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Advancing analytical methods for urban metabolism studies

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ABSTRACT

This article reviews conventional methods applied in current urban metabolism studies. Based on the limitations of these conventional methods, it highlights two urgent methodological needs for urban metabolism research: the need for using different spatial and temporal scales and the need for addressing issues of sustainable development. In order to meet these urgent needs, we propose a research framework based on 3D geovisualization. The article argues that GIS and visualization can play an important role in enhancing the transparency and comprehensibility of the results of urban metabolism studies. Furthermore, it is also an effective platform for investigating urban metabolism at various spatial and temporal scales. Specifically, introducing the various speeds of flows and incorporating the differences in the rhythm of these flows will be helpful. GIS and visualization can help to translate analysis results into urban policy suggestions.

1. Introduction

Rapid urban expansion is often accompanied by an increase in the input and output of various substances such as fuel, water, food, waste and electricity that enter, exit and/or accumulate within and outside of the boundaries of cities (Kennedy et al., 2007). The physical, chemical and biological processes of converting resources/materials into serviceable products as well as wastes in cities are analogous to the metabolic processes of the human body or an ecosystem (Newman, 1999). This process is similar to biological metabolism (Davoudi and Sturzaker, 2017). Therefore, researchers usually compare cities to biological organisms and carry out relevant research. Karl Marx first discussed urban metabolism in his *Economic & Philosophical Manuscripts* of 1844 (Marx, 1959). Later the urban metabolism concept was elaborated by Wolmanin in an article entitled "The Metabolism of Cities" (Wolman, 1965). Along this line of thinking, in the late twentieth century, urban metabolism theory was developed as a creative approach to understanding flows of urban resource use, energy conversion, carbon emission, and associated impacts on the urban system (Pincetl et al., 2012). Urban metabolism is still a nascent research field in urban development.

Urban metabolism studies have advantages in quantifying material and energy flows, and are valuable for assessing and predicting the development direction of specific cities (Kennedy et al., 2007). Cities are complex entities, notably when the population size runs in the hundreds of thousands and beyond. Consequently, the research context will determine the appropriateness of the analytical methods used (Long, 2016). Methods may have descriptive purposes (e.g., to generate coherent statistics and indicators). On the other hand, methods may be developed in the first place to better understand the interaction between selected entities, without aiming at a comprehensive representation of urban physical and social processes (Xiao et al., 2017). The use of different methods is not necessarily mutually exclusive. Various methods enable both descriptive studies and decision support oriented studies. Also, a suite of models is often a good solution (i.e., one or more comprehensive models are combined with supporting detailed models). Further, urban metabolism itself is an important conceptual basis for understanding how a city's development can affect local and regional environments and how urban sustainability can be reflected in urban design and planning (Conke and Ferreira, 2015). Over time various conceptual frameworks have been used to describe and integrate physical and social processes in cities. Examples are urban ecology models, and urban transport and access models. In addition, public health, urban climate, and urban governance are also important dimensions integrated in today's urban studies and urban modelling.

In this article, we first review conventional methods applied in current urban metabolism studies. Based on the limitations of these conventional methods, we highlight two urgent methodological needs for urban metabolism research: the need for examing different scales and the need for sustainable development. In order to meet these urgent

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needs, we developed a new research framework based on 3D geovisualization. GIS and visualization can play an important role in the enablement of transparency and comprehensibility. Furthermore, it is also a natural platform to investigate appropriate variation in spatial scales.

2. Review of conventional methods

Urban metabolism study focuses on the consumption and supply of various resources, the direction and connection of their flow within the urban system, as well as the emission, treatment, and recycling of wastes generated by urban activities (Zhang, 2013). Many kinds of methods are applied in current urban metabolism studies. But these methods can be divided into two major approaches based on the diffeences in the information, calculation and metrics used: material-based analysis and energy-based analysis.

2.1. Material-based analysis

Material-based analysis includes three different kinds of methods. They are Material Flow Analysis (MFA), Life-cycle Assessment (LCA), and Ecological Footprint Assessment (EFA). These three types of methods all follow the most fundamental physical principle that matter can neither be created nor destroyed but merely transformed. Therefore the mass of input material of the urban system including all kinds of energy and resources should equal to the mass of output as products, emissions, wastes and relevant change in stocks (Sahely et al., 2003).

