A literature review and categorisation of sustainability-aimed urban metabolism indicators: a context, indicator, mechanism, outcome analysis

Yan Song
Delft University of Technology
Department of Urbanism,
the Netherlands
E-mail: yan.song@tudelft.nl

Arjan van Timmeren
Delft University of Technology
Department of Urbanism,
the Netherlands
E-mail: A.vanTimmeren@tudelft.nl

Alexander Wandl
Delft University of Technology
Department of Urbanism,
the Netherlands
E-mail: A.Wandl@tudelft.nl

Keywords:
urban metabolism,
urban metabolism indicator,
sustainability,
CIMO approach

Urban metabolism has been advanced as an approach to quantifying energy and resource use and supply in the modern urban system. It is a multidisciplinary approach focused on providing insight into the behaviour of cities for drafting effective proposals for a more humane and ecologically responsible future. Urban metabolism indicators could play an important role in promoting the science and practice of urban metabolism for sustainability. This paper presents a systematic review of literature centred on defining sustainability-aimed urban metabolism indicators to improve the integration of urban metabolism and urban sustainability. Furthermore, this paper concentrates on two indicator sets (emergy synthesis and material flow analysis [MFA]), examining the relationship between these indicators and the three dimensions of sustainability (environment, economy, and society) in the literature. The paper thus builds a bridge between urban metabolism and urban sustainability in the hope that urban metabolism indicators can be used to measure and assess urban sustainability.

Introduction

With the onset of the Industrial Revolution and the rise of capitalism, the modern world has moved into an era of resource exploitation and intensity never seen before. To bring modern society's demands for energy, water, air, and other resources in line with the finite reserves of the earth, more needs to be done to quantify resource usage and to understand its political, economic, and ecological context.

One promising framework that has been advanced as an approach to quantifying energy and resource use and supply in modern society is "urban metabolism" (Ferrão–Fernandez 2013, Acebillo 2012). Wolman (1965) was the first to claim that the "metabolism" of a city comprises all the resources required by an urban system for economic production processes and the sum of waste streams emitted as a consequence of consumption. Urban metabolism can be defined as "the sum total of the technical and socio-economic processes that occur in cities, resulting in economic growth, production of energy, and elimination of waste" (Kennedy et al. 2007). In modern reference, urban metabolism has been distinguished as an analytical tool used to understand the essential energy, material, and waste streams between cities, their surrounding regions, and the planet. It is tangential to concepts of regenerative design, cradle-to-cradle design, and the emerging academic fields of industrial ecology and biomimicry (Richards et al. 1994, Benyus 2009, McDonough–Braungart 2002, van Timmeren 2013, Decker et al. 2000). Urban metabolism is an approach to modelling complex urban systems' material and energy streams as if the cities were organisms in the ecosystem (Fischer-Kowalski 2002, van Timmeren 2013). Urban metabolism thus forms a multi-disciplinary research domain that focuses on providing insights into the behaviour of cities for the purpose of advancing effective proposals for a more humane and ecologically responsible future.

Methodology and review of urban metabolism indicators for improving knowledge integration

The main objective of this paper is to present a systematic review of literature centred on categorising sustainability-aimed urban metabolism indicators to improve the integration of urban metabolism and urban sustainability. To achieve this, relevant research articles on urban metabolism were reviewed after searching through the Scopus database twice in October 2018. The literature was selected using three filters. First, 144 articles focusing on urban metabolism indicators and the concepts of sustainability were selected based on the content of their abstracts, titles, and keywords. Subsequently, these articles were filtered by subject area (environmental science and social science), source type (journals), document type (article), and language (due to language competence, two Spanish articles were excluded), resulting in 84 articles. Finally, these articles were read in depth and only those that provided specific indicator sets and mechanisms with sustainability concepts were selected, using qualitative content analysis. The articles that were excluded fell into the following categories: 1. no specific indicator set proposed; 2. sole focus on indicators in a limited research area; 3. indicator set only suitable in a specific site; and 4. an urban sustainability indicator set proposed rather than an urban metabolism indicator set. This filter process resulted in a total of 23 articles. Next, the adapted context, indicator, mechanism, outcome (CIMO) approach was applied to systematically capture the article information related to the main objective of the research. In our case, context (C) includes the research background and objective; indicator (I) is the quantifying item of each aspect, which is the intervention part of the original CIMO approach; mechanism (M) refers to the method of measuring or evaluating the indicator; and outcome (O) comprises the expected effects, which can be implemented in the general cases. Based on the results of the CIMO analysis, this paper concentrates on two indicator sets (emergy synthesis and MFA), analysing the relationship between these indicators and the three dimensions of sustainability (environment, economy, and society) in the literature. This could be the selection basis of sustainability-aimed urban metabolism indicators in future research.

The CIMO approach was used to process systematically the information in the 23 articles according to the objective of each paper. This approach originated from the domain of planning research (Soria-Lara et al. 2016, Straatemeier et al. 2010). The CIMO approach states that in a problematic context (C), the mechanism (M) can be used to explore generative intervention (I) to deliver some outcome (O) (Denyer et al. 2008). It offers a useful framework to identify and assess the mechanism and indicator sets in the selected literature. In this paper, we adopt the CIMO approach by using urban metabolism and sustainability indicators to represent I as shown in Table 1.

Table 1

Summary of mechanisms and indicators of urban metabolism and sustainability in the selected articles

	Context	Indicators	Mechanism	Outcomes
Barles (2009)	Presents the results of a research project aimed at a. examining the feasibility of MFA on a regional and urban scale in France; b. selecting the most appropriate method; c. identifying the available data; and d. calculating the material balance for a specific case	Balancing inputs and outputs, domestic material consumption, direct material input and output, local and exported processed output, the net addition to stock, total domestic output, total material input, total material output, and requirement	MFA	It reveals the need for new public policies, especially concerning waste management – to reduce construction material imports – and urban planning – to reduce their consumption. In addition, it states the need for more research and the development of action plans to link urban and agricultural policies to improve the use of urban fertilizers to favour local food supply.

