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## Exploring urban metabolism—Towards an interdisciplinary perspective

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## ABSTRACT

The discussion on urban metabolism has been long dominated by natural scientists focussing on natural forces shaping the energy and material flows in urban systems. However, in the anthropocene human forces such as industrialization and urbanization are mobilizing people, goods and information at an increasing pace and as such have a large impact on urban energy and material flows. In this white paper, we develop a combined natural and social science perspective on urban metabolism. More specifically, innovative conceptual and methodological interdisciplinary approaches are identified and discussed to enhance the understanding of the forces that shape urban metabolism, and how these forces affect urban living and the environment. A challenging research agenda on urban metabolism is also presented.

## 1. Introduction

In this anthropocene epoch (Crutzen, 2002) human-driven activities and associated impacts on the environment, such as CO<sub>2</sub> accumulation in the atmosphere, have become very pervasive and profound factors for the development of the earth system (Steffen et al., 2007; IPCC, 2014). Originally, natural forces dominated the processes in the world, but with the rise of industrialization and urbanization the natural system gradually became imbued with technologies that mobilized people, goods and information at an ever increasing pace (Steffen et al., 2007). Hence, today humankind has become a dominant force in moving materials around the world (Klee and Graedel, 2004).

Within a few decades, the vast majority of the global population will live in cities (70% by 2050; UN, 2015). Kennedy et al. (2015) showed that the current rapidly growing 27 megacities in the world are responsible for 9% of global electricity consumption, while generating 13% of the solid waste, and housing 7% of global population. Simultaneously, cities will generate a vast proportion of gross domestic product (GDP). This brings together large flows in goods, services, materials and energy in concentrated locations and supporting billions of lives. This network of heterogeneous flows in cities is called urban metabolism (UM). In the past years, we have seen an upsurge in UM studies (Weisz and Steinberger, 2010). Contemporary studies on UM draw largely on political economy or bio-physical sciences, as well as on system theory and thermodynamics (Rapoport, 2011). Increasingly, it is recognized that human activities should be an integral part of analyzing UM. To influence UM to meet future challenges, we need to have a better understanding of the relations between societies, mass and energy flows (production and consumption) that shape and sustain each other (Broto et al., 2012; Rosales Carreón and Worrell, 2017). In a still broader perspective, UM approaches and modelling developments can also be regarded as a particular branch of a spatially focused variation of integrated earth system modelling (Verburg et al., 2016).

Through the notions of flow and circulation, the concept of urban metabolism links material flows with ecological and social processes, and the potential for change to sustainable patterns of consumption and production (Broto et al., 2012). Therefore, UM should be understood in the context of a (stocks and) flow model. Wegener (2004) and Dijst (2013) have identified different types of urban processes which vary in their pace of change: the very slow processes of changing physical transport, communication and utility infrastructures and distribution of land uses; the long lifecycle of housing, workplaces and other non-residential buildings; the relatively fast change in employment and household composition; and the very fast daily mobility flows of people and goods (see Fig. 1). Although Wegener did not name information as an urban process, its identification as such seems to be justified by the widespread use of fixed and mobile ICTs (Schwanen et al., 2006; Kwan 2007; Urry 2007), together with the extremely fast and large flows of data, information, knowledge and money in the realms of business and personal life.

Besides these largely social and economic spatio-temporal processes, there are also natural spatio-temporal processes in the earth system – the geosphere, the biosphere, the atmosphere, and the hydrosphere – which differ in their speed of change. Climate change, water, energy and nutrient flows, erosion and other (human induced) natural processes in turn influence social and economic processes in urban systems.

Within this flow perspective on cities, we need to understand the drivers that affect the flows – and vice versa – to better understand the UM. This starts with the socio-demographics (e.g. gender, age, household type, income, educational level and ethnicity) and their impact on lifestyles which can be expressed in terms of activities and travel patterns, use of ICTs, consumption patterns and residential choices (Lyons et al., 2017). This can be followed by the built environment attributes (e.g. density, diversity and design of urban functions and infrastructures) and interaction with urban microclimates (e.g. urban heat island effect and air quality; e.g. Steeneveld et al., 2016). Finally, socio-cultural drivers (e.g. prevailing views on

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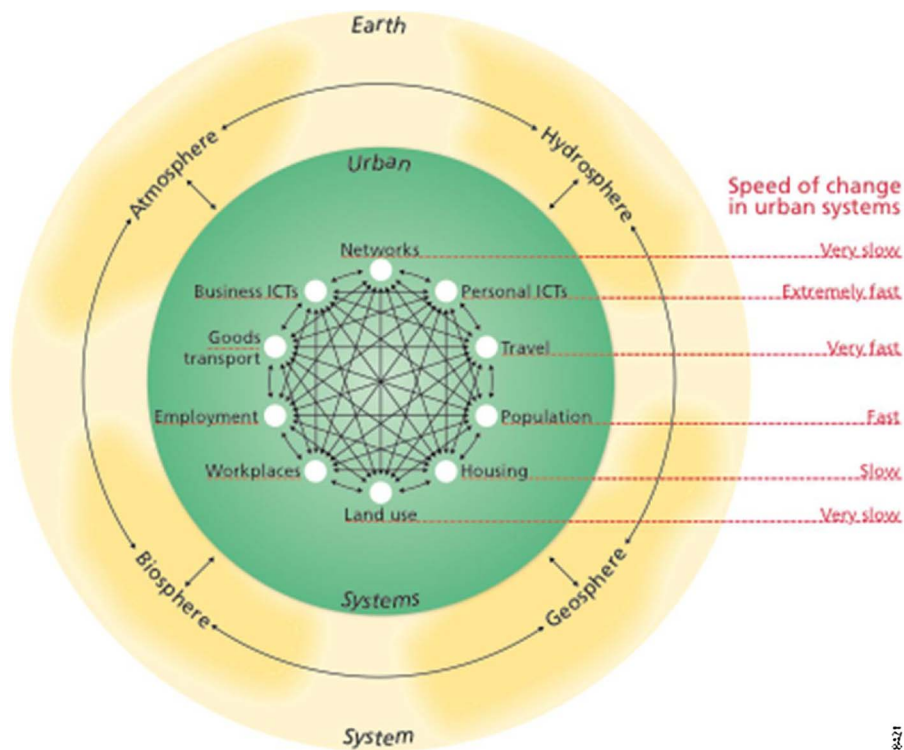


Fig. 1. A flow perspective on urban systems.  
Source: Dijkstra (2013)

openness, sharing, equity, responsibility and accountability) are affecting mobility and migration flows, networking, and other (urban) activities. These factors closely connect to macro developments in culture, economy, infrastructure, technology, environment, and climate. This demonstrates how all factors affecting the UM are connected, and that we need to develop an integrated view and vision to better understand UM and ways to shape UM within sustainable development paths (Rosales Carreón and Worrell, 2017).

In this white paper, we focus on the need to come to a better understanding of the different disciplinary perspectives on urban metabolism through identifying and analyzing the flows and drivers. Combining them will help to illuminate innovative interdisciplinary approaches to understand the forces that shape UM, and how these forces affect urban living and the environment. We will present suggestions for bringing together these perspectives to arrive at new scientific approaches. Our suggestions in this white paper are the result of an extremely stimulating debate between scientists from a wide variety of disciplines and backgrounds over the past few years. These results will certainly not be the final word, but rather set the stage for interdisciplinary analysis to come to a better understanding of the UM and ways to make cities sustainable, healthy and thriving places for humanity.

This white paper on UM addresses the needs for urban sustainability transitions. A growing body of international policies focus upon responsible and sustainable resource use. These include the Sustainable Development Goals (SDGs) announced in September 2015 (United Nations General Assembly, 2015) and the 'Paris Agreement' (COP21) in December 2015 (United Nations, 2015). The New Urban Agenda (NUA) was announced in October 2016 at Habitat III. It was developed in response to SDG-11 and calls for a 'new paradigm' that will "redress the way we plan, finance, develop, govern and manage cities and human settlements, recognizing sustainable urban and territorial development as essential to the achievement of sustainable development and prosperity for all". Actions to achieve this outcome would include "integrated urban and territorial planning and design ... to optimize the spatial dimension of the urban form and to deliver the positive outcomes of urbanization" (United Nations, 2016, pp. 3–4; Thomson and Newman, 2017). These policies set goals and targets, however, the process for monitoring, managing and meeting these agreements is not so clear. A holistic approach to analysis and monitoring, such as UM, is capable of driving urban sustainability transitions (Hajer, 2011). Recently, a holistic approach was also developed for urban atmospheric processes (Barlow et al., 2017).