Material Flow Analysis (MFA) has advantages in assessing urban materials, flows, and stocks. This approach is widely used in urban metabolism analysis (Barles, 2009). A general MFA system without quantification is illustrated in Fig. 1. As Fig. 1 shows, cities are like living organisms, both need materials input and convert them into different kinds of energy for the functioning of different organizations/tissues, and then produce waste. A general MFA system is its system boundary and there are 5 components within this boundary, including resource input, production, consumption (or use), waste management and obsolete stock. MFA examines the flux of resources used and transformed as they flow through a region. It investigates resource-oriented problems associated with the relationships between the activities of individuals and their environmental influences (Loiseau et al., 2012). The method focuses on three main areas in its analysis: definition of the system, quantification of the stocks and flows, and the interpretation of results (Kennedy et al., 2007). It provides a quantitative method for assessing the finite resources which are used for sustaining the metabolic processes in urban systems.

Life-cycle Assessment (LCA) is a method that can be applied to produce a cradle-to-grave accounting of specific production processes

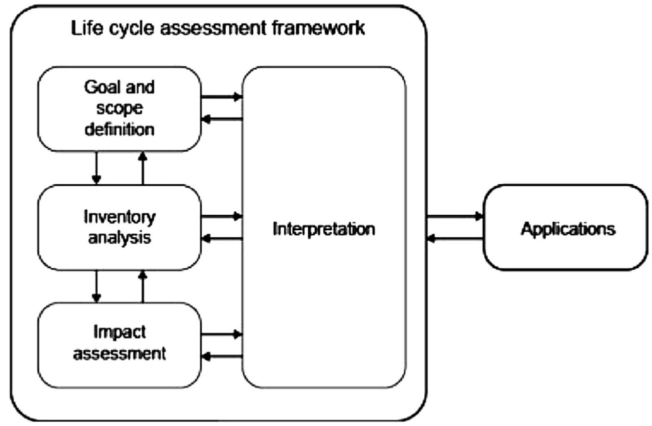

Fig. 2. Different phases for Life Cycle Assessment (Chau et al., 2015).

and evaluate the supply-chain effects of resource transformation and utilization. Fig. 2 (Chau et al., 2015) shows the five different phases of Life Cycle Assessment: goal and scope definition, inventory analysis, impact assessment, interpretation, and applications. These 5 phases do not exist in isolation, but interact and influence each other.

In the process of urban metabolism, the associated environmental impacts from extraction to final disposal can be taken into account by Life-cycle Assessment (Solli et al., 2009), and the environmental impacts of an urban product through its life cycle can also be assessed by LCA (Heijungs et al., 2010). More specifically, there are two approaches for performing LCA: process-based LCA and economic input-output LCA (EIO-LCA). Process-based LCA focuses on the processes of inputs and outputs, sub-processes moving through the supply chain, evaluating the direct components of interest. While the EIO-LCA method pays more attention to calculating, evaluating and predicting the urban inputs and outputs associated with the economic activities in various sectors of the economy. These two methods are often combined to carry out relevant research. This combination can reduce the constraints of data and resources in the modelling process when studying the entire supply chain of the economy.

Ecological Footprint Assessment (EFA) is another material-based analysis method widely used in urban metabolism studies. Ecological footprint expresses the amount of land area that a country, region, city, county or census block requires to meet its input and output metabolic needs. The urban ecological footprint is described as the amount of biologically productive area which is required to provide natural resources for urban development and to dispose wastes generated by the urban system. The equivalent land areas of ecosystems for sustaining urban development are approximately two orders of magnitude greater than that of the relevant urban area (Kennedy et al., 2007). This means