(Continued on the next page.)

(Continued)

	Context	Indicators	Mechanism	Outcomes
Browne et al. (2012)	Seeks to apply a number of biophysical sustainability metrics to an Irish city-region to evaluate the effect of methodological pluralism when measuring urban sustainability and to determine the outcome of using more than one method when measuring the sustainability of the same system boundary at a city-region level	1. Measuring energy flows for a. solid fuels, including coking coal, steam coal, sub-bituminous coal, lignite/ brown coal, peat, oven and gas coke, patent fuel, and brown coal peat briquettes, b. oil, including crude oil, refinery feedstocks, and petroleum products, c. liquid natural gas; 2. Measuring energy and emissions metabolism estimates: a. TFC of energy in a particular sector, disaggregated by fuel type, b. total emissions from that sector, including greenhouse gas emissions and air pollution, c. the ratio of total emissions to TFC in a particular year	1. Energy flow accounting 2. Energy flow-metabolism ratio analysis	It develops an approach to measuring energy metabolism by outlining and applying the 'energy flow-metabolism ratio analysis' methodology, which is used to measure the ratio of greenhouse gas emissions as a function of energy material inputs.
Chen–Chen (2014)	Investigates a way to balance economic development and ecosystem health within a workable framework	1. Sets of MFA, life cycle analysis, exergy-based analysis, and emergy analysis; 2. Ecological network analysis sets	1. Element-based method 2. Structure-based method	It is an up-to-date inspection of integrating eco-indicators, which has both wide academic interest among interdisciplinary scientific boards and realistic application meaning for better urban management.
Chen–Wang (2014)	Gathers insights from global cities, identifies best practices internationally, and discusses how cities and regions can play a leading role in creating a sustainable society	1. A new multi-layered indicator set for urban metabolism studies: definition information (spatial boundaries, constitu-ent cities, population, economy), biophysical characteristics (climate, population density, building floor area), and metabolic flows (water, waste, materials, and all types of energy) of megacities; 2. Accounting scheme and its indicators from 13 flow elements and 9 fund elements	1. Multi-layered urban metabolism 2. MuSIASEM	It probes into the regulatory measures to optimise the configuration of water resources and to realize the integration of fundamental research innovation and management practice, thus, providing reasonable decision support for the nexus of water security, ecological security, and sustainable socio-economic development of cities and regions.

(Continued on the next page.)

(Continued)

	Context	Indicators	Mechanism	Outcomes
Chifari et al. (2017)	Presents a useful method for organizing a process of production and the use of scientific information in which both scientists and other social actors can have a bidirectional and constructive exchange of information	Occupied land, power capacity electrical machinery, power capacity thermal machinery, process heat consumption, electricity consumption, fuel consumption, water consumption, fixed investments, running costs, cost of exports, electricity revenue, recyclables revenue, subsidies for electricity production	MuSIASEM	Its approach provides a detailed characterization of the material balance of waste flows through the Municipal Solid Waste Management System.
Chrysoulakis et al. (2013)	Improves the communication of new biophysical knowledge to end-users (such as urban planners, architects, and engineers) with a focus on sustainable urban metabolism	The indicators set used in BRIDGE evaluations: a. energy, b. thermal comfort, c. water, d. greenhouse gases, e. land use, f. mobility/accessibility, g. social inclusion, h. human well-being, j. cost of proposed development, and k. effects on the local economy (employment and revenue)	Based on sustainability objectives and associated indicators addressing specific aspects of urban metabolism	It shows how a tool like the BRIDGE DSS may not simplify the urban planning process, but can help urban planners deal more adequately with its complexity. Although implementation of the DSS during planning processes may be constrained by lack of resources and skills at municipalities, practitioners can gain significant insight for more informed decision-making.
Geng et al. (2011)	Employs the MSIASM approach to evaluate regional societal and ecosystem metabolism in China	Hour-based human time, Joule-based exosomatic energy throughput, exosomatic metabolism rate, and bio-economic pressure	MSIASM	It indicates that the MSIASM method provides a feasible way for different levels of government to recognize the main barriers and challenges to development.
Goldstein et al. (2013)	Advances the ability to quantify environmental impacts of cities by modelling pressures embedded in the flows upstream (entering) and downstream (leaving) of the actual urban systems studied, and by introducing an advanced suite of indicators	Indicators of environmental exchanges (material and energy inputs, air, soil, water emissions, etc.) for the modelled processes	UM–LCA	It shows that the urban metabolism approach can be embedded within the process-based LCA framework, yielding a hybrid UM–LCA model that can provide a complete measurement of the environmental pressures exerted by a city.

(Continued on the next page.)

