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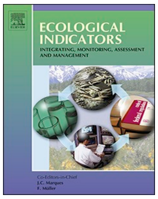

Integrating urban metabolism and life cycle assessment to analyse urban sustainability

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ABSTRACT

In recent decades, the close correlation between urban development and the concept of sustainability has become increasingly evident and important. This is demonstrated by European Union policies concerning EU cities and the United Nations 2030 Agenda for Sustainable Development, including sustainable development goal (SDG) 11: *Sustainable cities and communities*. In the context of increasing urbanization, it is essential to find innovative methods to manage urban living systems and to establish a standard method for assessing the environmental performance of cities and their infrastructures. A unified and complete methodology for assessing policies for urban sustainability that takes into consideration urban complexity is currently lacking. In this paper, we integrate the Urban Metabolism and Lice Cycle Assessment approach to assess urban sustainability by developing a multi-dimensional measure framework applied to cities. Our aim is to provide a holistic view of the city and unveiling the interconnections among a set of urban dimensions identified by means of an approach based on complex systems science and complex networks.

We also propose a specific survey to investigate the city in a multi-dimensional perspective and suggest key indicators based on network centrality measures for investigating and comparing the interconnections among a set of urban dimensions specifically identified (e.g. energy, material, transport). Finally, a case study based on Beijing is considered to show potential applications.

1. Introduction

Expansion of urban environments, while doubtless bringing advantages and merits, is linked also to global challenges of sustainability, particularly in regions where the process of urbanization is still unfolding. In urbanized regions such as Europe, where more than 70% of people are urban dwellers, sustainability is one of the most important challenges, especially regarding the use of energy, energy efficiency, and de-carbonization of infrastructures and cities (European Commission and European Investment Bank, 2016).

Cities and urban communities can play a crucial role in the global work of improving sustainability (Wolfram et al., 2016). The urban population in 2016 was 54% of the total global population and the proportion is expected to grow to 70% by 2050 (The World Bank, 2016). While cities are prized for being drivers of innovation, social experimentation, and economic growth, rapid urbanization has brought major social and environmental challenges. With increasing density and complexity of all elements of the energy system, e.g., energy generation and distribution systems, transportation, consumption of food, goods, and services, waste handling, supply of fresh water, and other ecosystem services, cities are responsible for more than 60% of energy consumption and generate an estimated 70% of human-induced greenhouse gas emissions, contributing strongly to climate change (UN-Habitat, 2011). As urbanization increases, cities will need to become more sustainable and the growing urban population will require new and innovative ways to manage urban living. This will require identification of new solutions to overcome problems such as overcrowding, social exclusion, declining human wellbeing, high energy consumption,

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inefficient resource management, and environmental degradation (European Parliament, 2014).

Within this vision, the European Union advocates improving sustainable development, contributing to a reduction in greenhouse gas emissions in line with the EU's 2020 Climate & Energy Package (European Commission, 2008), which defines targets for 2020 (20% domestic reduction in greenhouse gas emissions; 20% increase in renewable energy; 20% reduction in energy use). The new Climate & Energy Package (European Commission, 2014) recently defined further stricter targets for 2030 (at least 27% improvement in energy efficiency; at least 27% renewable in energy consumed; 40% domestic reduction in greenhouse gas emissions).

To meet these targets, the European Union is developing policies to improve the sustainability of EU cities. However, despite the fact that 'sustainable cities' are considered a game changer for the future of European urbanization, a standard method for assessing the environmental performance of cities and their infrastructures is not specified.

In general, the methods used to evaluate the sustainability of cities focuses on assessing the single points of view (e.g. transport, energy, policies, etc.) with the aim to build a set of measures able to provide the user with a wide view.

In this paper, we propose an approach to analyse urban sustainability by integrating urban metabolism (UM) and life cycle assessment (LCA) in a complex systems perspective. By means of a multiscale view of the city, we propose a synergy between UM and LCA with the aim to cope with urban sustainability both from the macroscale point of view (i.e. Urban Metabolism, requiring large-scale data) and both from the microscale point of view (i.e. LCA, requiring more detailed data), proposing a specific survey aimed at reducing the dichotomy between the macro and the micro scale, aiming to find an appropriate set of measures able to realize a trade-off between the granularity of the data that needs to be collected for the two scales, providing at the end a wide but detailed view of the urban system. As a guiding principle to decide to which granularity should be selected to appropriately develop both UM and LCA studies, we refer to the theory of complex systems, proposing a model based on urban subdimensions, following the approach based on ecological networks proposed by Zhang and colleagues (Zhang et al., 2015, Zhang et al., 2016) for urban energy systems. We also consider that sustainability of a city – a complex, dissipative system (Prigogine, 1997) – should be assessed considering energy, material, and information flows at scales that offer an overall view (as in the UM approach), while at the same time giving insights into processes going on in the city, i.e., how flows are transformed and efficiently used (as in the LCA approach). Our combined approach involves implementation of UM and LCA at an urban scale that is suitable for both approaches. We also formulated an appropriate data collection approach that considers the main dimensions of a city and its transformation processes. Such transformations include flows of material, energy and information, as well as the role that utilities, policy and decision makers play. These two aspects are further combined by the resulting quality of life for citizens. Urban metabolism is suitable for studying the city at a wider scale, without entering into spatial or temporal details, while LCA can be applied on smaller spatial and temporal scales and is usually applied to smaller subsystems.

This paper is organized as follows: in Section 1 we provide a basic introduction to cities as complex systems. Section 2 discusses indicators for sustainability assessment, introducing strengths and weaknesses of the main indicators proposed in the literature. Section 3 describes the method we developed for assessing urban sustainability involving UM and LCA. Section 4 describes the survey for data collection specifically designed according to the combined UM-LCA method, and introduces a case study based on Beijing. Finally, Conclusions are presented in Section 5.

1.1. Cities as complex systems

Complex systems are ubiquitous in nature and human society Waldrop (1993). In recent decades, complexity as an interdisciplinary theory has influenced a number of academic fields, including physics, human sciences, and economics (Fieguth, 2017; Northrop, 2017). In complex systems, processes occur simultaneously on different scales or levels, and result in intricate behavior of the whole system due to nonlinear feedback mechanisms among its components, that makes it hard to identify the role of the component parts. This means that complex systems require a paradigm shift, whereby linear concepts like causality or the principle of superposition are abandoned in favor of recognizing that the whole is more than the sum of its parts. The long-term behavior of a complex system cannot be predicted from aggregating the behavior of its parts, but rather emerges from the interactions of these parts (Axelrod and Cohen, 1999). Therefore, nonlinear problems must be considered *in toto* rather than fragmenting them into small sub-problems and combining sub-solutions.