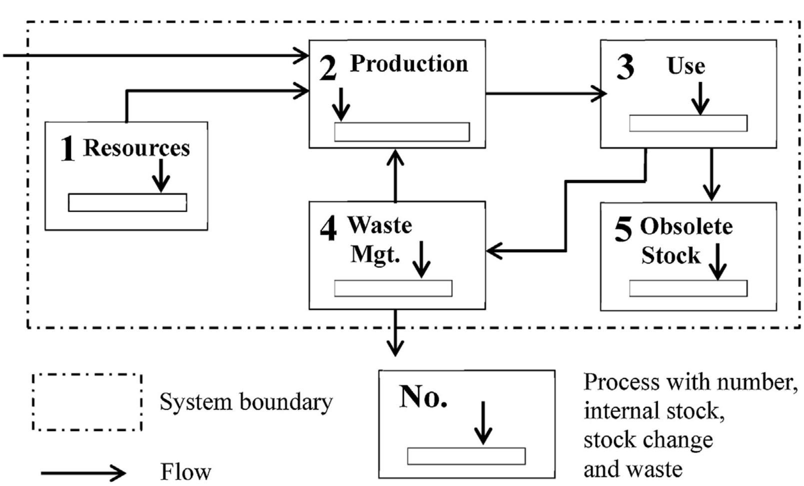

Fig. 1. A general MFA system without quantification.

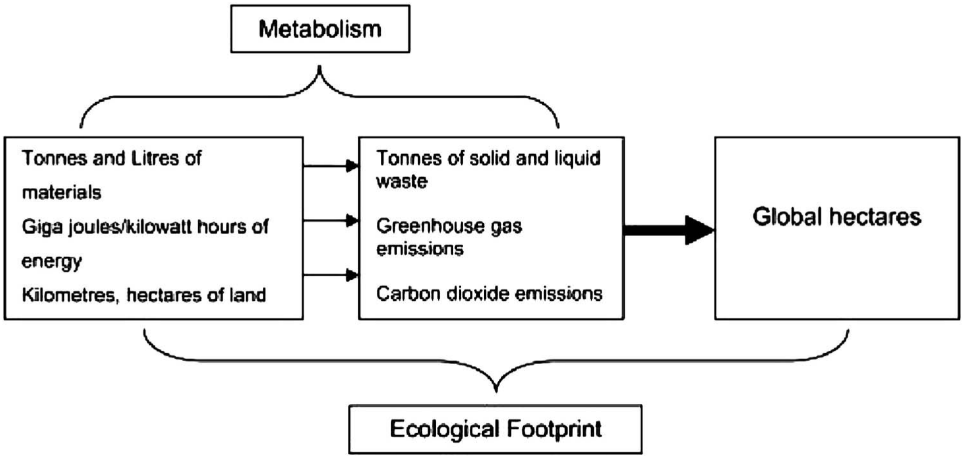

Fig. 3. Integrated urban metabolism and ecological footprint assessment (Moore et al., 2013).

that cities depend on a large quantity of land beyond their boundaries to provide input resources and handle waste outputs (Decker et al., 2000). Past research was often carried out by integrating urban metabolism and ecological footprint assessment, as illustrated in Fig. 3 (Moore et al., 2013). Nowadays, cities in developed countries are running "ecological deficits," and their urban metabolism is under great pressure. The sustainability of urban metabolism can be estimated by Ecological Footprint Assessment. Ecological Footprint Assessment estimates the biocapacity required to generate the material resources and energy that cities consumes and to assimilate the resultant wastes that cities produce. Ecological Footprint Assessment also enables comparisons between urban demand and supply − for example, comparison between current urban metabolic load and available biophysical carrying capacity (Moore et al., 2013).

