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A comparative evaluation of urban metabolism methodologies

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Abstract:
Globally, urban metabolism analysis has become a significant tool for the study of urban ecosystems. Urban metabolism as a concept represents an integrated platform for analyzing the urban dynamics and supporting the planning processes in cities as social-ecological systems within the concept of sustainability. Moreover, urban metabolism provides relevant information for cities in terms of energy efficiency, material flows, and waste management. Since the first study of urban metabolism by Wolman in 1965 until today the scientific committee developed and improved different methodologies and indicators for the urban metabolism analysis. This study focuses on the comparison of the three main methods that have been widely used for the study of urban metabolism which are emergy analysis, material flow analysis and ecological footprint analysis. Each one of the methodologies is based on specific principles and indicators, presenting different strengths and weaknesses. As a general conclusion, urban metabolism methodologies are facing problems related to data scarcity at the city level, the fluid nature of urban metabolisms, the lack of standardization, difficulty in tracking informal or decentralized systems, the lack of data accuracy, difficulty in understanding specific concepts.

Keywords: Urban metabolism, Emergy analysis, Ecological Footprint Analysis, Material Flow Analysis

1. Introduction

In recent decades, the world has been urbanizing rapidly. In 2019 the population living in urban areas accounts for more than half of the global population and is expected to reach approximately 90% in 2100 (UN, 2019; Kookana et al., 2020; Tang et al., 2021).

Cities have grown dramatically not only in size and density but complexity across the globe. This growing complexity is associated with their social structures, economic systems, geopolitical settings, and the evolution of technology (Kennedy et al., 2007). Nowadays cities are facing an era of opportunities, and challenges and fragility (Cui et al., 2019). The urbanization process brings demographic changes and results in economic, environmental, and social changes in the urban system, while it also inevitably causes a series of ecological environmental problems such as increased consumption of energy and material, water and air pollution, waste production etc. (He et al., 2017; Chen and Zhao, 2019; Fan et al., 2020). Although urban areas account only 4% of the Earth's land surface area, they are responsible for 80% of carbon emissions and 60% of water consumption.

1.1 Urban Metabolism

According to Kennedy (2007) urban metabolism (UM) is "*the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*" (Zorpas et al., 2018; Kookana et al., 2020 Voukkali et al., 2021). UM proposes that a city is not only a physical space that depends on planning and management, but is also a type of "living organism" that can be controlled during its metabolic procedure. These procedures lead to the dynamic and complicated material flows in cities, which could be changed by understanding their metabolic mechanism through time (Figure 1) (Cui 2019). An UM analysis aims at the following: (i) assessment of energy and materials flows throughout a city in order to evaluate the efficiency in resource use, its future need, and the existence of any environmental burden (ii) quantify greenhouse gas emissions, a part of UM, (iii) evaluation of material and energy use in order to support policy decisions, to deal with problems such as resource scarcity, air and water pollution, and waste treatment (Conke and Ferreira, 2015).

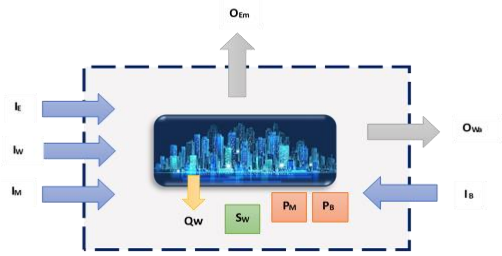

Figure 1. Defining system boundaries for the study of urban metabolism by determining inputs and outputs in a city [I: Inputs O: Outputs Q: Internal Flows, E: Energy/ W: Water M: Materials, S: Storage P: Production, B: Biomass, Em: Emissions, Wa: Waste]

2. Methods

Over the years the research community developed and evolved different methodologies and indicators for the study and monitoring of urban metabolism. Emergy analysis, Material Flow Analysis and Ecological Footprint Analysis are the three main methodologies that attempt to quantify flows of material and energy in complex systems at multiple scales and can be incorporate into the urban metabolism framework (Ansari et al., 2020; Liu et al., 2020; Niza et al., 2020)

