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**DOI**
10.7163/Eu21.2018.34.1

**Publication date**
2018

**Document Version**
Final published version

**Published in**
Europa XXI

**EUROPA XXI**
Vol. 34, 2018, pp. 05-22
http://doi.org/10.7163/Eu21.2018.34.1

Institute of Geography and Spatial Organization
Polish Academy of Sciences

# EVALUATING SUSTAINABLE URBAN DEVELOPMENT USING URBAN METABOLISM INDICATORS IN URBAN DESIGN

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**Abstract.** Urban metabolism is a multi-disciplinary approach to qualitatively and quantitatively evaluate resource flows in urban systems, which aims to provide important insights into the dynamics of cities to make them more ecologically responsible. It has been also introduced into the urban design domain, however most of the attempts concern only tracking of energy and/or material flows to reduce environmental impacts by redesigning closed loops in a specific area. The hypothesis of this paper is that the concept of urban metabolism, and its indicators, could play an important role in advancing the science and practice related to sustainability in urban design and development. At the moment, however we lack indicators to support evaluation of urban design related decisions from the perspective of urban metabolism. The aim of this paper is to explore the application of urban metabolism indicators in urban design based on their characteristics. It reviews development periods of the concept and analytical models of urban metabolism, in order to identify crucial urban metabolism indicators for urban design. Next, these urban metabolism indicators are classified regarding type of analytical model, accounting method, indicator type, and indicator level. Finally, several suggestions are offered on how to integrate urban metabolism indicators into urban design. In addition, directions for future research on the topic are discussed.

**Key words:** urban metabolism indicator, sustainable urban development, urban design.

## Introduction

The industrial revolution has taken the modern world into an era of massive resource exploitation that has never been experienced before. In order to reconcile modern society's resource demands with our finite resources, it is necessary to quantify resource usage and to evaluate its ecological, economic and social consequences. Even so, continuing urbanisation may potentially lead to rapid resource depletion, energy consumption, and environmental pollution. This imposes on urban designers a further need to include evaluation methods regarding urban metabolism and its effect on sustainable urban development.

After the concept of urban metabolism was first introduced, many scholars have developed different interpretations and extensions of the concept. A range of studies has explored using urban metabolism as an approach to improve urban sustainability. Newman (1999) noted that it is essential to reduce resource usage and waste emissions to achieve sustainability goals for a city. In the review article by Kennedy et al. (2011).

Besides of this introduction, this paper is organised into five sections. The first section reviews three time periods of the development of studies regarding the urban metabolism, viz., the initial, the stabilised, and the mainstream period. Next, three analytical models are demonstrated with respect to the use of urban metabolism indicators. Thirdly, a selection of current urban metabolism indicators is classified according to the analytical model, the accounting method, the indicator type, and the indicator level. The fourth section discusses the possible combinations of urban metabolism indicators with urban design. Finally, suggestions for future research into applying urban metabolism, and related indicators are made to support its importance for and use in the field of urban design.

## Development of the urban metabolism study

The concept of urban metabolism has been used for more than half a century. A city can be seen as an analogy of an organism, as it consumes resources from its surroundings and excretes wastes. Within such analogy, urban metabolism has been defined as an approach to understand and analyse cities as systems of resource and waste flows (Kennedy et al. 2011; van Bohemen 2012)disappearance in the 1980s, and reemergence in the 1990s, a chronological review shows that the past decade has witnessed increasing interest in the study of urban metabolism.

According to the international review articles by Dinarès (2014), Rapoport (2012), and Zhang (2013), the research range of urban metabolism is expanding with deeper research about city crises, therefore the concept of urban metabolism alters correspondingly. When Wolman (1965) first proposed this concept, it focused on the resource requirements and water elimination in the city, a large amount of research was conducted by using material flow analysis to explore the input-output of cities. As time goes on, the energy aspect was added to the urban metabolism concept. Odum (1971) suggested using energy as the basic unit to quantify the metabolism procedure, which is the prototype of 'emergy'. Entering 1990s, social aspects were also added in the urban metabolism, Kennedy et al. (2007) redefined urban metabolism as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste". The concept of urban metabolism has a much broader range than its original meaning.

Based on the review by Zhang et al. (2015), the study of urban metabolism can be divided into three periods: an initial period, a stabilised period, and a mainstream period. The pioneering researchers of every period are shown in Table 1.