In this paper, we start with the introduction of a central conceptual approach that will be followed by a discussion of the drivers of UM. Some of the drivers are actually the result of our past and current metabolism, resulting in feedback loops shaping the future metabolism. In practice, some of these drivers will be affected by our cultural background and normative issues, as well as by the institutions that we have developed to govern and manage our societies. We will explore the role of these factors in understanding the drivers of UM, and assess how these might affect the drivers. We will also discuss approaches to analyzing these factors, drivers and impacts on UM (and vice versa). We include suggestions for research needs and future methodological developments. We end this paper with a research agenda on UM.

## 2. Urban metabolism: state of the art

The study of UM builds on the premise that the urban system can be compared to the functioning of natural ecosystems, and various (normative) approaches have been developed from this perspective to study UM. In a review paper, Broto et al. (2012) provide an overview of the development of different perspectives on UM, and how they have shaped the field. Typically, UM is studied using material flow analysis (MFA) approaches to analyse the physical flow of energy and materials through a city (the 'natural science perspective' in Fig. 2). One could describe this as an accounting approach, using statistical data to view particular substances as they enter, are consumed, converted by, and exit a geographically-bounded urban system (Ayres and Ayres, 1996; Brunner and Rechberger, 2016).

MFA distinguishes stocks (*i.e.* an accumulation of materials residing in the system) and flows (*i.e.* entering and exiting the system). In a simple

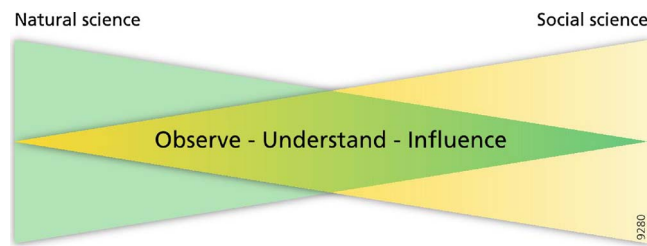


Fig. 2. The role of different disciplines (for simplicity shown as natural and social sciences) in understanding and managing urban metabolism.

form the stocks are the result of the inputs minus the outputs of the urban system over a specific period (most often a year, as that is the basis for most statistical sources used in MFA). In practice, conversions may take place (e.g. combusting imported fuels may lead to exports of CO<sub>2</sub>), and by using materials balance principles the conversions can be accounted for. The accumulation (as share of the imported materials) may change over time due to changing production, consumption and development patterns. In Western cities in 1969, 10–15% of the imported material in consumer goods accumulated as stocks. In 2009 this was reduced to only 1% for consumer goods (Leonard, 2010). The increased throughput of consumed resources results in waste flows that are either reused, recycled or discharged to the environment (inside or outside the urban area under study). Concepts of the circular economy (Ghisellini et al., 2016) in which reuse of products and materials is a core element appear to be applicable in urban environments, inter alia giving rise to new – metabolically important – concepts such as urban mining, whose breakthrough will often depend on changes in ownership, disposition, and responsibility of involved goods.

As the type of services demanded and the way that services are provided change, it will affect not only the flows but also the stock formation or accumulation. Growing cities demand large investments in infrastructure and hence accumulate (or store) materials in this infrastructure for a long time. In cities without this growth, infrastructure material accumulation will be much lower. However, we also witness other processes that affect the lifetime of products (e.g. planned obsolescence, fashion and marketing shaping consumer preferences), and hence the flows and accumulation of materials. A reduced lifetime of many appliances results in more rapid turnover, and hence an increased metabolism. In line with Fig. 1 and following Kurokawa's (1977) perspective of the urban system as an ecosystem, where the system is in continuous change, one might consider stocks also as very slow flows. This brings in time as an important aspect to study flows.

Many of the changes in the flows are the result of changes in the way that we choose to use a service or the way that services are offered to the consumer. Hence, the development of a city's metabolism should include the social system, as the energy and material flows enable and sustain these social systems (Fischer-Kowalski and Huttler, 1997; Newman 1999). Broto et al. (2012) distinguish different approaches to better understand the role of the social system in shaping the urban metabolism based on ecological economics and political ecology (the 'social science perspective' in Fig. 2). Currently, various methods are used to connect drivers to the flows. Most of the approaches build on information about national economies (e.g. Input/Output tables) that are connected to statistics and indicators of urban areas to model material flows (see e.g. Kalmykova et al., 2016) for urban areas. While the approaches from economics and political ecology entail different backgrounds and perspectives, they help to illuminate how flows are affected by one or more factors in the social and economic system. Yet, we need a better understanding of how these factors shape the UM. This demands linking social processes to temporal and spatial attributes of flows of services that can be translated to the temporal and spatial attributes of energy, water, and material flows. In the next section, we explain this further.

### 3. Identifying the interrelated elements of urban metabolism

Understanding the temporal and spatial attributes flows of services and how these are related to the temporal and spatial attributes of material and energy flows in urban systems is the subject of this section. *Flows and stocks* within the urban environment are a part of and a consequence of *activities* that are undertaken within this environment. Both activities, and the accompanying flows and stocks arise from and are a manifestation of *needs* and *facilitators/constraints* of individuals and communities (Dijst et al., 2013). There are endogenous and exogenous system *drivers* that set a context for such needs and constraints, while these factors themselves can influence drivers. Broadly speaking, drivers, needs and facilitators/constraints constitute *causal* determinants of activities; and flows and stocks represent *effects/impacts*. Flows and stocks will often be associated with problems facing the urban metabolism (notwithstanding the problems of unmet needs), while solutions to such problems are likely to be found in evaluating the drivers, needs and constraints.

In this section, we explore these five inter-related elements of urban metabolism. Fig. 3 offers a simple overview from which it is appropriate to begin with flows and stocks in order to then move upstream.

#### 3.1. Flows and stocks

UM can be seen as a metaphor for the flows and stocks of goods and services through a city. They can be relatively easy to quantify and to measure: material flows and stocks, like energy (MWh), traffic (veh./h), water (l/day), capital (euros), air pollution (pm, ppm), materials (ton); or they can be less easy to quantify directly: immaterial flows and stocks, like information, social capital, and culture. The difference between stocks and flows is that a stock denotes a certain quantity of a natural or man-made endowment at a certain time, and a flow denotes a certain quantity of endowment elements per unit of time, leaving from or arriving at a stock. The number of cars that belong to the inhabitants of a city is a stock, but if

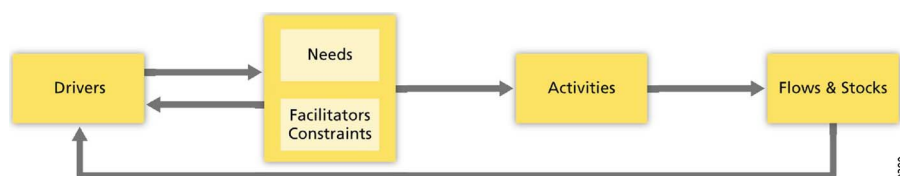


Fig. 3. The five inter-related elements of urban metabolism.

we want to measure congestion or traffic, we need to know some spatial decomposition of the stock and the details of the flows between these stock subsets, *i.e.* given the road capacity the number of cars per hour flowing from area A to area B. Yet, car stock dynamics could also be described in terms of sales transactions of new and second-hand cars in a city and the consequent changes of car holdership by urban population segments, *i.e.* trade flows rather than traffic flows. Energy is a particular case, as it is primarily a flow although some solid or liquid forms of energy are stored temporarily in the system or by individuals (Bristow and Kennedy, 2013). Stocks of energy are generally small compared to the flows, and stocks have typically a short lifetime, *i.e.* (far) less than a year. Energy (*e.g.* solar, wind, geothermal) may also be generated within an urban area. Some stocks can change very fast, like information, and some very slowly, like the building stock, or the spatial organization of a city/distribution of land uses. Flows are in some cases substitutes and in other cases complements, as the flows (and the drivers) may be interrelated.

