ANL/DIS-07-2

Argonne NATIONAL LABORATORY

NORTHWESTERN UNIVERSITY

Proceedings of the

Agent 2007 Conference

on Complex Interaction and Social Emergence

Co-hosted by

Argonne National Laboratory
Northwestern University

In association with
North American Association for Computational Social and Organizational Sciences

Northwestern University

Norris Center
1999 Campus Drive
Evanston, Illinois

November 15-17, 2007

ISBN 0-9679168-8-7

A U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC

Suggested Citations:

Proceedings: North, M.J., C.M. Macal, and D.L. Sallach (editors), 2007, *Proceedings of the Agent 2007 Conference on Complex Interaction and Social Emergence,* ANL/DIS-07-2, ISBN 0-9679168-8-7, co-sponsored by Argonne National Laboratory and Northwestern University, November 15-17.

Paper: Jones, A., and B.C. Smith, 2007, "Title of Paper," in *Proceedings of the Agent 2007 Conference on Complex Interaction and Social Emergence,* ANL/DIS-07-2, ISBN 0-9679168-8-7, M.J. North, C.M. Macal, and D.L. Sallach (editors), co-sponsored by Argonne National Laboratory and Northwestern University, November 15-17.

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Availability of This Report

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GEOSPATIAL EXOSKELETONS FOR AUTOMATA IN AGENT-BASED MODELS

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ABSTRACT

In this paper, I introduce a new approach to agent-based modeling in geospatial contexts. The novelty of the approach stems from introducing geospatial functionality as an exoskeletal wrapper around standard socio-communicative and goal-oriented agent-based AI. Operationally, I also introduce an integrated and symbiotic tight-coupling to motion capture and Geographic Information Systems, based on space-time Geographic Information Science. To prove the usefulness of the approach in simulation, I describe application of the model to a relatively well-understood (yet widely misrepresented) scenario involving crowd evacuation in constrained infrastructure.

Keywords: Geographic Information Science, geocomputation, geosimulation, multi-agent systems, agent-based models, geographic automata, urban simulation, crowd behavior, complex systems

INTRODUCTION

Geospatial functionality is essential in many agent-automata models. Geography is central to many agent rule-behaviors and is critical in defining agency. Indeed, for multi-agent systems that rely on environmental settings geography invariably occupies a pivotal contextual role in explaining and bounding actions and interactions between the system's constituent agents. There has been a recent surge in agent-based methodological development in Geographic Information Science and gecomputation and a steady growth in the application of agent-based models as experimental toolkits in physical and human geography studies.

Despite the flurry of activity in agent-automata modeling and enthusiasm for their potential in pushing the geographical sciences in new directions, both tool-forging and applied examples have, to some extent, missed opportunities to imbue the research agenda with geospatial science and spatial thinking. Geographers and other social scientists building spatial models have adopted tools and techniques often developed in non-spatial domains with the result that much of their work lacks real geospatial functionality or abstracts from the full geography of the systems or phenomena that they are actually modeling.

Chief among these problems is the use of cellular automata (CA) as agent-based models that require locomotion, even though they are relatively poorly suited to such applications. (As most developers of automata models know, gliders don't really exist outside the retina of the observing model-user (Faith 1998).) In many respects, this is a legacy of automata use in geographical models that was dominated by cellular models and a natural alliance between cells and digital geographic data structures and models based around rasters and raster-landscapes. Similarly, the first ABM development efforts in the geographical sciences were anchored in Geographical Information Systems that sported a slew of code libraries and common object models for reconciling raster layers over time, but treated dynamic vector models comparatively anemically. Similarly, spatial analysis is replete with methodology and algorithms for reconciling the composition and configuration of rasters through relatively straightforward schemes based on "map algebra". (These pattern-matching methodologies are

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hugely popular in validating geographical models, despite widely-acknowledged problems and fallacies in their use.) Raster-based techniques and skills are standard in a geographer's skill-set, while relatively more complicated calculus for vectors and computational geometry is often not as well-developed. Geographers' (and Geographic Information Scientists in particular) natural comfort with conceptualizing systems in cartographic terms and the standard training for social-scientific geographers that often emphasizes qualitative methods and multivariate statistics over approaches like artificial intelligence (AI) or computable heuristics also contribute to these difficulties.

