Advances in Urban and Environmental Modeling: Surveying the Terrain and Demarcating Frontiers

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Introduction

While urban and environmental models have evolved in separate domains of knowledge, they have always shared a common goal, that is, to maintain and advance the relationship between Earth and its inhabitants. This goal is implicit in the specific issues that typically concern urban planners and environmental scientists. However, it has rarely been stated in such broad terms and has often fallen prey to competitive models of the economic marketplace. Planning, as seen from most perspectives, is a tool for more efficient exploitation of resources to meet the ever-expanding demand of human societies. This is achieved through building better organizational structures and accompanying institutions that are primarily geared to enable smooth operation of the market. In contrast, environmental scientists have repeatedly taken human societies to task for ignoring Earth's real capacity limits and for increasing the human footprint at the expense of other species. Until recently, urban models have concentrated on the consumption and use of land through better access and improved infrastructure. Environmental models, in contrast, have focused on sustainability of resource use and the maintenance of species' habitats. In essence, the objectives of the two modeling paradigms were at odds. The conflict is often characterized as the tussle between "brown" and "green" issues.

Over the past decade the forces bringing the two disciplines of environmental science and planning together have become stronger. There is now little doubt about the dialectical relationship between "brown" and "green" given that issues concerning one cannot be addressed without invoking the other. The environmental movement and the accompanying interest in sustainable development provided another major impetus for bridging the gap in knowledge domains. A number of international agreements such as Agenda 21, the Rio Declaration on Environment and Development, adopted in 1992, and the Earth Summit in 1995 pushed the cause of sustainable development across the world. Several nations followed with specific policy directives to implement some or most of the environmental agenda. For example, President Clinton created the President's Council on Sustainable Development and Canada developed its own Sustainable Development Agenda. Urban planners and environmental scientists have now begun to emphasize the importance of developing an integrated framework for modeling ecological and socioeconomic processes. This volume highlights some of the progress made in that effort and provides a roadmap for future research in integrated urban and environmental modeling.

Methodological Issues in Integrating Urban and Environmental Models

Although there is little argument against the rationale for integrating the two domains of knowledge, the methodological issues in the bridging process have posed some serious problems. Most urban models are still limited in their ability to address the environment. These models are rooted in economic theory and focus primarily on economic and spatial interaction among jobs, housing, and transportation. An economic framework has limitations in incorporating ecological dynamics since price signals play a marginal role in environmental processes. Similarly, until recently ecological modelers have concentrated on modeling species behavior in nonurban landscapes primarily by accounting for the flows of energy and matter through various natural systems. Also, urban and environmental modelers have distinctly different concepts of spatial and temporal processes. Spatial categories enter urban models at a high level of aggregation with limited interaction between them, hence are unsuitable for integration with ecological models at spatially detailed levels. In addition, the fascination with cross-sectional equilibrium in urban-economic models relegates temporal issues to the background. However, recent advances in the literature on agent-based models, system-dynamic processes, and complexity theory offer important insights about integrating social and ecological knowledge domains.

Agent-based processes examine the dynamic interaction between the choices made by various entities such as institutions, governments, businesses, and households. Ecosystem modelers have been using agent-based models to simulate population growth and decline as well as changes in environmental resource endowments. Typically, the components entered in an agent-based model interact with each other in the form of feedback processes. Such feedback processes can be negative or positive. Negative feedback from one component in the model leads to a response in other components that counteract the original change. Positive feedback does the opposite—it evokes a response from other components of the model that strengthens the original change. The interplay between the negative and positive feedback processes lead to the dynamic characteristics of the system being modeled.

The system-dynamic approach is ideally suited for modeling agent-based processes. It is also well adept at capturing emergent processes that exhibit complexity. Complexity is often manifested from simple rules applied to local phenomena such that aggregate patterns are clearly distinct from local behavior. Complexity studies now contend that detailed micro level studies and their dynamic properties are essential to understanding macro behavior. This is in contrast to the reductionist perspective that assumes that simpler, local level characteristics can be disaggregated from macro processes. The systems approach provides an elegant means of observing complexity that is emerging from simple rules of expected behavior.

