Chapter 26

Building Mega-Models for Megacities[1]

Dr. Paul M. Torrens[2]

Urban simulations are an important toolkit for theorizing about cities, testing ideas and hypotheses, and evaluating plans and policies. As a field of research, urban modeling is at an important stage in its development. The pace of urbanization and city growth, and the ever-increasing rate of adaptation of urban phenomena, have, to some extent, accelerated beyond the abilities of previous generations of modeling methodology to remain practically relevant and diagnostically useful. These challenges are particularly significant for urban models tasked with representing the dynamics of the world's megacities, which manifest among the most complicated and complex human-environmental systems. A next-generation of urban modeling is perhaps needed to conceptualize the dynamics of the world's megacities, which are, in many instances, growing in number, size, and influence at unprecedented rates.

26.1 Introduction

The rationale for studying urban systems and phenomena is varied and compelling. Urban activities are among the most significant of the Earth's land-uses. Cities host vast amounts of the world's built and technical infrastructure, they are seats of innovation and creativity, they have served among the most important engines of land cover change through history, and they are significant sources of anthropogenic contributions to the Earth's climactic systems. Cities also serve as hubs of human activity: they provide the ambient human infrastructure for much of the world's social, economic, and cultural systems, as well as providing the

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[2] Associate Professor, Geosimulation Research Laboratory, School of Geographical Sciences & Urban Planning, Arizona State University, Tempe, AZ 85287-5303, USA. Email: torrens at geosimulation dot com.

substrate that houses the majority of the world's population. Urban systems are still growing in extent and volume throughout the world. In many areas, the pace of urban expansion is actually accelerating, sometimes strikingly so. This is particularly true in the world's megacities: unified urban agglomerations with populations of at least ten million inhabitants. It is here, in megacities, that the greatest engines of the world's urban activity – and all of its associated problems and promise – are to be found.

In the last thirty years, the number of megacities in the world has increased from three to twenty (Figure 26.1). The United States, for example, hosts three megacities: New York, Los Angeles, and the burgeoning Chicago megacity (Figure 26.2). The geography of this mega-urbanization is uneven. Most megacities in the developed world are projected to reach a level of stasis in their growth, growing at slower rates as their populations saturate their urban environment and the dominant role that they play in their constituent national systems – and globally – locks-in, at least for the time being. Growth in the Los Angeles-Long Beach-Santa Ana megacity is forecast to expand by only 6.5% (+0.8 million, to 13.1 million total) between 2005 and 2015, while that of Tokyo is set to appreciate by <1% (+0.3 million, to 35.5 million total) over the same time-frame (Moore and Gardner 2007). No net growth is projected for the Osaka-Kobe megacity over that period (its population is set to remain steadfast at 11.3 million in total) (Moore and Gardner 2007). Meanwhile, megacities in the developing world are forecast to accelerate in their growth: Lagos megacity is projected to expand by 48%, adding 5.2 million people (to 16.1 million total) between 2005 and 2015, Dhaka is estimated to grow by 35% (+4.4 million, to 16.8 million total), Karachi by 31% (+3.6 million, to 15.2 million total), Jakarta by 27% (+3.6 million, to 16.8 million total), and Kolkata (Calcutta) by 19% (+2.7 million, to 17 million total) over the same time period (Moore and Gardner 2007).

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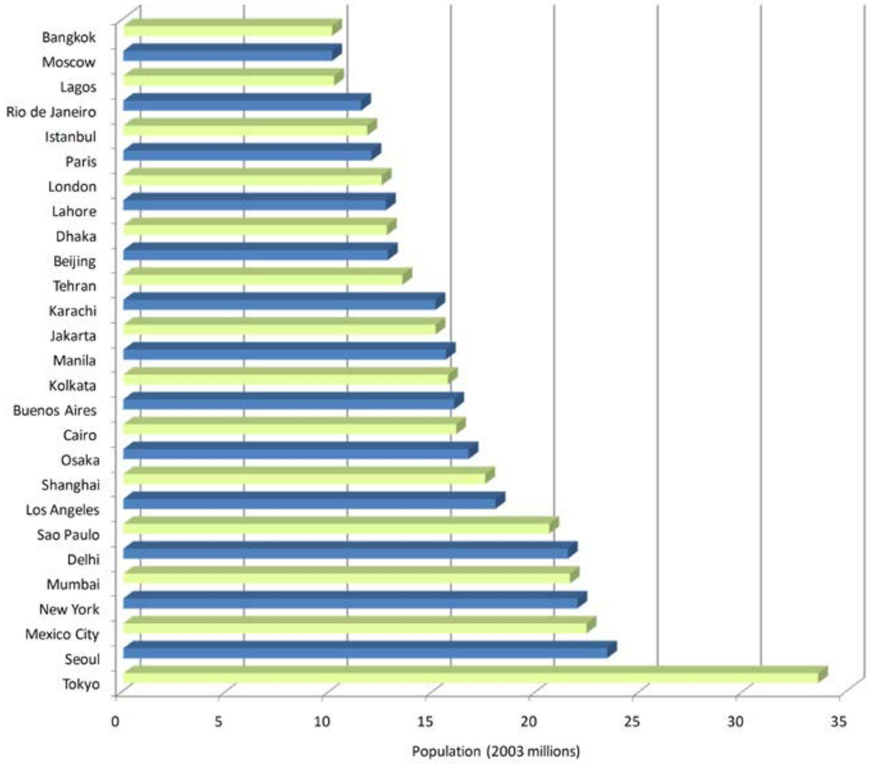