2.1 Material Flow Analysis

Material flow analysis (MFA) is a powerful tool that helps to understand urban metabolism at national and local level (Rosado et al., 2016). It is an important method for studying the circular economy and the level of sustainability of a given area (Cui et al 2019). The fundamental principle for the application of material flow analysis is based on the first law of thermodynamics for conservation of mass / energy. More specifically, MFA examines the materials flowing into a given system (private household, company, region, city, etc.), the stocks and flows within this system, and the resulting outputs from the system to other systems (Niza et al., 2020)

2.2 Emergy Analysis

Emergy represents the cumulative energy availability, expressed in equivalent-solar units (sej), supplied by the ecosystem for any of its component or process (either natural or human-made) during its formation or production. The method approaches urban metabolism based on energy equivalents and their theoretical basis is found in their laws of thermodynamics, in the general theory of systems and in their ecology. According to the 1st law of thermodynamics, energy can neither be created nor destroyed; it can only be converted from one specific form to another specific form; and the according to the 2nd in any energy flow process, there will be a decline in the quality of energy which is converted into waste heat (Li et al., 2018). The philosophy behind the Emergy analysis based on the evaluation of certain indicators for specific flows which are related to: a) renewable resources, b) non-renewable resources, c) exchange of resources between the urban system and the wider area (bio-region) d) exported products (outflows) and, e) waste production (Santagata et al., 2020)

2.3 Ecological Footprint Analysis

Ecological footprint (EF) is an accounting tool which has been widely used by the research and scientific community for the last 20 years as an approach to calculate the human pressure on Earth ecosystems (Ahmed & Wang, 2019;). The main purpose of this tool is to quantify the earth's ability to support human life while at the same time acting as an indicator of achieving more sustainable living standards. The EF, consisting of six sub-components namely carbon footprint, forest footprint, cropland footprint, grazing land footprint, built-up land footprint, and fishing grounds footprint takes into account the environmental pressures of human activities in all dimensions (Solarin, 2019).

3. Results and Discussion

3.1 Comparison of Urban Metabolism methodologies

The study of urban metabolism beyond the theoretical scientific approaches presents practical applications that are mainly related to sustainability issues, as it provides important information on resource consumption, energy efficiency and waste production as well as calculation of greenhouse gas emissions (Wang et al., 2020). Take into consideration the evaluation of the existing UM analyses methods, it's obvious that significant barriers and weakness are observed (Table 1).

Table 1: Comparison of the main accounting methods (Kennedy et al., 2011; Tang et al., 2021)

Method	Advantages	Drawbacks
Emergy	-The method ensures that the energy that underlies the creation and flow of all materials is accounted for along with the materials, and accounts for differences in the quality of the materials and energy. -Provides a holistic alternative for environmental decision making	-Insufficient connection with other thermodynamic concepts (exergy, enthalpy, etc.). -Impractical application due to the high degree requirements for scientific training in specific fields such as biochemistry. -Appropriate energy transformation rates must be determined for all flows, and the methods of accounting for wastes have not been unified
MFA	-Tracking hidden material flows can be used to improve the description of the pressures on the environment -Quantifies inputs / outputs for numerous products	-Adding the weight of different materials directly increases the substitution of resources, and ignores the quality differences among materials -Ignoring the important role of energy flows is crucial because these flows drive all material flows throughout the urban metabolic process. -Unable to evaluate the degree of sustainability
EFA	-Useful method as it calculates and presents in a simple and understandable way the interactions of cities with the environment -Completely oriented to the principles of sustainable development	-The method relies on an incomplete description of the resources provided by the natural system and the wastes eliminated by the natural system -The use of a single land function neglects other potentially important functions and the diversity of the land -Data scarcity

4. Conclusion

The main challenges in order to select the best methodology for UM are the difficulty of defining the system's functions and finding enough representative data to model the system's network and its effects on the environment. Therefore, in order to make the transition from theory to practice, the problems and difficulties related to the analysis of urban metabolism, must be taken into account: i) Lack of data at the city; ii) Inability to monitor informal, illegal or decentralized systems, which mainly concern food, material and energy flows; iii) Lack of a standardized method for examining urban metabolism; iv) The fluid nature of the systems makes the study of urban metabolism difficult for statistical quantification; and v) The characteristic of cities as an open system, extends the ecological footprint of cities in matters of administrative and political control.

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