Although system-dynamic approaches have been conceived as a "grand" approach that attempts to tie together multiple domains of knowledge, it cannot be expected to integrate different theoretical and epistemological domains that have framed disciplinary advances. System-dynamics is also limited in constructing theories since its principle purpose is to clarify, test, and unify a priori theoretical insights or "mental models." It is, therefore, a tool to refine and develop existing theories and extract insights about these theories as they play out in the real world. In addition, systems models lose their simplicity and elegance when spatial aspects of a system are included. The amount of computation increases exponentially with increasing resolution of spatial categories. However, spatially disaggregated dynamic-system models are being developed and tested. Some current and ongoing projects of such spatial models include the Spatial Modeling Environment being developed at the University of Maryland (Costanza et al. 1995; Voinov et al. 1999) and UrbanSim, a project housed in the University of Washington (Waddel 2002).

While there are several models available to address various aspects of the environment and economy, any one model would be too limited to capture this larger system. What is needed is a computing interface in which various models can be linked at spatial, temporal, and functional frames. The use of multiple models that interface with one another has several advantages. First, this approach would require fewer compromises and preserve, to a large extent, the integrity of the submodels. Second, it would allow greater examination of the model substructures and hence facilitate more vigorous discussions about the different epistemologies guiding model development. Third, this model would not be "owned" by any knowledge domain and would likely be truly interdisciplinary. Fourth, the use of multiple models would require a more conscious examination of the embedded narratives and allow the construction of a coherent plot. Thus the overarching narrative that weaves the model together serves as the glue for integrating different approaches.

Dilemma of Integration

The optimal extent of integration of multiple knowledge domains in a modeling framework has posed some theoretical and epistemological issues. The process of stitching together different theoretical frames inevitably entails some compromises and limitations. For example, levels of data accuracy required for some models may be unreasonable when applied to other models that work with heuristic approaches. Also the resolution of the data in space-time may be different for different aspects of the modeling exercise. In such cases, common frames need to be designed that can incorporate different approaches without compromising the integrity and elegance of individual model elements. More importantly, the ultimate goal of the modeling exercise has to be clearly defined, which can then guide the priorities structured within the model framework. Therefore, the model needs to reflect the goals as designed by the community of model users, rather than being just an academic showcase of modelers' individual or collective expertise.

Structuring the primary questions for the modeling exercise is a nontrivial activity. Especially in situations where "facts are uncertain, values in dispute, stakes high, and decisions urgent" (Funtowicz and Ravetz 1993: 744), conceptualizing the proper questions and casting the questions in the proper perspective can be extremely difficult. Even where there is agreement on broadly defined goals such as "economic justice" or "sustainability," operationalizing such goals within local realities is often unachievable due to ambiguity in interpreting these terms. Hence, a critical step in the modeling process requires the transformation of generic goals, usually encompassing an infinite information space, to a bounded information space serving specific objectives. This process sets into motion a series of uncertainties related to the selection of appropriate goals and assumptions that may not be well defined within the various disciplinary perspectives. This type of uncertainty is also known as the "problem structuring uncertainty" (Mayumi and Giampietro 2001).

A fundamental problem of urban and environmental models is their inability to conform to the strict rules of accuracy and testing that underlie physical models. According to Georgescu-Roegen (1971) in natural sciences "a model must be accurate in relation to the sharpest measuring instrument [and] there is an objective sense" in comparing the results of various formal systems of a physical model. Social scientists can rarely aspire to the level of formal testing that a natural scientist is familiar with. Hence, socioeconomic models are only "similes" that offer insights and guidance for decision making. Also, representations of shared perceptions require a level of sensitivity and transparency that elevate the modeling exercise to a skill that is acquired less formally. With the emergent awareness of the politics and limitations of expertise, particularly with the inability of experts to offer certainty or control, the credibility of models and modeling exercises have become eroded.