Cities are complex systems by nature. They are robust and adaptable, maintaining their long-term integrity, even when their integral parts (e.g., people, organizations, roads, or buildings) change or cease to exist. The ability of cities to self-organize under continuous change can be explained by "selective and decentralized flow of matter, energy and information among its parts" (Zellner and Campbell, 2015). The city is a unique and particular object. Moreover, compared with the evolutionary time scale of mankind, the city is a quite recent phenomenon, with the global urban population overtaking the rural population only very recently. Following the urban explosion of the last decades, cities are now interconnected in a network of exchange of goods, economies and ideas that overcomes the national boundaries: the global network of cities is nowadays considered one of the main engines of the global economy and is a system that is continuously evolving and increasing its complexity.

According to the operative definitions of complex systems listed above, a city no longer appears to be a set of static and individual parts that are isolated and disconnected. This leads to an approach of describing cities as patterns of flows and networks of relations, rather than sets of spaces, places, and locations (Batty, 2013). Therefore, each investigation or plan for a city must consider the network connecting all the parts and their links with the surrounding environments. The dynamics of the networks (flows of energy, matter, people, goods, information, and resources) are fundamental for understanding the evolving nature of cities. Furthermore, urban systems are nonlinear systems mixing the elements of both complex and complicated systems, and are thus not completely determinable and governed by irreversible and stochastic processes combining choice and chance (Tiezzi, 2006). It is also possible to recognize that urban systems share many aspects with complex systems (for a detailed description the reader is referred to Strogatz, 2016), and a first effort of this paper is to provide some examples in the following Table 1, where the main features of complex systems are reported on the left side, while the right side describes how the feature is reflected in the urban system.

The structural and functional organization of cities is a classic example of a multiscale system of systems (Scala and D'Agostino, 2014), in which new connections are established and new behaviors emerge. On a smaller scale, since their first emergence about 10,000 years ago, cities have always played an important role in concentrating goods, minds, and social relationships. It can be said that the city is an emergent phenomenon made of people who build social relationships on a larger scale, and that the development and growth of an urban system are directly related to the richness and the quality of relationships. This concentration of minds represents a formidable engine for technological, cultural, and social innovation and the city is the place where new behaviors, cultures, economies, and technologies emerge. Thus, cities are not only growing in size, but also in complexity, with more and more layers of interaction between their inhabitants and

Table 1
Similarities between complex systems and urban systems (cities).

Complex System	Urban System
(1) Composed of a large number of elements connected through a network of nonlinear and local interactions (bottom-up and top-down laws)	Citizens interact locally with institutions and establish socio-economic relationships
(2) Open: matter and energy can flow across the system boundaries	Cities are open systems that live and develop by means of flows of energy, materials, and information
(3) Dynamic, unpredictable and continuously create new structures (emergent behaviors)	Cities are the place where innovation naturally emerges
(4) Presence of a multilevel hierarchy among its parts; both spatial and temporal multi-scale events occur	Social interactions among citizens; infrastructures are interdependent and linked by means of a multi-level complex network. On a wider scale, cities establish network relationships with other cities.
(6) Can be influenced by, or adapt to, their surrounding environment	Historically, cities transform the surrounding environment (e.g., urban spread in the USA in the 1960s), and adapt to different stimuli
(7) Characterized by the presence of thresholds and bifurcations	Failures in infrastructural networks or social segregation practices are typical examples
(8) Evolve at the edge of chaos: the behavior is neither ordered or completely disordered, but they evolve between regularity and irregularity	A typical example is the dynamics of social interactions. From the infrastructure point of view, traffic congestion or supply of electricity and other basic services.

various actors as a consequence of the shifts from flows of energy to flows of information (Batty, 2013).

2. Assessing sustainability by means of urban flows

Evaluation of the applicability of some of the most common indices and indicators reveals a need to use a method with a holistic approach that can assess the sustainability of a city as a whole system, where all the parameters considered are deeply interconnected and influence one another (Böhringer and Jochen, 2007). The multiple interactions and interconnections that a complex city system shows should be managed considering the framework of urban thermodynamics Wilson (20090. This deals with the application of the thermodynamic laws and concepts to identify and support the quantification of city dimensions and subdimension, flows, links and correlations that are present in a complex system like a city (Filchakova et al., 2007).

The concept of urban metabolism provides a means of understanding the sustainable development of cities by drawing an analogy with the metabolic processes of organisms. The parallels are strong: “Cities transform raw materials, fuel, and water into the built environment, human biomass and waste” (Decker et al., 2000). In practice, the study of urban metabolism (in urban ecology) requires quantification of the inputs, outputs, and storage of energy, water, nutrients, materials, and wastes.

Urban metabolism (UM) is a suitable approach for quantification of raw materials and energy supply (Kennedy et al., 2015; Pincetl et al., 2012). This methodology is defined as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste” (Kennedy et al., 2007). In other words, UM is a metaphorical framework that can be used to evaluate the interactions (i.e., flows) between natural and urban ecosystems.

There is a variety of practical reasons for applying the UM approach. First, the metabolism parameters provide suitable measures of the magnitude of resource exploitation and waste generation for use as sustainability indicators (Kennedy and Hoornweg, 2012). The metabolism provides measures of resource efficiency and the degree of circularity of resource streams and may be helpful in identifying opportunities to improve these measures. As well as enabling comprehensive accounting of the stocks and flows through cities, UM also provides a context to understand critical processes such as rising or falling groundwater levels, urban heat islands, accumulation of nutrients, and the long-terms impacts of hazardous materials stored in the building stock (Kennedy et al., 2007; Kennedy et al., 2015). It is pertinent for urban policy makers to understand the metabolism of their cities, to consider to what extent their nearest resources are close to exhaustion and, where necessary, to develop appropriate strategies to slow exploitation.

