CellPress

Gold Standard for the Global Goals
1 ton of CO_2 offset

One Earth
Primer

Circular Urban Metabolism Framework

Giulia Lucertini[1,*] and Francesco Musco[1]
[1]Iuav University of Venice, Planning and Climate Change Lab, Santa Croce 191 Tolentini, 30135 Venice, Italy
*Correspondence: glucertini@iuav.it
https://doi.org/10.1016/j.oneear.2020.02.004

In our cities, the production and consumption of resources are achieved at an unsustainable rate. Combined with an increasing global population and accelerating urbanization, the absence of a new approach will almost certainly have dramatic environmental consequences. Potential solutions are emerging: the concepts of circular economy (CE) and urban metabolism (UM), which contrast the current and traditional linear extract-produce-use-dispose model of the modern economic and urban systems, offer a new approach. In this Primer, we present the principles of CE and UM as well as their origins and definitions, strengths and weaknesses, similarities, and limits. We introduce how these concepts can be used for designing a new urban framework called circular urban metabolism (CUM), which encourages urban planners and decision makers to study, design, and manage sustainable cities. CUM has the potential to unite research fields to promote collaboration across disciplines that operate on the planning, design, and management of cities and their complexities.

Introduction

Cities are the biggest consumer of global resources (inputs) and the greatest producer of waste (outputs). Cities occupy just 3% of the world's surface yet house more than 55% of the population, which is expected to grow to 70% by 2050. They consume 75% of the world's resources and generate 50%–80% of the world's greenhouse gas emissions and half of all global waste. This unsustainable consumption of resources is one of society's major challenges. The importance of this challenge is highlighted by the dedication of two Sustainable Development Goals (SDGs). SDG 11 aims to "make cities and human settlements inclusive, safe, resilient and sustainable," and SDG 12 aims to "ensure sustainable consumption and production patterns." Urgent actions are needed to make urbanization sustainable and to avoid over-extraction and degradation of environmental resources.

In recent years, several policies have been put in place to help overcome these problems. Policies associated with resource efficiency, waste reduction, and zero land consumption have emerged, and two main concepts have gained visibility: circular economy (CE) and urban metabolism (UM). Both are firmly centered on a change in paradigm from an unsustainable, wasteful linear model to one that is more circular, representing a closed loop.

In this Primer, we present the CE and UM concepts by pointing out their strengths and weaknesses. We describe their similarities and differences and how they can work together for a much needed new urban approach based on sustainable principles. Finally, we discuss the emerging circular urban metabolism (CUM) framework and how it can be applied to the field of urban planning.

Circular Economy Concept

The CE concept is not new—it has existed as a concept since the dawn of industrialization, but only in the last 5 years has it seen a growing interest to both scholars and practitioners, especially since the European adoption of the Circular Economy Package and the Circular Economy Action Plan. Attention has grown since the adoption of a CE apprach has been associated with the alleviation of environmental pressures and the promotion of sustainable development. Although there does not appear to be a unique and unambiguous definition of CE, one of the most known and shared descriptions is provided by the Ellen MacArthur Foundation, where CE is considered to be "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." CE provides the economic system with an alternative material-flow model, a model that is cyclical and designed to overcome the traditional linear model based on an extract-produce-use-dispose aproach. The cyclical and restorative model emphasizes product, component, and material reuse, remanufacturing, refurbishment, repair, cascading, and upgrading; it uses a cradle-to-cradle life cycle for the entire value chain (Figure 1). There are no wastes associated with CE; there are only secondary raw materials ready for a new life process. CE, if fully developed, will promote high-value material cycles instead of traditional recycling to extract as much value as possible from environmental resources. A CE necessitates substantial transformations in design, production, consumption, use, waste, and reuse practices. With such a purpose in mind, several frameworks have evolved, beginning with the three Rs: reduce, reuse, recycle. This later evolved into the four Rs—reduce, reuse, recycle, and recover—which were adopted by the EU, and more recently, the nine Rs: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover. These R frameworks share a similar R hierarchy as their main feature: in each case, the first R is viewed as the preferred option, and if it isn't possible, the second should be considered, and so on and so forth.