### 3.2. Activities

Stocks and flows are generated or (directly) influenced by activities. Activities can be economic (*e.g.* education, employment), political, domestic (*e.g.* eating, sleeping, cleaning; caring for others), social and so on. Mobility is itself an activity but also a result of decisions to take part in the before mentioned activities. Mobility can refer to the movement of people and goods (material flows), or to the movement of information, knowledge, values and norms (immaterial flows). The activity determines the flows and contributes to the stocks and indirectly through flows/stocks influences drivers. Historically, activities have been strongly location-dependent and often time-dependent. Being ‘at work’ defined the activity of an individual in both time and place. However, the UM may now be subject to an increasing spatial-temporal flexibility in the context of the digital age and knowledge economy. People do not always need to be co-present with others or with services to interact and transact. Processes of governance, which in turn are evolving, mediate activities and are diversifying with both centralized and decentralized forms (Section 6). Activities are also mediated by an evolution in technologies. Population’s consumptive patterns of activity strongly influence the shape and rate of UM. Such patterns are mediated by cultural and social factors (*e.g.* world views, policy, fashion, media, marketing), economic factors (*e.g.* costs, wealth) and environmental factors (*e.g.* availability and accessibility of resources, public health, quality of urban life).

### 3.3. Needs and facilitators/constraints

Activities and services exist to fulfill certain needs. These can be the needs of individuals or of communities, where the latter are formed either by shared interests, or by geography (*e.g.* cities, towns). To a great extent needs are shaped by cultural values (also called ‘drivers’) that are influenced by media and marketing. The increased volume may create pressures on the sustainability of the UM. For example, car dependence started with the desire of people to own their mode of transport. As time passed and infrastructure for cars became widespread and influenced urban planning, it became very inconvenient in some cities not to travel by car (urban fabric lock-in).

Activities are triggered by needs and dependent on facilitators/constraints. Constraints (‘barriers’) and facilitators are two sides of the same coin, depending on whether a given factor is present in a positive or negative sense. For example, high cost is a constraint, while low cost is a facilitator. These factors may include technology, governance, markets (all of which can influence cost), space, and culture. The same factor (*e.g.* social norms) could conceivably be considered a driver in one study and a facilitator or constraint in another study. The distinction between the two elements is that the absence of binding constraints is not sufficient for a given behavior to occur; there must be one or more drivers to motivate action (Mokhtarian and Salomon, 1994).

People differentiate in opportunities offered to participate in activities. These refer to environmental attributes such as supply of transport alternatives and distance to destinations (Dijst et al., 2013). In this respect, accessibility (being able to reach people, goods, and services) is an example of a need, which can then be substantiated by the activity of mobility. People also differentiate in their abilities to participate in activities. Abilities refer to the available time, money, skills and capacity (*o.c.*). Depending on the type of mobility (by car, bike, plane, public transportation, or of information) there will be different flows.

### 3.4. Drivers

The drivers are in the background of the UM, and can influence needs, facilitators/constraints, activities, flows and stocks but are also the context in which they take place. Drivers refer to macro developments which have an impact on needs and constraints experienced at the micro (individual or community) level. We can distinguish various types of drivers: socio-cultural (*e.g.* values and norms), economic (*e.g.* growth and decline), political (*e.g.* power relations and policy aims), demographic (*e.g.* ageing and population decline), urbanization, climate change and natural resources. There are endogenous and exogenous system drivers that set a context for such needs and constraints but needs and constraints themselves can influence drivers. Accordingly, problems are more commonly identified at the level of flows/stocks, particularly in terms of material flows/stocks, and solutions at the level of drivers, needs and constraints. This understanding gained through observation can be used to influence the spatio-temporal nature of metabolic patterns of a city. Understanding the causal relationship between different urban metabolisms provides information for various actors (policy makers, individuals, institutions) to substitute (through choice or flexibility) delivery of similar services or functions with reduced environmental impact. Some drivers are more predictable while others are uncertain. In taking steps to examine future UM, critical uncertainties are especially important to address since by their nature they defy prediction.

## 4. An individual interpretation of urban metabolism

As shown in Section 2, analysis of the metabolism of cities often takes place at the aggregate level. However, we suggest that aggregate analyses of drivers, input and output flows and stocks would benefit from complementary analyses at the micro-level to better understand the relationships between needs, facilitators/constraints, activities and material flows and stocks. There might be two major reasons for doing this. First, aggregate processes are based on individual actions of people, firms and institutions which help to explain developments at the macro-level. For example, increasing car-ownership and use to enable a household’s daily life to be organized more time-efficiently can lead to greater consumption of fossil fuels and production of air pollution. Understanding changes in lifestyles (*e.g.* widespread digitalization of life or collaborative consumption) and the implications for the nature and spatio-temporal configuration of consumption of material products and production of waste can lead to identifying ways to influence UM (Lyons et al., 2017). Second, aggregate processes might superimpose constraints on the organization of daily life but also on health conditions of people. For example,

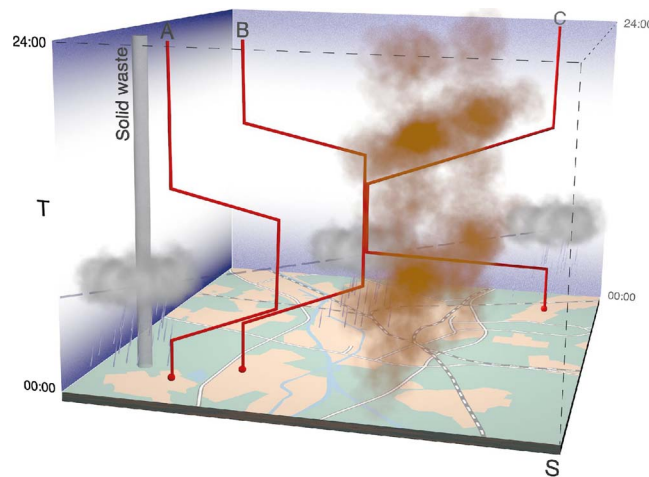


Fig. 4. Paths in the time-space.

(sub-)urban design will affect the choice of transportation modes, resulting in space demands, air quality, and health impacts. High concentrations of air pollution will harm people who live close to highways or are travelling through polluted areas. These relations will shape the UM of a given area when aggregated. Similar considerations can be applied to the evolution of urban resilience, which is receiving increasing attention in relation to adaptation to climate change of cities (Wilbanks et al., 2007; Dawson et al., 2014). For example, improved transparency on natural hazard risks is reflected in housing price corrections in exposed and directly adjacent (safe) areas (Votsis and Perrels, 2016) and – depending on the flexibility in zoning policies – the same transparency can incrementally affect future urban morphology (Votsis, 2017) and hence metabolism. These articles also indicate that the understanding of these corrective mechanisms can be (or even should be) analysed with both formalized economic analysis (indicating the size and effectiveness of the correction) and with sociological analysis (disclosing the degree of information sharing among (groups of) citizens).

Understanding the individual behavior and choices will then help us to better understand future trends in UM, and how these may be influenced in the pursuit of sustainable urban development. Yet, these macro-micro relations in UM have hardly been explored. In line with the plea of Coleman (1986) for the social sciences to pursue such a ‘methodical individualism’ we will introduce a time geographical individual perspective on UM.