The unfortunate situation that ABM modelers in geography are left with is that physics-inspired random walks and potential-field-following heuristics dominate geospatial models, ignoring over one hundred years of behavioral geography cataloging the myriad ways in which people differ from particles in fluid-flows or mobile pebbles under the sway of gravity or their own kinetic energy. Automata-based modeling in geography, having enjoyed a period of infancy in its development up until relatively recently, has not had to face these issues. However, as the methodological and applied research agendas of agent-based modeling and the geographical sciences have grown more closely aligned, the inability of the tools that are available to answer the questions to which we would like to deploy them has become quite problematic.

In this paper, I introduce a novel approach to agent-based modeling by wrapping agents in a geospatial exoskeleton that affords them geospatial AI for their actions and interactions. (I refer to this as an exoskeleton because we leave certain core agent-based functionality intact, essentially "geospatializing" it via exoskeletal interfaces.) Semantically, the agent-automata that I deploy become geographic automata and the systems they form are better thought of as geographic automata systems. There is more to the scheme than semantic nuances, however. The conceptual foundation for the model is steeped in behavioral and urban geography theory. Mechanically, our modeling methodology is integrally bound to geosimulation, geocomputation, Geographic Information Systems, space-time analytics, and geovisulization. Introducing geographic agency from first principles in this way produces fantastic insight into the space-time processes driving even a relatively simple system such as crowd movement.

GEOSIMULATION AND GEOGRAPHIC AUTOMATA

Geosimulation (Benenson and Torrens 2004) sits in the background for the work that I will present, offering distinct advantages over conventional approaches. First, the traditional consideration of average and spatially-modifiable geographical units or (statistically) mean individuals is replaced in geosimulation. Instead, units are regarded as spatially non-modifiable entities, with individual descriptions and independent functionality. Where aggregates are considered, they are formulated generatively, built from the bottom up by assembling individual entities for the purposes of accomplishing an aggregate task or amassing an aggregate structure. Second, simulated entities are independent and autonomous in their geospatial behavior, turning attention to specification of individual-level behaviors when model-building. Entity behavior is not necessarily treated as spatially or spatiotemporally homogenous across the system being considered. Third, models are commonly designed as event-driven, rather than time-driven, and are built with packets of spatiotemporal change based on the independent internal clocks of simulated components. When put together to form a system, update of these clocks may be flexibly-defined and the methodology can reconcile diverse spatiotemporal scales.

The idea of geosimulation has caught-on in agent-based modeling, thanks in part to development of operational toolkits that allow people to build their own geosimulation models (Benenson and Torrens 2005), or to use of geosimulation as an interfacing mechanism (Bernard et al. 2002). In addition to its use in dynamic Geographic Information Science (Albrecht 2005), agent-based modelers in computer animation (Ali and Moulin 2005; Moulin et al. 2004), social geography (Koch 2003), location-allocation modeling (Ligmann-Zielinska et al. 2005), machine learning and data-mining (Filho et al. 2004), human-computer interaction (Furtado et al. 2007; Furtado and Vasconcelos 2007), criminology (Melo et al. 2006), and medical epidemiology (Ward et al. 2007) have developed geosimulation models. Geosimulation has also been used to extend neighborhood functionality for CA methodology (Zhao and Murayama 2007). The work reported in this paper is part of our efforts to develop more core geospatial functionality for geosimulation-based agent models.