(Continued)

	Context	Indicators	Mechanism	Outcomes
González et al. (2013)	Enables the formulation of planning and policy recommendations to promote the efficient use of resources and enhance environmental quality in urban areas	Water (i.e. water balance, including evapotranspiration and run-off, and risk of flooding); air and climate (i.e. air quality in terms of pollutant concentration and dispersion; as well as CO_2 emissions, carbon sinks, and energy balance); and material assets (i.e. energy/fuel consumption and associated heat fluxes, including heat island effects)	Analytical hierarchical process multi-criteria assessment technique	It shows how the DSS can support impact assessment processes associated with the development and implementation of plans and projects, as well as contribute to monitoring and forecasting indicator performance in a planning context.
Hoekman–von Blottnitz (2017)	Contributes to the number of urban metabolism case studies using a standardized methodology	Domestic extraction used, imports, exports, domestic processed output, direct material input, domestic material consumption, physical trade balance, and direct material output	Economy-wide MFA	The study provides insights into the city's metabolism through various indicators including direct material input, domestic material consumption, and direct material output, among others.
Hoornweg et al. (2012)	Presents urban metabolism case studies, the data gathering challenges outlined, and the recommendations made as to how local governments can institutionalize the collection of metabolism information and use it to inform local sustainability programs and projects	Inflows, outflows, internal flows, storage and production of biomass, minerals, water, and energy	Abbreviated urban metabolism (a standardized listing of urban metabolism measures that ideally should be included in basic level reporting)	It states that by making citizens and companies more aware of their own impact on their city's metabolism, advances in information and communications technology and open data can help promote society-wide collaboration, smarter public decision-making, and a 'race to the top' to improve a city's resource efficiency and sustainability.
Huang–Hsu (2003)	Incorporates resource and MFA to investigate the Taipei area's urban sustainability due to urban construction	Indicators include the categories of a. intensity of resource consumption; b. inflow/outflow ratio; c. urban liveability; d. efficiency of urban metabolism; and e. emergy evaluation of urban metabolism	MFA and emergy synthesis analysis	It shows that the material flow accounting approach and the emergy evaluation of urban construction have important implications for evaluating the sustainability of urban development.

(Continued on the next page.)

(Continued)

	Context	Indicators	Mechanism	Outcomes
Inostroza (2014)	Proposes a new indicator to measure this process of material accumulation, namely, technomass	Technomass aspects (e.g. buildings, roads, cars, furniture, clothes, machines, and technological assets) and flows (e.g. water, food, energy, and supporting flows)	MFA	The study shows, in metabolic terms, how the indicator looks into the black box, providing the possibility of linking metabolic behaviours with urban forms and attempting to fill the gap between urban planning, urban metabolism, and MFA. This new indicator offers a broad scope of applications. Further possibilities and links to urban research and policymaking are explored in the discussion section.
Kennedy–Hoornweg (2012)	Presents a standardized, comprehensive urban metabolism framework and some degree of agreement on which parameters, out of the many possible, should ideally be included in basic level reporting	Inflows, outflows, internal flows, storage, and production of biomass, minerals, water, and energy	Urban metabolism framework	The study results indicate that the urban metabolism methodology is sufficiently robust, standardized, and practical to allow quick uptake by cities and ease of continued monitoring.
Kennedy et al. (2014)	Proposes a new 'multi-layered' indicator set for urban metabolism studies in megacities	Information on the definition (spatial boundaries, constituent cities, population, economy), biophysical characteristics (climate, population density, building floor area), and metabolic flows (water, waste, materials, and all types of energy) of megacities	Multi-layered urban metabolism indicator set	It shows that use of the standardized indicator set will ease inter-city comparisons of urban metabolism, while enhancing knowledge of megacities and their transformation into sustainable systems.
Kennedy et al. (2015)	Quantifies the energy and material flows of the world's 27 megacities, based on 2010 population, and identifies physical and economic characteristics that underlie the resource flows at multiple scales	Resource flows of electricity consumption, heating and industrial fuel use, ground transportation energy use, water consumption, waste generation, and steel production in terms of heating-degree-days, urban forms, economic activity, and population growth	MFA	It shows that overall energy and material flows vary considerably among megacities. It provides previously unidentified insights into the relationship between electricity consumption and urban forms.

(Continued on the next page.)

(Continued)

	Context	Indicators	Mechanism	Outcomes
Li et al. (2016)	Applies MFA in conjunction with specific socio-economic indicators to model urban metabolism and evaluate appropriate urban metabolism changes for the study case	Four major component inputs and outputs of the city: metals and industrial minerals, energy consumption, construction materials and biomass (predominantly from the surrounding farming areas)	MFA	The study shows that MFA techniques can be used as valuable tools for understanding urban metabolism, evaluating urban sustainability, and suggesting strategies for timely addressing urban sustainability issues.
Rosado et al. (2016)	Contributes to the discourse on urban area typology as well as to identifying urban metabolism characteristics	Eight urban metabolism characteristics: needs, accumulation, dependency, support, efficiency, diversity of processes, self-sufficiency, and pressure on the environment	MFA	It presents the extent of the imbalance between the types of materials extracted, consumed, and stocked, which makes urban areas vulnerable to external changes in resource supplies.
Sun et al. (2017)	Develops an integrated MFA and emergy evaluation model to investigate the environmental and ecological benefits of urban industrial symbiosis implementation	Urban statistics (urban level input and output flows), and micro level material and energy flow analysis (input and output flow within the symbiotic network)	Integrated MFA	This paper provides a useful modelling approach to understand the ecological benefits and trade-offs of local circular economy practices and fundamental insights on natural capital accounting.
Yang et al. (2012)	Assesses resource exchanges and environmental emissions, urban household metabolism is investigated using an emergy synthesis framework	The emergy self-sufficiency ratio and the emergy investment ratio	Emergy synthesis analysis	It helps foster alternative household consumption strategies that could result in more equitable resource allocation and effective mitigation of cross-boundary environmental influences.
Yang et al. (2014)	Presents how creating sustainable cities has led to increasing concern over achieving healthy spatial metabolic interactions and system sustainability	Emergy-based indicators: renewable resources, non-renewable resources, local agriculture products, agricultural consumption, agricultural pollutants, residents' consumption, imports, exports	Emergy synthesis analysis	It shows how emergy synthesis can effectively integrate economic, social, and ecological dimensions and provide insights into cross-boundary metabolic interactions and system metabolic sustainability.

(Continued on the next page.)