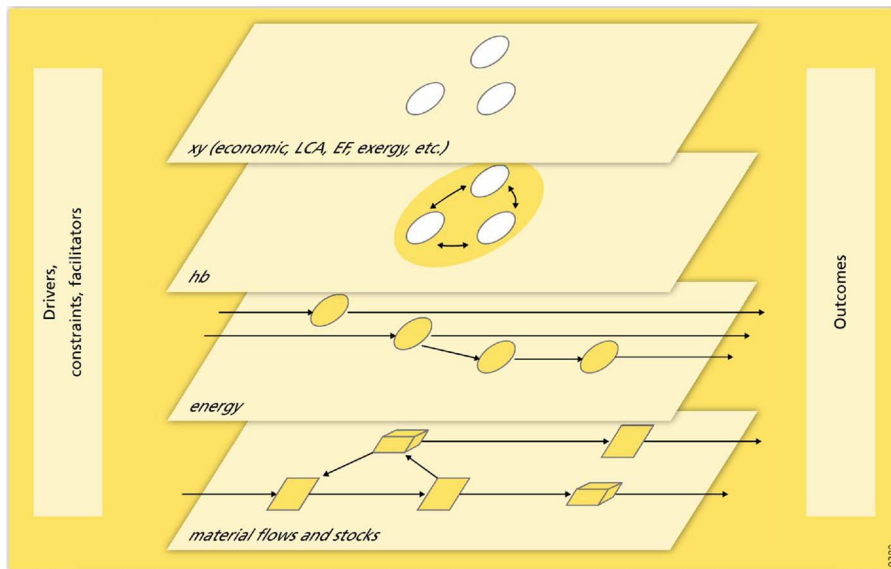
Time Geography is a human ecological approach focused on the physical world, comprising all inorganic and biological existents as well as their artefacts, which sets limits to human life (Hägerstrand, 1985; Dijst, 2009; Kwan, 2004; Miller, 2005). In the time-space uninterrupted ‘paths’ through time and across space couple and decouple (see Fig. 4). These paths are travelled by individual people but also by other organic and inorganic entities and natural phenomena such as sunrise, sunset and weather phenomena. Individual paths of human beings are based on preferences (needs and desires) for activities but constrained by various biological (e.g. health conditions) and instrumental (e.g. having a private car and computer with internet) limitations of the person (‘capability constraints’). To perform useful activities people have to be connected with other people, entities and natural phenomena which is dependent on their spatio-temporal locations (‘coupling constraints’). ‘Authoritative constraints’ such as business hours and entrance fees regulate access to places that can be differentiated by time (Dijst, 2009, 2018).

In Fig. 4 the paths of people (A–C) are drawn for a time span of 24 h. This time span could be extended to a year or even the lifetime of persons. In addition, the horizontal paths in a certain time span and the diagonal paths of (rain) clouds are depicted which influence the spatio-temporal paths of people. Changes in preferences for activities and in constraints will lead to changes in spatio-temporal consumption of food, goods and energy and in production of heat, pollution and waste, hence the flows in UM. In turn, these changes will affect the sustainability and public health of an area. Fig. 4 shows the vertical path of solid waste, such as a car wreck or household waste and the paths of air pollution generated by the use of private cars over the day on a specific road. Along their paths individuals are exposed to paths of heat, air pollution and other waste which could harm their health and life expectancy.

Aggregation of the individual actions creates a web of spatio-temporal paths that shape the UM. The patterns of these networks can be analysed. One suitable approach is called *Rhythm analysis*. For Lefebvre (2004, 15), a rhythm is a spatio-temporal concept: “Everywhere where there is interaction between a place, a time and an expenditure of energy, there is rhythm”. Rhythm involves repetition and interferences between linear and cyclical processes. Each flow has its own rhythm and may interact harmoniously (‘eurhythmic’) but often in complex ways with other rhythms in a local network, thereby maintaining the network in equilibrium or normatively in a ‘state of sustainability or health’. However, the network might also become destabilized (‘arrhythmic’) when the rhythms are discordant and cause a ‘pathological state’ or disorder (Lefebvre, 2004, 16; Meyer, 2008). These rhythms – which differ in speed, frequency and intensity – influence the spatio-temporal use of resources, production of waste and emissions and exposures of entities to unhealthy situations belonging to different flows in UM (see also: Winston, 2008). Rhythm analyses of biophysical and social flows in urban systems and their interactions can help to identify the ‘hotspots’ of metabolism problems. Hotspots could be places where flows come together and have an increased impact, or could be ‘factors’ (i.e. businesses, infrastructure) that shape the flows. Linking the hotspots to the individual and integrated flows allows defining more effective actions to limit the impacts, through a better understanding of the various drivers shaping the UM.

## 5. Towards integration

The challenge is to come to an integrated view of the relationships of the various drivers to the multiple flows and stocks in the UM. Such an approach needs to build on contributions from various areas of research and scientific disciplines and connect them through inter- and multi-disciplinary approaches. For this we put forward a conceptual model comprising a series of layers with each layer representing a field of knowledge/discipline, which combined can help to come to an improved understanding of the UM, the factors that shape it, and how it may develop towards a *sustainable UM* (see Fig. 5). Note that each layer has specific – spatial-temporally framed – outputs such as congestion, energy shortage or health status (‘outcomes’), while drivers such as economic growth, population growth and climate change (with their accompanying constraints and facilitators) are influential across the layers. The layers we distinguish are the material flows and stocks layer which are both part of MFA (Section 2),



**Fig. 5.** Basic elements of the integrated urban metabolism model.

Note: Arrows represent flows within each layer

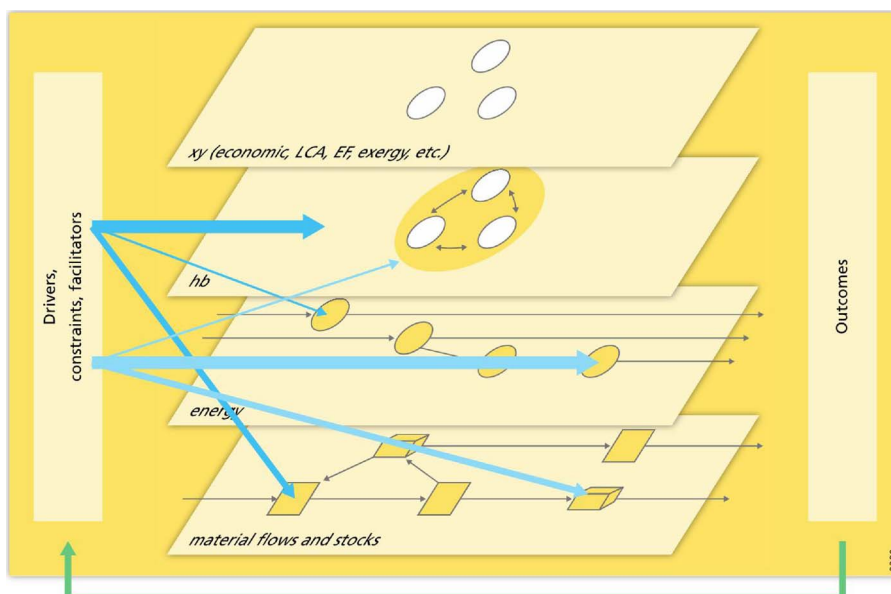
energy flows layer, and the human behavior (hb) layer (including activities in daily life and over the life course). Based on the issue being studied new or different layers (xy) can be added.

Not all drivers need to (directly) influence all layers. Moreover, a driver will not influence each layer in the same way (see Fig. 6). Besides the drivers, outside all layers one can find ‘outcomes’ which can and will be different for each layer (see Fig. 5). Outcomes may also influence drivers (see Fig. 6). Constraints or facilitators will shape the impact of the drivers.

Besides the layers, drivers, and outcomes, the most crucial element of the conceptual model consists of the linkages between the separate layers (see Fig. 7). The identification of these linkages, their content, strength, and direction forms (potentially) the main added value of this conceptual model. Due to the identification of these linkages between elements and/or processes in different layers (parts of) new knowledge fields will be generated and taken into account in understanding the UM.

The system boundaries (spatial and temporal scales) can be determined individually for each layer, and are utilitarian, *i.e.* based on what is considered useful for a given analysis rather than on purely theoretical considerations. As a consequence, the issue at hand will dictate what the most appropriate spatial and/or time scaling is, including the option to cover multiple scales, and where the system boundaries should be drawn (Barrera and Rosales Carreón, 2017).