Figure 26.1 The world's 27 megacities

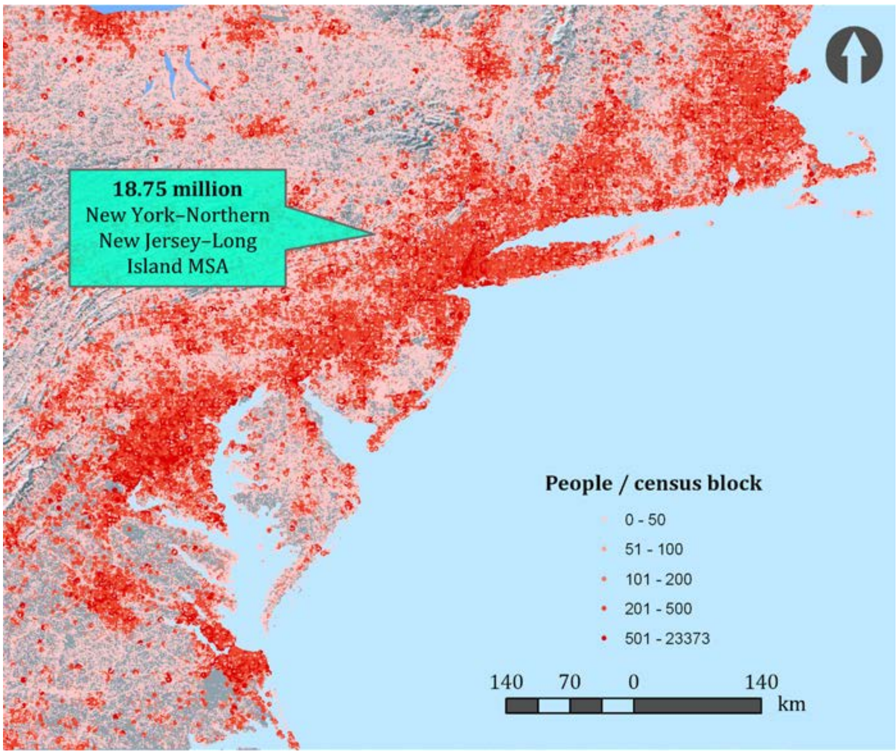

Figure 26.2(a) The New York megacity

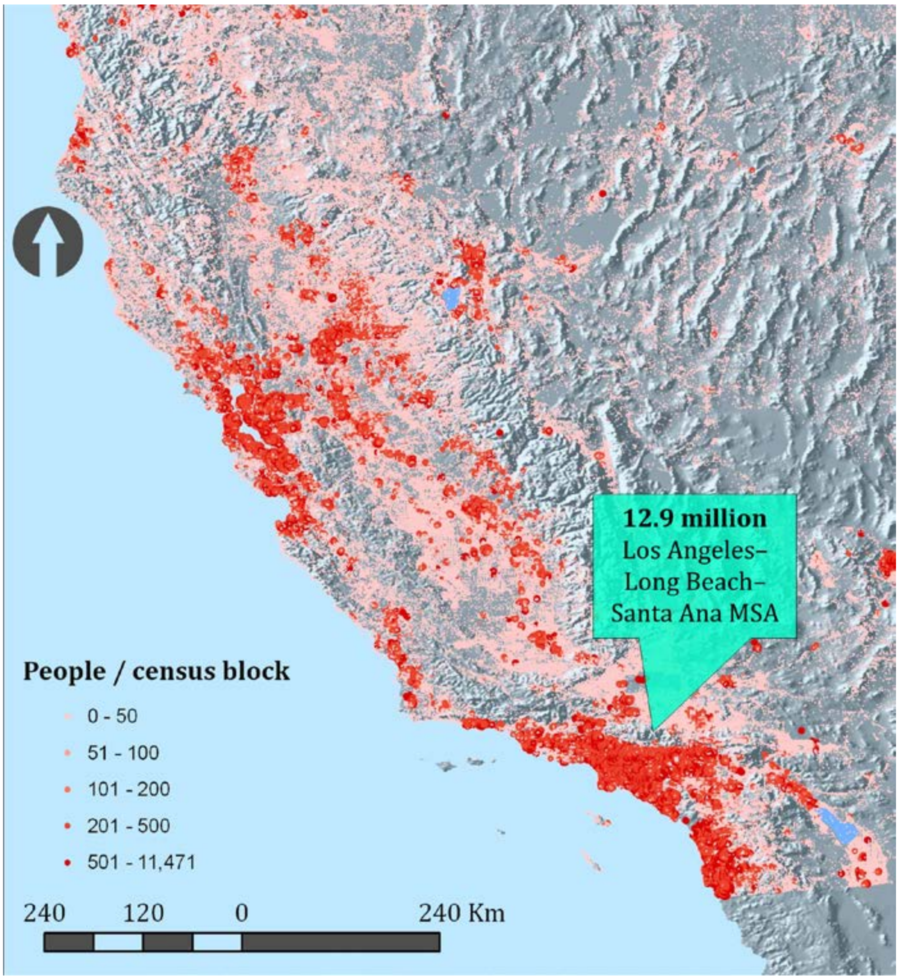

Figure 26.2(b) The Los Angeles megacity

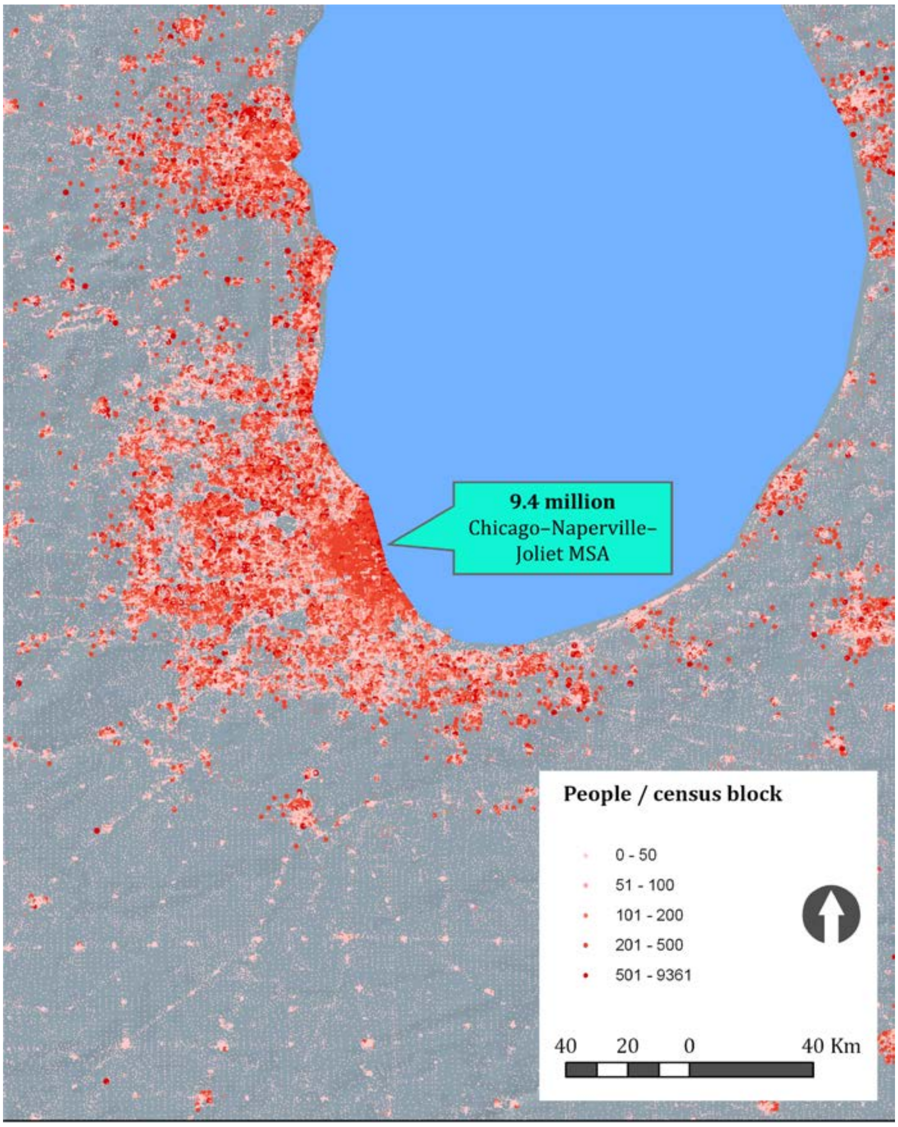

Figure 26.2(c) The burgeoning Chicago megacity

Understanding how and why megacities form in diverse locations, at varying times, and how they develop over diverse time-scales are important goals for science across disciplines and interests. Indeed, megacities hold the answers to many "big science" questions that remain to be answered (see, for example, the special issue of *Science* magazine on "cities" (American Association for the Advancement of Science 2008; http://www.sciencemag.org/cities/video/). As megacities grow and consolidate with massive tangible footprints and huge populations, so also will their influence on the world's physical, natural, social, and technical systems expand and intensify. The pace of their emergence, development, and growth has, to a certain extent, outpaced our ability—as scientists—to keep track of their driving mechanics. Appreciating and understanding the future evolution of megacities is critical in explaining the futures of the world's demography, economic markets, climate variability, innovation, and in postulating about many other factors.

Exploring these issues is largely intractable without the use of computer models. Yet, the traditional cadre of simulation methodology that we have at our disposal is largely inadequate for examining the complexity of megacities in any serious fashion and serves to limit the range of questions that scientists can pose in simulation.