CE appears as a positive and acceptable concept that could help address environmental challenges and foster a more

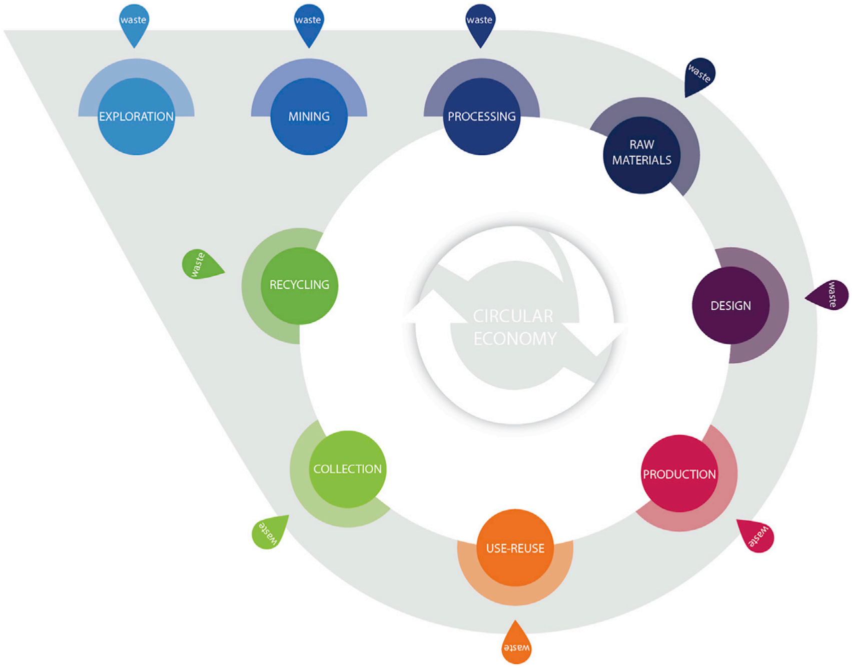

Figure 1. The Circular Economy Concept

The CE concept is designed as a process of steps that ensure, from the initial input of resources, that it is possible to construct and reconstruct a material value chain and reduce waste as much as possible. The first two steps, exploration and mining, are outside the circularity of the system. Circularity begins with the processing step, in which resources are transformed into raw materials ready to become products. The model then champions efficient design and production in order to minimize material waste and maxmize the potential for material recovery while minimizing lost value. The "use and reuse" step is intented to maximize the produce lifetime. The collection and recycling steps appear at the end of the cycle, at which point products are ready to be recovered and transformed into secondary raw materials, and the cycle begins again with the processing step. Waste, although reduced in the CE system, is still present as a result of the laws of thermodynamics, for which the dissipation of matter and energy at each step is unavoidable.

sustainable economy. However, it also has some criticisms and limits. Although there is a great deal of growing interest and literature surrounding the CE concept, it remains in its infancy, and a number of fundamental open questions remain. In terms of scientific research, CE can sometimes appear vague and based on a fragmented collection of ideas extracted from different fields. In terms of empirical applications, clear limitations posed by spatial and temporal boundaries, governance, and management of material and energy flows are arising. At this stage of concept development, it continues to be discussed primarily in the economic and production fields; it is, after all, at its core an economic concept. As a result, there is often limited consideration of the spatial dimension and scalability of the circularity. However, if a CE model is to prevail, its steps—such as processing, production, and collection—must be considered in the context of a physical place with physical distances, infrastructures, and buildings taken into account.

Urban Metabolism Concept

The concept of UM, like CE, is not new but has re-emerged recently after many years. The origin of the concept is usually attributed to Abel Wolman, who coined the term when considering the process of supplying material, energy, and food to a hypothetical city, as well as the resulting waste products. UM is based on a metaphor that conceptualizes cities as living organisms that need resources to support their activities (inputs) and discard waste as a result of the process of transformation (outputs). According to one of the best-known definitions provided by Christopher Kennedy, UM is "the total sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste." The UM concept considers flows of natural and industrial materials, energy, people, and information (it is important to note that people and information are not considered in CE). Moreover, UM also represents the flows into the city space.