Furthermore, we make a distinction between material and immaterial aspects of UM. This interest is first to highlight the existence of needs that are not easily measured quantitatively (for example the need for social contact, quality of life) and are, thus, often overlooked. Secondly, this dichotomy of material vs immaterial, hints to the possibility of substitution, up to a certain extent. Some needs (such as for food, clothing, and shelter) will remain essentially material as long as bodies are materially constituted, although even in this case some dematerialization can occur in the production of the needed components (*e.g.* through the substitution of lighter building materials, through automation reducing the number of human employees required, or through logistical efficiencies reducing the number of freight vehicles needed). Other needs can be more readily fulfilled in ways that range between more and less material – for example, a desire to listen to music can be fulfilled by physically attending a concert, buying physical albums, or downloading or



**Fig. 6.** Interactions between the basic elements of the integrated urban metabolism model.

Note: Arrows from drivers to layers and from outcomes to drivers represent influences

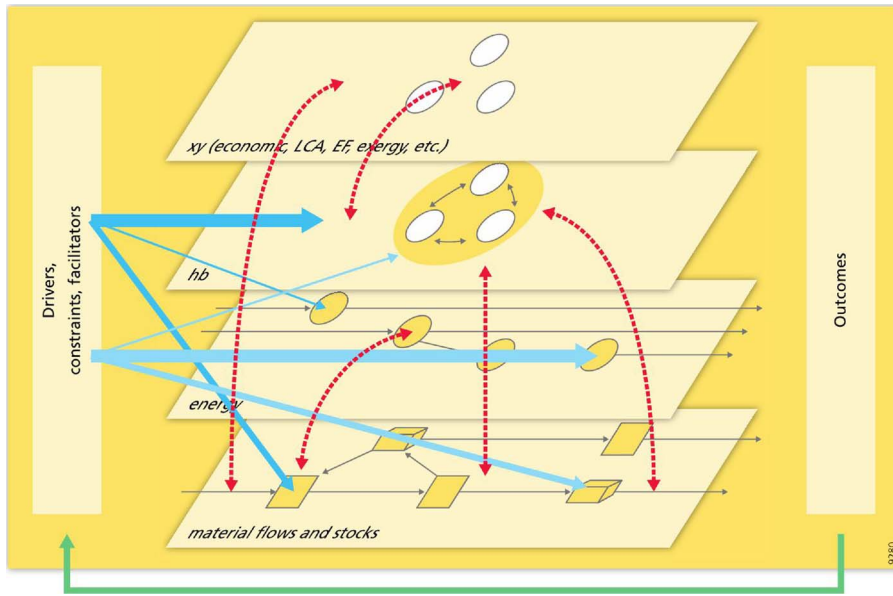


Fig. 7. Linking the layers to come to an inter-disciplinary understanding of urban metabolism. Note: Arrows between the layers represent influences between the flows (and stocks) of one layer to another layer

streaming completely immaterial electronic files (which nevertheless involve considerable volumes of material and energy in the production, transmission, and reception of those files). To the extent that the fulfilment of such needs could be shifted from a focus on the material to the immaterial, it is possible that this would cause a similar shift in activities and flows, resulting in a decrease of material flows.

### 6. Equity and governance dimensions of urban metabolism

Urban metabolism is about how we use resources. It deals with understanding and measuring flows and stocks. The normative claim in urban metabolism studies is that resources should be used efficiently in both production and consumption. We argue that in governance of UM there should be equal emphasis on equity because both efficiency and equity are prerequisites for social wellbeing (see Fig. 8).

In this section, we focus on equity (Fig. 8) by drawing on environmental justice debate which has a long history dating back to the environmental justice movement (EJM) and its close connection with the civil rights movements of the 1950s and 1960s in the United States. EJM was ignited by the disproportionate burden of toxic waste being born by minority groups (Bullard, 1999) and soon moved beyond toxicity and race to include a wider range of environmental burdens and benefits and their disproportionate distributions according to socio-economic status, cultural differences, physical abilities, and other forms of vulnerabilities. More importantly, the framing of environmental justice moved beyond a singular concern with the geographical distribution of environmental benefits and burdens to incorporate the particular circumstances of places and people and their vulnerabilities and capabilities. It became clear that uneven distribution of resources can have profoundly different impacts on different localities and groups of people because of not just their differential income levels, but also the differences in their culture, health, life experiences and values.

Furthermore, distributional inequalities *per se* are no longer seen as the only indication of injustice or a cry for policy intervention. Contemporary political philosophers such as Nancy Fraser, Amartya Sen and Martha Nussbaum have highlighted other aspects of understanding justice, notably; recognition; participation; capability; and responsibility (see Fig. 9). Drawing on this broader understanding of justice, Davoudi and Brooks (2014) have developed a pluralistic framework to provoke: when does unequal become unjust?

Recognition is about acknowledging social and cultural differences when seeking fair distributions of resources in such a way that the beneficiaries of redistributions are not stigmatized. So, Fraser (1996) calls for a theory of justice which combines redistribution with recognition by emphasising 'parity of participation' in society and fair distribution of political power. Nussbaum (2011) and Amartya Sen (2009) have gone further to suggest that we "should focus not so much on individuals' happiness or pleasure (utility-based approach) or their income and wealth (resources-based approach), but on their freedom and capabilities" (Davoudi and Brooks, 2014: 2690). For them, justice is about the capacity of people to function in the lives they choose for themselves. A capability approach to justice shifts the focus from equal resources to considering what those resources mean to

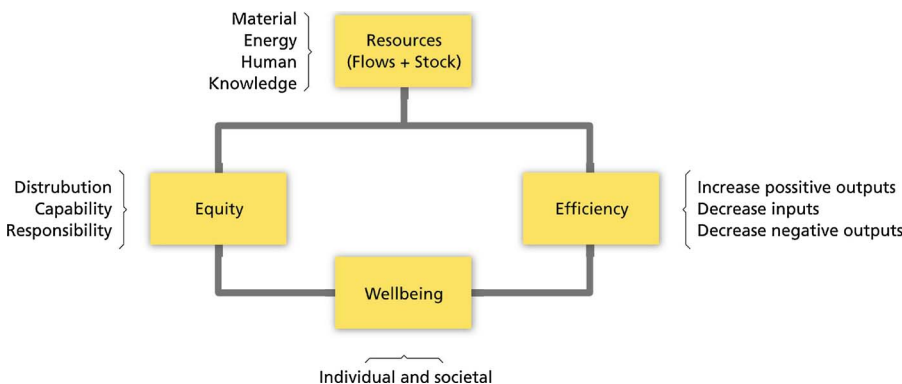


Fig. 8. Efficiency and equity aspects of urban metabolism.



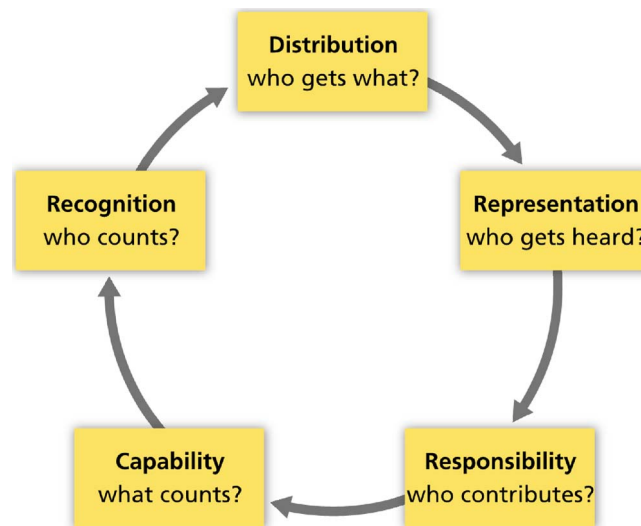


Fig. 9. A pluralistic framework of justice.  
Source: Adapted from Davoudi and Brooks (2014)

people and what they can do with them. The notion of wellbeing referred to in Fig. 8 is therefore not necessarily about possession of material goods but about a broader understanding of social wellbeing which impinges on other values such as sense of belonging, being valued, feeling of fair treatment and meaningful social relations. Indeed, the efficiency dimension of urban metabolism demands a decoupling of wellbeing from the excessive consumption of material goods. The responsibility dimension is particularly relevant to the debate about urban metabolism. As Sen suggests: “Freedom to choose gives us opportunity to decide what we should do, but with that opportunity comes the responsibility for what we do ... accountability ... is part of the capability perspective, and this can make room for demands of duty” (Sen, 2009:19). This suggests that responsibilities that emanate from freedom and capabilities are a critical part of environmental justice. This raises ethical questions about responsibility towards the environment. As Davoudi and Brooks (2014: 2690) suggest, it “places the discourses of environmental ethics firmly in the framework of social justice in much the same way as a focus on sustainability places ‘the discourse of justice firmly within the framework of sustainability’ (Agyeman and Evans, 2004: 156). Justice for people becomes entwined with justice to nature”.