**Table 1.** Pioneer researchers in the urban metabolism study development

| Development period | Pioneer researchers |
|---|---|
| Initial period (1965-1980s) | Hanya & Ambe (1975); E. P. Odum (1975); H. T. Odum (1971); Wolman (1965); J. Zucchetto (1975). |
| Stabilised period (1980s-2000s) | Baccini (1997); Baccini & Brunner (1991); Decker, Elliott, Smith, Blake, & Rowland (2000); Girardet (1992); Huang (1998); Newman (1999); E. P. Odum (1989); H. T. Odum (1983). |
| Mainstream period (2000s-present) | Codoban & Kennedy (2008); Ferrão & Fernandez (2013); Fischer-Kowalski (2002); Goldstein, Birkved, Quitzau, & Hauschild (2013); Kennedy, Pincetl, & Bunje (2011); Kennedy & Hoornweg (2012); Kennedy, Stewart, Ibrahim, Facchini, & Mele (2014); Krausmann & Haberl (2002); Niza, Rosado, & Ferrão (2009); Pincetl, Bunje, & Holmes (2012); Quinn & Fernández (2005); Zhang, Liu, & Chen (2013). |

Source: authors' elaboration based on Zhang et al. (2015).

## Initial period: exploring urban metabolism methods

In the initial period, urban metabolism research resulted in two main methods: material and/or energy flow analysis and preliminary 'emergy' analysis. The research in that time was not only exploring these theoretical methods but also their utilisation.

After Wolman (1965) introduced the concept in his article "The Metabolism of Cities", many researchers focused on achieving the quantitative analysis of urban metabolism, mostly based on cities as case studies, e.g., Miami (Zucchetto J. 1975), Tokyo (Hanya & Ambe 1975), Brussels (Duvigneaud & Denaeyer-De Smet 1977), and Hong Kong (Newcombe et al. 1978). To do so, authors used material and/or energy flow analysis, using units of either mass or energy to quantify the flows of materials and energy through an urban system (Baccini & Brunner 1991). Based on the material flow analysis method in the 1970s, an urban system's heterotrophic characteristic model was developed by E. P. Odum (1975), which laid the foundation for quantitative analysis of urban metabolism.

Built on previous research by Wolman (1965), H. T. Odum (1971) used metabolic energy to represent the production of organic matter (like photosynthesis in plants) and its consumption (like respiration in plants) by the metabolic processes of ecological systems, and analysed the relationship between humans and their environment from an energy perspective. He proposed the concept of embodied energy ('emergy'), which founded the research on the emergy analysis method (Odum H. T. 1973; Zucchetto J. J. 2004). The concept 'emergy' is defined as the sum of all the energy required to produce any good or service, considered as if that energy was incorporated ('embodied') in the product itself from the original solar energy (Lei et al. 2016). By applying the concept of emergy, H. T. Odum could compare different kinds of resource flows (materials, energy, and currency) with a consistent system of units. Therefore, the relationships between socio-economic systems and their external environment could be more comprehensively studied (Zucchetto J. 1975). In this stage, emergy analysis still faced some problems, such as double counting, apportioning emergy among the outputs of multi-output systems, and the inaccuracy of the transformative values (Zhang et al. 2015). These problems led to the expansion of emergy (synthesis) analysis.

## Stabilised period: developing urban metabolism models

In the stabilised period, urban metabolism research continued to see steady development. Four main research topics could be distinguished: standardisation of traditional material/energy flow analysis, black box and sub-system models, circular metabolism, and extended input-output models.

Since the concept of urban metabolism had been widely accepted, standardisation became necessary. On the one hand, after the publication by J. Zucchetto (1975), H. T. Odum (1983) introduced the concept of hierarchies among the urban metabolic components, which led to a further exploration of energy flow analysis. E. P. Odum (1989) proposed the concept of urban parasitism aiming for accounting nonreciprocal relationships within an urban system. On the other hand, other researchers focused on material flow analysis to account for the resource storage and flows. Baccini & Brunner (1991) described the characteristics of material stocks and flows of human settlements and introduced the method of material flow analysis for urban metabolic studies. Moreover, Baccini & Bader (1996) introduced the concept of '*Regionaler Stoffhaushalt*' (Regional Material Budgets) to account for flows of materials. In addition, the European Union initiated research to examine material flows in Vienna and the Swiss lowlands (Baccini 1997; Hendriks et al. 2000). Outside of Europe, material/energy flow analysis was also applied in case studies on Taipei (Huang 1998), Sydney (Newman 1999), Brisbane (Mullins et al. 1999), five coastal cities (Timmerman & White 1997), and the world's 25 largest cities (Decker et al. 2000).

Besides the standard methods, researchers also started to explore urban metabolism analysis models in order to systematically analyse urban metabolism. Akiyama (1989) proposed two main models to study urban metabolism: the black box model and the sub-system model, which are the prototypes of the black-box and grey-box models, as described by Beloin-Saint-Pierre et al. (2015.