While UM has to be considered a mature framework (Kennedy and Hoornweg, 2012), its influence on sustainable urban development is still restricted due to a number of limitations (Shahrokni et al. 2014). These include: a) lack of data at the city scale; b) lack of follow-up and evaluation of the evolution of a city’s UM; and c) difficulties in identifying cause-and-effect relationships for the metabolic flows. As a response to these limitations and to the growing digitalization of cities worldwide, the concept of smart urban metabolism (SUM) has been suggested by Shahrokni et al. (2015). Implementation of the SUM concept in the case of Stockholm Royal Seaport demonstrated its potential to improve data quality, both with regards to resolution and frequency, and to reduce the number of assumptions and simplifications required when using statistical data. Basically, smart urban metabolism aims at considering the information flows and the increasing role of ICT technologies in influencing the energy and material flows. By example one can also consider internet of things (IoT), real-time heterogeneous data sources, and real-time analytics as important parts of the study of flows of materials and energy in urban areas. Furthermore, by integrating information and communication technology (ICT) and smart-city technologies, the SUM model can provide real-time feedback on energy and material flows, from the level of the household to that of the urban district and the city. Despite the high potential, it should be noted that SUM is a real-time, data-dependent approach with a number of challenges that must be overcome to unleash its potential. While open datasets relevant to urban metabolism may exist in some circumstances, much of the real-time data or big data needed is contained in silos owned by public or private utilities. Gaining and securing long-term access to such data is thus an essential but challenging task.

Life cycle thinking (LCT) is a systemic approach for assessing sustainability in a comprehensive way based on articulate and critical information, by complementing and integrating the environmental profile of a system with its socio-economic aspects (Valdivia et al., 2011). Within this context, LCA is a standardized methodology that allows for the evaluation of environmental burdens associated with the whole life cycle of a product, process or service. This analytical and quantitative method primarily deals with the environmental dimension of the system under study, and it allows the assessment of the burdens and loads characterizing the system, starting with raw materials use and going through all the life cycle phases till the end-of-life (i.e., cradle-to-grave approach). However, the most powerful features characterizing the LCA approach are: the ability to map the interactions among the elements composing the system and the interdisciplinary approach (Bravi et al., 2010; Parisi et al., 2013, Parisi et al, 2019; Maranghi et al., 2019). Thus, LCA could be considered an appropriate tool to account for the relationships between flows, objectives and indicators in analysis of a city. In fact, LCA can supply results that take into account the multiple factors affecting environmental impacts, allowing a more extensive and detailed evaluation than that permitted by the use of individual indicators.

On the other hand, one drawback in the use of LCA for urban systems is represented by the contradiction between the non linearity of complexity and the linear approach based on LCT metrics. Considering that the evolution of complex systems is unpredictable (although deterministic) and the analytical tools need to be replaced by stochastic algorithms (processes), a possible, at least partial, solution of this problem could be found by introducing a prospective consequential modelling approach in the LCA analysis. Such approach is the methodological modality to consider environmental consequences resulting from a marginal change in demand for the function provided by the product system (i.e. the city) and thus to take into account, to a certain extent, all those aspects affected by dynamics and complexity that fall out of the static framework of LCA. A detailed description of the consequential LCA approach is beyond the scope of this study, as an extensive literature on this topic is available (among the others, the forerunner papers of (Ekvall and Weidema, 2004) and (Weidema. 2000).

It should be noted that the metabolism of a city is largely site-specific and dependent upon the geographical, economic, demographic, and climate context. LCA is already designed to take into account the territorial specificity of a system, since such studies are based on a life cycle inventory built on geographically specific databases (Rossi et al., 2019; Rossi et al., 2020; Facchini et al., 2017).

Examples of LCT methodological tools applied for the assessment of urban sustainability, or more specifically for the environmental dimension of urban sustainability, are numerous in the scientific literature (Alberti et al., 2017; Beloin-Saint-Pierre et al., 2017; Huang et al., 2015; Petit-Boix et al., 2017). Nevertheless, the application of LCT methods highlights substantial methodological gaps and drawbacks, such as the huge amount of data needed to provide a reliable and accurate analysis.

In the present study, we combined UM and LCA to produce a sustainability assessment method for investigating the environmental dimension of cities. Based on previous work by others (Chester et al., 2012; Goldstein et al., 2013), we devised an approach that fits the framework of complex systems and urban thermodynamics.

3. Collecting data for a UM-LCA study of urban sustainability

We devised a methodical process specifically designed to collect data for a LCA-UM study of the urban environment. Aim of this process is to identify a set of data and a granularity suitable to perform the UM LCA analysis of the city. The operational scales at which the two methods are implemented is basically different; UM accounts for flows at a city scale, not entering into details of the processes exploiting the flows, whereas LCA operates on a different, finer scale in order to account for all those transformative processes occurring in the exploitation of flows (Fig. 1). In principle, both methods collect similar data. The main difference is the scale, e.g., collecting data for an extensive city-scale LCA of an urban environment would require an amount of information that would be difficult to analyze and, in some circumstances, impossible to find because of lack of appropriate sources.

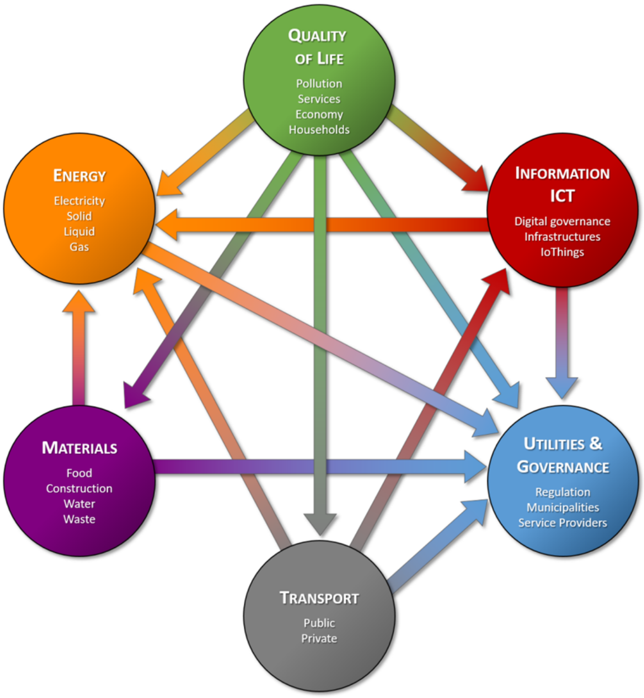

Fig. 1. The six urban sub-dimensions taken into account in the combined urban metabolism-life cycle assessment (UM-LCA) approach and their interrelations. Out-coming arrows express the dependence from a specific sub-dimension.