Operationally, we use automata as the vehicle for geosimulation. We have developed a scheme for building Geographic Automata Systems (GAS), fusing the computational properties of automata with Geographic Information Science (GISci) functionality (Torrens and Benenson 2005). GAS are, fundamentally, automata and retain components from cellular automata and intelligent agents. We add the ability to express spatiotemporal relationships based on the full range of spatial analysis routines available in GISci. Geographic Automata (GA) may be located by any geo-referencing convention (L) and can also move through the spaces they occupy by any locomotion regime (R_L). L allow GA to be registered in space and time (i.e. $L = L_t$), either directly or indirectly, on a one-to-one, one-to-many, many-to-one, or many-to-many basis. A typology or ontology (K) of GA entities mediates the nature of L and R_L. Input to GA is considered *geographically* as neighborhoods of interaction and influence. GA neighborhoods may differ heterogeneously in extent and shape per GA and may change dynamically so that $N = N_t$. Neighborhood rules (R_N) determine these changes. Neighborhood relationships, expressed as cognitive filters, social relationships, lines-of-sight, and so on can be introduced and allowed to vary over space and time. Many GA (G below) may be combined in a systems context, with each GA in the collective GAS coded heterogeneously:

$$G \sim (K, S, R_S, L, R_L, N, R_N), \text{ where } R_S: S_t \rightarrow S_{t+1}\,;\ R_L: L_t \rightarrow L_{t+1}\,;\ \text{and } R_N: N_t \rightarrow N_{t+1}\,.$$

Among other things, this allows us to distinguish agent types based on their geospatial behavior. In the models to be described, five *entity types* (classes in an object-oriented sense) are used: World, FixedObjects, MobileObjects, Goals, and Probes. World represents the simulated environment (a city). It subsumes (contains, encapsulates) all other entities in the simulation. It also acts as a template for georeferencing, handling entities' absolute position in the World and their position relative to other entities in the World. FixedObjects is used to represent the urban infrastructure and thus handles buildings and obstacles (parked cars, trees). FixedObjects do not move, although they can influence the movement of other mobile entities. MobileObjects represent people in isolation, crowds and the groups that they form, as well as particles (smoke, embers, mobile toxins). MobileObjects move, as the nomenclature suggests. Goals are used to structure events. They are used as space-time anchors, operating as beacons for actions to be executed. Goals may be used by specific groups or individuals, in specific places and/or at specific times. Probes function as data-collecting entities that linger in the model world with the intent to capture attributes of the simulation (as an executable computer program), the simulated system (as a synthetic representation of phenomena of interest or under study), and model entities' states and actions. Probes are endowed with the ability to sift through data, sort it, and exchange it with caches for input/output to/from GIS as well as spatial and statistical analysis.

GEOSPATIAL FUNCTIONALITY FOR A GEOSPATIAL MODEL

The next step is to imbue this modeling scaffold with theory-driven heuristics. The sub-field of behavioral geography is replete with theory and explanation for human geospatial behavior. We take our cues, in developing geospatial functionality for our modeled agents, from decades of work in behavioral geography.

First, we acknowledge that geospatial behavior is largely determined by heterogeneous geospatial traits per-agent. While seeming to behave with universal behavior at a macroscopic scale of observation, people move and navigate through urban settings with a great deal of individuality and their movement behavior is formed heterogeneously from independent geospatial and geotemporal characteristics. Infrastructure characteristics are established and assigned to geometry in GIS. Pedestrian agents are endowed with characteristics from a synthetic data population, using statistical, geostatistical, and geodemographic inference to down-scale aggregate data sources to micro-levels. Motion capture and motion editing are used to produce realistic-looking movement, heterogeneously, per-agent. The technique also provides upper- and lower-bounds for pedestrian velocity, as well as free speed. This allows us to calibrate rates of acceleration/deceleration per agent, accounting for differences in habits, gait and allows us to encode body language into simulations geometrically.