Mega-models are not commonly developed for megacities, although their potential usefulness as planning and decision support systems, and as synthetic laboratories for trying-out ideas, hypothesizing about possible urban futures, and testing what-if scenarios has, perhaps, never been greater. In this chapter, I will take a look at why robust mega-urban models do not feature more prominently in the scientific record and I will focus, in particular, on the limitations that have prevented their proliferation, as well as the promising avenues of academic and applied inquiry that might move the state-of-the-art in directions that might accelerate the pace of innovation in urban simulation and its applied use.

26.2 Massive, unwieldy megacities

Megacities are extraordinarily large and cumbrous phenomena. Their enormous size and complicated details veil many of their attributes to inquiry. These massive urban behemoths are complex mega-systems (if we consider their role in a world ecology of billions of people, we can perhaps consider them as giga-systems) composed of many interacting parts, each intertwined through a bewildering array of non-linear and dynamic phenomena that scale up and down and weave throughout the fabric of the past, present, and future. In the case of these huge urban agglomerations, the orders of magnitude in scaling from the individual to the system are many times greater than one would usually encounter in urban studies. The number of state descriptors and linkages required to explain the functioning of megacities are also substantially greater, as are the potential trajectories for the system's state-space (land-use, land cover, zoning, etc.) over time. Pinpointing the emergence of novel patterns and phenomena in megacity evolution is an arduous task considering the cacophony of actions and interactions within the megacity that must be scrutinized in order to identify such innovation.