(Continued)

	Context	Indicators	Mechanism	Outcomes
Zhai et al. (2018)	Combs through input-output analyses with ecological network analysis to help academics shed light on complicated system interactions and interior energy flows	Embodied ecological energy element intensity, direct integral flow control intensity, average mutual information, residual uncertainty	Energy ecological network model and Input-output analysis	This is a detailed study on the direction of energy; the flows uncover the relationship between social production activities and energy circulation. A thorough insight into robustness creatively provides a reference for improving the system efficiency.
Zhang et al. (2013)	Identifies the main metabolic actors responsible for these problems and analyses the characteristics of their metabolic structure.	Metabolic evaluation indicators: metabolic scale; metabolic intensity; metabolic efficiency (resources); metabolic impact (wastes).	The urban metabolic network model	It states that this improved resolution would provide a clearer picture of the network's characteristics, which cannot be represented accurately by small networks, such as the one example in the study, and would provide a more realistic simulation of an urban metabolic system.

Note: Results are listed alphabetically. MFA – material flow analysis; TFC – total final consumption; MuSIASEM – multi-scale integrated analysis of societal and ecosystem metabolism; MSIASM – multi-scale integrated analysis of societal metabolism; DSS – decision support system; UM–LCA – urban metabolism–life cycle assessment

From the CIMO literature review, there are two basic accounting and assessment mechanisms for urban metabolism indicators based on MFA and energy (emergy synthesis) analysis. Most recent urban metabolism mechanisms expand on or supplement these two mechanisms, such as the integrated MFA, the multi-layered urban metabolism indicator framework, the abbreviated urban metabolism, and the energy flow-metabolism ratio analysis (Sun et al. 2017, Kennedy et al. 2014, Kennedy–Hoornweg 2012, Hoornweg et al. 2012, Chen–Wang 2014, Browne et al. 2012). The MFA begins with material classification and concludes with a balance sheet that accounts for the categorised materials (Zhang et al. 2015). Similarly, emergy synthesis analysis starts with multiplying each flow of energy by its solar transformity and results in the assessment of emergy flow analysis (Zhang et al. 2009). Recently, researchers have begun to explore the possibilities of using life cycle assessment to account for and assess urban metabolism, which will be a further development of the model using consequential life cycle inventories (Zhang et al. 2013, Goldstein et al. 2013).

An approach for integrating urban metabolism indicators and sustainability

As urbanisation develops, so do environmental problems associated with it (Yang et al. 2017). Therefore, cities are seeking transformative methods to support sustainability in the future. To date, there are several urban-centric approaches that attempt to initiate radical innovations in this area such as the compact city (Dempsey 2010), smart growth (Kolbadi et al. 2015), the eco-city (Caprotti 2014), the zero-carbon city (Abbasi et al. 2012), the smart city (Townsend 2013), and the just city (Fainstein 2010). All of these schemes contain urban sustainability characteristics (Wei 2011, van Timmeren et al. 2015). The term 'sustainability' refers to a particular relationship between the human and environmental systems – one that ensures meeting human needs in the long term (World Commission on Environment and Development 1987, Alberti 1996). From the perspective of urban metabolism, a sustainable city is one in which the inflow of material and energy resources and the disposal of waste do not exceed the capacity of the city's surrounding environment (Kennedy et al. 2007). The aim of sustainability is to create the smallest possible ecological footprint and to produce the lowest quantity of pollution possible, to use land efficiently, compost used materials, recycle or convert waste to energy, and to make the city's overall contribution to climate change minimal (McCormick et al. 2013, Yang et al. 2017, Nassauer et al. 2014, Rotmans 2006). As a focus of sustainable development, urban sustainability has become increasingly prominent on political agendas and among scientific studies during recent decades, especially the indicator study that became a pronounced requirement of decision-makers (Huang et al. 2015, Shen et al. 2011, Wu 2014, Valkó et al. 2017). Based on the current study, researchers agree that sustainability depends on social, economic, and environmental factors (INTRASOFT International 2015, Sustainable Cities International 2012, Wu 2014). In the literature, many researchers have begun to explore urban metabolism within the context of urban sustainability (Li et al. 2016, Kennedy et al. 2014) (see Table 2).

Table 2

Summary of the relationship between urban metabolism indicator sets and urban sustainability

Urban metabolism indicator sets	Urban sustainability factors		
	Environmental	Social	Economic
Material flow analysis	The efficient urban metabolism would first result in the built environment of the city (Voskamp et al. 2016, Huang–Hsu 2003, Kennedy et al. 2014). Resource and waste management are two key aspects among the environmental factors that are also MFA concerns (INTRASOFT International 2015, Huang et al. 2015, Mori–Christodoulou 2012, Kennedy et al. 2014).	Li et al. (2016) and Zhang (2013) use the structural decomposition of material flows to build a relationship between input/output with social wealth, which can depict the interindustry relationship of the whole economy (Szabó 2015). Dinarès (2014) also proposes social metabolism to question the apparent separation between human beings and their environment, the society-nature duality. Barles (2009) and Broto et al. (2011) attempt to integrate social aspects and influences on material and energy flows.	In the comprehensive framework for evaluating sustainability, Ness et al. (2010) and Li et al. (2016) implement economy-wide MFAs based on regional flows and non-integrated environmental pressure indicators. Furthermore, the decoupling model is a widely used method to analyse economic activities and their dependence on material consumption which can be utilized to build the relation between urban metabolism and the economy (Falb–Wolovich 1967, Li et al. 2016, Tapio 2005).
Emergy synthesis analysis	Metabolic flux references the structure of the metabolic flux in terms of resource consumption (Zhang et al. 2009, Huang–Hsu 2003). It expresses the amount of material and energy from within the urban metabolic system's internal environment as well as from its external environment.	Yang et al. (2014) and Lei et al. (2016) indicate that emergy synthesis can be adapted to quantify the flow of resources through complex ecological-socioeconomic systems. The indicator of metabolic efficiency reflects the resource utilization efficiency (i.e. the economic cost) of urban development (Zhang et al. 2009).	Economic metabolic activities can result in energetic interactions (Yang et al. 2014, Zhang et al. 2015). In addition, emergy products are useful to the economic system in the form of fuels, lubricants, and so on (Ulgiati et al. 1995).