Table 2
Subdimensions chosen for the network model.

Dimension	Subdimension	Dimension	Subdimension
Energy	Production	Utilities	Electric Mobility
Energy	Industry	Utilities	Transport Reg
Energy	Household	Utilities	Energy Reg
Energy	Services	Utilities	Waste Reg
Energy	Water	Utilities	TLC Reg
Energy	Transportation	Utilities	Water Reg
Energy	Waste	Information	Mobile Phones
Material	Industry	Information	ADSL
Material	Construction	Information	TLC
Material	Water	Information	OpenData
Material	Waste	QoL	Air pollution
Material	Food	QoL	Access to services
Material	Electric Appliances	QoL	Unemployment
Transport	Public		
Transport	Car		
Transport	Private transport		

Table 2 lists the components of a combined UM-LCA study, which accounts for all energy, material, and information flows required to perform a city sustainability assessment with a life cycle approach without losing the wide perspective of UM and detailed perspective that LCA provides on processes occurring in the city. Such a study comprises the temporal variation of energy and material flows (as a measure of the impact of the city with time), the information flows together with their relation to infrastructures and the role of regulation and quality of life. These three aspects are not considered in isolation, but in a wider perspective of complex systems. This is done by following the multi-layered model recently introduced for UM studies of megacities (Kennedy et al., 2014). Here we devised a set of six urban dimensions to represent the main aspects of the urban environment (Energy, Quality of life, Information, Materials, Utilities & governance, Transport) (Fig. 1). These are measured and analyzed according to their interdependencies, both functional and infrastructural (out-coming arrows mean dependence on the specific sub-dimension). These dimensions consider flows (Energy, Materials, Information) and aspects related to the functional sectors of a city (Transport, Utilities & governance, Quality of life. Although incomplete, especially in light of the more sophisticated methods proposed in both the UM and LCA literature (e.g., the societal metabolism method proposed by Giampietro and Mayumi, 2000), we regard these sub-dimensions as the minimum set required to describe the urban environment in a complex systems perspective, considering that the granularity of the survey specifically designed to represent these subdimensions has the scale needed for both the UM and LCA approaches. We therefore suggest that the bound for data granularity (i.e. how detailed must be data collection) is the minimum set that maintains the connection between the urban sub dimensions. This minimum set is also advantageous when considering cities in developing and emerging countries, where specific data are difficult to locate or unavailable.

As mentioned, a study using combined UM-LCA needs both coarse-grained information and fine-grained information. We determined the actual degree of granularity needed in the data for LCA by considering a threshold at which the connections between urban subsystems are still intact.

In more detail, the six sub-dimensions of the combined UM-LCA approach comprise the following:

1. **Energy**: Includes electricity, solid, liquid, and gas fuels. Energy depends on Utilities & governance, while it influences Transport, Quality of life and Information flows (other indirect dependences from Materials are neglected in the model)
2. **Materials:** Include food, the construction sector, water, wastewater, and solid waste. Material flows depends on the Utility & governance sub-dimension, while they influence the Quality of life sub-dimension.
3. **Transport:** Includes both public and private, and depends on Energy and Utilities & governance, while it influences the Quality of life sub-dimension.
4. **Utilities & governance (and access to basic services):** Do not properly represent a flow but are a fundamental component of the urban environment. They include regulations, providers of public services like water, energy, and telecommunications, and governance/decision makers in municipalities.
5. **Information:** Flows include ICT, telecommunication infrastructures, and the internet. It is worth mentioning that, in the complex systems perspective, information flows are a fundamental part of the system, while in individual UM and LCA studies the role of information is rarely considered and not in a systemic way (e.g., Zhang et al., 2010). In our approach, information flows are the unifying factor influencing metabolic flows and digital integration of urban infrastructures, reinforcing their resilience and interdependencies.
6. **Quality of life:** Another sub-dimension that is not related to specific flows. In the language of complex systems, it represents an emerging dimension resulting from the mutual interaction of flows and sub-dimensions in urban systems. Quality of life depends on all the other sub-dimensions and is a valuable element in evaluation of how effectively metabolic flows are used to develop the city.

These different sub-dimensions require different amounts of data (see Table 2), depending on the complexity of the sub-dimension, the interconnection with the other sub-dimensions, and common practices in UM and LCA studies. Data availability is also a driving factor for exclusion of fine-grained data that, although useful for LCA studies, would be too difficult to find. Therefore, together with the usual data on energy consumption, for the Energy sub-dimension we included energy production and consumption, entering into details for the aspects concerning production from different sources and consumption in different urban sectors, including aspects related to the sub-dimensions (e.g., transport and water distribution/sanitation/treatment).

With regards to the Material flows sub-dimension, we followed the usual UM approach, collecting construction, food, and waste flows. In this sub-dimension we included details of waste and water flows, both directly connected with the sub-dimensions Energy, Quality of life, and Utilities & governance. In particular, considering waste, we distinguished different treatment plants, recycling facilities, and incineration. In the approach we also included the number of new buildings per typology, as a measure of urban expansion and soil consumption.

When considering the Transport sub-dimension, we entered into finer detail by considering the type of vehicles and fuel, distinguishing between public and private transport modes. The interrelation with the Energy sub-dimension was investigated by including data on the type of fuel and the emissions levels of engines. Quality of life aspects were considered by including data on transport modes, while greater detail was introduced in the part describing the Utilities & governance sub-dimension. In fact, since Utilities & governance are not associated with data collection on specific flows, the latter was driven by the interdependencies with the other sub-dimensions (as stated, considering energy in Basosi et al, 2017), with the aim of providing information about the governance of the flows and the main regulations affecting the utilities. With regard to the provision of public services (i.e., energy, water, TLC), we included the number of distributors, suppliers, and renewable energy sources, while access to basic services provides a measure of infrastructure development over time. Electronic meters and policies for energy efficiency and demand response were included in the case of electricity. Links with the Transport sub-dimension were included through considering public transportation, but also through considering the existence of policies to limit the use of private cars. Finally, electronic meters for water, electricity, and gas were included as a basic link with the Information sub-dimension.