2.2. Energy-based analysis

The flow of energy, which is measured in solar emjoules, through the ecosystem mainly follows the two laws of thermodynamics: (1) Energy can neither be created nor destroyed; it can only be converted from one specific form to another specific form; and (2) In any energy flow process, there will be a decline in the quality of energy which is converted into waste heat. Odum (1983) described the product or service provided by the use of solar energy, either directly or indirectly, to interpret the metabolic flow and referred to this method as an Emergy (Odum, 1983). Emergy indexes (Table 1) are normally designed to evaluate specific urban metabolism. However, the measurement of emergy renders the fundamental dependence of the cities on the ecological process being taken seriously, and the essence of these processes is based on the availability of solar energy (Huang and Chen, 2009; Huang et al., 2006). Solar emjoules measures the achievements of nature and humans in producing commodities and offering services. It plays a role as a common metric of environmental, social and economic values. Emergy analysis seeks to provide a common value basis to study the material and energy flows in urban metabolism. Normally it has five steps (Campbell et al., 2004): (1) Draw a detailed system diagram containing all relevant energy flow pathways between human and natural components of the urban system. (2) Address specific pathways by translating variables into an aggregated diagram. (3) Translate energy flow pathways into emergy analysis tables. (4) Change the raw data gathered from authorities into emergy units by using transformity conversion factors. (5) Calculate indices from subsets of data to evaluate systems, predict trends, and suggest alternatives to improve emergy efficiency.

Table 1
Summary of emergy index system of urban metabolism research.

Emergy Index	Expression/Formula
Renewable resource emergy	R
Local nonrenewable resource emergy based on extensive use	N_0
Local nonrenewable resource emergy based on intensive use	N_1
Nonrenewable resource emergy	N
Input emergy	IMP
Total emergy	$U = R + N_0 + N_1 + IMP$
Metabolic flux (reflect emergy circulation)	$F = (N_1 + IMP)/P$
Metabolic stock (reflect emergy reserve)	$S = U/Area$
Metabolic rate (reflect urban competition rate)	$E = U/GDP$

2.3. Limations of conventional methods

However, these conventional methods applied in urban metabolism research have some common shortcomings. Both material-based and energy-based analysis are strechted too far as many concepts are borrowed from other disciplines. The application of relevant concepts from natural sciences to social sciences, like the concepts of life-cycle and ecological footprint, involves viewing social processes and problems as phenomena that follow the laws of nature (Bohle, 1994). Most of these methods have their origins from outside the realm of urban studies, planning or geography. They are 'merely' adapted so as to be applicable to the urban context. However, being urban also has inherent spatial and social connotations, which tend to be ignored or oversimplified in a metabolism-oriented approach. To understand cities, it is also important to pay attention to a myriad of spatiotemporal and social phenomena, such as agglomeration, access, and social networks. Space is related to the geographic dimension of a city, while time is related to the historical dimension. The form of a city is the crystallization of space in time. Thus, city or urban studies should be based on spatiotemporal dimensions. The material flow, energy flow and information flow in a city also have space-time characteristics. Various flows are integrated into the processes of a city's development. The relevant temporal attributes (e.g., duration and seasonality) and limits of the urban space affect the scope and scale of flows. However, spatiotemporal analysis has seldom been conducted in urban metabolism studies when applying conventional methods.

More specifically, material-based analysis is apt to draw researchers' attention to the constant changes of resources through tracking material flows and how these flows degrade over time. However, urban metabolism research normally lacks consistent classification of data. This has frequently been one of the greatest barriers to the integration of different datasets when applying material-based analysis method. On the other hand, energy-based analysis emphasizes standard energy units for all resources including nutrient flows in biophysical systems. Although theoretically possible, it is practically difficult to express all urban processes and activities in unified common units. Therefore energy-based analysis often encounters the problem of inadequate and disparate data as well as difficulties in integrating different kinds of energy being represented in different units. Actually the complexity of energy-based analysis and the resulting limited application are due to the conversion of energy flows to the solar emjoules metric (Huang, 1998; Huang and Hsu, 2003)

3. Urgent methodological needs for urban metabolism studies

An often overlooked aspect of urban metabolism studies is data management and data quality management. With an ever-larger diversity of data sources and data types, coherence and quality assurance call for more serious attention. In this respect, it should be realized that urban data collection will involve more diverse and distributed data sources, such as mobile phones and stakeholder-user-producer input (e.g., from active citizens and relevant companies). Thus urban modelling should not be a process of imagination without real urban data. It should be designed based on actual production activities of different sectors in the city. On the other hand, a developed urban model also should be tested by real urban data and suitable for spatiotemporal analysis. Therefore, urban modelling requires a framework which can integrate co-design and co-production