Therefore, at the root of the issue of model integration is not the methodological problem of integrating spatial and temporal scales, or even the formulation of a bounded information space within which to construct an integrated model or interacting models. The foundational issue is the issue of trust. The issue of trust emerges at various levels, from the disciplinary suspicions of the motivations and hidden agendas of other disciplines represented in the team, to the stakeholders' skepticism of technical experts who often disregard critical local knowledge in favor of formal knowledge. In addition, it is not unknown for experts to be skeptical of tacit or local knowledge and, in the process, assume a sense of arrogance about their own expertise. Often ensuring that experts are sensitive and responsive to lay people is more problematic than developing a sense of confidence among the stakeholders associated with the modeling process.

In the context of planning, the distribution and management of risk and reduction of uncertainty have always been an important objective of planners. Given that most situations in the social sphere have attributes of reflexivity and adaptability, they are difficult to predict with a high degree of certainty. However in the real world, decisions are routinely made under circumstances where knowledge and information are sparse. Models help in limiting the risks of decision making under less-than-ideal conditions through intelligent speculative inquiry. Such models are only "similes" that focus attention on some attributes of our social and ecological environment and sharpen our understanding of the social order. Therefore they should only be treated as learning tools, and not predictive tools. In so far as an integrated model allows us to explore the various interactions between the parts modeled and allows debate/discussion to influence it, this model would serve a useful purpose. However, if the integrated model only serves to generate results within an opaque, "black-box" environment, it would fail to deliver any benefits from the modeling exercise.

Making Models Reflexive and Pedagogic

Reflexivity means "the application of a theory's assumptions to the theory itself, or, more broadly, the self-monitoring of an expert system, in which the latter questions itself according to its own assumptions" (Lash and Urry 1994, 5). Reflexive models are models that go beyond the accepted theory and formal methodologies of traditional research to enable the evaluation of a multiplicity of perspectives, which are derived from both formal and informal sources. In so doing, the models are themselves interactively transformed to accommodate each new information or perspective. Such models are also pedagogic in the sense that the objective of modeling is not to predict and control, but to learn about actions, reactions, causes, and consequences of social and ecological processes. Reflexive and pedagogic models have a dual nature: 1) they are intrinsically dialogic given that the process moves through debate and dialog and engenders further discussion beyond the model boundaries; and 2) they provide a means of dealing with, as well as adapting to, complexity.

Reflexivity ensures that knowledge is informed by praxis and vice versa. Increasingly the relevance of science is becoming ever more crucial, but at the same time less sufficient, in uncovering social truths. Hence as long as discourse about science and scientific modeling remains limited to experts, the process will simply reinforce the underlying biases and continue to shut out the large community of peer groups and stakeholders. There is a need for a new organizing principle for integrated modeling that is dynamic, systemic, and pragmatic. While there are no standard methods for building reflexive and pedagogic models, some overarching guiding principles can be distilled from critical inquiry and earlier experience.

Undoubtedly these guiding principles do not provide easy solutions and can be hairy to implement, especially when team dynamics become problematic. Regardless, keeping the guiding principles in focus opens up several pathways to building useful models of social behavior, its causes, and implications.

First, building reflexive models requires a commitment from all participants to focus on an iterative open process rather than an activity happening at a limited point in space and time. This becomes a major sticking point especially since most modeling efforts have limited resources and strict deliverables at various stages. Given the shift in focus in this approach from the technical aspects to the social aspects of modeling, such onerous expectations can be stifling and counterproductive. However, some benchmarks are needed to measure progress of the modeling process. The outcome measures that work best are those that relate to decisions made along the way rather than to the number and specifics of the tasks accomplished.