In practice, however, there is no necessary or taken-for-granted positive correlation between environmental efficiency (metabolically closed cycle of resource flows) and environmental justice. Indeed, there are examples of the opposite. For example, focusing on the distributive aspect of justice, Fragkou et al. (2014) apply the concept of urban metabolism to 12 coastal municipalities of Barcelona’s Metropolitan Region. For each municipality, the metabolism of the municipal solid waste (MSW) flows are analysed to examine a) the system’s efficiency to close its MSW cycles (environmental efficiency), and b) the MSW export and import flows (social equity). Their results show a positive correlation between socioeconomic status and the externalisation of MSW treatment-related hazards. They show that MSW-management schemes in municipalities with higher socio-economic profiles are typically export-oriented whereas municipalities with lower socio-economic profiles are primarily net importers of MSW.

Another example relates to the compact city which has been hailed as a more environmentally efficient urban form as regards transportation energy consumption. However, research by Burton (2000) has raised question marks about the social effects of compactness. Despite the narrow definition of justice and ‘primary goods’, her research shows that not all aspects of the compact city form have positive social outcomes. Focusing on medium-sized English cities, she concludes that higher urban densities may be positive for some aspects of social equity and negative for others. This confirms the point raised above that a singular focus on metabolic efficiency can miss out important environmental justice issues.

These examples highlight the need for holistic policy measures so that environmental policies incorporate measures that reduce social inequalities, while social policies incorporate measures that enhance environmental efficiency and sustainable urban metabolism. A pertinent example of how such synergies can be achieved is the use of energy efficiency measures which can at the same time reduce fuel poverty. Holistic policy formulation is also advocated by Davoudi and Sturzaker (2017) in relation to sustainable urban metabolism and urban form. They argue that policies should focus on drivers of unsustainable practices and address them in a coherent and consistent way. More specifically they suggest that policies should: “be packaged to fit the purpose, target all relevant actors, and address user’s behaviors and social practices” (Davoudi et al., 2017; Davoudi and Sturzaker, 2017: 62–63). This requires an integrated and multilevel approach to governance capable of overcoming fragmented and sector-based decision making.

Climate change adaptation planning has raised new attention to equity aspects of vulnerability and resilience in communities with respect to effects of climate change and measures to alleviate these effects. Vulnerability and resilience have both individual and social dimensions, while other factors than socio-economic position, such as age, cultural or ethnic background, can be crucial, for example because individual and social learning capabilities can be more important than wealth (Carter et al., 2016).

Moreover, efficient and equitable urban metabolism requires ‘good’ governance. Yet, defining what is good and how it should be assessed is a contested task. Several international organizations have put forward criteria for good governance. For example, the United Nation defines good governance as ‘an efficient and effective response to urban problems by accountable local governments working in partnership with civil society’ (UN-Habitat 2009: 74). In its Global Campaign on Urban Good Governance launched in 2002, the UN considered the seven main characteristics of good governance as follows (UN-Habitat, 2002): Sustainability, Subsidiarity, Equity, Efficiency, Transparency and accountability, Civic engagement and citizenship, and Security. Similar principles are advocated by the EU White Paper as underpinning good governance (CEC, 2001: 10–11): Openness, Participation, Accountability, Effectiveness, Coherence, Proportionality, and Subsidiarity. Drawing on these and the findings of a European project (called ESPON TANGO) Davoudi and Cowie (2016) develop twelve indicators of ‘good’ governance as related to five dimensions of territorial/urban governance (Table 1) identified in the project (Schmitt and Van Well, 2015). These can be a starting point for exploring the nature and quality of urban governance and their capacity to steer cities towards efficient and equitable urban metabolism.

**Table 1**  
Dimensions and indicators of 'good' governance.  
Source: Davoudi and Cowie (2016).

Dimensions of territorial governance	Indicators of good territorial governance
Co-ordinating actions of actors and institutions Integrating policy sectors	Governing Capacity Leadership Subsidiarity Public Policy Packaging Cross-Sector Synergy
Mobilising stakeholder participation	Democratic Legitimacy Public Accountability Transparency
Being adaptive to changing contexts	Reflexivity Adaptability
Realising place-based/territorial specificities and impacts	Territorial relationality Territorial knowledgeability

## 7. Analytical methodological considerations

Urban metabolism is still a developing field. Given the roots of the approach, material flow analysis (MFA) remains an important method or an important building block in more comprehensive methodologies (Baccini and Brunner, 2012). Over time other conceptual bases have also been used to describe (integrated) physical and social urban functioning. Examples include urban ecology models (Chen et al., 2014; Zhang et al., 2006), urban energy (Keirstead et al 2012), ecosystem service – land use models (Kroll et al., 2012; Perino et al., 2014; Haase et al., 2014) and urban transport and accessibility models (Wegener, 2011). Nowadays, other dimensions such as public health, urban climate and governance, among others, are also integrated into urban studies and in urban modelling (Chrysoulakis et al., 2015).

Cities and urban systems are complex entities, especially when the population size runs in the hundreds of thousands and beyond. Consequently, the research context in which a method is applied, will determine the appropriateness of the method. Methods may have descriptive purposes (e.g., to generate coherent statistics and indicators). Methods may also be devised in the first place to better understand the interaction between selected entities, without aiming at a comprehensive representation of urban physical and social processes. The use of different methods is not necessarily mutually exclusive. Various methods enable both descriptive studies and decision support oriented studies. Also, a suite of models (i.e. one or more comprehensive but coarse models are combined with supporting detailed models) is often a good solution.

Methods are necessary in different stages of data handling, ranging from observation via representation, accounting, and statistical analysis to simulation and decision support. Data availability and quality are important pre-conditions for methodology development. Most metabolism studies are developed at the scale of the whole city using approximations (e.g. by downscaling national flows based on population share, surface share, share in GDP or a weighted composite factor) and are thus driven largely by restrictions in data availability (Keirstead and Sivakumar, 2012). Further, in most models, supply and demand of goods are treated exogenously (Keirstead et al., 2012). In order to design and operate efficient urban infrastructures such as energy systems, greater spatial and temporal resolutions are required in the underlying resource demand data (Keirstead and Sivakumar, 2012), often only available at the national level. Spatial averaging can lead to different results which was shown for the case of planning of low carbon energy systems (Simoes et al., 2017). For modelers, the goal should be to formulate the spatio-temporal boundaries with minimum complexity while still addressing the goals of the analysis (DeCarolis et al., 2017). When spatially and temporally explicit data is unavailable, the modeler can generate the needed high-resolution data through simulation instead of choosing to model at an aggregated scale. As an example, Keirstead and Sivakumar (2012) simulate demand profiles using activity-based modelling and Zeyringer et al. (2015) using standardized load profiles in combination with spatial information on housing types and number of employees. On the other hand, the growing supply of satellite and remote sensing data and of cheap remoting sensing technologies offers alternatives for overcoming data deficiency. However, such new observation methods will need their own error correction and interpretation mechanisms before reliable widespread application can take place.