Second, we base our modeled agents on an assumption that they plan their paths geographically and use waypoints to develop a general sense of how to get somewhere. Path planning is introduced to the modeling framework per-agent as a low-level search heuristic that determines (graph-based) nodal waypoints through which agents then ambulate using a second, higher-level way-finding heuristic, whereby agents plan their route between waypoints before mobilizing.

Third, we wrap agents with spatial cognition as part of their behavioral AI. A traditional automata-based socio-communicative and goal-oriented agent AI sits at the core of modeled entities' behaviors, but those routines are passed through a second layer of geospatial AI, thereby dictating when, where, and in what spatiotemporal contexts that functionality should be employed. Agent walkers are endowed with an individual-centric geography around themselves, used to filter the world as they move. This is formed as a vision cone centered on the agent and cast (as a ray) in a forward direction. Cone properties vary heterogeneously and spatiotemporally based on changes in pedestrians' behavior, characteristics, and surroundings. Potential collisions are registered in an array and sorted for relevance (angry dogs may get priority for some people, but not others, for example). Once free from encounters, pedestrians navigate to return to their shortest path route.

Fourth, we make use of the fact that people's activities strongly structure their use of space and time. Walkers may organize their paths through space-time as events fashioned around their activity goals and these serve as spatiotemporal anchors. We have developed an integrated GIS-based analytical toolkit for sweeping the parameter-space of simulations and for registering simulations to real-world conditions, based on space-time paths and prisms for individual, dyad, and group behavior and isochrones for individuals, groups, and events.

AN APPLIED EXAMPLE

I will now demonstrate the usefulness of this approach through discussion of the model's application to evacuation of agents through confined urban infrastructure. The physics of such effects have been well-modeled on the basis of association between the physical properties of crowd evacuation in such contexts and those of fluid and excitable media in granular or gas-kinetic environments (Helbing et al. 2000). However, true behavioral models have not been developed to model such situations, save a "social force" extension of Newtonian dynamics.

The simulation is set-up as follows. Synthetic pedestrians were arbitrarily loaded to an urban scene and run with innate behavior. Motion capture data dictate their free, upper, and lower speeds and acceleration/deceleration (figure 1). They possess one higher-level driver, an impulse to evacuate from their seed position to a goal at the end of the modeled world. Only one exit exists.

Time t Time t +1 second

FIGURE 1. Velocity data are derived from motion capture of a real-world actor's movement.

An A* algorithm is run to find the shortest route to that exit for each pedestrian. Pedestrians will follow this track unless their innate behavior dictates otherwise. At the onset of the simulation, pedestrians orient themselves in the direction of the exit. Taking a prompt from higher-level behavior (i.e., to proceed calmly to the exit, or flee at all costs), they quickly scale their velocity from a position of rest to their free speed, navigating, path-planning, and mobilizing to an assembly point on the other side of the exit (figure 2). Some pedestrians have line-of-sight to the destination, while others must steer clear of infrastructural objects (walls) before they can see the goal.

Agents that make it to the exit early are able to evacuate the enclosed space relatively freely. However, a bottleneck soon forms at the mouth of the exit. As the crowd of pedestrians builds up behind and to the sides of this obstruction, a characteristic arch forms at the entry to the exit corridor, which impedes escape further. The crowd begins to wedge at ± 45 degree angles on either side of the exit. This is a well-known emergent property (Helbing et al. 2001).

Probes continually report pedestrians' positions. Those data are run through a space-time GIS that builds space-time paths as graphics and geometry, allowing the parameter-space of the simulation to be swept. As seen in figure 3, Agent 1 exits (the space-time path becomes a vertical, indicating rest) quickly, following the shortest path relatively free of collisions. Agent 2 encounters crowded conditions, however, taking longer to exit. Agents 3 and 4 proceed well until their geospatial AI is impeded by a jam toward the end of their space-time path. Compaction and expansion of their space-time paths is evident, illustrating frustrated cycles of speeding-up and slowing-down. These signatures are similar to those in car traffic jams following accidents (Nagel and Schrekenberg 1995). The onset of a traffic jam is clear (figure 2c, 3a). The slope of the space-time path of individual walkers rises sharply as pedestrians enter the exit corridor, leveling out somewhat thereafter (figure 3).

