimulation methodology. Liu and Andersson base their research on the hierarchical structure of urban space, and investigate a cellular automata model where land-use information is simultaneously stored at the level of elementary cells and at aggregate hierarchies, each three times less detailed than the previous. The influence of nearest neighbors is considered in the model at the highest possible resolution, while an increase in the distance of neighbors' influence is considered in a more and more aggregated manner. Based on this approach, the authors investigate the consequences of the changes in the model's time scale and reveal essential differences in model dynamics when model time-units vary from months to years. We especially recommend their results, all obtained by means of synchronous updating and we suggest that the reader think about possible alterations were asynchronous updating to be employed.

An application of the SLEUTH self-modifying urban cellular automata (Clarke, Hoppen, & Gaydos, 1997) is investigated by Goldstein, Candau, and Clarke, based on maps of urban growth for Santa Barbara, California, during the period 1929–2001. The SLEUTH model is calibrated on the basis of several available high-resolution maps of the area for this period and the paper compares SLEUTH forecasts of urban growth for the intermediate years with the results of direct spatial interpolation of the growth tendencies and demonstrates. The authors find that the SLEUTH CA model serves as a very reliable forecasting mechanism.

Straatman, Engelen, and White present a new approach to the calibration of the popular ''constrained cellular automata'', in which potentials of cells' transitions are governed by linear transition rules (White, Engelen, & Uljee, 1997). The method is based on minimization of the number of cells, for which maximum likely transition is *not* realized, and is an important step toward a general methodology for calibrating practical cellular automata, which are always multi-parametric on the one hand, and far from mathematically investigated frameworks on the other.

To conclude, we hope that the reader will enjoy the papers just as we enjoyed working with them when compiling this issue. We believe that the next decade of geographic modeling is the decade of geosimulation, and that this issue can be one more step towards this future.

References

Balzter, H., Braun, P. W., & Koehler, W. (1998). Cellular automata models for vegetation dynamics. *Ecological Modelling*, *107*, 113–125.

Batty, M., Couclelis, H., & Eichen, M. (1997). Special issue: urban systems as cellular automata. *Environment and Planning B 24*(2).

Batty, M., & Longley, P. (1994). *Fractal cities*. London: Academic Press.

Benenson, I. (1998). Multi-agent simulations of residential dynamics in the city. *Computers, Environment and Urban Systems*, *22*(1), 25–42.

Benenson, I. (1999). Modelling population dynamics in the city: from a regional to a multi-agent approach. *Discrete Dynamics in Nature and Society*, *3*, 149–170.

Benenson, I., Omer, I., & Hatna, E. (2002). Entity-based modeling of urban residential dynamics: the case of Yaffo, Tel Aviv. *Environment and Planning B: Planning and Design*, *29*, 491–512.

Berec, L. (2002). Techniques of spatially explicit individual-based models: construction, simulation, and mean-field analysis. *Ecological Modelling*, *150*, 55–81.

Berger, T. (2001). Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes, and policy analysis. *Agricultural Economics*, *25*, 245–260.

Brookings Institution. (2001). *Ascape. 1.9 (Software)*. Washington, DC: Center on Social and Economic Dynamics.

Cetin, N., Nagel, K., Raney, B., & Voellmy, A. (2001). *Large-scale multi-agent transportation systems*. Paper read at Computational Physics Conference, at Aachen.

Clarke, K. C., Hoppen, S., & Gaydos, L. (1997). A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B*, *24*, 247–261.

Epstein, J. M., & Axtell, R. (1996). *Growing artificial societies from the bottom up*. Washington DC: Brookings Institution.

Gilbert, G. N., & Conte, R. (Eds.). (1995). *Artificial societies: the computer simulation of social life*. London: UCL Press.

Gimblett, H. R. (2002). *Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes, Santa Fe Institute Studies in the Sciences of Complexity*. Oxford: Oxford University Press.

Grimm, V. (1999). Ten years of individual-based modelling in ecology: what have we learned and what could we learn in the future. *Ecological Modelling*, *115*, 129–148.

Gulyás, L., Kozsik, T., Corliss, J. B. (1999). The multi-agent modelling language and the model design interface. *Journal of Artificial Societies and Social Simulation*, *2*, n3 Available at http://www.soc.surrey.ac. uk/JASSS/2/3/8.html

Holland, J. H. (1995). *Hidden order: how adaptation builds complexity*. Reading, MA: Addison-Wesley.