Urban modelling is constrained by the spatial course of the historically grown infrastructure. Spatial models can take into account both stocks (existing infrastructure) and flows to construct, use and demolish this infrastructure (OIR, 2008). The use of georeferenced data and GIS databases are nowadays a prerequisite for state-of-the-art metabolism-based analysis of urban processes and urban planning. They also facilitate the use of research results to guide and support practical decisions (Zhang et al., 2015). This is particularly important when results of urban metabolism studies are used for spatial planning. Spatial planning affects the use of urban resources and can therefore help reduce the consumption of a city. Spatial planners need to take the current structure of cities into account. This structure is usually not the result of a continuous planning process but often of uncontrolled development (Weisz et al., 2008; Weisz and Schandl, 2008). As infrastructure decisions are long-term investments, the spatial form of cities – which can be characterized by the layout, density and utility grids (water, electricity, heating, cooling and transport) – has a long-standing impact on the daily resources needed.

Usually, infrastructure is planned to meet peak demand (e.g. generation capacity to supply electricity during the time of peak consumption, road and train capacity to transport commuters during peak hours). If the peak consumption is much higher than the average one, planning for peak demands leads to very expensive solutions. Spatial diversification resulting in areas with more mixed land uses (living, working) leads to a smaller difference between peak and average consumption. For example, Zeyringer et al. (2013) show that for distributed photo-voltaic power generation (PV) it can be advantageous to deploy it in areas with commercial consumers instead of residential only as the peak of PV production occurs at the peak of commercial consumption. Shifting of demand (e.g., commuting outside the peak, shifting electricity consumption to the night) leads to a flatter demand curve, reducing the need for increased power distribution or storage capacity. Further, locating demand close to supply (e.g., using renewable energy sources, locating work places close to residential areas) or vice versa reduces the need for infrastructure. More complex spatial spill-overs and substitution effects will be hard to detect and equally hard to demonstrate for others, once analysed. GIS play a generic enabling role in urban planning and analysis. Multiple new observational methods are emerging such as citizen participatory observation through e.g. mobile phones (and similar devices), product tagging, public cameras, satellites, drones, ICT data from utilities, smart meters and sensors in homes,

**Table 2**  
Metabolism approaches and indicators (non-exhaustive).

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Energy analysis
<ul style="list-style-type: none"> <li>● Generation and distribution of energy carriers</li> <li>● Energy demand, consumption and efficiency</li> <li>● Flows through the entire energy chain including useful energy and energy services; energy service needs</li> </ul>
Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) and products derived from it
<ul style="list-style-type: none"> <li>● Life cycle analysis (LCA) (product oriented; can be derived from comprehensive MFA/SFA)</li> <li>● Material input per service unit (MIPS)</li> <li>● Ecological footprints</li> <li>● Total material requirement (TMR)</li> </ul>
Ecosystem services
<ul style="list-style-type: none"> <li>● Non-monetary units (original unit of delivery, <i>i.e.</i> grams, litres, etc.)</li> <li>● (Change in) value per unit delivered or enjoyed – by type of ecosystem service</li> <li>● (Change in) value per unit of land (m<sup>2</sup>, km<sup>2</sup>) – compound effect of considered ecosystem services</li> <li>● (Change in) value of real estate stock, object or unit (m<sup>2</sup> floor space)</li> </ul>
Efficiency and endowment indicators
<ul style="list-style-type: none"> <li>● Physical units per capita (<i>e.g.</i> kWh/cap) – availability (stock) or use (flow)</li> <li>● Physical units per m<sup>2</sup>, m<sup>3</sup> (<i>e.g.</i> monthly rainfall/m<sup>2</sup>; N particles/m<sup>3</sup>; residential floor space/ha)</li> <li>● Net annual (out)flow/total (known) stock – exhaustion indicators</li> <li>● Monetary units per capita (<i>e.g.</i> energy costs per cap) <ul style="list-style-type: none"> <li>○ Actual monetary outlays</li> <li>○ Total attributed costs (including indirect effects and monetized non-market effects)</li> </ul> </li> <li>● Costs as share of regional GDP – competitiveness indicator</li> <li>● Physical units per regional GDP (<i>e.g.</i> MWh/USD1000) – economic efficiency indicator</li> <li>● Distance to or overshoot of critical threshold or target (<i>e.g.</i> CO<sub>2</sub>/cap in year T)</li> </ul>
Health and health risk indicators
<ul style="list-style-type: none"> <li>● Exposure to health risks in relation to metabolic stocks and flows (<i>e.g.</i>, housing, air quality, green areas, safe drinking water)</li> <li>● (Change in) healthy life years</li> <li>● (Change in) number of people exposed to conditions beyond a critical threshold</li> <li>● (Change in) occurrence of illnesses related to environmental conditions</li> </ul>
Socio-economic indicators
<ul style="list-style-type: none"> <li>● (Change) in population and population structure (age categories) <ul style="list-style-type: none"> <li>○ In- and outflows</li> <li>○ Endogenous changes</li> </ul> </li> <li>● (Change in) disposable income (per capita; per household); income distribution by age category</li> <li>● (Change in) free disposable time by household type</li> <li>● (Change in) consumer expenditures per household type</li> <li>● (Change in) living space per capita</li> <li>● (Change in) ownership rates of large durables (cars, boats, ...)</li> <li>● (Change in) turnover and value added per sector</li> <li>● (Change in) import- and export flows by sector or product group in quantities and value</li> <li>● (Change in) local government debt and tax base</li> </ul>

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businesses, public spaces. These can yield personalized dynamic and extremely high-resolution data. Collecting and analyzing real-time user generated data helps to improve the real-time dynamic understanding of urban energy and material flows (Shahrokni et al., 2015). These data collection methods may lead to data protection and privacy issues, and in due course these possibilities may also create new ethical dilemmas.

Regarding data processing, estimation and modelling stages, various types of metabolism approaches typically produce information as shown in Table 2.

### 7.1. Disciplinary (layers) methodological needs

Except for the system dynamics based approaches and urban climate and dispersion models, most methods are predominantly descriptive, and generally do not cover more than two dimensions of urban metabolism fully (while possibly covering a few other dimensions superficially (see Fig. 5)). Indeed, simulation models, such as climate models, have generally a narrower scope. This, however, does not apply to systems dynamics models. Before building and refining more comprehensive multi-dimensional models, we first need a better understanding of the interactions between the main entities (*e.g.*, land use, ecosystem services, material flows, population and mobility, employment and production, interactions with the hinterland) and typical critical thresholds for various sub-systems.

A key factor in urban planning is density gradient (*e.g.* Larson et al., 2012; Holden and Orland, 2005). There are limits to its ideal level from the point of view of reducing greenhouse gas emissions. Reduction of environmental loads in so-called compact cities are recommended (Thomson and Newman, 2017), which means high densities, high modal shares for public transport and non-motorized modes, and restraint degree of restriction in living space per inhabitant. Meanwhile – at least given particular urban circumstances – urban weather and climate studies indicate that high

densities may undermine resilience regarding extreme downpours and heat waves. Furthermore, when inhabitants are asked about their residential preferences, a majority indicates variations of some kind of sub-urban environment (e.g., with sufficient green and safe places to play). Similarly, urban ecosystem studies often plead for a minimum amount of (ongoing) urban nature providing a more versatile and resilient ecosystem structure in an urban region. There is also a socio-economic and equity issue, with high income neighborhoods having a similar energy density to poorer suburbs of apartment buildings that accommodate more people per km<sup>2</sup> but who use less energy for heating and cooling and own fewer appliances (IEA, 2009). A similar notion, as considered in Section 6, is environmental justice implying that low income neighborhoods tend to be located in areas with higher exposure to human-made and natural hazard risks, which often has to do with differences in material endowments regarding infrastructure and housing – hinting at differences in power over the control of metabolic flows.