3.1. Methodological needs for different scales

Scale is an important concept for organizing and linking methods and models. This means that urban metabolism can be examined at different scales. Global urban metabolism studies look at the global anthroposphere with the geo-biosphere as the corresponding urban ecosystem. At the national or regional scales, such as national economy or a watershed, spatiotemporal analysis methods are urgently needed. Some functional units, such as firms, households, or industrial sectors, are considerd microscopic entities in urban metabolism studies. While no matter at which scale, highly aggregated data are used in most urban metabolism studies that only provide a snapshot of resource, materials, energy inputs and waste outputs without any reference to spatiotemporal locations and individuals activities (Pincetl et al., 2012). But studying urban metabolism requires versatile methodological frameworks that allow for different levels of complexity and aggregation. The selection of the appropriate scale or unit of analysis still lacks a solid basis in most cases. Instead, practical reasons such as the scale and categorization of available data tend to prevail. Clearly, much more research on appropriate scales is needed. Scale here refers in the first place to spatial scale, but similarly temporal scales are equally important for distinguishing different processes and their interactions.

The scales of the spatial and temporal dynamics of urban processes should be taken into account in urban metabolism studies (Mostafavi et al., 2014). Generally data for urban metabolism research at the census block level is far from readily available, and much more so for individual-level data. So there is an urgent need for knowledge about how much energy and material is used in specific locations and industrial sectors, for special purposes, and by particular groups of people. In urban metabolism research, if we are unable to attribute material and energy flows to particular groups of people, places, and industries, it is nearly impossible to evaluate the metabolism of a specific city reasonably. Different scales need different methods to understande what flows are used by whom and what needs to be added to urban metabolism analyses (Pincetl et al., 2012). The same method applied in different scales may lead to different results. For instance, simulating changes in population and waste output at the scale of building or individual level is relatively meaningless in terms of overall urban environmental and social impacts. But at the regional or national scale, it can reflect how the urban system may be influenced by the changes in metabolism. By dividing the urban system into subsystems based on the type of social, political, economic and environmental drivers, the modelling structure of urban metabolism can be underpinned by several levels of resolution. This process requres certain types of methods for different scales. Thus depending on the output, including products and wastes, or the specific phenomena being analyzed, urban metabolism studies must be carried out at different scales applying different methods.

3.2. Methodological needs for sustainable development

Nowadays, heavy environmental pollution and its negative consequences hinder ecologically sustainable urban development. Besides, growing socio-economic disparities in cities lead to various problems in providing for the adequate quality of life to urban dwellers. The inability of policy-makers and administrators to implement environmentally sound and socially just strategies for sustainable urban development aggravates these problems (Bohle, 1994). On the other hand, it has also been argued that processes within urban areas can threaten urban sustainability itself, including changes in urban population, exhaustion of local resources, accumulation of toxic heavy metal, aggravating heat island effect, and irregular accumulation of nutrients (Kennedy et al., 2007). So in urban metabolism studies, there exists urgent methodological needs for sustainable development, which should be based on an increasing use of renewable resources, should maintain biological diversity, and should not reduce future generations' freedom by leaving to them a polluted environment (Baccini, 1997). Urbanization in developing countries needs additional tools and methods for adequately managing the urban metabolic process. On the other hand, urban metabolism in developed nations face many new challenges (e.g., shrinking populations). Methodological needs for urban metabolism in the sustainable development field pertinent to the environment, economy, governance and resilience is practically universal. Such methodological needs should be combined with the definition that the urban system is sustainable if (1) more than 80% of the essential “mass goods” are available locally in the long term, (2) the other 20% essential “mass goods” can be supplemented by the “external market” and (3) the urban emissions or outputs are not burdens for future generations (Baccini, 1997). Hence sustainable urban development is the overarching theme to which methodological development is supposed to contribute.