Holland, J. H. (1998). *Emergence: from chaos to order*. Reading, MA: Perseus Books.

Hortsmann, C. S., & Cornell, G. (2001). *Core Java 2. (Vol. 1) Fundamentals*. Saddle River, NJ: Sun Microsystems Press & Prentice Hall.

Horstmann, C. S., & Cornell, G. (2002). *Core Java 2. (Vol. II) Advanced features*. Palo Alto: Sun Microsystems Press & Prentice Hall.

Kohler, T. A., & Gumerman, G. (2001). *Dynamics in human and primate societies*. New York: Oxford University Press.

Luna, F., & Stefansson, B. (Eds.). (2000). *Economic simulation in Swarm: agent-based modelling and object oriented programming*. Dordrecht: Kluwer.

Maxis. (2002). *SimCity 4 Software*. Redwood City, CA: Electronic Arts.

Openshaw, S. (1983). *The modifiable areal unit problem, CATMOG 38*. Norwich: GeoBooks.

O'Sullivan, D., & Torrens, P. M. (2000). Cellular models of urban systems. In S. Bandini, & T. Worsch (Eds.), *Theoretical and practical issues on cellular automata* (pp. 108–117). London: Springer-Verlag.

Portugali, J., Benenson, I., & Omer, I. (1997). Spatial cognitive dissonance and sociospatial emergence in a self-organizing city. *Environment and Planning B*, *24*, 263–285.

Schenfisch, B. (2001). Simple individual based models of movement, alignment and schooling behaviour. *Future Generation Computer Systems*, *17*, 873–882.

Schreckenberg, M., Neubert, L., & Wahle, J. (2001). Simulation of traffic in large road networks. *Future Generation Computer Systems*, *17*, 649–657.

Schumacher, M. (2001). *Objective coordination in multi-agent system engineering: design and implementation*. Berlin: Springer.

Sun, R. (2001). Individual action and collective function: from sociology to multi-agent learning (Editorial). *Journal of Cognitive Systems Research*, *2*, 1–3.

Swarm Development Group. (2001). *Swarm. 2.1.1 (Software)*. Santa Fe: Swarm Development Group.

Tesfatsion, L. (1997). How economists can get a life. In W. B. Arthur, S. Durlaf, & D. Lane (Eds.), *The economy as an evolving complex system II* (pp. 533–564). Reading, MA: Addison-Wesley.

Tesfatsion, L. (2002). *Agent-based computational economics: growing economies from the bottom up*. Ames: Iowa State University.

Torrens, P. M. (2000). *How cellular models of urban systems work CASA working paper 28*. London: University College London, Centre for Advanced Spatial Analysis, Available at http://www.casa.ucl.ac.uk/how_ca_work.pdf

Torrens, P. M. (2001). *New tools for simulating housing choices Program on Housing and Urban Policy Conference Paper Series CO1–006*. Berkeley, CA: University of California Institute of Business and Economic Research and Fisher Center for Real Estate and Urban Economics. Available at http://urbanpolicy.berkeley.edu/pdf/torrens.pdf

Torrens, P. M. (2002). Cellular automata and multi-agent systems as planning support tools. In S. Geertman, & J. Stillwell (Eds.), *Planning support systems in practice* (pp. 205–222). London: Springer-Verlag.

Torrens, P. M., O'Sullivan, D. (2001). Cellular automata and urban simulation: where do we go from here? *Environment and Planning B*, *28*(2), 163–168

University of Chicago. (2001). *RePast. 2 (beta) (Software)*. Chicago: Social Science Research Computing Program.

White, R., & Engelen, G. (1993). Cellular automata and fractal urban form. *Environment and Planning A*, *25*, 1175–1199.

White, R., Engelen, G., & Uljee, I. (1997). The use of constrained cellular automata for high-resolution modelling of urban land use dynamics. *Environment and Planning B*, *24*, 323–343.

Wiener, N. (1961). *Cybernetics: or control and communication in the animal and the machine*. Cambridge, MA: MIT Press.

Itzhak Benenson
Department of Geography and Human Environment
and Environment Simulation Laboratory
University Tel Aviv, Tel Aviv, Israel
E-mail address: bennya@post.tau.ac.il

Paul M.Torrens
Department of Geography
University of Utah
260 S. Campus Centre Dr., Room 270
Salt Lake City, UT 84112-9155, USA