New Frameworks for Urban Sustainability Assessments: Linking Complexity, Information and Policy

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1. Introduction

Cities are spatial patterns that persist in time, in which no single constituent remains in place (Holland 1995). Urban systems emerge as distinct entities from the complex interactions among social, financial, and cultural attributes, and information, energy, and material stocks and flows that operate on different temporal and spatial scales. Urban environmental problems (e.g. air pollution, open space fragmentation and excessive fuel consumption) create the pressing need for urban sustainability. Environmental planning has traditionally addressed these problems with policies regulating the location and intensity of urban activities, often based on assumptions about urban and environmental dynamics that are rarely revisited (Alberti 1999; Chin 2002; Ewing 1994, 1997; Neuman 2005). Given the complexity of urban systems and the environment that supports them, the key intellectual challenge of urban sustainability is a fuller understanding of the dynamic spatial interactions among the components of the coupled urban-environmental system. Such understanding can inform urban decision-makers of the environmental consequences of responding to urban needs. We seek to contribute to this understanding by developing an assessment framework with two main components. The first includes the development of a generic agent-based model that integrates data on spatial economic decisions, energy use and environmental dynamics. The second involves defining the stability, degree of order and sustainability of an urban system using information theory and indexes that can explain the system-wide states and trends. This integrated framework enables us to make meaningful comparisons among urban scenarios, directly contributing to decision-making and policy development with appropriate tools for practical advances in urban sustainability.

Our paper also seeks to question and clarify the assumptions about the relationship between specific land-use patterns and energy use and concentration of pollutants. Empirical findings are inconclusive, suggesting not that either position is necessarily wrong, but that this relationship may be nonlinear or may vary with the scale of analysis (Zellner, In Review-a). For example, increases in density support energy efficiency by shortening trips and reducing household energy requirements. Beyond a certain area size, however, high urban densities generate negative externalities due to congestion and concentration of pollutants beyond the environment's assimilative capacity, while low densities allow for pollution dispersion. This observation depends on the scale of measurement, however. Low densities may be accommodated in different layouts, e.g. uniform or clustered, which may significantly affect energy use and pollution. While the density is equally low at a regional scale in both scenarios, the local high densities in the second layout support the decentralization of activities and shorter trips. In contrast, the first layout imposes longer distances and lower household energy efficiency, resulting in overall higher energy consumption and congestion, more so if trip destinations are located outside the region and if densities are such that public transportation modes cannot be supported. The implications for policy are different in each scenario, as the justification for intervention varies to reflect the different market failures (congestion versus distortions of transportation costs and land prices).

2. The Agent-Based Model

We present a generic agent-based model, the Urban Sustainability Assessment Framework for Energy (USAFE), that draws from urban economics and environmental science and planning to represent the land-use decisions and pollution dynamics, integrated with life-cycle modelling of flows of energy and stock of pollutants in an urban system. We chose agent-based modelling over other spatial modelling tools because our research questions require the analysis of forces and behaviours originated in, and modified by, the interaction of heterogeneous landscapes and actors operating at different spatial and temporal scales. The explicit representation of socio-economic, political and natural processes in space and time, and the feedback mechanisms connecting them, makes agent-based modelling useful to examine the inevitable uncertainties in complex multi-dimensional systems that other methods have more difficulties in handling (Hoffman et al. 2003, Parker et al. 2003, Zellner In review-b).

USAFE is built with the Java RePast[1] simulation platform. The purpose is to test the effect of various corrective land-use, infrastructure and resource management policies on an array of sustainability measures applied to urban regions, including aggregate and disaggregate physical and social variables. Physical variables indicate energy use, pollution emission and carbon sequestration. Social variables include agent utility measures. These variables are used to compute information indexes, discussed in the next section, to determine the stability of the urban system under each policy regime.