Conclusion and future directions

After over 60 years of research, urban metabolism has been advanced as a promising approach for quantifying energy and resource use and supply in modern society. This paper investigates the most relevant urban metabolism mechanisms and indicators for improving urban sustainability. To that end, a literature review of relevant mechanisms and indicators in the field of urban metabolism and sustainability was conducted. The literature selection shows that a sizeable number of studies focus on urban metabolism, but only a limited number (23) explore indicators related to sustainability. These studies were reviewed following an adapted version of the CI-MOapproach.

In analysing the literature, several findings arise: 1. most of the study objectives for urban metabolism lie in ecosystem health, energy, environmental technology, urban planning, waste management, and water technology; 2. in these articles, most of the proposed indicators are subject-oriented, which means there is still a lack of systematic indicator frameworks; 3. the most common methods for accounting urban metabolism are MFA and emergy synthesis analysis, which represent two main research streams in urban metabolism studies; 4. in the outcomes, most case studies do not explore the universal application of their research. The review also shows that there are relationships between urban metabolism and sustainability among environmental, social, and economic factors. Based on the integration of urban metabolism and sustainability, urban metabolism indicators can be used to build a connection between the two. This can provide a promising model for guiding urban development towards sustainability. Take MFA and emergy synthesis analysis as examples, the urban metabolism indicators can reflect urban sustainability in terms of environmental, social, and economic aspects.

The body of knowledge around urban metabolism is still growing. Indicator analysis, as one of the most common ways to assess organisational sustainable performance by municipalities, can collect specific quantitative and qualitative information on cities to enable comparisons of multiple areas (Mapar et al. 2017). Therefore, urban metabolism indicator analysis can be applied as an approach to assess sustainability. Future research directions on urban metabolism indicators could move in the following directions:

1. Quantitative correlation research on urban metabolism indicators with sustainability factors. The amount of the extant research implies the potential for using urban metabolism indicators to assess sustainability, for example, using energy flow accounting to measure urban sustainability (Browne et al. 2012). However, the correlation is not explored yet for all urban metabolism indicators.

2. Develop a standard classification system for stocks and flows, as Kennedy et al. (2011) mentions. Based on the review of urban metabolism literature, we found that the accounting methods and units vary among different studies. The non-standard classification differences can be a big barrier when comparing urban metabolism among multiple cities/regions.

3. Explore the application in urban design and planning. Several researchers attempt to connect urban metabolism to urban design and planning but most still focus on the process optimisation rather than quantifying resource flows using indicators. However, urban metabolism could be used to develop an approach that informs the design process for sustainability.

4. A comprehensive sustainability-aimed urban metabolism indicator system. To date, there is no comprehensive urban metabolism indicator list. However, an urban metabolism indicator list could be identified after a comprehensive selection by experts. It could be a useful tool for assessing the performance of urban metabolism to measure the shift in urban development towards sustainability.

Acknowledgements

The funding for this study was provided by the China Scholarship Council (CSC No. 201606260044). We would also like to thank the members of the Horizon 2020 Research and Innovation Action project REPAiR (REsource Management in Peri-urban Areas: Going Beyond Urban Metabolism) who helped collect the literature material and provided constructive comments.

REFERENCES

ABBASI, T.–PREMALATHA, M.–ABBASI, S. A. (2012): Masdar City: A Zero Carbon, Zero Waste Myth *Current Science* 102 (1): 12.

ACEBILLO, J. (2012): *A New Urban Metabolism : Barcelona/Lugano Case Studies*. Mendrisio, U.S.; Barcelona, Spain; New York, U.S.: I. CUP, Accademia di architettura, Università della Svizzera Italiana ; AB Publishers ; Distributed by Actar.

ALBERTI, M. (1996): Measuring Urban Sustainability *Environmental Impact Assessment Review* 16 (4-6): 381–424. https://doi.org/10.1016/S0195-9255(96)00083-2

BARLES, S. (2009): Urban Metabolism of Paris and Its Region *Journal of Industrial Ecology* 13 (6): 898–913. https://doi.org/10.1111/j.1530-9290.2009.00169.x.

BENYUS, J. M. (2009): *Biomimicry: Innovation Inspired by Nature* Harper Collins Publishers, New York, U.S. https://www.overdrive.com/search?q=D9D9103D-AD2D-41C4-B953-41DC68EF3899.

BROTO, V. C.–ALLEN, A.–RAPOPORT, E. (2011): Interdisciplinary Perspectives on Urban Metabolism *Journal of Industrial* Ecology 16 (6): 851–861. https://doi.org/10.1111/j.1530-9290.2012.00556.x

BROWNE, D.–O'REGAN, B.–MOLES, R. (2012): Comparison of Energy Flow Accounting, Energy Flow Metabolism Ratio Analysis and Ecological Footprinting as Tools for Measuring Urban Sustainability: A Case-Study of an Irish City-Region *Ecological Economics* 83: 97–107. https://doi.org/10.1016/j.ecolecon.2012.08.006.

CAPROTTI, F. (2014): Critical Research on Eco-Cities? A Walk through the Sino-Singapore Tianjin Eco-City, China *Cities* 36: 10–17. https://doi.org/10.1016/j.cities.2013.08.005.