Second, among the decisions made early in the modeling project, perhaps the most critical would involve the definitions and formal identities of relevant ecological subsystems that would form the core of the model. Such definitions would rely on perspectives from various stakeholders and participants. Also, the institutional and political settings, technological possibilities and limitations, as well as cultural traditions would come into play in solidifying the subsystem definitions. This process would entail a movement from generic goals that are easy to articulate to more specific, often contentious, objectives. While the formulation of clear definitions and decisions on a specific system boundary are necessary steps, a reflexive process must also be amenable to change if at some point the definitions are reshaped requiring a restructuring of relevant subsystems. Hence the initial agreement on an iterative, open process is important.

Third, it is important to pay some attention to selecting appropriate criteria for judging the performance of the model. These criteria should relate to the objectives defined in the second step. However, given the multidimensionality of social and ecological processes, any selected range of indicators based on specific objectives can provide a complex and conflicting picture. Hence, it may be difficult to obtain an unambiguous picture without debating the relative weights on various objectives defined within the modeling scope. The model itself needs to be transparent in the way it provides information about different aspects being modeled. An interactive model in which the relative weights on indicators can be changed to show different possibilities is ideal in this context. Such a model would facilitate discussion of priorities and focus attention on those objectives that are critical and others that may need attention at a later date.

Fourth, nitty-gritty technical issues need to be resolved before the model is constructed. These issues include the choice of theoretical models, measurement schemes and analysis scales, data collection methods, desired accuracy of information, and the space-time horizon to be modeled. Often such technical issues limit the boundary conditions of the model, which in turn leads to a model that does not address all defined objectives. Although efficacy dictates the use of familiar, albeit limited, models, this may defeat the purpose of developing the model itself. Hence concerted effort is needed to address the technical issues by employing knowledge base developed in multiple disciplines. A multidisciplinary approach provides a rich base of theory and methods that apply across various contexts with minimal modifications.

Finally, there is a need to maintain a level of humility among the participants of the modeling exercise since social and ecological models are inherently gross simplifications of reality. Most complex systems are also self-modifying systems that cannot be modeled with a high level of certainty over long periods. As Mandlebrot (1982) has shown, such systems also exhibit nested hierarchies, making them indeterminate across scales. Therefore, a certain degree of uncertainty is unavoidable. It is important to keep in mind the pedagogic nature of the exercise and focus on the learning process, which may provide clues about dealing with complex issues on the ground. To expect unambiguous answers about specific tasks from the model is unreasonable. Even if the modeling exercise raises interesting questions instead of providing (often incorrect) answers, it would have made an important contribution to our knowledge.

Constructing Narratives from Simulation Models

Simulation models have several useful properties that allow effective communication, discussion, and learning. Many simulations involve physical models that are scaled down replicas of the original processes. Examples of such physical models include wind tunnel experiments in aviation, automobile crash tests using dummies, and other complex natural processes like the physical model of the Mississippi River that the Army Corp of Engineers uses to study the impacts of flooding. Over the last three decades computer simulations have slowly replaced many physical models and have allowed several other forms of simulations to be constructed relatively cheaply. Computer simulations have revolutionized meteorological studies, aviation and missile technology, design and development of nuclear reactors, and the study of environmental change.

When testing simulation models, emergent properties can be observed that have not yet been analytically described. In fact, many emergent properties are difficult to describe analytically with a high degree of precision. However, by repeated observations under test conditions, an appreciation of the resultant effects can be gained that may either provide valuable information for decision making or illuminate certain properties requiring further scrutiny. In such cases the computer simulation bridges the gap between "speculative inquiry," a domain of philosophy, and the empirical techniques that have dominated scientific research over the past two centuries. The computer program serves as an analogy of an explanatory theory, which is tested within the controlled "virtual" environment and modified if the results do not conform to observed facts. The testing of simulation models may continue through a structured analytical process or through an unstructured iterative (sometimes numerical) process or both. The objective is to express, refine, and test the underlying explanatory theory under specific contexts, which may lead to the application of the simulation model within this context for decision making.