Information flows are not generally accounted for in UM or LCA. However, we included them in the combined approach because of the increasing development of digital infrastructures and the increasing digitalization of society. In the Information sub-dimension, we included use of the internet and mobile phones by urban residents, the existence of open-data policies in cities, and initiatives on digital governance.

In the Quality of life (QoL) sub-dimension, we included air quality and well-established indicators of human wellbeing, like the Gini index and the human development index developed by UN-Habitat (UN-Habitat, 2012).

3.1. *Example based on Beijing urban metabolism*

Starting from the model described in the previous section, we now show a possible application example focused on Beijing. Data have been collected in previous megacity study (Kennedy et al, 2015), and only partially are reflected in the survey presented in Table 2.

To develop the example, we proceed according to the following steps:

1. According to the specific city and available data:
   a. Identification of the set of subdimensions, as depicted in Table 2.
   b. Compilation of the survey reported in Table A1.
   c. Data processing and filtering: verification of the data (unit of measures, conversion factors, etc.), removal of outliers, integrity check of the database.
2. Connect urban subdimensions according to data collected (subdimensions may be linked in different ways, by example thermal use of waste may be implemented or not in the city). This step leads to Table 3, where we distinguish between Inter-dimensional links, i.e. all the links that are established inside a specific dimension, and Intra-dimensional links, i.e., all the links that are established among the different dimension. Table 3 also shows for each link the numerical value of the flow, the unit of measure, and the motivation of each link.
3. Construction of a network according to the model depicted in Fig. 1.
4. Computing of network metrics according to the weighted network obtained.

As an example of inter-dimensional links, we may consider the materials dimensions. Indeed, water flows also influence construction, food consumption and production, while the waste section is connected to the construction sector, the food sector and the water sector (e.g. wastewater). With regards to the intra dimensional links, energy production is connected with water, construction sector and waste.

Fig. 2 shows an example of how the urban domains described in Fig. 1 are reflected in the survey presented in Table 1. As the reader can notice, we considered from the survey the subdimensions listed in Table 2. These are connected according to their dependence, as

Table 3
Ranking of network centrality metrics for the urban network of Beijing.

Out Degree	In Degree	Eigenvector	PageRank	Betweennes
Production	OpenData	Basic Services	Opendata	Opendata
Waste	Basic services	Opendata	Basic services	Water
Water	Air Pollution	Air pollution	Waste	Waste
OpenData	Waste	Waste	Air Pollution	Production
Construction	Water	Household	Water	Electric Mobility
Energy Reg.	Household	Construction	Household	Construction
Private Transport	Public	Water	Public	Household
Electric Mobility	Construction	Food	Transportation	Air Pollution
Industry	Production	Public	Construction	Energy reg.
Waste Reg	Transportation	Water Reg.	Food	Transport Reg.

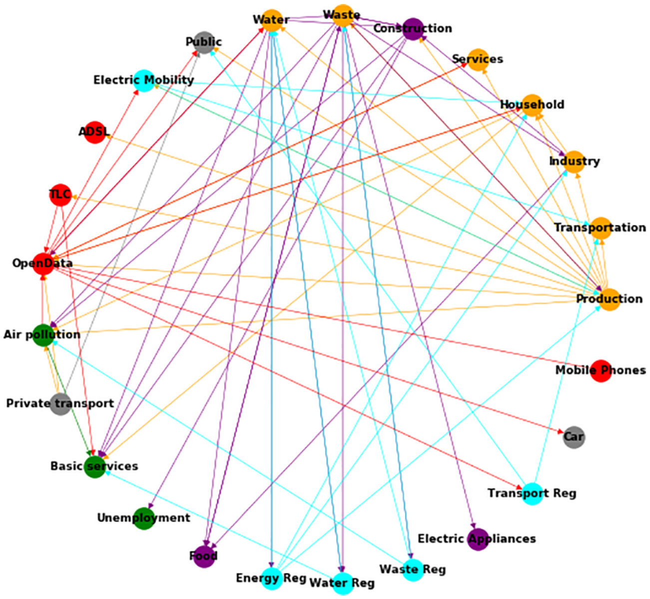

Fig. 2. Network associated to the list of links presented in Table 2. Colour of nodes reflects the different urban dimensions.

described before, and a link is established if there is a flow or if there is a direct, non numerical relation, as sometimes happens for the regulation subdimensions. A complex network is therefore modeled by considering weighted edges: where flows are present (i.e. energy, material, information) the weight is corresponding to the flow (by example, the weight of the link between the nodes production and transportation corresponds to the total amount of energy used for transportation), while were a functional dependence is present the value of the weight is left to 1.

Fig. 2 shows how the subdimensions are connected according to the links described in Table 4. In the network, node colour is consistent with the urban dimension, while links connect the subdimensions identified in step 1. A full analysis of the network is limited by missing data, and here we could only describe the network by means of its general topology using the unweighted links (for a full description of networks methods the reader is referred to (Estrada and Knight, 2015). Table 3 shows the ranking of centrality metrics for the first 10 subdimensions.

Node centrality is used to rank the importance of nodes according to some specific features (e.g. the number of connections, the importance as hub or bridge, etc.). Here we have computed the following metrics:

1. In degree centrality: ranking nodes according to the number of incoming connections with the other nodes. High values are related to the importance of the node in receiving flows from other nodes. This is typical of transformation sectors, receiving primary sources and transforming them in goods.
2. Out degree centrality: measures the importance of nodes in supplying the other nodes with flows. An example is the energy production sector.
3. Betweenness centrality: measures the importance of a node with respect to the flows passing through it. Vertices with high betweenness may have considerable influence within a network by virtue of their control over information passing between others. They are also the ones whose removal from the network will mostly disrupt communications between other vertices because they lie on the largest number of paths taken by messages
4. PageRank centrality: measures the importance of the node according to the fact that other important nodes are pointing to it (i.e. it receives flows from other important nodes).

The analysis of the centrality metrics shows non uniform results in the ranking of subdimensions. This is not surprising, since each one of the chosen metrics highlights a specific aspect. In particular, out degree stresses the importance of energy production, water and waste flows in supplying resources for the urban metabolism, while the other metrics highlight the important role of data flows and access to basic services in cities. Indeed, opendata, basic services, and water are the most central sectors when considering centrality measures based on the importance of the node as hub for the other flows.