The black-box model also led researchers to the notion of 'circular metabolism'. Girardet (1992) proposed a circular metabolic model for a sustainable city that can explicitly distinguish linear and circular metabolic flows and analyse how these flow changes impact the urban systems. He also stated that a linear metabolic process in a city would accelerate the global sustainability crisis. Therefore, it is necessary to encourage material circularity, and transform wastes into resources as much as possible. Ideally, there should be fewer consumers and more transformers in a city (Zhang et al. 2015).

In order to achieve sustainability goals, Newman (1999) extended the traditional input-output model of urban metabolism by including liveability and health. He noted that urban sustainability presents not only a decrease of metabolic flows (resource input and waste output), but also an increase in human vitality (infrastructure and health). He used this extended input-output model to explore a liveability model of Sydney which became an important tool in an Australian Department of Environment report (Newton et al. 1998).

## Mainstream period: utilising urban metabolism

From the 2000s onwards, research both widened in scope and made steps to the further deepening of tools and approaches. Kennedy et al. (2007) defined urban metabolism as 'the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste', which includes consideration of ecological and economic aspects. With a more consistent focus on urban metabolism, a large number of articles, reports, conferences, journals, and projects began to explore it further. In this rising period, the research can be summarised as applying the methods developed in the previous periods. This is reflected in the main topics of this period: multi-scale urban metabolism, the metabolic network model, and its application in other domains.

All cities exist within a specific environmental context, and it is difficult to understand the characteristics of an urban metabolism by examining only the city itself (Zhang et al. 2015). Therefore, it is necessary to consider urban systems within a hierarchy that accounts for multiple scales. Current research divides the research scope into several levels (Zhang et al. 2015), which are the supra level (global), macro level (national and regional), meso level (urban) and micro level (neighbourhood and household). At the supra level, research focuses on the environmental effects of human activities by applying either the MRI/O (Multi-Region Input-Output) framework (Herfray & Peuportier 2010; Goldstein et al. 2013;) or emergy values (Huang et al. 2007; Zhang et al. 2009a; Liu et al. 2011) for the global assessment of impacts and solutions for better environmental performance. Studies that consider the regional environmental effects of urban metabolism and its links to the hinterlands environments at the macro level analyse the flows of materials within the entire region (Browne et al. 2012). At the meso level, studies only assess the metabolic processes that occur inside the city, neglecting to include background processes beyond the city's borders, which only limits them to the use of the black-box or grey-box model (Barles 2009; Kennedy et al. 2007)(2. Due to the limited scale of the micro level, these studies focus the consumption of buildings and transport within the communities, or of a single household (Codoban & Kennedy 2008; Engel-Yan et al. 2005).

Meanwhile, other studies attempted to explore the application of urban metabolism in other research domains. Kennedy et al. (2011) discussed the four typical applications of urban metabolism research in urban design and planning: urban sustainability indicators; greenhouse gas emissions calculation; mathematical models for policy analysis; and sustainable urban design. Baynes et al. (2011) used input-output analysis to understand urban energy futures and economic transitions. Su et al. (2009) used emergy synthesis combined with set pair analysis to establish the urban ecosystem health assessment system. In addition, there were attempts to apply the urban metabolism concept in global warming (Kendall 2012), public and private transportation systems (Kennedy 2002), the industrial process (Krausmann & Haberl 2002), land use (Lu et al. 2016) and the water environment (Lauver & Baker 2000; Baker et al. 2001).

In order to put the urban metabolism concept into practice, the European Union has launched several research projects related to it, such as SUME, BRIDGE, ECO-URB, Urban_Wins, and REPAiR (the last two projects – still ongoing). The SUME project (Sustainable Urban Metabolism for Europe) analysed the influence of spatial structure on resource utilisation from the perspective of the construction environment (Schremmer et al. 2009). The BRIDGE project (SustainaBle uRban plannIng decision support accountinG for urban mEtabolism) quantified flows of energy, water, carbon, and wastes and evaluated the outcomes by considering influences of the environment and society (González et al. 2013). The ECO-URB project (Analysing Urban Metabolism and Ecological Footprint – A Multi-Scale Approach to Urban Sustainability Accounting and its Policy Implications) developed a multi-scale analysis of urban metabolism and eco-footprint (European Commission 2010). The Urban_Wins project (Urban metabolism accounts for building Waste management Innovative Networks and Strategies) aims to develop and test methods for designing and implementing innovative and sustainable strategic plans for waste prevention and management in various urban contexts (European Commission 2016b). The REPAiR project (REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism) aims to provide local and regional authorities with an innovative trans-disciplinary open source geodesign decision support environment developed and implemented in living labs in six metropolitan areas (European Commission 2016a; Geldermans et al. 2016).