CHEN, B.–CHEN, S. (2014): Eco-Indicators for Urban Metabolism *Ecological Indicators* 47: 5–6. https://doi.org/10.1016/j.ecolind.2014.09.021.

CHEN, B.–WANG, R. (2014): Integrated Ecological Indicators for Sustainable Urban Ecosystem Evaluation and Management *Ecological Indicators* 47: 1–4. https://doi.org/10.1016/j.ecolind.2014.09.020.

CHIFARI, R.–RENNER, A.–LO PIANO, S.–RIPA, M.–BUKKENS, S. G.F.–GIAMPIETRO, M. (2017): Development of a Municipal Solid Waste Management Decision Support Tool for Naples, Italy *Journal of Cleaner Production* 161: 1032–1043. https://doi.org/10.1016/j.jclepro.2017.06.074.

CHRYSOULAKIS, N.–LOPES, M.–SAN JOSÉ, R.–GRIMMOND, C. S. B.–JONES, M. B. – MAGLIULO, V.– KLOSTERMANN, J. E. M. (2013): Sustainable Urban Metabolism as a Link between Bio-Physical Sciences and Urban Planning: The BRIDGE Project *Landscape and Urban Planning* 112 (1): 100–117. https://doi.org/10.1016/j.landurbplan.2012.12.005.

DECKER, E. H.–ELLIOTT, S.–SMITH, F. A.–BLAKE, D. R.–ROWLAND, F. S. (2000): Energy and Material Flow Through the Urban Ecosystem *Annual Review of Energy and the Environment* 25: 685–740. https://doi.org/10.1146/annurev.energy.25.1.685.

DEMPSEY, N. (2010): Revisiting the Compact City? *Built Environment* 36 (1): 5–8. https://doi.org/10.2148/benv.36.1.5.

DENYER, D.–TRANFIELD, D.–VAN AKEN, J. E. (2008): Developing Design Propositions through Research Synthesis *Organization Studies* 29 (3): 393–413. https://doi.org/10.1177/0170840607088020.

DINARÈS, M. (2014): Urban Metabolism: A Review of Recent Literature on the Subject *Documents d'anàlisi Geogràfica* 60 (3): 551–71. http://dx.doi.org/10.5565/rev/dag.134.

FAINSTEIN, S. S. (2010): *The Just City* Cornell University Press, Ithaca, U.S. https://login.proxy.bib.uottawa.ca/login?url=http://ebookcentral.proquest.com/lib/ottawa/detail.action?docID=3138037.

FALB, P. L.–WOLOVICH, W. A. (1967): Decoupling in the Design and Synthesis of Multivariable Control Systems *IEEE Transactions on Automatic Control* 12 (6): 651–59. https://doi.org/10.1109/TAC.1967.1098737.

FERRÃO, P.–FERNANDEZ, J. E. (2013): *Sustainable Urban Metabolism* The MIT Press, Cambridge, U.S.; London, U.K. http://site.ebrary.com/id/10752785.

FISCHER-KOWALSKI, M. (2002): Exploring the History of Industrial Metabolism. In: AYRES, R. U.–AYRES, L.: *A Handbook of Industrial Ecology* 1st ed., pp. 35–45. : Edward Elgar. Cheltenham, U.K.; Northampton, U.S.

GENG, Y.–LIU, Y.–LIU, D.–ZHAO, H.–XUE, B. (2011): Regional Societal and Ecosystem Metabolism Analysis in China: A Multi-Scale Integrated Analysis of Societal Metabolism(MSIASM) Approach *Energy* 36 (8): 4799–4808. https://doi.org/10.1016/j.energy.2011.05.014.

GOLDSTEIN, B.–BIRKVED, M.–QUITZAU, M.-B.–HAUSCHILD, M. (2013): Quantification of Urban Metabolism through Coupling with the Life Cycle Assessment Framework: Concept Development and Case Study *Environmental Research Letters* 8 (3): 1–14. https://doi.org/10.1088/1748-9326/8/3/035024.

GONZÁLEZ, A.–DONNELLY, A.–JONES, M.–CHRYSOULAKIS, N.–LOPES, M. (2013): A Decision-Support System for Sustainable Urban Metabolism in Europe *Environmental Impact Assessment Review* 38: 109–19. https://doi.org/10.1016/j.eiar.2012.06.007.

HOEKMAN, P.–VON BLOTTNITZ, H. (2017): Cape Town's Metabolism: Insights from a Material Flow Analysis *Journal of Industrial Ecology* 21 (5): 1237–49. https://doi.org/10.1111/jiec.12508.

HOORNWEG, D. A.–CAMPILLO, G.–LINDERS, D.–SUGAR, L.–SALDIVAR-SALI, A. N. (2012): Mainstreaming Urban Metabolism: Advances and Challenges in City Participation In: *World Bank Sixth Urban Research and Knowledge Symposium – Rethinking Cities* Barcelona, Spain.

HUANG, L.–WU, J.–YAN, L. (2015): Defining and Measuring Urban Sustainability: A Review of Indicators *Landscape Ecology* 30 (7): 1175–93. https://doi.org/10.1007/s10980-015-0208-2.

HUANG, S-L.–HSU, W-L. (2003): Materials Flow Analysis and Emergy Evaluation of Taipei's Urban Construction *Landscape and Urban Planning* 63 (2): 61–74. https://doi.org/10.1016/S0169-2046(02)00152-4.

INOSTROZA, L. (2014): Measuring Urban Ecosystem Functions through 'Technomass' – A Novel Indicator to Assess Urban Metabolism *Ecological Indicators* 42: 10–19. https://doi.org/10.1016/j.ecolind.2014.02.035.