Under the vulnerability point of view, out degree indicated that energy, is the most important node, while the role of ICT as enabling factor for the digital integrated infrastructures is stressed by the Pagerank metric.

4. Discussion

The above-mentioned sub-dimensions have been identified following a review of the current literature on urban sustainability. In addition, we took inspiration from the Prosperity of cities report edited by UN-Habitat (UN-Habitat, 2012). Our foundational idea is that both tangible and intangible aspects compose the urban environment. While form one side we find tangible aspects like infrastructures (hardware) and regulation (software), we also need to take into consideration all those aspects that are related to intangible factors, like quality of life, citizen behaviour, and connections among sub-dimensions, that are not always straightforwardly identified in systems modelling. Of course, we do not claim that the proposed set is perfect and/or self-consistent, but its aim is to shed a new light on urban sustainability.

We also present connection between the proposed survey and a model based on complex systems. In particular we show that, from the survey, a set of urban subdimensions can be extracted and links can be established in order to build a networked representation of the urban domain, considering both flows of energy, material, and information. A more detailed analysis may be done by considering the different dimensions as layers of a multiplex networks, but because of data availability this task cannot be performed at this stage of the research. In perspective, the six dimensions and their interdependencies identified

Table 4
List of links used to model the network of subdomains flows showed in Fig. 2 (zero values mean that data is missing).

Source	Target	Dimension	Weight	Unit of measure	Rational/explanation
Production	Transportation	Energy	52.257	TJ	Energy for transportation
Production	Industry	Energy	349.303	TJ	Energy for industry
Production	Household	Energy	256.094	TJ	Energy consumed by the Household sector
Production	Services	Energy	98.169	TJ	Energy consumed by the service sector (Wholesale, Retail Trade and Hotel restourants)
Production	Construction	Energy	28.147	TJ	Energy consumed by the construction
Production	Waste	Energy	0	TJ	Energy used by the waste sector (energy used to manage the infrastructure)
Production	Water	Energy	0	TJ	Energy used by the water sector (Sanitation, conservation, distribution)
Production	Public	Energy	353.455	TJ	Energy consumed by the public sector
Production	Electric Mobility	Energy	0	TJ	Energy for electric mobility
Production	ADSL	Energy	0	TJ	Energy used for web servers and internet exchange points
Production	TLC	Energy	0	TJ	Energy used for TLC
Production	OpenData	Energy	1	bit	Data production: Smart meters, smart grids
Production	Air pollution	Energy	0	ug/m3	Polluttants emitted by the energy production sector
Private transport	OpenData	Energy	1	Amount	Logical-data connection: origin destination matrix etc
Private transport	Air pollution	Energy	0	ug/m3	Pollution due to the transp. Sector
Household	OpenData	Energy	0	bit	Logical connection: smart meters data
Household	Air pollution	Energy	0	ug/m3	Pollution due to the household sector (e.g. Heating)
Household	Access to services	Energy	100	%	Share of people with electricity connection
Production	Transportation	Energy	262.281	TJ	Energy used by transportation
Services	OpenData	Energy	0	bit	Data connection: consumption data
Industry	Household	Energy	0	TJ	District heating
Industry	Construction	Material	12.129	kt	Material used for construction
Water	Construction	Material	0	kt	Waterused by the construction sector
Construction	Waste	Material	0	kt	Waste produced by the construction sector
Construction	Air pollution	Material	0	µg/m^3	Air pollution produced by the construction sector
Construction	Access to services	Material	0	Amount	Number of new buildings
Construction	Unemployment	Material	1	Amount	Number of persons employed in the sector
Water	Food	Material	0	kt	Water used for food production (e.g. agriculture)
Water	Energy Reg	Material	1	Amount	Energy-related policies for water (e.g. energy efficiency in water distribution)
Water	Waste	Material	2.006.230	ML	Wastewater collected
Water	Water Reg	Material	1	Amount	Regulation of wastewater policies
Water	OpenData	Material	0	bit	data on water consumption
Water	Access to services	Material	99	%	Access to drinkable water
Waste	Food	Material	700.000	kt	Recycled water, compost, etc
Waste	Waste Reg	Material	1	Amount	logical connection
Waste	Water Reg	Material	1	Amount	logical connection
Waste	Electric Appliances	Material	0	kt	Electrical and electronic waste collected
Waste	Air pollution	Material	0	µg/m^3	pollutants emitted by the waste sector
Waste	Access to services	Material	100	%	Share of household with public waste collection
Waste	Production	Material	944	kt	Waste Incinerated
Waste	Construction	Material	0	kt	Waste recycled in the construction sector
Waste	Industry	Material	0	kt	Waste recycled in the industrial sector
Industry	Food	Material	6.376	kt	Material used Food production
Food	Waste	Material	1.780	kt	Waste produced by citizens, industries and agriculture
Private transport	Public	Transport	0	Amount	Number of people commuting from cars to public transport
Electric Mobility	Transportation	Utilities	21.628	Amount	Number of electric vehicles (public)
Electric Mobility	Household	Utilities	0	Amount	Number of electric vehicles (private)
Electric Mobility	Production	Utilities	0	TJ	Vehicle to grid production
Transport Reg	Public	Utilities	0	%	Share of people using public transportation
Transport Reg	Transportation	Utilities	0	Amount	policies to limit private transportation
Energy Reg	Production	Utilities	0	TJ	Effect of energy efficiency policy
Energy Reg	Industry	Utilities	0	TJ	Effect of energy efficiency policy
Energy Reg	Household	Utilities	0	TJ	Effect of energy efficiency policy
Energy Reg	Water	Utilities	0	TJ	Effect of energy efficiency policy
Waste Reg	Water	Utilities	0	ML	Effect of wastewater management policies (e.g. wastewater subject to treatment)
Waste Reg	Waste	Utilities	0	kt	Effect of recycling policies (e.g. recycled volume Vs Landfilled)
Waste Reg	Air pollution	Utilities	0	µg/m^3	Effect of protection policies
Water Reg	Water	Utilities	0	ML	Effect of conservation policies
Water Reg	GINI	Utilities	100	%	Share of people with access to drinkable water
OpenData	Household	Information	0	bit	Domotics
OpenData	Services	Information	0	bit	Digital services for the consumers
OpenData	Water	Information	0	bit	Consumption data through electronic meters
OpenData	Public	Information	0	bit	Digital services for the citizens
OpenData	Car	Information	0	bit	Information about traffic congestion and pollution
OpenData	Electric Mobility	Information	0	bit	Information about car sharing, position and actual consumption
OpenData	Transport Reg	Information	0	bit	Information flow to data banks
Mobile Phones	OpenData	Information	0	bit	Internet and voice traffic
TLC	OpenData	Information	0	bit	Bit flow from internet exchange
Air pollution	OpenData	Information	0	bit	Data on air quality from distributed sensors
TLC	GINI	Information	95	%	Share of people with access to internet
Air pollution	GINI	QoL	178	µg/m^3	PM10 concentration