Moreover, there have been attempts to apply urban metabolism in the design process. It was used as a tool to guide sustainable design at the neighbourhood level by the students at the University of Toronto, which traced the flows of water, energy, nutrients and materials through an urban system and designed closed loops (Kennedy et al. 2011). In the book 'Netzstadt', Oswald et al. (2003) proposed a combination of morphological and physiological tools that attempt to move beyond urban metabolism analysis towards design. MIT students used material flow analysis to provide a more ecologically sensitive urban design proposal for New Orleans (Quinn & Fernández 2005). In 2012, the International Architecture Biennale Rotterdam also used urban metabolism as an approach to explore the sustainable development of Rotterdam (IABR 2012).

However, most of those attempts only tracked energy and material flows to reduce environmental impacts by redesigning closed loops in the specific area. There has been little research providing feasible and categorised sustainability-oriented urban metabolism indicators. It could, however, be developed towards an approach to inform the design process of the built environment to more accurately support sustainable development of cities and the creation of circular systems.

## Urban metabolism analytical models

For urban metabolism, the indicators can provide quantitative information and analysis for the accounting and/or assessment of the metabolism of a city. An indicator presents information on the state or condition of something. The impacts and challenges of sustainable policies and plans on the urban environment can be shown through indicators (Munier 2006). In addition, indicators can provide information to support urban design and allow for comparisons to be made across municipalities, cities, and regions. Many researchers have focused on urban metabolism indicators for the topics of material flow analysis, emergy synthesis, industrial ecology, and life cycle assessment (Zhang et al. 2009b; Chen & Chen 2014; Inostroza 2014; Rosado et al. 2016; we developed an emergy-based indicator system for evaluating urban metabolic factors (flux, structures, intensity, efficiency, and density). For urban designers, more information can be obtained from combining analysis results with their spatial distribution. Therefore, indicators are useful in urban design and planning when linked to sustainability thresholds or targets to assess the results (Sustainable Cities International 2012).

As a result of the development of the urban metabolism concept, understanding of the urban metabolic process has continuously improved. As aforementioned, there are three analytical models for describing the flows and sections of a city's urban metabolism: the black-box model, the grey-box and the network model (Beloin-Saint-Pierre et al. 2015).

### Black-box model

The black-box model describes the inputs and outputs of the flows in the metabolism of a city. It simplifies the retrieval of data because of its aggregation at the city level, which makes it easy to analyse and it is therefore commonly used in the initial period of urban metabolism research. Currently, many researches still use this model to explore the metabolism of cities, especially in the methods of input-output analysis (Baynes et al. 2011), material flow analysis (Newman 1999; Douglas et al. 2002; Sahely et al. 2003; Browne et al. 2012; Conke & Ferreira 2015; ;) and ecological footprint analysis (Neset & Lohm 2005; Wackernagel et al. 2006; Swilling 2016). However, because this model regards the whole city (or urban area) as a single unit, it is unsuited to support the identification of the dynamic and complex patterns of a resource within the city. Yet, it is hard to support the identification of the dynamic and complex patterns of a resource inside the urban area. Although plenty of research provides a number of indicators to assess urban metabolism in this model (Newman 1999; Wackernagel et al. 2006; Beloin-Saint-Pierre et al. 2015), it is still hard for urban designers to utilise them due to the difficulty in combining with spatial elements.

### Grey-box model

In contrast to the black-box model, the grey-box analysis model disaggregates the input and output flows of urban metabolism for different material components. It requires the consideration of environmental effects for entire supply chains, from cradle (e.g., resource extraction) to grave (e.g., waste management) of products, services, and systems (Beloin-Saint-Pierre et al. 2015). This model combines top-down and bottom-up data collection. The most-used methods are life cycle assessment (Goldstein et al. 2013), emergy synthesis analysis (Huang & Hsu 2003; Huang et al. 2006), and material flow analysis (Baldasanomanga et al. 1999; Barles 2009; Alfonso Piña & Pardo Martínez 2014; Kennedy et al. 2014). These methods provide several attempts to use indicators to analyse sustainability. However, the grey-box model does not have a systematic indicator set

like the black-box model (Beloin-Saint-Pierre et al. 2015). Since this model combines complex data acquisition and large-scale system analysis, it is used to identify the most relevant environmental impact flow(s) of the urban metabolism. As for the application in urban design and planning, the identified linear processes can provide a perspective on the metabolic products, in order to improve the material flows' metabolic efficiency and/or suitability for sustainable development. Nevertheless, the linear process cannot cover the entire urban spatial area, which may lead to the neglect of spaces that are not passed by the material flows.