Megacities are highly variable. Some, such as London, Tokyo, and New York, are long-standing global cities (Sassen 1991) that have dominated atop the world's urban hierarchy for hundreds of years. In other cases, megacity emergence is a relatively recent phenomenon. The developing Guangzhou megacity in China, for example, had a population of just 2.7 million thirty years ago; by 2015 it is expected to reach 10.4 million (Moore and Gardner 2007). Although it is now home to 11 million people, the Lagos megacity in Nigeria had a population of 1.9 million thirty years ago (Moore and Gardner 2007). Traditionally, megacities have grown in developed countries with relatively advanced economies: France, Japan, South Korea, the United Kingdom, and the United States, but more recently, megacities have emerged in developing countries (Bangladesh, Egypt, Indonesia, Nigeria, Pakistan, the Philippines) and newly-industrializing nations (Brazil, China, India, Mexico, Thailand, Turkey). Moreover, the rate of emergence and expansion of city-systems in non-traditional host countries is growing. Economic output and the quality of life in these diverse megacities vary considerably: the Gross Domestic Product of Bangladesh is $73.7 billion and the average life expectancy is 63/63 (male/female), while GDP in the United States is 186 times greater, at $13.8 trillion and the average life expectancy is 75/80 (male/female) (using GDP figures from the International Monetary Fund, 2007 and life expectancy averages from the World Health Organization, 2007).