UM is generally considered to represent six main themes (Figure 2): (1) the city as an ecosystem, (2) material and energy flows within the city, (3) economic-social relations within the city, (4) economic drivers of rural-urban relationships, (5) reproduction of urban inequality, and (6) attempts to resignify the city through new visions of socio-ecological relationships. In UM, the city and its boundaries become a relevant issue. Flows are located in "space;" thus, to understand and assess the various flows, we must define the physical boundaries and space. This element is absence in the CE approach.

Although the UM concept has a broader theoretical conceptualization with possible positive impacts on urban planning and management, until now it has been studied and formalized mainly through methods of accountability. UM studies tend to focus on generating a means of understanding, from a quantitative point of view, the metabolism of urban systems. These quantitative methods are split between those that account for material or energy flows in cities and city regions and those that attempt to provide indicators to understand the changes in resource use and the relations within the city ecosystem and the environmental impacts of their metabolisms. Conventional UM assessment methods include the following:

(1) Accounting approaches try to understand UM by quantifying the extent to which the system is able to reduce the consumption of materials or works and energy use. Material-flow analysis is a tool used for quantifying the flows and stocks of materials in a system; it provides useful information regarding the patterns of resource use and the losses of materials entering the environment. Exergy analysis is a tool used for quantifying the amount of useful work that can be performed by the energy in a system, whereas emergy analysis quantifies the amount of energy