INTRASOFT INTERNATIONAL (2015): *Science for Environment Policy IN-DEPTH REPORT: Indicators for Sustainable Cities* European Commission, Bristol. https://doi.org/10.2779/61700.

KENNEDY, C.–STEWART, I. D.–IBRAHIM, N.–FACCHINI, A.–MELE, R. (2014): Developing a Multi-Layered Indicator Set for Urban Metabolism Studies in Megacities *Ecological Indicators* 47: 7–15. https://doi.org/10.1016/j.ecolind.2014.07.039.

KENNEDY, C. A.–CUDDIHY, J.–ENGEL-YAN, J. (2007): The Changing Metabolism of Cities *Journal of Industrial Ecology* 11 (2): 43–59. https://doi.org/10.1162/jie.2007.1107.

KENNEDY, C. A.–HOORNWEG, D. (2012): Mainstreaming Urban Metabolism *Journal of Industrial Ecology* 16 (6): 780–82. https://doi.org/10.1111/j.1530-9290.2012.00548.x.

KENNEDY, C. A.–STEWART, I.–FACCHINI, A.–CERSOSIMO, I.–MELE, R.–CHEN, B.–UDA, M. (2015): Energy and Material Flows of Megacities *Proceedings of the National Academy of Sciences* 112 (19): 5985–90. https://doi.org/10.1073/pnas.1504315112.

KENNEDY, C.–PINCETL, S.–BUNJE, P. (2011): The Study of Urban Metabolism and Its Applications to Urban Planning and Design *Environmental Pollution* 159 (8–9): 1965–73. https://doi.org/10.1016/j.envpol.2010.10.022.

KOLBADI, N.–MOHAMMADI, M.–NAMVAR, F. (2015): Smart Growth Theory as One of the Main Paradigms of Sustainable City *International Journal of Review in Life Sciences* 5 (9): 209–19.

LEI, K.–LIU, L.–HU, D.–LOU, I. (2016): Mass, Energy, and Emergy Analysis of the Metabolism of Macao *Journal of Cleaner Production* 114: 160–70. https://doi.org/10.1016/j.jclepro.2015.05.099.

LI, Y.–BEETON, R. J. S.–HALOG, A.–SIGLER, T. (2016): Evaluating Urban Sustainability Potential Based on Material Flow Analysis of Inputs and Outputs: A Case Study in Jinchang City, China *Resources, Conservation and Recycling* 110: 87–98. https://doi.org/10.1016/j.resconrec.2016.03.023.

MAPAR, M.–JAFARI, M. J.–MANSOURI, N.–ARJMANDI, R.–AZIZINEJAD, R.–RAMOS, T. B. (2017): Sustainability Indicators for Municipalities of Megacities: Integrating

Health, Safety and Environmental Performance *Ecological Indicators* 83: 271–91. https://doi.org/10.1016/j.ecolind.2017.08.012.

MCCORMICK, K.–ANDERBERG, S.–COENEN, L.–NEIJ, L. (2013): Advancing Sustainable Urban Transformation *Journal of Cleaner Production* 50: 1–11. https://doi.org/10.1016/j.jclepro.2013.01.003.

MCDONOUGH, W.–BRAUNGART, M. (2002): *Cradle to Cradle: Remaking the Way We Make Things*. 1st ed. North Point Press., New York, U.S.

MORI, K.–CHRISTODOULOU, A. (2012): Review of Sustainability Indices and Indicators: Towards a New City Sustainability Index (CSI) *Environmental Impact Assessment Review* 32 (1): 94–106. https://doi.org/10.1016/j.eiar.2011.06.001.

NASSAUER, J. I.–WU, J.–XIANG, W.-N. (2014): Actionable Urban Ecology in China and the World: Integrating Ecology and Planning for Sustainable Cities *Landscape and Urban Planning* 125: 207–8. https://doi.org/10.1016/j.landurbplan.2014.02.022.

NESS, B.–ANDERBERG, S.–OLSSON, L. (2010): Structuring Problems in Sustainability Science: The Multi-Level DPSIR Framework *Geoforum* 41 (3): 479–88. https://doi.org/10.1016/j.geoforum.2009.12.005.

RICHARDS, D. J.–ALLENBY, B. R.–FROSCH, R. A. (1994): The Greening of Industrial Ecosystems: Overview and Perspective In: ALLENBY, B. R.–RICHARDS, D. J *The Greening of Industrial Ecosystems* pp. 1–19. The National Academy Press, Washington D.C., U.S. https://doi.org/10.17226/2129.

ROSADO, L.–KALMYKOVA, Y.–PATRÍCIO, J. (2016): Urban Metabolism Profiles. An Empirical Analysis of the Material Flow Characteristics of Three Metropolitan Areas in Sweden *Journal of Cleaner Production* 126: 206–17. https://doi.org/10.1016/j.jclepro.2016.02.139.

ROTMANS, J. (2006): Tools for Integrated Sustainability Assessment: A Two-Track Approach *The Integrated Assessment Journal* 6 (4): 35–57.

SHEN, L.-Y.–OCHOA, J. J.–SHAH, M. N.–ZHANG, X. (2011): The Application of Urban Sustainability Indicators – A Comparison between Various Practices *Habitat International* 35 (1): 17–29. https://doi.org/10.1016/j.habitatint.2010.03.006.

SORIA-LARA, J. A.–BERTOLINI, L.–TE BRÖMMELSTROET, M. (2016): Towards a More Effective EIA in Transport Planning: A Literature Review to Derive Interventions and Mechanisms to Improve Knowledge Integration *Journal of Environmental Planning and Management* 60 (5): 755–72. https://doi.org/10.1080/09640568.2016.1180282.