## Network model

Zhang et al. (2009a) proposed the network analysis method, which goes beyond the traditional black-box and grey-box models. Its aim is to 'analyse the internal characteristics of an urban metabolic system and the interactions among the components of the system's structure by transforming processes and nodes into mathematical descriptions of flows among pairs of components'. On this basis, more research began to not only disaggregate the component inputs and outputs in urban metabolism, but also describe the links between different components. This structural-information based model is known as the network model. It is considered a thorough and systematic analysis model of urban metabolism (Baccini & Brunner 2012). However, the network model is time-consuming and therefore challenging in its implementation due to the large amounts of required data. Theoretically speaking, this model uses bottom-up data to specify the material amount in each node and flow. Current research uses top-down data as proxies of these processes. The model is widely used in material flow analysis (Barles 2009; Baccini & Brunner 2012; Sun et al. 2016), life cycle analysis (Lei et al. 2016), and emergy synthesis analysis (Zhang et al. 2009b; Yang D. et al. 2012; Yang D. et al. 2014; ). The network model has been preliminarily applied in the urban domain (Samaniego & Moses 2008), water (Zhang et al. 2009a), energy (Zhang et al. 2009b), and material related studies (Yang Z. et al. 2014). Several researchers tried to use indicators to analyse the network system in the urban metabolism, but the study of indicators in the network model is still in the initial stage of development ( Niza et al. 2009; Beloin-Saint-Pierre et al. 2015).

The complexity of the data requirements and of the model's analysis increases from the black-box model to the network model. Similarly, these increased complexity is also observed in the integration with urban space, and the potential of utilisation by urban designers. Therefore, the network model is a better analytical model to apply in urban design. However, the urban metabolism indicators are still incomplete in the network model (Table 2).

**Table 2.** Comparison of three analytical models used to assess the urban metabolism

| Model | Data availability | Combination with urban space | Utilisation by urban designers | Indicators |
|---|---|---|---|---|
| Black-box model | Top-down | No possibility | Hardly possible | Systematic |
| Grey-box model | Top-down & bottom-up | Design from a linear perspective | Limited possibility (cannot design for the overall urban area) | Complete, but unsystematic |
| Network model | Bottom-up | Linear and nodes perspective | Strong potential | Incomplete |

Source: summarised by the authors.

# Indicator analysis from different perspectives

At the moment, there is no agreed indicator system that can fully describe urban metabolism (Li et al. 2016). Different researchers propose different indicator sets from the perspective of their own research (Song et al. 2017). Therefore, in this section, the explicit urban metabolism indicators will be analysed from different perspectives, in order to explore the common urban metabolism characteristics that these indicators address.

## Selection of current urban metabolism indicators

The indicators are selected from the body of urban metabolism literature. A search of urban metabolism research articles was conducted in the Scopus database by keywords and filters, resulting in 96 articles. Subsequently, these articles were reviewed in depth and 17 review articles on urban metabolism indicators were systematically selected (Song et al. 2017). Among them, 13 articles are selected for further indicator analysis, since the remaining 4 articles do not propose a detailed indicator list.

## Perspectives of urban metabolism indicators

The indicators are analysed from four perspectives, namely analytical model, accounting method, indicator type, and indicator level (Table 4):

- Analytical model: the indicators are associated with a suitable model of urban metabolism analysis, namely the black-box model (BB), the grey-box model (GB), or the network model (NE). Due to the different characteristics of the indicators, the kind of models that they fit varies. An indicator can also fit multiple models, for instance, 'electricity' can be analysed in all the three models by different database levels.
- Accounting method: the accounting methods of urban metabolism indicators can be summarised in material flow analysis (MFA) and emergy synthesis analysis (ESA), since the integrated material flow analysis is also a branch of material flow analysis. In general, one study will only apply one accounting method, but the indicator can be used in both methods. For instance, 'food import' is both contained in the food flow of material flow analysis and also calculated in the import emergy of emergy synthesis analysis.
- Indicator type: different indictors have different types. This research categorises indicators into two types: descriptive (D) indicators and performative (P) indicators. The descriptive indicators are the ones that describe urban metabolism using direct indices, such as 'water consumption' and 'waste emergy'. The data of descriptive indicators can be accessed from statistical bureaus, companies or local governments. In contrast, performative indicators are the result of mathematical analysis using the direct indices, in order to measure or assess urban metabolism with a specific purpose, such as 'environmental pressure' and 'emergy balance'. The results are acquired after the mathematical analysis rather than through direct measurement.
- Indicator level: indicators describe urban metabolism on different levels, based on the different databases. One is the material level (M), which measures/assesses the category of materials, such as 'wood import' and 'embedded mass ratio'. The other level is the functional level (F), which measures/assesses the materials at a lower, finer-grained level based on their various functions, such as 'number of inhabitants affected by heat waves' and 'emergy turnover ratio'.