Another important feature of simulation models is that they explicitly include the element of time. Although real world processes evolve dynamically over time, most urban models have failed to incorporate this important element other than as an explanatory variable among many others. This is especially true of urban models based on economic theory. In contrast, a simulation model unfolds over time, hence capturing, in a compressed form, the passage of time during the evolution of the process being modeled. By structuring a process as a sequence of events, decisions, and circumstances, a simulation model offers the possibility of describing the model in a narrative form. If, as suggested by Aristotle, a narrative is a representation of events, circumstances, and processes presented by a narrator, then simply running a simulation model does not constitute a narrative. However, an observed simulation result that is described logically by a narrator to construct a meaningful story would indeed constitute a narrative. The progression of a narrative is selective because the events are chosen and structured by individuals specifically to suggest a coherent plot. A narrative based on a simulation is therefore intersubjective as well as communicative since the plot renders meaning to specific experiences or logical deductions. The simulation narrative is also fundamentally different from a novel or a drama. In the words of Janet Murray, “whereas novels allow us to explore character and drama allows us to explore action, simulation narrative can allow us to explore process. Because the computer is a procedural medium, it does not describe or observe behavioral patterns, the way printed text or moving photography does; it embodies and executes them” (1993, 181).

Acknowledging the narrative aspects of simulation models allows for a significant switch in our cognitive perception from the “paradigmatic” to the “narrative.” According to Bruner (1986), the “paradigmatic” realm is the world of abstract and general theories that are empirically verified in the objective world. In contrast, the “narrative” mode of thought focuses on particular events and experiences over time that gain credence through their lifelikeness. It is the quality of meaningfulness rather than factual accuracy that renders a narrative credible. Rendering meaning to a simulation model is as much related to an act of interpretation as is communicating a story because meaning does not preceed the interpretation of experience. Concepts such as “explanation,” “validity,” and “verification” are redefined in the narrative forms of inquiry. The search is not for mathematical certainty but for results that are believable, meaningful, and verisimilar.

Projecting the Trends in Urban and Environmental Modeling

The traditions of urban and environmental modeling have now begun to move in a common direction. The growing interaction between these two academic domains has indeed improved our understanding of social and ecological relationships. More importantly, it has helped in developing an appreciation among the modeling community of the inherent uncertainties of complex adaptive systems and the inadequacy of most existing tools in uncovering the intricate dynamics of social and ecological processes. The current approach acknowledges that the multidimensional character of social and ecological systems necessitates a multidisciplinary approach to modeling. Most current modeling projects in the United States and abroad relies on multidisciplinary teams. This has allowed the possibility of particularistic knowledge domains to address similar problems outside of that domain in a different context. The social sciences are replete with examples of theories that have filtered down from other disciplines. Some well known examples include the "gravity model" used mostly in transportation forecasting and based on Newtonian Physics and "social ecology" models based on Darwinism. Currently, optimization of network signal flows, a standard and well-known process in chip design, has been shown to have significant application in transportation planning (Tayal 2001). Multidisciplinary approaches have improved the pace and efficiency of knowledge diffusion across knowledge domains. Current trends indicate that the use of multidisciplinary teams in building urban and environmental models will be the norm rather than the exception.

The complex-adaptive character of social and ecological problems will require a reevaluation of model purpose and function. Models will tend to be primarily pedagogic tools for learning, communication, and decision making. This pedagogic aspect of models is facilitated by a modular approach that uses a common framework to selectively and interactively bring together a set of sub models. Therefore, a modeling environment, within which models are constructed from a modular toolkit and other helper applications, would replace the large, integrated model. This modeling environment would provide a basis for critical inquiry that informs and is informed by the modeling exercise. Given that dynamic simulations and visualization offer several advantages—such as (1) the ability to address unstructured problems, (2) the possibility of visualizing emergent properties that are often unexpected, and (3) the ability to communicate through narratives—it is likely that most urban and environmental models would include some aspect of simulation. Shifting the emphasis from empirical/deterministic models to simulation leads to a new form of expression that may offer a different understanding of the social and ecological evolution.

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