Mapping textures to simulated pedestrians (cloth, hair) and infrastructure (concrete), lighting, and shadow-mapping is useful in generating realistic-looking simulations (figure 2). This is particularly important in conveying the themes of modeled scenarios to viewers of the simulation. Buildings may be rendered as transparent or reflective so that the dynamics of crowd flow can be viewed through dense simulated infrastructure as the simulation runs.

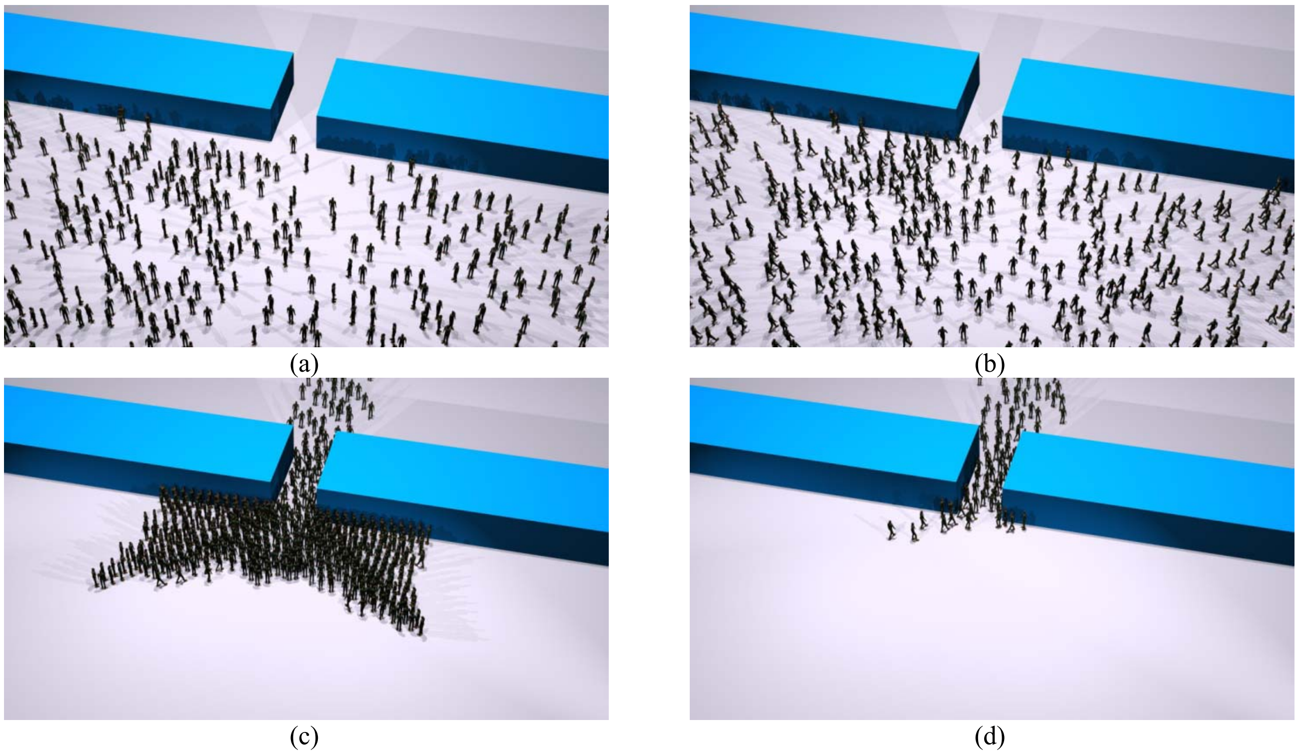

FIGURE 2. (a) Seed conditions. (b) Nearby agents exit quickly (t = 3 seconds). (c) Gridlock forms for agents that arrive at the exit later; pressure builds as the crowd compacts (t = 33 seconds). Characteristic lateral wedges of jammed agents form at the exit's sides, further obfuscating evacuation (t = 66 seconds). (d) As the pressure in the congested crowd subsides, evacuation proceeds more efficiently (t = 133 seconds.