In its current version, USAFE includes diverse agents (e.g. residents, firms, farms) making choices about development, location, transportation, and energy consumption. The environment is represented as a two-dimensional lattice of cells containing natural, infrastructure and policy attributes, including forest cover, soil quality, presence of roads, zoning density restrictions and municipal water and sewer coverage. Agents' decisions are affected by their individual preferences for location (e.g. proximity to cities and natural areas, crime rate, the ranking of public school districts and density of development), by policy (e.g. zoning restrictions and infrastructure) and by

[1] http://repast.sourceforge.net/index.php

landscape characteristics (e.g. soil quality and land availability for urban development). Energy consumption and pollution emissions result from operational use and transportation, both dependent on density of development, distance to main destinations, type of fuel and fuel efficiency. Agents' land-use decisions affect the assimilative capacity of the environment through forest clearing and re-growth, and subsequent urbanization through adjacency effects.

The parameter values and mechanisms of the models are based on existing literature and expert knowledge about the various decision-makers and processes that are represented in the model. Ultimately, we will use historical data from actual metropolitan areas, starting with the Chicago region and later expanding to other geographical areas. Interaction effects between the various components of the model are assessed by varying alternatively the behavioral and the biophysical dimensions and examining their impacts on the simulations.

3. The Fisher Information Index

We use the outputs generated by USAFE to calculate the Fisher Information Index for each scenario. This index can be interpreted as a dynamic measure of disorder in a system. In this manner, we are able to estimate the current stability and assess the possible impacts of specific policies on the future sustainability of the urban system.

We view information in the context of information theory and its application to complex systems. Information theory is most closely identified with signal processing, specifically distinguishing meaningful signals from noise. It is always possible to express the content of any measurement, regardless of what it pertains to, in the form of information. The Fisher Information Index, formulated by Ronald Fisher, provides a quantitative framework by which one can describe systems for which only partial knowledge is available (Fisher, 1925). More specifically, it is the amount of information that an observable random variable carries about an unobservable parameter; the probability distribution of the observable variable depends on the unobservable parameter. The Fisher Information Index uses data gathered over time. Since it can operate on different types of data (e.g. physical, technical and social) it offers the ability to integrate across social, economic, and material and energy flow regimes. Data are supplied in the form of probability density functions, thus data variability and uncertainty can be included in the analysis.

Recently, Cabezas and colleagues at the US Environmental Protection Agency have applied the Fisher Information Index as a means of defining the stability, degree of order, and sustainability of a variety of systems, beginning with ecological, but progressing to industrial, economic, social, and governmental systems (Cabezas et al. 2003; Cabezas et al. 2005, Fath et al. 2003; Pawlowski et al. 2005; Mayer et al. 2004; Mayer et al. 2006). The results show remarkable consistency across systems and explain many system-wide dynamic shifts. Hence, the Fisher Information Index is a promising source from which to derive trends that describe the current state of a system and in some cases anticipate its future state.

4. Theoretical and policy implications

Detailed modeling and assessment results will be made available at the time of presentation. The broader implications of these results suggest that combining agent-based modeling and information indexes can help scholars and policy-makers evaluate the common theoretical and practical assumptions about the sustainability, efficiency and equity of specific urban patterns and their effects on energy consumption and air quality. This framework can be easily expanded to include other environmental indicators, such as water supply and quality. Both regulatory policies and market-based instruments can be evaluated within this framework to assess their effect on the long-term sustainability of the urban system. Examples of market-based incentives include pricing mechanisms on energy use, to reflect increasing external costs of pollution. Examples of regulatory approaches include zoning and infrastructure decisions, and forestation. Alternatively, surprising policies may be found to significantly influence the environmental stability of a metropolis, e.g. funding for public education or crime reduction. In any case, the complexity of urban systems the review and adjustment of policy decisions on an ongoing basis. The proposed framework facilitates policy adaptation as more knowledge is produced through the assessment and as conditions of the metropolitan system changes.

5. References

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