Although some methods have been developed to meet sustainable urban metabolism, they still have their own limitations.Take Integrated Urban Metabolism Analysis Tool (IUMAT) for instance, which enables urban metabolism researchers to assess the impact of changes in urban systems and it is expected to promote better understanding about the impact of human activities including making policies, developing strategies, and planning at an urban scale (Mostafavi et al., 2014). However, all the above merits are constrained in the two-dimensional (input-output) framework which hampers spatiotemporal analysis. Sustainable urban development, which does allow for sustainable hinterlands, will entail principles of the so-called ‘circular economy’. Both in terms of understanding its functioning and in terms of societal and political feasibility, the closure of various material and natural cycles needs further study in terms of minimum scales, transfer of (financial) resources, and resilience against natural and human-made hazards.

4. 3D geovisualization in urban metabolism studies

Conventional urban metabolism research methods are predominantly descriptive. However, urban metabolism is highly complex and consists of many different elements (e.g., infrastructure and flows in transportation, solar energy, and wind energy systems). Further, both the infrastructural elements and flows of energy in these systems have complex spatial and temporal characteristics. Traditional approaches to the analysis of these elements and flows tend to rely mainly on system diagrams and mathematical models. However, GIS methods can add to these traditional modes of analysis to provide further insights at high spatial and temporal resolution for planning and related purposes. An important type of GIS methods applicable to the analysis of urban metabolism is geovisualisation. Geovisualisation is the visualization of explicitly geographic or spatial information. It focuses on the use of concrete visual representations and human visual abilities to generate insights about geographic problems (Maceachren et al., 1999). Going beyond the conventional mode of two-dimensional (2D) geovisualization methods, GIS software nowadays has the ability to visualize geographic data in 3 dimensions (3D) and thus can greatly enhance our ability to make sense of complex metabolic processes and patterns in space-time. Three examples of the application of 3D geovisualization in urban metabolism research are discussed as follows.

4.1. Analyzing urban metabolism with 3D density surfaces

Urban metabolism has close relationship with the density of population and businesses. Analyzing urban metabolism at high spatial resolution would facilitate planners and researchers to identify optimal solutions that take urban sustainability into account. It is thus helpful to be able visualize the density patterns of people, businesses, and their activities. GIS offers several powerful methods for exploring these patterns with 3D density surfaces that represent and compare the density patterns of different population groups, businesses, and their activities. The 3D density surfaces can be generated using a nonparametric density estimation method called kernel estimation (Silverman, 1986). An example is provided below in Fig. 4, which is a 3D scene that shows the density surface of the home location of survey participants (Kwan, 2000). 3D density surface can be applied in urban metabolism studies to identify the density location of input and output within an urban system. The gathering area of resources input and waste output can be seen clearly. Higher peak has higher input or output. It is valuable for resource optimization configuration. Generation and visualization of 3D density surfaces is conducive to the optimal allocation of resources in urban space。

4.2. Visualization of the flows of material and energy with 3D GIS

3D density surfaces cannot visualize the flows of material and energy. Thus another step to make urban metabolism studies more vivid and effective is to superimpose the flows of material and energy with specific locations, industries and land use changes that are metabolizing the inputs and generating the outputs including products and wastes, and then overlay these with other relevant spatiotemporal data. Here we recommend a new method, space-time aquarium, for visualizing the flows of material and energy. The space-time aquarium was first implemented to visualize individual-level activity patterns (Kwan, 1999) and can be used in urban metabolism studies to visualize the flows of

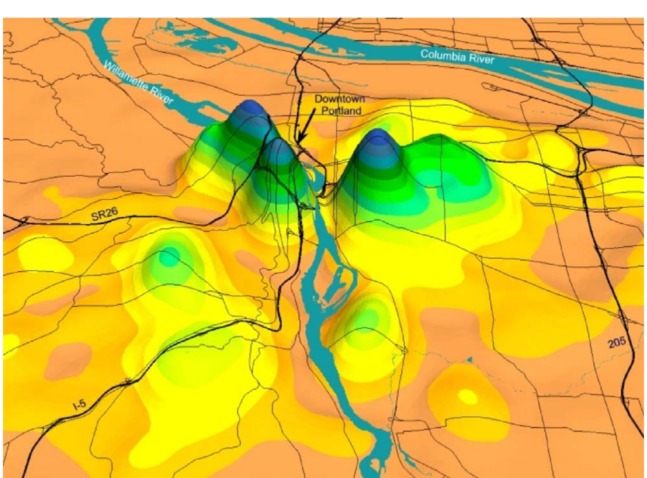

Fig. 4. 3D Density Surface.