Experimenting with such mammoth and rapidly adapting systems in any sort of tangible fashion on the ground is, understandably, prohibitively difficult. In these instances, we may turn to simulations as an alternative (or ancillary) medium for exploring the processes and phenomena that drive megacity dynamics. Simulations can serve as an artificial laboratory for experimenting and theorizing about their present conditions, as well as their past and future trajectories.

There are, however, fundamental challenges in representing megacity systems in simulation. Traditional toolkits and methods for modeling cities and city-systems are limited in their ability to treat the complexities that drive urbanization on a mega-level. Those toolkits largely dictate the sets of questions that can be posed in simulation, constrained within the limitations of the specific assumptions that they make, rather than being flexible in handling multiply-interacting city systems across a variety of scales (Batty and Torrens 2005).

26.3 Simulations, simulacra and the synthetic city

A plethora of models exist for simulating urban *sub-systems* at macro-scales (e.g., inter-regional migration (McHugh and Gober 1992), scaling and allometry in global city-size distributions (Batty 2008), and the geography of national urban agglomeration economies (Fujita *et al.* 2001; Krugman 1996)), as well as characterizing sub-systems at meso-scales (e.g., intra-urban traffic flow (Nagel and Schreckenberg 1992), formation of urban heat islands (Brazel *et al.* 2000), and urban epidemic dynamics (Eubank *et al.* 2004)), and micro-scales (e.g., pedestrian activity along city streets (Haklay *et al.* 2001), vehicle parking behavior (Benenson *et al.* 2006), and emergency evacuation behavior (Nara and Torrens 2007)). Such sub-systems are found in megacities, but sub-system models do not address megacities as entities in their own right and seldom consider the dynamics of these systems as special cases in megacity contexts. Global climate models, for example, often treat cities as a simple binary classification – urban or not urban – in accounting for land cover in the boundary-layer of the Earth's climate systems.

Much of the innovation in city simulators has been achieved in building models of urban-scale traffic systems, at the level of individual drivers, their decisions, actions, and interactions, propagated up-scale and down-scale between the city and the road (Barrett *et al.* 1999; Torrens 2005). Sophisticated models of property markets and residential formation at the geography of interacting households and communities have also been built (Benenson *et al.* 2002; O'Sullivan 2002; Torrens and Nara 2007). In these instances, the path from individual agent to larger-scale system (and back again), and all of the complex interactions that take place in between can be relatively easily identified and expressed algorithmically, within spatial, temporal, and system confines, largely because there are long traditions of social science, behavioral, and economic research into these sub-systems, and data for calibrating and verifying models against ground-truth are often available at these scales. These remain, however, limited cases and they explain only one of many (isolated) components that drive the development and day-to-day functioning of megacities.

In an ideal situation, we could couple many sub-system models together to generate a *mega-model* that explains the intricate inner-workings of megacities at the detail of its constituent components. This is insufferably difficult to achieve in practice because individual models are often developed for independent purposes, with purpose-specific data models, methodological approaches, spatial resolutions, constraining assumptions, system closures, time-scales, and so on. Nevertheless, some researchers have made attempts to develop such mega-models, thereby proving the concept of the mega-model and its potential promise.

Some urban mega-models are developed from a systems engineering perspective, coupling the information flow between diverse sub-system models as "stocks and flows" models that determine the elasticity in intra-system relationships (Forrester 1969). These are not strictly integrated models, but capture massive urban systems at a synoptic scale nonetheless, and explain the relative exchange of materials and goods on an intra-urban level.