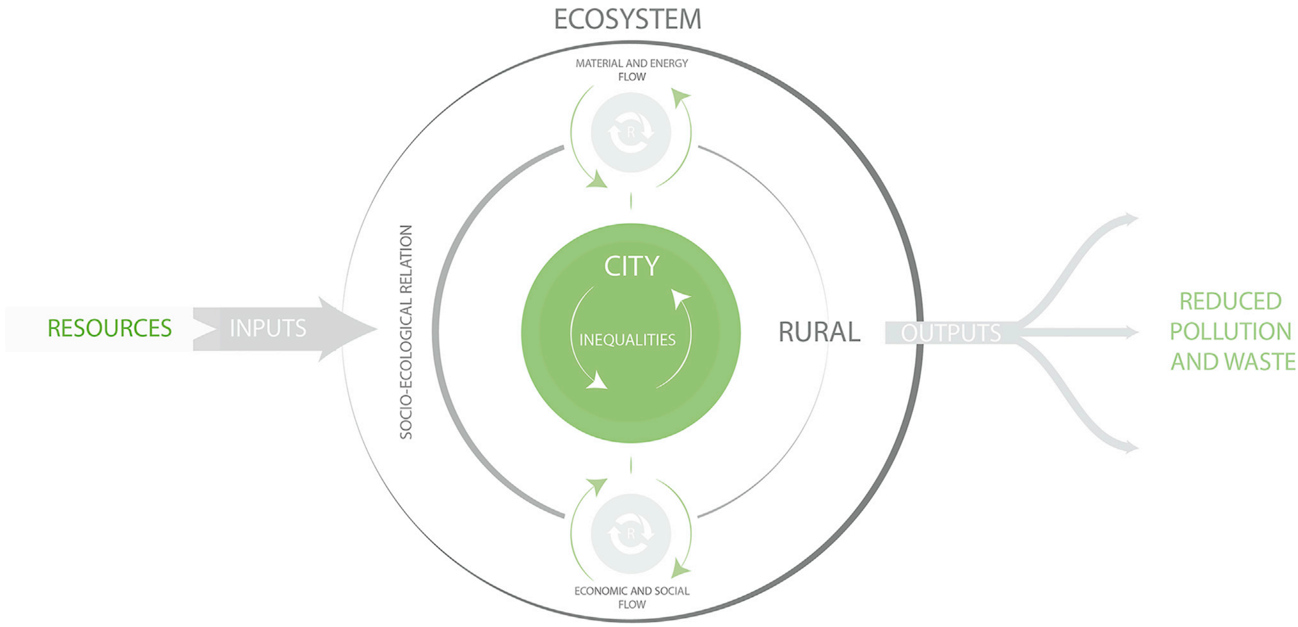

Figure 2. Urban Metabolism Concept
The UM concept is shown as resources that enter the boundaries or interaction space of a city. This space considers flows of materials and energy and economic and social flows embodied in urban-rural interactions. It also considers any potential inequalities that might emerge as a result of such flows. Once qualified and analyzed, the UM approach can potentially maximize the efficiency of flows and reduce outputs such as pollution and waste.

that is consumed in direct and indirect transformations in a system. Input-output analysis accounts for commodity flows between the various production and consumption sectors by considering actors and their interactions.

(2) Indicator approaches try to synthesize information about consumption and impact with unique data. Ecological footprinting is a method developed as a sustainability indicator of a human economy; it is based on an analysis that converts a population's resource consumption into a single index, i.e., the land needed to sustain the life style of a certain population. Life-cycle analysis refers to the analysis of material flows and is designed to enable the identification of the broader impact of products and services. It evaluates the effects of all stages of the life cycle of a product or service from the extraction of raw materials to the creation of the product or service to its disposal into the environment. Then, in a different category, there are simulation methods such as system dynamics, which is a method for understanding the behavior of systems over time in order to address long-term policy problems, namely the problems that could be solved with policies and whose results will be visible in the distant future (i.e., climate-change policies). It identifies non-linear, interlinked causal relationships between its components.

The primary purpose of UM approaches is to analyze and assess resource flows in a quantitative fashion in order to inform and support policies or targeted recommendations for reducing consumption or increasing access to specific resources. Many authors have highlighted its potential uses in urban planning; however, until now its application in city planning processes has been relatively limited. This is primarily because it is difficult to translate the data used for calculating the dimension of flows into a usable format for urban planners and decision makers. In fact, in order to inform urban decisions, information elaborated by data flow should be related to space and time. This means that knowing where and when flows or stocks of materials, energy, or even people are located is fundamental. This raises the question of the freshness of data, i.e., it is impossible to develop a useful urban mobility policy in 2020 by using data from 2015.

The UM concept, although developed earlier and independently from CE, endorses some of the same principles. Both are based on the circularity of flows and the minimzing of waste, but UM also considers the flow of people and information. The main difference is that in UM, space is relevant and boundaries are necessary because resources have to remain within the urban ecosystem as much as possible. Conversely, in CE, space is not defined and the ecosystem is the whole world.

Circular Urban Metabolism as the New Urban Framework

Urban systems are becoming more complex, cities are growing, and levels of production, consumption, and waste are increasing. The more we learn about the complexity of the urban system, the more apparent it becomes that traditional theories and approaches are no longer appropriate. If we are to alleviate the environmental pressures, we must develop a new urban framework that is able to provide policymakers and urban planners with the tools and information they need.

The concepts of UM and CE both show a great deal of promise in this regard. Both concepts recognize the need to use circularity to achieve sustainability, but neither approach is sufficient