**Table 3.** List of urban metabolism indicators (ordered alphabetically) and their characteristics

| Indicator | Source[a] | Analytical model[b] | Accounting method[c] | Indicator type[d] | Indicator level[e] |
|---|---|---|---|---|---|
| Air temperature | 2, 7 | BB | MFA | D | M |
| Annual precipitation | 7 | BB | MFA | D | M |
| Anthropogenic heat | 1, 2 | BB | MFA | D | F |
| Average household expenditure ratio | 2 | GB, NE | MFA | P | M |
| Bowen ratio | 1 | BB | MFA | P | M |
| Brownfields re-used | 1 | BB | MFA | D | M |
| Carbon sinks | 4 | BB | MFA | D | M |
| Concentrations ($NO_x$, PM10, PM2.5, $O_3$, CO, $SO_2$) | 2, 4, 5 | GB | MFA | D | F |
| Construction material import | 5, 6, 7, 9-12 | GB | MFA, ESA | D | F |
| Cost of proposed development effects | 2 | BB | MFA | D | M |
| Density of development | 2 | GB | MFA | P | M |
| Effects on local economy (employment) | 2 | BB | MFA | P | M |
| Effects on local economy (revenue) | 2 | BB | MFA | P | M |
| Electricity | 5-12 | BB, GB, NE | MFA, ESA | D | M |
| ELR (environment load ratio) | 10, 13 | NE | ESA | P | F |
| Embedded energy ratio | 3, 7 | GB | MFA | P | M |
| Embedded mass ratio | 3, 7 | GB | MFA | P | M |
| Emergy density | 10-13 | BB, NE | ESA | P | F |
| Emergy per capita | 10, 11, 13 | BB, NE | ESA | P | F |
| Emergy self-support ratio | 12 | BB | ESA | P | F |
| Emergy turnover ratio | 12 | BB | ESA | P | F |
| Emissions ($CO_2$, $CH_4$) | 1-12 | BB, GB, NE | MFA, ESA | D | F |
| Employee numbers | 1 | BB | MFA | D | M |
| Energy balance | 4, 7, 8 | GB,NE | MFA, ESA | P | M |
| Energy consumption by cooling/heating | 1, 2, 4, 6, 7, 10-12 | GB | MFA, ESA | D | F |
| Energy consumption by transport | 6, 7 | GB | MFA | D | F |
| Environmental pressure | 3 | BB, NE | MFA | P | M |
| ESI (emergy sustainable indices) | 10, 11, 13 | BB, NE | ESA | P | F |
| Evapotranspiration | 1, 2, 4, 6, 7 | GB | MFA | D | F |
| Exceedances ($NO_x$, PM10, $O_3$, $SO_2$) | 2, 4 | GB | MFA | D | F |
| Exported emergy | 10-13 | BB | ESA | D | M |
| EYR (emergy yield ratio) | 10, 11, 13 | NE | ESA | P | F |
| Food import | 5-12 | BB | MFA, ESA | D | M |
| GDP | 7 | BB | MFA | D | M |
| GDP emergy ratio | 12 | BB | ESA | P | F |
| Heat island effects | 4 | BB | MFA | P | M |
| Imported emergy | 10-13 | BB | ESA | D | M |
| Incoming solar radiation | 5-7, 9-12 | BB, GB | MFA, ESA | D | F |
| Infiltration | 2, 4, 6, 7 | GB | MFA | D | M |
| Length of cycle-ways provided | 2 | GB | MFA | D | F |
| Length of new roads provided | 2 | GB | MFA | D | F |
| Metabolic efficiency | 1 | BB,NE | MFA | P | F |
| New urbanised areas | 2,7 | GB | MFA | D | M |

| Indicator | Source[a] | Analytical model[b] | Accounting method[c] | Indicator type[d] | Indicator level[e] |
|---|---|---|---|---|---|
| Non-renewable emergy | 10-12 | BB, GB | ESA | D | F |
| Number of days above air temperature threshold | 2, 7 | GB | MFA | D | F |
| Number of inhabitants affected by flash flooding | 2 | GB | MFA | D | F |
| Number of inhabitants affected by heat waves | 2 | GB | MFA | D | F |
| Number of inhabitants with access to public transport | 2, 7 | GB | MFA | D | F |
| Number of inhabitants with access to services | 2, 7 | GB | MFA | D | F |
| Number of inhabitants with access to social housing | 2, 7 | GB | MFA | D | F |
| GWP (Gross World Product) per capita (tons $CO_2$ equivalents/person/year) | 3 | GB | MFA | P | F |
| Percentage of energy from renewable sources | 2, 7 | GB | MFA | D | F |
| Percentage of use of public transport | 2 | GB | MFA | D | F |
| Potential flood risk | 2, 4 | BB | MFA | P | M |
| Potential population exposure ($NO_x$, PM10, $O_3$, $SO_2$) | 2 | GB | MFA | P | F |
| Quality of pedestrian | 2 | GB | MFA | P | F |
| Ratio of population | 1, 7 | BB | MFA | P | M |
| Renewable emergy | 10-12 | GB | ESA | D | F |
| Socio-economic efficiency | 11 | BB | ESA | P | M |
| Solid, liquid and gaseous fossil fuels | 1, 4, 5, 7-12 | BB,GB | MFA, ESA | D | F |
| Surface run-off | 2, 4, 5, 7 | BB | MFA | D | F |
| Thermal comfort | 2 | BB | MFA | D | M |
| Total emergy | 10-13 | BB | ESA | D | M |
| Waste emergy | 10-13 | GB | ESA | D | F |
| Waste water emission | 6-8, 10 | BB, GB, NE | MFA, ESA | D | F |
| Water balance | 4 | BB | MFA | P | F |
| Water consumption | 1-12 | BB, GB, NE | MFA, ESA | D | M |
| Water import | 5-12 | BB, GB | MFA, ESA | D | M |
| Wood import | 6, 7, 9-12 | BB, GB | MFA, ESA | D | M |