The closest analog to the ideal of a mega-model is the large-scale urban model, most commonly developed for operational use by metropolitan planning organizations in estimating the ability of the city to provide future urban services. Generally, large-scale urban models are designed to couple land-use and transport simulations, with occasional connections to air quality models or air quality analysis through their predictions of aggregate vehicle emissions to the boundary-layer atmosphere. Previous generations of these models were developed as coupled land-use and transportation simulators, in which a land-use model generated trips that are subsequently simulated over large-geography urban systems as traffic flows; the DRAM/EMPAL model (the Disaggregated Residential Allocation

Model and the Employment Allocation Model) was a widely-deployed example of such a trip-generator, focusing on the push and pull factors that anchored trips in the urban system (Putman 1983). These models were often built on microsimulation (Clarke 1996) and regional science (Isard 1975) methodologies, which for the most part used relatively simple heuristics (often based on physics of spatial interactions (Fotheringham and O'Kelly 1989) and parametric statistics for estimating discrete choices for activity types and locations (Louviere *et al.* 2000)) to extrapolate future values from coarse-resolution socioeconomic data-sets. Large-scale urban models have been applied in evaluating planning and policy alternatives in many megacities, with mixed usefulness (Batty 1994). In traditional form, large-scale models tend to treat urban dynamics in a crude, abstract fashion, and although they may be loose-coupled to environmental models in some cases (Wegener 1994a), they largely fail to treat the full range of sub-systems that account for megacity formation and adaptation in sufficient detail to be maximally useful for robust experimentation *in silico* (to use a term I have borrowed from Steven Levy (1992))**.**

More recently, a next generation of large-scale urban models has been developed as planning support systems, which more closely approach the ideal of an integrated, intricate model of an entire city-system. Detail has been added to these systems, in large part, by developing a slew of sub-models that handle demographics, lifecycle transition, migration patterns, a diversity of modes of transportation, land-use change, and property markets. Two planning support systems stand out in particular—the California Urban Futures models (Landis 2001), and UrbanSim (Waddell 2002). Urbanism, in particular, is relatively widely used in operational city planning. It was initially developed as an urban economic model, designed to estimate the future trajectories of urban land markets, but several efforts are underway to extend the model by integrating it with ancillary activity, travel, and traffic models, as well as models of urban natural environments, and the lifecycle of resource use in constructing large city-systems (Li *et al.* 2007).

A parallel thread of model development has been carried out in the sustainability sciences, focused predominantly on modeling the role of human-environment interactions upon land-use and land cover change. The sustainability science community has benefitted greatly from increasing availability of remotely-sensed data at finer-grained resolutions and covering longitudinal periods of time. Many of these models are focused on large city-systems, with an emphasis on the extension of expanding cities into the urban-rural interface through suburban sprawl, edge city formation, and exurban development (Parker *et al.* 2003).

Many model-developers have turned to complexity studies in search of methodology for treating the complexities inherent in large city-systems. Most have been built around automata (cellular automata, agent-based models, individual-based models, multi-agent systems, geographic automata) (Benenson and Torrens 2004), following the success of such tools in generating signature complexities in the Artificial Life community, economics, mathematical sciences, ecology, computer science, and physics (Wolfram 2002). These bottom-up approaches, representing city-systems at the scale of individual actors and their activities, are perhaps the most intricate urban mega-models. Development work at Sandia National Labs' National Infrastructure Simulation and Analysis Center (NISAC) in New Mexico in the United States is perhaps the exemplar of these approaches. Using a shared simulation architecture, NISAC is working to develop bottom-up agent-based and graph-based models of diverse but integrated socio-technical systems (public health, utility infrastructures, network infrastructures, vehicle traffic flow, and the economy) for whole cities and the entire United States (Eidson and Ehlen 2005).

26.4 The challenges of developing megacity models

A number of constraints have slowed progress in developing and applying more robust models of megacities. Perhaps the greatest challenge in building more useful models of megacities as artificial laboratories is the sheer size and complexity of the urban systems that they encapsulate. To a certain extent, abstract models that at least represent megacities in a proxy fashion should be sufficiently useful as experimental toolkits, but other challenges remain in advancing beyond proxies.

The constituent drivers of megacities remain largely unknown in social science, behavioral science, and even in the design and engineering sciences. Megacities are organic, bottom-up, dynamic, and adaptive systems that do not readily make sense microscopically, synoptically, or from vistas in between. The science of modeling megacities is being developed at the same time that theories are being forwarded, evaluated, accepted, rejected, and modified. Concurrently, megacities are growing, adapting, accelerating, and reaching relative equilibrium in different places and contexts. There is a need for a simulation methodology that can flexibly keep step with these developments on the ground and in our theoretical discussions. Most urban models are unrealistic representations of the systems that they simulate and this does not help to advance the state-of-the-art. Algorithmically, urban models generally retain an overarching focus on simple rule-of-thumb heuristics from urban studies (grow on the edge of the urban mass, don't build on steep slopes, fill-in interstitial urban sites if they are surrounded by sufficient development, and so on (Clarke *et al.* 1997)). In other cases the models are largely data-driven: their algorithms focus on spatially distributing the data that is fed to them; these models are generally only as good as the data that they are fed and little reliance can be placed upon their future extrapolations. They are, as the cliché goes, "tools to think with" (Negroponte 1995) rather than serving as decision support systems. Consequently, few models make it out of sheltered laboratory settings to engage with theory or to be used on the ground in informing decisions.