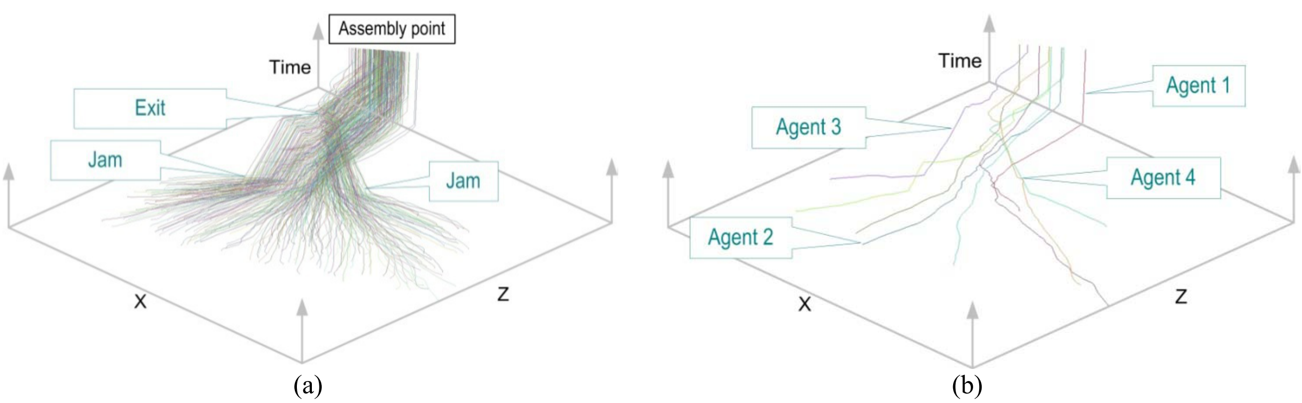

FIGURE 3. (a) Space-time paths for all agents. Spatial movement is shown in (x,z), temporal movement in y. (b) Agent 1 evacuates quickly and easily, as shown by the relatively straight and flat space-time profile. Agent 3 encounters some traffic over the last two-thirds of her journey. Agent 3 evacuates relatively slowly, while agent 4 has a difficult evacuation, as shown by the tortuous and steep space-time path of her movement.

CONCLUSIONS

A demonstration of the usefulness of behaviorally-driven models and analyses in developing realistic and intelligent synthetic representations of geospatial behavior in urban environments has been shown in this paper. The advantages of this approach have been illustrated through application of the scheme to evaluation of large-scale evacuation dynamics in downtown settings. The scheme that has been described is valuable in proving the underlying computation, but also demonstrates the potential for approaches of this kind in exploring and generating theory in studying spatial cognition, sociality, collective behavior, and human-environment interaction.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0624208 from the Human and Social Dynamics program and Grant No. 0643322 from the Geography and Regional Science and the Methods, Measurement, and Statistics programs, and support from Autodesk, Inc. and Alias Research.

REFERENCES

Albrecht, J. 2005. A New Age for Geosimulation. *Transactions in Geographic Information Science* 9 (4):451-454.

Ali, W., and B. Moulin. 2005. 2D-3D Multiagent GeoSimulation with knowledge-based agents of customers' shopping behavior in a shopping mall. Paper read at Conference on Spatial Information Theory, at Ellicottville, NY.

Benenson, I., and P. M. Torrens. 2004. *Geosimulation: Automata-Based Modeling of Urban Phenomena*. London: John Wiley & Sons.

———. 2005. A minimal prototype for integrating GIS and geographic simulation through Geographic Automata Systems. In *GeoDynamics*, eds. P. Atkinson, G. Foody, S. Darby and F. Wu, 347-369. Florida: CRC Press.