[a] 1 – Browne et al. (2012), 2 – Chrysoulakis et al. (2013), 3 – Goldstein et al. (2013), 4 – González et al. (2013), 5 – Hoornweg et al. (2012), 6 – Kennedy et al. (2014), 7 – Kennedy et al. (2015), 8 – Li et al. (2016), 9 – Rosado et al. (2016), 10 – Sun et al. (2016), 11 – Yang et al. (2012), 12 – Yang D. et al. (2014), 13 – Zhang et al. (2013).
[b] BB – black-box model, GB – grey-box model, NE – network model.
[c] MFA – material flow analysis, ESA – emergy synthesis analysis.
[d] D – descriptive, P – performative.
[e] M – material, F – functional.
Source: summarised by the authors.

From the above analysis of urban metabolism indicators and their characteristics, various typical perspectives on urban metabolism indicators can be discerned. Some notable patterns are as follows:

- Indicators of material import and consumption are important in the indicator sets.
  Material input and output indicators were listed to be the main indicators when Wolman (1965) proposed the concept of urban metabolism and are an important indicator group until today. In material flow analysis and emergy synthesis analysis, items related to material import and consumption indicators are all accounted/assessed, such as 'water consumption'

and 'food import'. Current research articles add additional social and economic indicators to extend the urban metabolism analysis.

- Current indicator research focuses on the black-box and grey-box model.
  Table 4 shows that the black-box and grey-box models are more used in the indicator sets, and only a small number of indicators fit the network model. The study of the indicator in the network model can, therefore, be a promising area for future research.
- Material flow analysis and emergy synthesis analysis focus on different indicator levels.
  Material flow analysis based indicators include both material and functional indicators. In contrast, emergy synthesis analysis based indicators are predominately functional indicators. A reason for that may be that the concept of 'emergy' was meant to eliminate various material limitations, already making it a functional concept. Also, from a data acquisition perspective, data at the material level are easier to obtain; data at the functional level need more bottom-up collecting sources, which can be difficult to obtain in some countries/regions.
- Descriptive and performative indicators are both commonly used.
  Comparing the indicator type with the analytical model, accounting method, and indicator level, we can conclude that no specific difference exists among the various perspectives. Both the descriptive and performative indicators can be applied in different accounting methods or analytical models. Descriptive indicators display the basic characteristics of urban metabolism and performative indicators are better suited for further analysis.

## Exploring the connection of urban metabolism indicators with urban design

Urban metabolism studies have made significant progress over the past decades. Several researchers have attempted to relate urban metabolism to urban planning or design (Oswald et al. 2003; Codoban & Kennedy 2008; Agudelo-Vera et al. 2012; Montrucchio 2012). Still, the application in urban design and planning has not fully benefited from urban metabolism research, especially applying urban metabolism indicators research. Based on the analysis of current urban metabolism indicators, their application in urban design varies when seen from different perspectives.

### Analytical models of indicators for urban design

The main reason why urban metabolism(-like) methods are used in sustainable urban design and planning is their quantitative nature. For the black-box and grey-box models, their inability to be combined with spatial elements does not meet the needs of urban designers. However, the network model provides a strong potential to connect indicators with spatial elements. By analysing the material flows on the network, core flows (material life cycles) and nodes (spatial elements) can be identified and evaluated, which can inform urban design. Table 4 presents the key differences among different models.

