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Dynamic analysis method to open the "black box" of urban metabolism

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ABSTRACT

Urban metabolism is a complex system problem that takes into account urban dynamic behavior such as material, energy, and capital flows. The available methods for urban metabolism are all approaches that consider an urban system to be a "black box", accounting the input and output flows of energy and material, but lacking an analysis of internal elements and the metabolic processes. This study introduced a system dynamics model to study the stocks, flows, activities, and drivers within an urban system, and developed a double-layer model to implement metabolic modeling at two spatial scales. The system dynamics model is built from the perspective of demand-driven to simulate the input of different resources and materials in the urban metabolism. Emergy analysis was used to calculate the value of variables and evaluate metabolic status. A detailed case study for Jing-Jin-Ji agglomeration of China is used to validate the model and identify major drivers. Results show that the system dynamics approach is suitable for the research of urban metabolism. In future work, more metabolic details should be developed in the model to reduce the impact of data limitations, and more component drivers that affect urban metabolism and relationships within the system should be considered.

1. Introduction

Urban metabolism is the focus of urban ecological research, emphasizing the conversion, utilization and processing of internal material and energy in the urban ecological system, as well as material and energy exchanges with other ecosystems. Wolman presented the theory of urban metabolism, providing a new perspective for the study of urban ecological problems (Wolman, 1965). Urban metabolism is introduced as a lens to understand major resource and energy flows, which facilitates resource management at the local level (IRP, 2018).

Scholars have undertaken urban metabolism research from the perspectives of natural science and social science (Carreon and Worrell, 2018). A city is considered to be an ecosystem within the natural sciences, and material and energy flow analysis is a typical approach to studying the physical flows of a city (Broto et al., 2012). The material-based methodology embraces material- (Zhang et al., 2013) and energy-flow accounting (Liang and Zhang, 2012), ecological footprint accounting (Moore et al., 2013), and ecological network analysis (Zhang et al., 2017b). *Emergy Analysis*, proposed by Odum (1996), and *Material Flow Analysis*, proposed by Baccini and Brunner (1991), are highly influential in urban metabolism research (Cespedes Restrepo and Morales-Pinzon, 2018). Material flow analysis distinguishes stocks and flows (Dijst et al., 2018), analyzed the particular substance of anthropogenic systems using an engineering approach. In emergy analysis, all energy is converted into solar energy equivalents, expressing all urban processes and activities in a unified unit, which makes it possible to study various types of material, energy, and capital in one system (Zhang and Yang, 2007). In China, emergy analysis has been used to evaluate the economic development, environmental pressure, and sustainability of Beijing (Liu et al., 2011; Zhang et al., 2011), Xiamen (Yang et al., 2014), Fuzhou (Hu and Huang, 2007), Ningbo (Li and Zhang, 2003), Guanzhou, and Shanghai (Sui and Lan, 2006), and the structure of input and output, resource use efficiency, agricultural productivity, and performance of biogas engineering (Jin and Chen, 2014) of agricultural eco-economic systems in Gansu Province (Zhang, 2007) and Hebei (Du et al., 2008). Some scholars have analyzed the resource intensities of industry sectors (Zhang et al., 2017a) and grain production and trade (Wang et al., 2018) based on emergy analysis. In social science reviews, political context and social relationships are considered (Fischer-Kowalski, 1998). While the available methods for

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urban metabolism are all accounting approaches that are sustained by large volumes of historical data, they say little about the internal dynamics that shape urban metabolism (Carreon and Worrell, 2018). Athanassiadis et al. (2015) concluded that most urban metabolism research only provides a synthetic environmental profile but no internal specificities of a city, and thus consider urban systems to be a "black box." Urban systems are complex; the inner metabolic components connect with and influence each other in particular ways at certain times. These internal activities should not be ignored in urban metabolism research. The governance of flows, including the role of lifestyle and urban practices in material exchanges, and the role of local and territorial stakeholders must be figured out in the urban metabolism research (Barles, 2010). Some scholars are aware of this limitation, and have begun to study the driving factors of urban metabolism. Lu and Chen (2015) proposed a four-causes-map for urban metabolism wherein urban metabolic research is interpreted as having four components: material composition, morphology and structures, interactions (driving forces), and function and purpose, which are in accordance with the essential factors of a system: elements, connections, and function or target. Athanassiadis et al. (2015) proposed the idea that combining the identification of drivers, input-output analysis, and temporal evolution is better for understanding urban metabolism. Kalmykova et al. (2016) used historical data to study the dynamics of resource use in Stockholm and Gothenburg, Sweden and discussed the impact of the economy, lifestyles, and policies on resource consumption. Thomson and Newman (2017) characterized three types of urban systems and found that urban metabolism is different under different urban fabrics. Carreon and Worrell (2018) suggested a conceptualization of urban metabolism based on urban energy services, and summarized the drivers (including environmental, technological, economic, and social drivers) for urban energy services. However, the research of internal elements of urban metabolism is still at an initial stage, and the majority of studies use qualitative rather than quantitative analysis. A method for the quantitative research to open the "black box" of urban metabolism is urgently needed.