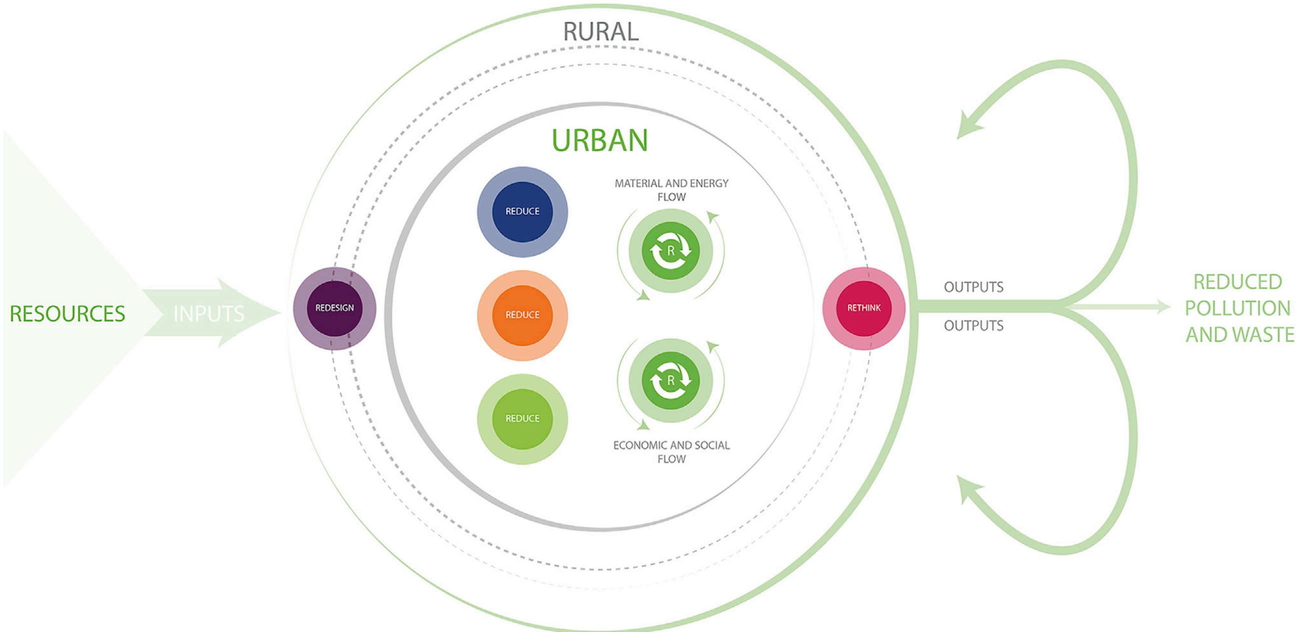

Figure 3. Circular Urban Metabolism Framework

The CUM framework is the result of the CE concept applied in a UM context. The CUM framework can aid planners and policymakers to rethink urban activities, such as transport or food production, within the urban-rural space and through time (in the short and long term). By identifying spatial and temporal connections among material, energy, and economic and social flows, the approach is able to identify the potential to implement CE principles such as reducing, reusing, and recovering resources. For clarity, this figure depicts CE principles such as reducing, reusing, and recovering, but other aspects of the nine Rs (such as refurbishing or remanufacturing) are applicable as well. Redesign and rethink principles appear outside the urban sphere in order to strengthen connections for certain CE principles between the rural and urban spaces. In such a CUM framework, even pollution and waste products can be reintergrated into the circular system as secondary raw materials.

by itself. In order for a circular metabolism approach to achieve sustainability within the urban space, it must be nested within a supportive economic system—an economic system that champions new business models, technological innovation, and logistical and behavioral change. UM and CE can therefore benefit from each other. Both concepts can be adopted simultaneously and will mutually complement one other. For example, UM enables us to map and quantify urban flows of resources and energy; once these are understood, stakeholders will be armed with the necessary information to make their supply chains more efficient, reduce waste, and introduce CE R-framework principles.

The CUM concept, which marries the two approaches, has the potential to become a new urban framework that simplifies the complexity and realizes the vision of sustainable cities.

Several authors have emphasized that the implementation of CE principles (the R framework) can contribute to the achievement of sustainable development if it is contextualized in the UM context. The CUM framework aims to join the R framework developed in CE with the UM idea of the urban ecosystem. This new way of thinking can help us understand how urban flows interact with the spaces over time and thus enable us to rethink and redesign them in a more sustainable way. This could occur through application of the CE model at the city level, the development of connections among flows (nexuses) and thus the rethinking of urban activities, the redesign of urban and social infrastructures, and the reduction, reuse, and recovery of resources. In particular, CE activities can be intended as a practical means (stepping stones) of achieving a more sustainable UM (Figure 3).

