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A framework for integrated urban metabolism analysis tool (IUMAT)

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ABSTRACT

IUMAT (Integrated Urban Metabolism Analysis Tool) is a system-based sustainability analysis tool. It quantifies and aggregates the social, economic and environmental capitals of urban activity in an integrated framework focusing on the metabolic flows of urban development. This paper builds on previous work on urban metabolism and advances an analytical framework that defines how the consumption of resources and resulting environmental impacts are calculated as indices of sustainability in an urban region. The benefits of integrated urban modeling using the proposed framework as well as the data sources are detailed. The underlying analytical framework for the proposed tool applies the dynamics of choice, time, and scale towards dynamically interpreting demographic and economic factors. IUMAT's calculative modules for land cover, transportation, and energy/water/resource use are described as well as the modality of connections between the modules.

1. Introduction

Cities are on the front line of climate change. Government officials are aggressively targeting cities to reduce energy waste and cut carbon emissions. Today, cities are major consumers of resources and producers of waste having extended their ecological footprints far beyond their official borders. A secure plan for future global development will require cities to evolve into more sustainable ecosystems [1,2]. However, due to their large size, socio-economic structures and geopolitical attributes the patterns of change in cities are very complex [3]. A comprehensive analysis of the dynamic of urban resource flows is critical to understand and address ecological challenges in the path towards a sustainable urbanized planet [4,5]. In this context, urban planning researchers have made great strides in developing methods to understand and model resource usage among different demographic populations [6]. This knowledge base has extended to quantify how building type, location, and clustering impacts urban flows [7]. This paper describes the framework for an integrated urban metabolism analysis tool (IUMAT) to enable policymakers to assess the impact of changes to demographics, economics, land cover, transportation, energy and water and material resources. IUMAT is expected to promote greater understanding about the impact of environmental policies and development strategies at an urban scale, focusing on areas where sustainable urban planning and growth are critical to climate change mitigation and greenhouse gas reduction.

Urban metabolism is an analytical method for understanding the impact of urban development [8]. It is a way of integrating and rationalizing the disciplinary boundaries between urban analysis, planning and policy [9]. The use of urban metabolism in planning urban developments has the potential to greatly advance efforts to assess the overall sustainability in urban regions [10]. A major challenge for policymakers and planners is to bridge the gap between field measurements and numerical studies [11], associated with connecting and integrating the different functions and outputs to characterize the total urban system [12]. While urban scale analytical tools exist for a wide range of applications, including land use/cover mapping, wind and solar analysis, traffic simulations, and building performance, integrated assessments of the aggregate environmental consequences of urban development remain a grand challenge [13]. This limitation may critically undermine our understanding of the benefits and tradeoffs of programs and policies intended to improve the overall sustainability of a city.

2. Background

There are a multitude of methods and tools available for analyzing urban processes and activities. In general, urban policymakers use BMPs, or Best Management Practices, rather than quantitative data to support policy decisions [14]. Many BMPs are derived from singular case studies that have been scaled up for an

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urban region. For example, greening the roof of one building may alleviate storm water management for the building, improve the microclimate around the building, and reduce energy loads for the building. However, this does not mean that greening all the roofs on all the buildings will necessarily have the same benefits for an entire city.

The concept of simulating urban sectors to support design decisions is not new. In 1989, SimCity, a city management simulation environment was released for gamers to build houses, streets, factories, airports, and parks with metrics for crime, pollution, and economic stability. The most recent version, SimCity 4, offers sustainable design measures such as solar and wind power generation, sustainable transportation choices, and energy efficient building standards [15]. SimCity and others, such as ESRI's CityEngine, are mainly design tools that emphasize visualization and data reporting, and offer little opportunity for quantitative analyses. In the research community, tools to quantify urban performance measures are emerging.

UrbanSim, developed at the University of Washington, combines land use and transportation development with economic impacts, and has been applied to actual urban contexts [16]. The intended users are Metropolitan Planning Organizations (MPOs) and non-governmental organizations. UrbanSim calculates the effects of infrastructure and policy decisions with outcomes, such as motorized and non-motorized accessibility, housing affordability, greenhouse gas emissions, and the protection of open space and environmentally sensitive habitats. SUNtool is a European urban neighborhood modeling tool that integrates building performance with its surrounding microclimate effects [17]. The focus of SUNtool is buildings, particularly predicting the optimal built form of an urban neighborhood with regard to optimizing pedestrian comfort and building energy efficiency. At the Massachusetts Institute of Technology, the Sustainable Urban Design Lab is developing an urban modeling tool that analyzes daylighting potential, walkability, and operational energy use [18]. UMI is a Rhino-based design environment that is intended to be used at the early stages of urban design and planning interventions to assess the environmental performance of urban neighborhoods. Mostafavi et al. (2013) [13] present a comprehensive perspective of the characteristics of existing urban scale modeling tools.