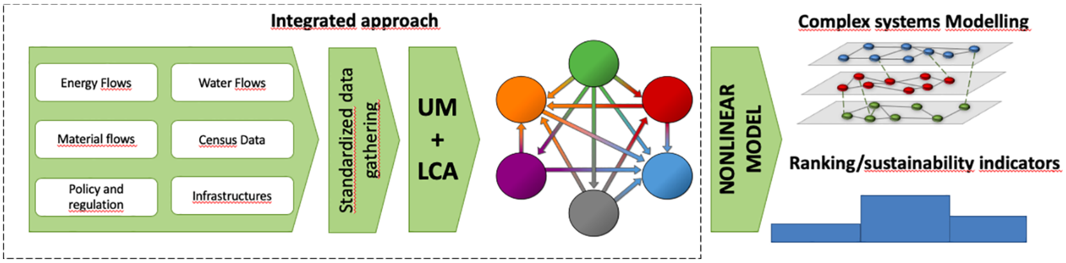

Fig. 3. The integrated approach proposed in this paper and its follow-up suggesting a nonlinear model for the urban environment based on the multiplex network theory. Following (Fath, 2009) we model each subdimension as a layer in which an ecological network is present. According to Fig. 1, connections are established among the different layers and data collected by means of Table 2 allow for the disentanglement of interdependences.

in the previous section compose a multi-dimensional measure framework for the sustainability of cities, aimed at unveiling those interconnections that, in turn, can be transformed into a multi-dimensional model. Such model unknown a priori due to the intrinsic non-linearities present in the urban system, can be characterized by using a multilayer network (Scala and D'Agostino, 2014). Indeed, starting from the ecological network model (Fath et al., 2007), proposed by Fath and colleagues (also used by (Zhang et al., 2015; Zhang et al., 2016) for the characterization of the sole energy system of a set of Chinese megacities), the multi-dimensional model proposed in Fig. 3 aims at going beyond their findings by modelling each subsystems as an ecological network layer, where connections between nodes are also present among the layers (i.e. the subsystems). The level of detail of the model is specified by the granularity of the data, here collected by a multi-scale standardized gathering method realising a trade-off between the needs of LCA and Urban metabolism. Furthermore, referring to data granularity, in a complex networks approach, down scaling is done by aggregating nodes (i.e. reducing data granularity of some sub dimensions), while up-scaling is done by including other data to the sub-dimension. This may lead (according to the specific case study) to a set of non homoegenous granularity, that is perfectly consistent with the theory of multilayer networks (Scala and D'Agostino, 2014).

The survey proposed in this paper open a set of modelling possibilities allowing for a better comparative characterisation of urban sustainability based on synthetic indicators, going beyond (Pulselli et al, 2015), who proposed a framework consistent with an input-state-output (environment–society–economy) scheme based on logical, physical and thermodynamic dimensions of sustainability. Indeed, having a more detailed representation of urban flows and their interdependeces, finding synthetic indicators and ranking is eased by the fact that we can use the typical metrics of multilayer complex networks.

Following this, for getting the best result from the set of measures presented in Table A1 we recommend investigating the city over a time span of about 10 years, as made by Kennedy et al. (2015), Facchini et al. (2017) for the metabolism of megacities.

Finally, policy and decision makers will also find insights on urban sustainability. In particular, we leverage on network measures aimed at ranking nodes in terms of importance (e.g. centrality measures) or in terms of vulnerability and resilience, as shown by Scala and D'Agostino (2014)).

5. Conclusions

In this paper, we propose an approach for investigating cities as complex systems using a combination of urban metabolism and life cycle assessment our aim was to devise a common framework for investigating and comparing the urban thermodynamics of cities as complex systems. Treating the urban environment as a complex system led us to identify a set of six urban sub-dimensions characterized by flows showing interdependency both under the infrastructural and the quality of life (as well as for utilities/regulation) point of view. We also provide a direct connection between the survey presented in Table A1 and a urban model based on complex networks that can be characterized by a set of topological measures. A complex systems perspective also helped us to cope with the issue of data granularity, where LCA studies usually require more detail in the data and UM studies usually require higher levels of data aggregation. The underlying idea with the combined approach is to decide the granularity of the data in order to maintain the connections between subsystems and enter into greater detail when required by the specific sub-dimension (e.g., data on energy). This approach extends the multi-layered survey proposed for UM and includes in UM and LCA information flows, which are rarely considered in such studies. Together with information flows, we included data on quality of life, as a measure of how effective metabolic flows are in the development of a city. This includes a qualitative aspect into the framework of material flow analysis, e.g., it can be useful to assess how the same quantity of energy is used differently. In addition to this, we also pointed out how our multi-level approach may represent a significative advantage for the application of this kind of analysis yielding a multiplex network approach to urban systems. Under the point of view of the wide application of the proposed approach, the particular aspect of risks and cost must be taken into consideration. Indeed, data collection is itself a research activity, and data, especially in emerging countries are sometimes found from different, non uniform sources, compromising the inhomogeneity of the dataset and thus requiring a further phase of filtering. Data granularity is a further limitation for urban studies, in that case, downscaling methods can be implemented as discussed in Kennedy et al. (2015). In addition, the cost of data collection may vary from country to country and from city to city, and such cost should not be omitted when planning research activities.