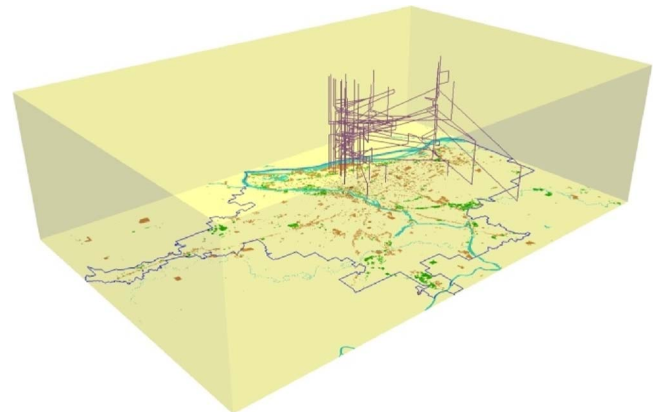

Fig. 5. Space-time Aquarium.
Source: Kwan (2012). Used by permission of Taylor & Francis.

material and energy (Fig. 5). This method can also be used to generate detailed visualizations of material and energy patterns using high-resolution GPS data that become increasingly available in recent years. Fig. 6 below illustrates this possibility with GPS data first carried out in Kwan's research (Kwan, 2004).

Contemporary GIS software offers many possibility for visualizing the flows and movement of material and energy as well as waste in the forms of space-time trajectories or space-time paths. These 3D geovisualization methods, such as space-time aquarium and trajectories (Fig. 5), were first developed and applied in human activity patterns research (Kwan 1999, 2004). The vertical axis represents the time of a day or a period of time and the boundary of the horizontal plane is the spatial scope of the urban area. Similarly, resource flow, energy flow and waste flow have their own space-time paths. They can be portrayed as trajectories in the 3D aquarium to represent the dynamic processes of urban metabolism.

4.3. A 3D space-time framework of flows with thematic layers

A 3D space-time framework not only includes the geographical map of the study area. It also includes other types of layers that interact with each other (e.g., flows related to human activities and various processes of urban metabolism) (Fig. 6). Instead of using only one layer for each type of flows, we can introduce multiple layers. These layers are thematic in nature and show the conditions of the flows only at one moment in time. Each thematic layer and the conditions of the flows can be repeated for each moment in time. A 3D space-time framework makes clear that all flows have both a temporal and a spatial dimension. The draft of this figure (based on Fig. 1 in Kwan 2012) was first developed by the organizers of TIPUM and has already been included in the white paper titled as Exploring Urban Metabolism.

We envision the conceptual model as a series of stacked data layers. Outside all layers lies a set of "drivers" which can influence the processes in the layers. Therein, not all drivers need to influence all layers. Moreover, a driver will not influence each layer in the same way. Besides the drivers and outside all layers, one can find "outcomes" which can and will be different for each layer. Some outcomes will be foreseen and/or intended, others will be unforeseen and/or side-effects. Outcomes may also influence drivers. Besides the layers, drivers, and outcomes, the most crucial element of the conceptual model consists of the linkages between the separate layers. The identification of these linkages, their contents, strengths, direction, and so forth forms (potentially) the main added value of this conceptual model. Due to the identification of these linkages between elements and/or processes in different layers, a wide range of flows and themes can be taken into account.