In other fields (climatology, cosmology, macroeconomics, for example), standard models have been in place for many decades and these serve as a foundation for innovation in their respective scientific communities. There is no (robust) standard model for cities or megacities, largely because each city is rather unique in its composite patterns and processes in a much more variable way than (imaginatively) comparable structures in climatology, cosmology, and macroeconomics might be considered. Invariably, then, model-builders must start anew in constructing new tools and this slows the pace of innovation. Building a common platform for urban simulation, one that treats some of the more generic components of city-systems, may help to ease this constraint.

Sophistication in urban simulation is almost always closely allied to the availability of data, and the plentitude of data at high spatial and temporal resolutions, covering a multitude of urban sub-systems. With the exception of remotely-sensed imagery relating to land-cover, such data are often in short supply, particularly at the micro-scale (Torrens 2006). Recent developments in cyberinfrastructure for automated sensing and data collection over distributed sensor webs suggest that issues of data availability may be resolved in the near future, but sufficiently complete data-sets will most likely be in short supply perpetually for many urban sub-systems, particularly those relating to human decision-making. These data are simply too difficult to collect over megacities or to infer, even using cell-phone records or patterns of vehicle or currency mobility, for example (although attempts to do so have been made (Brockman *et al.* 2006; González *et al.* 2008)).

For systems in which data may be available, they are often required in massive volumes to feed ravenously data-hungry urban simulations. Similarly, the data that complex simulations output often spill-out in volumes that are many times greater in size than the resources that are initially input. Sophisticated dataware are therefore needed to visualize inputs and outputs in a scientific fashion and to mine data for knowledge discovery and generation. There has been a fantastic amount of innovation in visualizing complex information, in the development of information systems for handling massive data-sets, and in crafting intelligent routines for knowledge discovery, data-mining, and reality-mining of large data reservoirs. With few examples (Batty *et al.* 2001), much of this innovation has not yet been introduced to urban simulation, particularly as a decision support system.

Issues of calibrating, validating, and verifying complex urban simulations often compound these problems. Because megacities are such large and unwieldy phenomena, garnering ground truth for the purposes of model-fitting is a very difficult task. Models are therefore often built blindly, as proofs-of-concept, or are built from theory, which is almost always anecdotal, qualitative, and even normative in nature. Building robust models on such a permeable foundation is quite a difficult undertaking. Improving data resources and related dataware may help to resolve such issues, but complicating factors remain as grand challenges, particularly in treating uncertainty and stochasticity in the interface between models, data, and ‘truth’.

Large-scale urban models, if simulated with any serious degree of fidelity to the mega-systems that they are tasked in representing, are usually massive software engineering projects that require considerable computing resources. To some degree, principles of encapsulation, abstraction, clustering, scheduling, and distributed processing from high-performance computing may be used to great advantage in urban simulation and already are, for example, in traffic modeling (Nagel and Rickert 2001), where road segments may be neatly parsed and passed between processing units on parallel systems. Considering megacities more comprehensively, however, involves treating massively dynamic and interacting agents and agencies with many-to-many relationships that scale-up, scale-down, and act and interact with complex and fluid feedback contingencies. Such processes and phenomena are not as easily and discretely packaged as computable packets.

26.5 Pushing the state-of-the-art beyond current research difficulties

It is, perhaps, readily apparent to the reader that the number of constraints upon advancing large-geography and large-scale (at small resolution) urban modeling are many. Progress is being made, however, in overcoming the problems that I have detailed.

The most promising development has come in the form of research into flexible future methodologies for urban simulation that will allow models to be constructed with a greater level of realism and at improved spatial and temporal resolutions. The most encouraging advances have come from the adaptation of older technologies, based around automata and information processing, and their modification for use in building models of cities from the bottom-up, popularly referred to as geosimulation (Benenson and Torrens 2004). Modeling tools developed under these approaches have a number of advantages in representing cities. Automata are universal computers and can process any data and compute any algorithm that is input to them; they are therefore flexible in their ability to be configured to represent the myriad of entities and processes that constitute massively unwieldy megacities. Specifying how each of these components should be designed and allowed to interact, however, is a huge undertaking (Torrens and O'Sullivan 2001).