Finally, this paper aim at paving the way to a multiscale model of the city based on multiplex complex networks, extending the approaches based on ecological network analysis by suggesting a holistic analysis based on complex networks theory. In fact, every city, every local economic system, produces services, goods, and cultures, playing a complex role in the general dynamics of global sustainability, which cannot be described as a simple numerical balance. It is important to highlight the urban flows in a multiscale perspective, both in qualitative and quantitative terms. The same energy has a different meaning in Mumbai or Detroit, so a new global geography, equipped with physical, flow-based, and economic indicators, is needed in order to consider the *quality of the flows* crossing urban boundaries, and to indicate and reinforce those flows, thereby contributing to the development of a city rather than to its growth. In this perspective, we do not conclude a numerical balance should be avoided (this would be against both the UM and LCA approach, and is a broader sense against the principles of thermodynamics). Our indication is that complexity should be governed with complexity (Tiezzi, 2006), and that in order to better interpret the numerical balance, i.e. the numerical evidence of the analysis of urban flows, we also propose a method to provide a broader perspective on the city.

6. Credit author statement

All the authors contributed equally to the research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Table A1

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Table A1
Input flows in the combined urban metabolism-life cycle assessment (UM-LCA) approach.

General information on the city area	Units
Population	Amount
Gross domestic product, GDP	PPP$
Land area	sq. km
Urban area (Include boundary polygon file)	sq. km
Residential	%
Commercial & institutional industrial	%
Agricultural area	sq. km
Green areas (public)	sq. km
Urban tree canopy cover area (refer to Endreny, et al. 2017)	sq. km
Public space	sq. km
SUB-DIMENSION 1: ENERGY	Units
Number of energy production plants:	Amount
Hydroelectric	%
Natural gas	%
Photovoltaic	%
Wind	%
Geothermal	%
Other (specify)	%
Gross energy production	TJ
Gross energy consumption	TJ
Thermal energy	%
Electricity	%
Energy consumption by sector	
Energy transformation	TJ
Non-energy use	TJ
Industry sector	TJ
Transport sector	TJ
Residential	TJ
Services	TJ
Water distribution/sanitation/treatment	TJ
Other (specify)	TJ
Energy sources (also indicate the number of power plants)	
Coal	TJ
Oil	TJ
Natural Gas	TJ
Nuclear	TJ
Hydropower	TJ
Wind	TJ
Solar	TJ
Geothermal	TJ
Biomass	TJ
Waste recovery	TJ
Other (specify)	TJ
SUB-DIMENSION 2: MATERIALS	Units
Construction	
Cement	kt
Steel	kt
Iron	kt
Glass	kt
Other (specify)	kt
Water	
Water production	kt
Water consumption	kt
Water losses	kt
Wastewater	kt

(*continued on next page*)

Table A1 (*continued*)

General information on the city area	Units
Purified water	kt
Other (specify)	kt
Waste	
Waste disposal	kt
Waste incineration	kt
Waste in landfill	kt
Waste recycling	kt
Other (specify)	kt
Waste management system plants (specify)	
Waste management system plants (area)	
Food	
Vegetables	kt
Meat	kt
Fish	kt
Oils	kt
Sugar	kt
Grain	kt
Number of new buildings	Amount
Residential	%
Industrial	%
Municipal	%
Other (specify)	%
Number of plants for wastewater treatment (specify the typology)	Amount
Number of plants for urban solid waste treatment (specify the typology)	Amount
Percentage of separate collection (specify recovered materials)	%
Number of vehicles	Amount
Public	%
Private	%
Other materials (specify)	kt
SUB-DIMENSION 3: TRANSPORT	Units
Transport modes	
Public	km
Private	km
Type of vehicle	
Car	km
Bus	km
Motorbike	km
Bike	km
Other (specify)	km
Fuel consumption	
Gasoline	kt
Oil	kt
Methane	kt
GPL	kt
Electricity	kt
Type of fuel	
Gasoline	Amount
Oil (EURO 6)	Amount
Oil (EURO 5)	Amount
Oil (EURO 4)	Amount
Oil (EURO 3)	Amount
Oil (EURO 2 and older)	Amount
Methane	Amount
GPL	Amount
Electric/hybrid	Amount
Sub-dimension 4: utilities & governance	Units
Policies implemented	
Describe in a separate report eventual sustainability policies that are specifically implemented both at national and urban level. Target fields are corresponding to the other urban domains described in this survey	NA
Electricity	
No. of local distributors	
No. of power suppliers	
No. of buildings with PV	
% consumption from independent generators	
Ownership (public/private)	
Independent regulator (yes/no)?	
% of electronic meters	
No. of storage systems and nominal power	
Policies for energy efficiency and demand response (if Y please detail)	
Electric mobility	Units

(*continued on next page*)

Table A1 (*continued*)

General information on the city area	Units
No. of electric vehicles (private)	
No. of electric vehicles (public or sharing)	
No. of electric vehicle charging points	
No. of service providers (public or private)	
Transportation	
No. of taxis	
No. of people using public transport per year	
Existence of policies to limit private transportation	
No. of people moved using public transport	
Natural gas	Units
No. of local distributors	
No. of natural gas vehicles	
No. of electronic meters	
Independent regulator (Yes/No)?	
No. of electronic meters	
District heating or cooling	Units
No. of district heating/cooling distributors	
% city heating/cooling consumption from district schemes	
Water	Units
No. of local distributors	
Independent regulator (Yes/No)?	
No. of water treatment plants	
No. of electronic meters	
Wastewater	Units
No. of local collectors	
Ownership (public/private)	
Telecommunications	Units
% of people using mobile phones	
% of ultrafast broadband customers (optical fiber)	
% of ADSL broadband customers	
Quality of service	Units
% of households without direct access to water	
% of households without direct access to drinking water	
% of households without sewerage	
% of wastewater subject to treatment	
% of households living without public waste collection	
% of households without grid electricity connection	
Average no. of hours per year without electricity supply	
Average no. of hours per year without water supply	
Average no. of hours per year without natural gas supply	
SUB-DIMENSION 5: INFORMATION FLOWS	Units
% of people using mobile phones	
No. of optical fiber broadband users	
No. of ADSL broadband users	
TLC flows	bits/year
Mobile phone internet flows	bits/year
Digital interaction with institutions	
Open-data projects involving the municipality	
SUB-DIMENSION 6: QUALITY OF LIFE	Units
Particulates PM10 12 M average	$\mu g/m^3$
Particulates PM25 12 M average	$\mu g/m^3$
Average cost of Houses (Buy/rent per sq. meter)	$PPPUS\$/m^2$
Gini index	
City prosperity index	
Unemployment rate	%

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