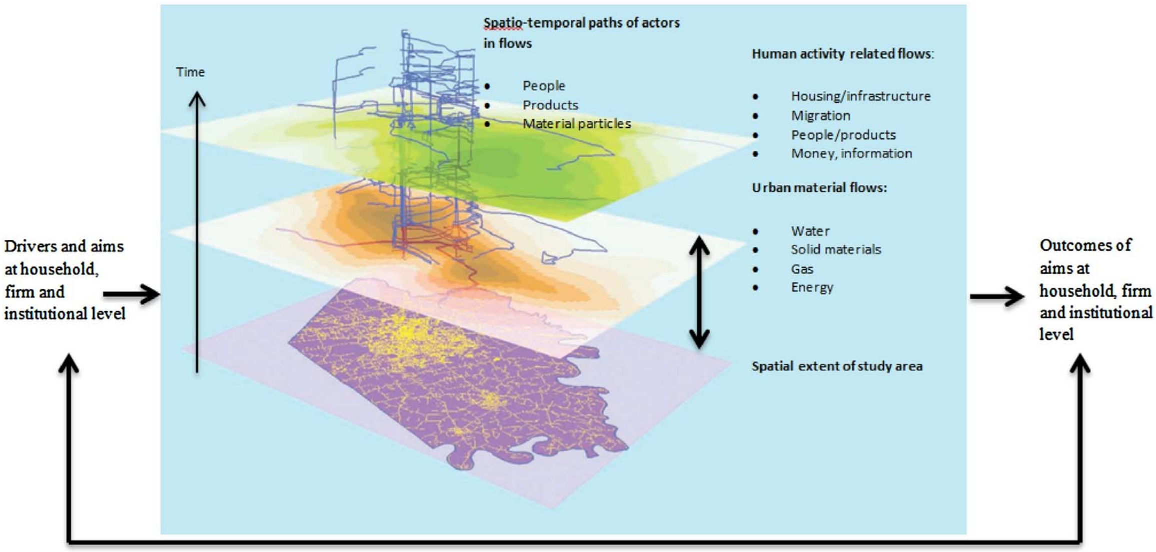

Fig. 6. Spatio-temporal framework of flows with thematic layers.

5. Conclusions

In urban metabolism research, if we are unable to attribute material and energy flows to particular groups of people, places, and industries, it is nearly impossible to evaluate the metabolism of a specific city reasonably. Different scales need different methods to understande what flows are used by who and what needs to be added to urban metabolism analysis. Applying the same method at different scales may lead to different results. However, it is still extremely important to design a method that can be applied for investigating urban metabolism at various spatial and temporal scales. 3D Geovisualization introduced in Section 4 in this paper can meet this need and be helpful in introducing the various speeds of flows and incorporating the differences in the rhythm of these flows.

On the other hand, there exists urgent methodological needs not only at the technical level but also for sustainable development, which should be based on increasing use of renewable resources, should maintain biological diversity, and should not reduce future generations' freedom by leaving to them a polluted environment. Methodological needs for urban metabolism in thesustainable development field pertinent to the environment, economy, governance and resilience is practically universal. 3D Geovisualization method makes clear that all of these have both a temporal and a spatial dimension. It is useful for undestanding and projecting the sustainable development of a city based on a spatiotemporal perspective.

What should be done in future research? We proposed a 3D framework and geovisualization methods for urban metabolism studies. While they are useful for undertaking spatiotemporal analysis of urban metabolism at different scales, they are still weak in translating analysis results into urban policy suggestions. With the rapid growth of cities, understanding their resource consumption and metabolism becomes more important for policy makers and decision makers. In order to produce useful results, new research methods should be sufficiently transparent for decision makers and stakeholders. GIS and visualization can play an important role in enhancing the transparency and comprehensibility of the results of urban metabolism studies.

Acknowledgments

Fig. 6 in this paper is based on a figure developed by the organizers of the workshop “Towards an Integrated Perspective on Urban Metabolism” (TIPUM) which is included in the white paper titled as Exploring Urban Metabolism – Towards an Interdisciplinary Perspective. The figure is in turn based on Fig. 1 in Kwan 2012. We thank Taylor & Francis for kindly permitting the use of this previously published illustration. We also thank the helpful suggestions and comments of Ernst Worrell and Martin Dijst which helped improve this paper considerably. Mei-Po Kwan thanks the support of a National Natural Science Foundation of China grant (Grant No. 41529101) and Grant 1-ZE24 (Project of Strategic Importance) from the Hong Kong Polytechnic University.

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