Almost concurrently, research into the complex signatures and properties of urban systems has grown in popularity (and focus). Advances are slowly being made in understanding the mechanisms that determine how cities function as complex adaptive systems (Batty 2005). To the extent that deterministic laws can be considered as describing those mechanisms, plausible theories of what they might be, how they might work, and how they may interconnect are being postulated and examined, particularly as regards the scaling and allometry of urban systems under conditions of self-organization (Batty 2008; Batty and Longley 1994; Bettencourt *et al.* 2007; Gabaix 1999; Portugali 2000; Portugali 2006; Rozenfeld *et al.* 2008; Zipf 1949).

Efforts are being made to remedy data shortages through artificial generation of realistic-enough data through statistical manipulation of group information. Originally pioneered as micro-analysis (Orcutt *et al.* 1976; Orcutt *et al.* 1961), much of the recent work in this area has been carried out in the field of microsimulation (Ballas *et al.* 2005; Clarke 1996). Microsimulation involves statistical down-scaling of coarse-resolution (often zonal) data, generally recorded for census-taking units such as enumeration districts, blocks, blockgroups, traffic analysis zones, tracts, and so forth, to micro-level, perhaps even at the scale of individual households. Similar schemes are employed in the derivation of synthetic data populations for agent-based models, for example, as used in the TRANSIMS traffic model (TRansportation ANalysis SIMulation System) developed at Los Alamos National Laboratory in the United States (Bush 2001). Nevertheless, these approaches suffer from well-known difficulties posed by ecological fallacy and modifiable areal unit problems (Openshaw 1983), and likely always will.

While no standard urban model exists, the Federal Highway Administration in the United States has launched an initiative to foster its development (among other goals): the Travel Model Improvement Program (http://tmip.fhwa.dot.gov/). Earlier collaborative efforts to benchmark and consolidate large-scale urban models in Australia, Germany, the Netherlands, Japan, Sweden, the United Kingdom, and the United States, established in 1981 and run until 1991 under the International Study Group on Land-Use Transport Interaction (ISGLUTI) Program, have continued in a similar fashion to the Travel Model Improvement Program in the United States, but with greater emphasis being placed on modeling land-use activity and change (Wegener 1994b). That scheme was succeeded by the SPARTACUS (System for Planning and Research in Towns and Cities for Urban Sustainability) project, applied to Europe and supported by the European Union’s Fourth Framework for Research and Technology Development from 1996 to 1998 (Wegener 2000). SPARTACUS focused on modeling land-use and transportation, in addition to modeling related environmental impacts in the form of air pollution, noise pollution, and resource consumption; social impacts in the context of health, equity, and accessibility to opportunities; and economic effects of urbanization. The PROPOLIS (Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability) Project, organized under the European Union’s Fifth Framework, continued this work further, running from 2000 to 2002 (Lautso *et al.* 2004). Under PROPOLIS, integrated urban models were applied at city-level to test cases in Bilbao, Brussels, Dortmund, Helsinki, Naples, Swindon, and Vicenza.

26.6 Conclusions

The relationship between urban modeling and megacities is circular. Megacities are ungainly entities and they do not lend themselves to an ease of observation or understanding. Their massively complex nature prohibits tractability in modeling their patterns, processes, pasts, and potential futures. Nevertheless, models are needed in assisting researchers, planners, policy-makers, urban managers, and citizens to study the inner-workings of mega-cities, *because* urban complexity veils megacities to inquiry by tangible means.

Despite the awkward relationship between models of megacities and their real-world counterparts on the ground, there is an urgent need for advancing the science of urban simulation to the level that it can begin to serve as a robust and flexible laboratory for experimenting with ideas and theories that might better explain why megacities form where and when they do, how they work, how they adapt, and what their future trajectories might be. The argument for using simulation as an artificial laboratory for formulating and testing plans and policies to guide future urban sustainability is equally compelling.

The barriers to pushing the state-of-the-art in developing mega-models for megacities are numerous, but they are not insurmountable. Significant progress in understanding the bewildering complexity of such behemoth systems has been made, researchers are beginning to distill that understanding to methodology that can support a next generation of mega-models, and the first signs of this science filtering into practice on the ground are beginning to show. This seems like a really good time to jump on the bandwagon and join in.

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