Also, the selection of the appropriate scales of analysis still lacks a solid underpinning; instead practical reasons, such as the available categories in the data, tend to prevail. Clearly, much more supporting research regarding appropriate scales is needed. Scale refers here in the first place to spatial scale, but temporal scales are equally important for distinguishing different processes and their interactions. The identification of appropriate scales is needed for addressing research questions around the following topics in the field of urban metabolism:

- The interactions between population/energy/resource density, productivity and ecological density and associated thresholds
- Ecosystem carrying capacity
- Health effects
- Consequences of substituting between manmade and natural capital based solutions

### 7.2. Methodological needs for the analysis of high-resolution space-time data

Urban metabolic systems are highly complex (e.g. an urban energy system) and consist of many different elements (e.g., infrastructure and flows in transportation, solar energy, and wind energy systems). Complexity increases when less easily measurable, but crucial quantities are concerned, such as useful energy and energy services (Nakicenovic et al., 1993). Both the infrastructural elements and flows of energy of these systems have complex spatial and temporal characteristics. Traditional approaches to the analysis of these elements and flows tend to average over space and time, and rely mainly on system diagrams and mathematical models. Analysing energy supply and demand as well as energy service needs in spatially and temporally explicit fashion allows finding more optimal solutions. This becomes even more important when studying energy systems with variable renewable energy sources, demand side measures and smart grids. GIS methods can augment these traditional modes of analysis to provide further insights at high spatial and temporal resolution for planning and related purposes (see Li and Kwan, 2017). An important type of GIS method applicable to the analysis of urban energy systems is geovisualization – the visualization of explicitly geographic or spatial information. It focuses on the use of concrete visual representations and human visual abilities to generate insights about geographic problems (Kwan 2000, 2004). Involving the geographical dimension in the visualization process greatly facilitates the identification and interpretation of spatial patterns and relationships in complex data in the geographical context of a particular study area. Geovisualization performed with the help of advanced GIS software, including their 3D visualization capabilities, can be a powerful method for urban metabolism studies (see Li and Kwan, 2017). Two examples of the use of geovisualization in this kind of research is the analysis of energy supply/consumption and flows and movement of people.

Analysing energy supply and demand at high spatial resolution would facilitate planners and researchers identifying optimal solutions that take urban sustainability into account. It is thus helpful to be able to visualize the density patterns of people, businesses, and their activities. GIS offers several powerful methods for exploring these patterns with 3D density surfaces that represent and compare the density patterns of different population groups, businesses, and their activities. The 3D density surfaces can be generated using a nonparametric density estimation method called kernel estimation.

Transport entails the movement of people and goods in space. Contemporary GIS software offers many possibilities for visualizing the flows and movement of people and goods (e.g., real-time movement of people). For instance, a powerful 3D method for visualizing the flows and movement of people is the space-time trajectory or space-time path (see Section 4 and Fig. 4). In a schematic representation of the aquarium, the vertical axis is the time of day and the boundary of the horizontal plane represents the spatial scope of the study area. Individual space-time paths are portrayed as trajectories in a 3D aquarium. This method can also use the high-resolution GPS data that has become increasingly available in recent years to generate highly detailed visualizations of human movement patterns.

### 7.3. Integrative methodological needs

Ensuring the sustainable nature of the state and development of an urban area requires a versatile methodological framework, which allows for different levels of complexity and different ways of exploration or decision making (see also Fig. 7). Scale is also at this level an important concept for organizing and linking methods and models. For example, linking material and energy flows and optimising systems for a sophisticated sum of these might bring different optimalities in cities than solutions optimised only in one UM methodological layer. Another easily overlooked issue is data and data quality management. With increasing diversity of sources and data types, coherence and quality reassurance call for ever more serious attention. In this respect, it should be realized that urban data collection will use more distributed sources, such as mobile phones, as well as stakeholder-user-producer input (e.g., from active citizens and companies). In other words, future urban modelling requires methods and an overall framework that can integrate co-design and co-production by stakeholders.

Sustainable urban development, which also allow for a sustainable hinterland, will entail principles of the so-called ‘circular economy’. Both in terms of understanding of its functioning and in terms of societal and political feasibility, closing various material and natural cycles needs further study in terms of minimum scales, transfer of (financial) resources, and resilience against natural and human-made hazards.

To produce acceptable results, such frameworks should also be sufficiently transparent for decision makers and stakeholders. GIS and visualization will play a key role in enabling of transparency and comprehensibility. Furthermore, it is also a natural platform for investigating appropriate variations in (spatial) scales.

## 8. The way forward

Research into urban metabolism is thriving. Given the globally growing role of urban centers in housing people and in economic development, as well as in consumption of energy and resources, there is a strong need to better understand the metabolism. Especially, as cities are also taking the front seat in actions to mitigate climate changes while developing a healthier environment for their people, it is of importance to not only understand

the metabolism itself, but also the levers for changing the patterns to meet the needs and challenges of a sustainable future for humanity. In this paper, we argue that this better understanding can only be achieved if we fully understand the complex dynamics of the system underlying the metabolism, *i.e.* the urban ‘ecosystem’. In contrast to biological ecosystems, understanding the urban ecosystem needs the contribution of many scientific disciplines. We have provided some initial thoughts on combining the lessons learned from the different disciplines in an integrated vision, by seeing them as interconnected layers. There is a wealth of knowledge on the different layers, and new and interesting findings are published frequently. The challenge is in the integration of the knowledge in the layers to appreciate and understand the ‘urban rhythm’, and in the simplification of the complex relationships among these disciplines into key schematic interactions so that these can be described/modeled.

The integration spans not only different disciplines, but also the levels and system boundaries of analysis, *i.e.* from individual to aggregate consumption patterns and behavior, the element of time to dynamically link stocks and flows, and the element of space to connect the metabolism to exposure and public health. This will allow a better understanding of the drivers for the observed patterns, and identification of those areas (‘hot spots’) that are most suitable from a governance perspective to manage the urban metabolism from a sustainable development perspective.

From this perspective, the first need is to develop a common language that will enable clear communication on the issues raised above. In the workshop and the debate thereafter on which this paper is based, we were lucky to bring together a group of scientists from completely different disciplines and backgrounds that do not normally meet. It showed the wealth of information available in the different disciplines, and it also laid out the need to develop a common language that will enable integration of the various perspectives on urban metabolism and its drivers.

Based on our thoughts presented in this paper we draw up a research agenda. In this agenda, we make a distinction between substantive and methodological issues.

### 8.1. Substantive issues

We suggest include the need to answer the following major questions:

- What are the implications of major needs and constraints in the residential choices and activities of different population categories for the size, nature and spatio-temporal consumption of energy and resources and waste production at the urban system level?
- What are the implications of major changes in climate and economy for the size, nature and spatio-temporal consumption of energy and resources and waste production?
- What are the major characteristics of rhythms of biophysical and social flows in urban systems and at which spatio-temporal locations do these flows interact harmoniously or lead to crossings of critical thresholds and by that to destabilization of the urban metabolism?
- What are the implications of urban microclimates and air quality for spatio-temporal activity patterns and health and labour?
- Which balances between efficiency and equity in use of resources in urban systems are possible and what is the effectiveness of policies to stimulate both?
- If some of the complex interrelationships between the different UM approaches are accounted for, how do these affect optimal solutions towards the more standard policy questions, such as climate change mitigation priorities, energy supply system optimisation, etc.?

### 8.2. Methodological issues

We suggest include the need to answer the following major questions:

- How can the complex relationships among the various disciplinary/methodological layers of UM be simplified for certain purposes such as modelling or finding solutions to specific policy questions?
- How should we organize data management, data quality and data privacy in a context of increasing use of distributed (open) data sources and types of data?
- At which spatial and temporal scales of the urban system should data collection and analytical methods and models be organized?
- For analytical and planning purposes, which GIS (visualization) methods should be used and developed to supplement system analyses and mathematical models?
- What are the major capabilities of multi-dimensional and multi-disciplinary models to develop a more comprehensive understanding of urban metabolisms at various spatial and temporal scales?
- Which planning and participatory methods should be developed to change the biophysical and social flows at different speeds in the urban system?

As mentioned in the introduction of this white paper, the holistic approach of urban metabolism addresses the needs for urban sustainability transitions. Standardized application of an interdisciplinary urban metabolism approach as proposed in this paper can function as a tool to link the high-level policies of NUA, SDGs and the Paris Agreement across governance scales (local, regional, national and international). Linking urban metabolism to policy may be the missing tool needed to measure and change urban sustainability performances, but in order to do this it is necessary to develop an interdisciplinary practice of urban metabolism.

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