UrbanSim, SUNtool, and UMI are important to understanding how targeted features within an urban environment perform. These urban simulation packages are designed for specific areas and with specific goals. Yet, the interdependence of subsystems in a city necessitates the application of methodologies that bring together the social, economic and environmental capitals of urban life to predict, analyze, and evaluate sustainability measures.

For most of the existing tools, singular static components of urban activity/life are the focus. In some cases, a few subsystems are combined (transportation and land use for instance), but the relationships within the flux of urban flows are not aggregately investigated. IUMAT aims to develop an integrated modeling structure that defines the urban area as a single system, rather than dividing it into different sectors to be solved separately. It is capable of handling overlapping features. The IUMAT integrative/analytical framework defines *buildings and spaces that connect them* as indicators of an urban area. In other words, the existence of building or land defines the study area for IUMAT. This perspective forecloses the rural-urban dichotomy in planning tools and approaches.

Developing a simulation framework for urban metabolism analysis is not trivial. The framework must include different scales of spatial interaction that dynamically influence how urban system parameters are affected. The resulting model must balance precision and accuracy, parsing the range of variables that characterize an urban area. Increased complexity may lead to loss of flexibility or unmanageable time steps. The boundaries of the system need to be well defined and the statistical dependences between random variables need to be meticulously tracked to minimize the chances of correlations being interpreted as causation patterns.

In self-organizing systems, dynamics will automatically drive the system toward a state of equilibrium. In cities that are large disordered systems, some properties can be reliably described by averaging over a sufficiently large population that can represent the whole system [19]. Quantities that are regarded as self-averaging produce a normal distribution of variations around a frequent mean, which itself is generated as the result of random interplays between factors from highly disordered subsystems. The challenge is where these borders should be drawn to make use of averaging techniques.

Buildings are complex systems and that complexity is intensified when combined with other urban systems such as transportation or land use. The major task in simulating complex systems is simulating the complexity itself. This may require maximizing the number of independent variables that affect the desired dependent variable. Moreover, the mathematical formulation must describe real world interdependency and nonlinearity. Designing an urban simulation methodology that can capture all the complexities of the real world examples is not possible. Even if it is assumed that the paths of change are governed by simple mechanisms in an urban region, complexity still exists due to the number of possible initial conditions the subsystems might have. In addition, due to the interdependence of subsystems in a city, the system is always oscillating between different possible equilibriums. Regional system mathematical models can be used as triggers that enable pointing out the separating leaps from one specific state of equilibrium to another. The IUMAT framework will determine these critical points for different states in different urban arrangements.

The format of results and visualizing techniques for the simulation outcomes need to be analyzed. The display of large collections of urban data should take aggregation approaches that combine city blocks and buildings into legible clusters without limiting the user's perspective on the data or obstructing their mental model of the urban region [20]. The efforts toward urban modeling visualization are mostly independent, with graphics researchers focusing on visualizing spatial representations while the planning community focuses on quantifying urban dynamics and patterns [21]. A participatory urban planning decision making platform can reasonably take advantage of improvements in visualization techniques [22] to produce complex spatial descriptions of the urban region that are consistent with cognitive insight. IUMAT will advance this further with coherent simulation results view models.

3. Overview of IUMAT framework

The IUMAT framework focuses on the urban region primarily as a collection of buildings, rather than an economic system. Therefore the urban dynamics are modeled in terms of any kind of change caused to these core elements of the city, whether it is variation in the number of existing buildings or changes in building program or demographic and economic factors inside the buildings. Any of these changes can affect the spatial distribution of transportation patterns and other urban flows or even the shape of urban development during the desired time intervals of study. The IUMAT framework simulates changes in demographics, economics, land cover, transportation, energy and water and material resources as reflected in the core urban elements. Three specific analytical models characterize the dynamics of choice, time, and scale in the