STRAATEMEIER, T.–BERTOLINI, L.–TE BRÖMMELSTROET, M.–HOETJES, P. (2010): An Experiential Approach to Research in Planning *Environment and Planning B: Planning and Design* 37 (4): 578–91. https://doi.org/10.1068/b35122.

SUN, L.–LI, H.–DONG, L.–FANG, K.–REN, J.–GENG, Y.–FUJII, M.–ZHANG, W.–ZHANG, N.–LIU, Z. (2017): Eco-Benefits Assessment on Urban Industrial Symbiosis Based on Material Flows Analysis and Emergy Evaluation Approach: A Case of Liuzhou City, China *Resources, Conservation and Recycling* 119: 78–88. https://doi.org/10.1016/j.resconrec.2016.06.007.

SUSTAINABLE CITIES INTERNATIONAL (2012): *Indicators for Sustainability: How Cities Are Monitoring and Evaluating Their Success* Vancouver, Canada. www.cashewstory.com.

SZABÓ, N. (2015): Methods for Regionalizing Input-Output Tables *Regional Statistics* 5 (1): 44–65. https://doi.org/10.15196/RS05103.

TAPIO, P. (2005): Towards a Theory of Decoupling: Degrees of Decoupling in the EU and the Case of Road Traffic in Finland between 1970 and 2001 *Transport Policy* 12 (2): 137–51. https://doi.org/10.1016/j.tranpol.2005.01.001.

TOWNSEND, A. M. (2013): *Smart Cities: Big Data, Civic Hackers, and the Quest for a New Utopia* W. W. Norton & Company, Inc., New York, U.S.

ULGIATI, S.–BROWN, M. T.–BASTIANONI, S.–MARCHETTINI, N. (1995): Emergy-Based Indices and Ratios to Evaluate the Sustainable Use of Resources *Ecological Engineering* 5 (4): 519–31. https://doi.org/10.1016/0925-8574(95)00043-7.

VALKÓ, G.–FEKETE-FARKAS, M.–KOVÁCS, I. (2017): Indicators for the Economic Dimension of Sustainable Agriculture in the European Union *Regional Statistics* 7 (1): 179–96. https://doi.org/10.15196/RS07110.

VAN TIMMEREN, A. (2013): *Reciprocities: A Dynamic Equilibrium.* 2nd ed. Delft University of Technology, Delft, the Netherlands. https://doi.org/10.13140/2.1.3708.0964.

VAN TIMMEREN, A.–HENRIQUEZ, L.–REYNOLDS, A. (2015): *Ubikquity and the Illuminated City.* 2nd ed. TU Delft publication, Delft, the Netherlands.

VOSKAMP, I. M.–STREMKE, S.–SPILLER, M.–PERROTTI, D.–VAN DER HOEK, J. P. –RIJNAARTS, H. H M. (2016): Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism: A Material Flow Analysis of Amsterdam *Journal of Industrial Ecology* 21 (4): 887–902. https://doi.org/10.1111/jiec.12461.

WEI, H. (2011): Strategy of Urban Transformation in China *Journal of Urban and Regional Planning* 1: 3.

WOLMAN, A. (1965): The Metabolism of Cities *Scientific American* 213 (3): 179–90. https://doi.org/10.1038/scientificamerican0965-178.

WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT (1987): *Our Common Future* Oxford University Press, Oxford, U.K.; New York, U.S.

WU, J. (2014): Urban Ecology and Sustainability: The State-of-the-Science and Future Directions *Landscape and Urban Planning* 125: 209–21. https://doi.org/10.1016/j.landurbplan.2014.01.018.

YANG, B.–XU, T.–SHI, L. (2017): Analysis on Sustainable Urban Development Levels and Trends in China's Cities *Journal of Cleaner Production* 141: 868–80. https://doi.org/10.1016/j.jclepro.2016.09.121.

YANG, D.–GAO, L.–XIAO, L.–WANG, R. (2012): Cross-Boundary Environmental Effects of Urban Household Metabolism Based on an Urban Spatial Conceptual Framework: A Comparative Case of Xiamen *Journal of Cleaner Production* 27: 1–10. https://doi.org/10.1016/j.jclepro.2011.12.033.

YANG, D.–KAO, W. T. M.–ZHANG, G.–ZHANG, N. (2014): Evaluating Spatiotemporal Differences and Sustainability of Xiamen Urban Metabolism Using Emergy Synthesis *Ecological Modelling* 272: 40–48. https://doi.org/10.1016/j.ecolmodel.2013.09.014.

ZHAI, M.–HUANG, G.–LIU, L.–SU, S. (2018): Dynamic Input-Output Analysis for Energy Metabolism System in the Province of Guangdong, China *Journal of Cleaner Production* 196: 747–62. https://doi.org/10.1016/j.jclepro.2018.06.084.

ZHANG, Y. (2013): Urban Metabolism: A Review of Research Methodologies *Environmental Pollution* 178: 463–73. https://doi.org/10.1016/j.envpol.2013.03.052.

ZHANG, Y.–LIU, H.–CHEN, B. (2013): Comprehensive Evaluation of the Structural Characteristics of an Urban Metabolic System: Model Development and a Case Study of Beijing *Ecological Modelling* 252: 106–13. https://doi.org/10.1016/j.ecolmodel.2012.08.017.

ZHANG, Y.–YANG, Z.–YU, X. (2009): Evaluation of Urban Metabolism Based on Emergy Synthesis: A Case Study for Beijing (China) *Ecological Modelling* 220: 1690–96. https://doi.org/10.1016/j.ecolmodel.2009.04.002.

ZHANG, Y.–YANG, Z.–YU, X. (2015): Urban Metabolism: A Review of Current Knowledge and Directions for Future Study *Environmental Science and Technology* 49 (19): 11247–63. https://doi.org/10.1021/acs.est.5b03060.