In the process of urban development, new structures are being created and complexity is increasing. Urban metabolic system produces levels as well as other self-organization. Multi-scale research on urban metabolism has gradually developed. The research scale includes households (Biesiot and Noorman, 1999; Liu et al., 2005), buildings (Assefa et al., 2010; Kibert et al., 2000), communities (Li and Wang, 2009), and cities, and some scholars have explored a multi-scale analysis method (D'Alisa et al., 2012; Li and Kwan, 2018). Urban metabolic systems are restricted not only by the components at the lower levels, but also by the environment and policies at the higher level. In China, the rise of urban agglomeration (a set of urban regions) makes it necessary to consider the research scale in urban metabolism research.

System dynamics (SD) is a computer simulation of a complex dynamic feedback system that studies system issues by analyzing structures, functions, and dynamic behavior. SD has been widely used in many research fields, such as water resource management (Winz et al., 2009), sustainable development of a social economy (Yang et al., 2016), and land use planning (Shen et al., 2009). Urban metabolism relies on socio-economic activities. The driving force of inner development, generated under multiple interrelations between population, society, economy, and environment, has a positive effect on the kinetics of an urban ecological system (Kok et al., 2000). Dijst et al. (2018) explored five inter-related elements of urban metabolism: flows and stocks, activities, needs, facilitators or constraints, and drivers. They offered an overview of the relationship of these elements: stock and flows are generated or influenced by activities, and activities and services exist to fulfill certain needs and are dependent on facilitators or constraints. The drivers are not only the influencing factors of need, facilitators/constraints, activities, and flows and stocks, but also are dependent on the context in which they took place. The five inter-related elements constitute a feedback loop in urban metabolism. The dynamicity, complexity, and feedback of an urban metabolic system contribute to SD. Introducing SD into the research of urban metabolism to study operation mechanisms and dynamic feedback behavior has positive effects on understanding urban metabolism and finding a solution for urban problems. However, current SD models have only been developed at a single scale. To satisfy a multi-scale analysis, we are proposing a multi-scale method to improve existing models.

The objective of this paper is to introduce SD into urban metabolism research for internal elements, drivers, relationships, and feedback process analysis, with an extension of the SD model to double layers for a multi-scale analysis of urban metabolism. We will first introduce the study area and data source. Then we will present a framework of the metabolic model, and introduce the developed model and its formulations, calculation method and parameters. Assessment indicators for urban metabolism will be presented at the end of method part. In next section, we will validate the model and discuss the advantages and limits of the SD approach for urban metabolism. Simulation results will also be analyzed in this part.

2. Study area and data

This study takes the Jing-Jin-Ji agglomeration as a case study. The Jing-Jin-Ji urban agglomeration is located in northern China, with 1/8 of the population and 1/10 of the economy of China. It includes Beijing, Tianjin and Hebei province, and the three urban areas are distributed in a triangular space. The position of these three urban areas is shown in Fig. 1. In 2015, the coordinated development planning for the Jing-Jin-Ji region was published, making implementation arrangements on the spatial allocation of the population and resources of Beijing, Tianjin and Hebei. As the core city of the Jing-Jin-Ji urban agglomeration, Beijing is the most developed city and possesses most of the available resources and population, although it only comprises 21.76% of the built-up land. Tianjin and Hebei have been developing slowly over a long period. The percentages of built-up land in Tianjin and Hebei are 34.56% and 11.60%, respectively. The problem of misallocation of resources and unbalanced development is an urgent issue demanding a solution.

The raw data used in this study are from the China Energy Statistical Year Book, the China Industry Statistical Year Book, the Chinese Rural Statistical Year Book, the Beijing Statistical Year Book, the Tianjin Statistical Year Book, and the Hebei Economic Year Book. Statistical yearbooks of China are published continuously on a chronological basis by government departments, in which most of data comes from complete survey and another part is from sample survey and administrative files. Annual data will be verified and corrected by comparing with historical data before publishing. The data is a true reflection of reality that can be used in this research.

3. SD approach

3.1. Model framework

An urban system may contain several subsystems, and could itself be a subsystem contained in a larger system (urban agglomeration or country). We established a double-layer SD model to study urban metabolism by combining the metabolisms of two different spatial scales. In this model, the first layer is at the scale of urban agglomeration, and the second layer is at a smaller scale – the urban scale. As shown in Fig. 2, the metabolism of urban agglomeration in the first layer can be considered as a metabolic system, and the system is separated into several subsystems. The metabolism of each subsystem will be discussed in the second layer.

The SD model of the metabolic subsystem (the urban scale) was developed in the second layer. Each subsystem can be considered to be an independent metabolic system, and the internal relationships in the system should be considered in order to overcome the limitation of the "black box" of urban metabolism. Within industrialization and

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