Bernard, L., I. Simonis, and A. Wytzisk. 2002. Dynamic interoperable geoprocessing and geosimulation: An OpenGIS/HLA based interoperability architecture. Paper read at European Interoperability Workshop, June 24 to 26, at London.

Faith, J. 1998. Why Gliders Don't Exist: Anti-Reductionism and Emergence. In *Artificial Life VI: Proceedings of the Sixth International Conference on Artificial Life*, ed. C. Adami. Cambridge, MA: MIT Press.

Filho, E. V., V. Pinheiro, and V. Furtado. 2004. Mining data and providing explanation to improve learning in geosimulation. In *Lecture notes in computer science 3220: Intelligent Tutoring Systems*, eds. R. M. Vicari and F. Paraguaçu, 821-823. Berlin: Springer.

Furtado, E., V. Furtado, and E. Vasconcelos. 2007. A conceptual framework for the design and evaluation of affective usability in educational geosimulation systems. In *Lecture Notes in Computer Science 4662: Human-Computer Interaction (INTERACT 2007)*, eds. M. C. C. Baranauskas, P. A. Palanque, J. Abascal and S. D. J. Barbosa, 497-510. Berlin: Springer.

Furtado, V., and E. Vasconcelos. 2007. Geosimulation in education: A system for teaching police resource allocation. *International Journal of Artificial Intelligence in Education* 17 (1):57-81.

Helbing, D., F. Illés, and T. Vicsek. 2000. Simulating dynamical features of escape panic. *Nature* 407 (September 28):487-490.

Helbing, D., P. Molnár, I. Farkas, and K. Bolay. 2001. Self-organizing pedestrian movement. *Environment and Planning B* 28:361-383.

Koch, A. 2003. Sozialgeographische agentenbasierte geosimulation: Zur komplementarität von raumsemantik und raummodell. In *Klagenfurter Geographische Schriften 23: Multi-Agenten-Systeme in der Geographie*, eds. A. Koch and P. Mandl, 35-64. Klagenfurt: Institut für Geographie und Regionalforschung der Universität Klagenfurt.

Ligmann-Zielinska, A., R. L. Church, and P. Jankowski. 2005. Exploring multiobjective urban land allocation with geosimulation: Are optimized spatial alternatives doable in practice? Paper read at Geocomputation 2005, at Ann Arbor, Michigan.

Melo, A., R. Menezes, V. Furtado, and A. L. V. Coelho. 2006. Self-organized and social models of criminal activity in urban environments. In *Lecture Notes in Computer Science 4150: Ant Colony Optimization and Swarm Intelligence*, eds. M. Dorigo, L. M. Gambardella, M. Birattari, A. Martinoli, R. Poli and T. Stützle, 518-519. Berlin: Springer.

Moulin, B., W. Chaker, and J. Gancet. 2004. PADI-Simul: an agent-based geosimulation software supporting the design of geographic spaces. *Computers, Environment and Urban Systems* 28 (4):387-420.

Nagel, K., and M. Schrekenberg. 1995. Traffic jams in stochastic cellular automata. Los Alamos, NM: Los Alamos National Laboratory.

Torrens, P. M., and I. Benenson. 2005. Geographic Automata Systems. *International Journal of Geographical Information Science* 19 (4):385-412.

Ward, M. P., S. W. Laffan, and L. D. Highfield. 2007. The potential role of wild and feral animals as reservoirs of foot-and-mouth disease. *Preventive Veterinary Medicine* 80:9-23.

Zhao, Y., and Y. Murayama. 2007. A new method to model neighborhood interaction in cellular automata-based urban geosimulation. In *Lecture Notes in Computer Science 4488: Computational Science (ICCS 2007)*, eds. Y. Shi, G. D. Albada and J. Dongarra, 550-557. Berlin: Springer.