### Material flow analysis as accounting method

Currently, urban metabolism indicators are accounted in either material flow analysis or emergy synthesis analysis. In general, material flow analysis is used in the material component-related domains, such as industrial ecology, civil engineering, and circular economy. Urban design and planning can also use the indicators based on this method by studying the flows of various materials

**Table 4.** Differences among analytical models in urban design

| Area | Black-box model | Grey-box model | Network model |
|---|---|---|---|
| Design aim | To study input and output of a city as a single unit. It can be used for the overall urban planning and development strategy. | To explore flows of different material components. It can be used in the specific material flow optimisation for a specific industry. | To analyse the relations of different urban components. It can be used in a specific urban/community design project. |
| Spatial consideration | No | No | Yes |
| Spatial scope | National level<br>Regional level<br>Urban level | National level<br>Regional level<br>Urban level | Urban level<br>Neighbourhood level<br>Household level |
| Data availability | Easy to access | Easy to access | Hard to access |

Source: summarised by the authors.

used and/or produced in different urban infrastructures, functions or activities of the plan, and then modify the plan towards improving the urban flows and their effects on sustainable development. Since the concept of emergy is proposed from an energy perspective, the method is applied mostly in the energy-related domains. From the perspective of urban design and planning, emergy is hard to apply, except in the final assessment of a design proposal at the city/neighbourhood level.

## Using different types of indicators during urban design

There are two types of urban metabolism indicators, namely descriptive indicators and performative indicators, which can both be applied in urban design. The descriptive indicators describe urban metabolism using direct statistics and indices. They can be used as a design support by presenting the site characteristics to inform the urban designers during the design process. For example, the indicator 'water consumption' shows the current water usage within the site and it informs the designers about the water situation in comparison to the areas. The performative indicators analyse statistics and indices to measure or assess urban metabolism with a specific purpose or target. They can also be used as design support, but in this case, analysing the impact of a design proposal. By using urban metabolism indicators to assess the design proposals, they provide useful information for the revision of the design. For example, the indicator 'metabolic efficiency' shows the efficiency of the overall material flows, and designers can adjust the material flow design in order to improve their efficiency, by the analysing iteratively result of the indicator.

## Indicator level depends on data availability and spatial scope

Since the analysis of urban metabolism indicators needs large amounts of precise and empirical data, data availability is one of the key issues the analysis faces. Additionally, it is important to be able to compare the metabolic process of different areas accurately, that the data are in the same functional unit. Due to the different governments administering the various areas, the data will be hard to collect and merge, posing a severe challenge for a further comparative research. Therefore, differences in data availability will also have implications for the indicator level. High data availability typically results in the indicator analysis on the functional level. More information can be acquired after a thorough and systematic analysis on a comprehensive database. In contrast, low data availability typically results in the indicator analysis on the material level, therefore, urban designers can get the information from the analysis of limited data. The spatial scope

is another basis for selecting of the indicator level. There is no need to specify detailed functional indicators at the macro level (national and regional). Also, material indicators are too abstract at the micro level (neighbourhood and household). In general, functional indicators can present the situation of urban metabolism more accurately and comprehensively than material indicators. However, the indicator level should be defined based on both data availability and spatial scope.

## Conclusion and suggestions for future research

This paper described the evolution and analytical models of urban metabolism study as well as the combination of urban metabolism indicators with urban. From the perspective of analytical models, the network model can combine urban metabolism indicators with spatial elements, which can be a promising model to apply in urban design. Material flow analysis is still one of the mainstream accounting methods and is more applicable than emergy synthesis analysis in urban design. Every type of indicators (descriptive or performative) should be used in different periods of the urban design progress. Although the functional indicator level can present the urban metabolism situation with the very detailed description, choosing the indicator level still depends on data availability and the spatial scope of the design.

However, many research gaps still remain for the application of urban metabolism indicators to urban design. There are three major areas in which additional research is required:

- Development of a more thorough and comprehensive indicator set
  Several researchers try to understand urban metabolism by indicator analysis. Individual indicators, such as input-output and urban metabolism efficiency, have been explored in urban design. However, a more thorough and comprehensive indicator set is still lacking. Therefore, more indicators need to be explored and tested in future studies, resulting in a thorough and comprehensive urban metabolism indicator set for urban design and planning.
- Practical test of urban metabolism indicators by urban designers
  For urban metabolism indicators, the problem of urban design applicability has not yet been resolved. Therefore, urban designers need to be gathered to discuss how to apply the indicators in urban design. Series of workshop or seminars should be organised to explore pragmatic methods to apply urban metabolism indicators. Each indicator should be analysed and tested in empirical case studies.
- The impact of human activities on the metabolic flows of an urban area
  More research is needed to study the impact of human activities on the metabolic flows of an urban area. Quantifying material flows received much attention in current research, but without understanding why people favour one flow path over another, or creating new links among different components. With the help of the network model, spatial elements and material flows can be connected, thereby enabling the analysis of how human activities impact the metabolic flows in a particular space.

## Acknowledgements

Funding for this research has been provided by China Scholarship Council. We would also thank the members in the Horizon 2020 Research and Innovation Action project REPAiR (REsource Management in Peri-urban Areas: Going Beyond Urban Metabolism), who helped to collect literature materials and provided constructive comments.

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