In the context of urban planning and design, CUM can improve the resilience of neighborhoods within cities and that of cities within regions. Once interactions, dependencies, and cause-effect relatioships between cities and their hinterlands and neighboring regions are understood, flexibility and resilience can be built into urban design. CUM has the potential to maximize co-benefits, strengthern relationships, help rewrite urban regulations, redefine land use, reproject infrastructure use, and improve our ability to respond to the pressures of climate change and usher in an age of urban sustainability.

Emerging Issues in CUM

The CUM framework is, however, still in its infancy and requires further analysis. Like the CE concept before it, it remains a fragmented collection of ideas derived from separate fields and lacks a well-established and shared scientific field of its own. CUM, considered a framework for creating sustainable and resilient cities, will face many of the same problems currently associated with CE and UM.

A priority for research is the space dimension both as flow boundaries and as flow locations. The definition of boundaries (should they exist) is essential for closing and isolating the urban system; however, in spatial planning, like in reality, the urban system is connected to other systems and is not truly isolated. Thus, considering the urban system as an isolated system is a simplification, which although necessary can be misleading.

Moreover, to make proper urban decisions, it is essential to know where the flows of resources are spatially located, where they transit, and how they are connected rather than just their volume or weight.

The second issue, strictly linked to space, is the time horizon. Planners and policymakers need to know when the flows of resources are in a specific place. They need to know the information almost in real time rather than years later, and especially they need to know how the flows change through time and how flows affect each other in the long term. Providing dynamic data and future scenarios will be essential.

Data type can also pose a problem; statistical data are often not relevant for small or medium cities. It is challenging to understand and translate data that are aggregated or too disaggregated for use by policymakers, and data are often analyzed in a way that is not conducive to the urban challenges and goals that the data are needed to address.

The fourth issue is about resource-flow relationships or nexuses. Resource production, transportation, consumption, and storage have impacts on other resources whereby each affects the others. Further studies on resource nexuses (physical and political) are needed.

Further consideration of these issues and research gaps is important not only for planners and policymakers but also for researchers in industrial ecology, industrial ecosystems, industrial symbioses, cleaner production, eco-efficiency, cradle-to-cradle design, biomimicry, resilience of social-ecological systems, the performance economy, natural capitalism, zero-emissions accounting, and material-flow accounting, among others. There is potential here to unite these separate fields under a broader umbrella of research and to improve their collective application.

We want to underline that resource management is the critical factor for sustainable urban planning, and this will gain importance in the future only as pressure mounts. The city must manage its resources in such a way that (1) the renewable resources that it requires do not exceed their rate of regeneration, (2) the city's emissions do not exceed the capacity of ecosystems to assimilate waste, and (3) the non-renewable resources required are not exploited in such a way that their depletion rate exceeds the creation rate of renewable alternatives. From that perspective, the CUM framework would be a very useful tool for analysis and research.

RECOMMENDED READING

Ellen MacArthur Foundation (2013). Towards the circular economy. https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition.

Ellen MacArthur Foundation (2015). Growth within: a circular economy vision for a competitive Europe. https://www.ellenmacarthurfoundation.org/publications/growth-within-a-circular-economy-vision-for-a-competitive-europe.

Geissdoerfer, M., Savaget, P., Bocken, N., and Hultink, E. (2017). The circular economy - a new sustainability paradigm? J. Clean. Prod. *143*, 757–768.

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. *114*, 11–32.

Kennedy, C., Cuddihy, J., and Engel-Yan, J. (2007). The changing metabolism of cities. J. Ind. Ecol. *11*, 43–59.

Kirchherr, J., Reike, D., and Hekkert, M. (2017). Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycling *127*, 221–232.

Korhonen, J., Honkasalo, A., and Seppälä, J. (2018). Circular economy: the concept and its limitations. Ecol. Econ. *143*, 37–46.

Lee, S.E., Quinn, A.D., and Rogers, C.D. (2016). Advancing city sustainability via its systems of flows: the urban metabolism of Birmingham and its hinterland. Sustainability *8*, 220.

Longato, D., Lucertini, G., Dalla Fontana, M., and Musco, F. (2019). Including urban metabolism principles in decision-making: a methodology for planning waste and resource management. Sustainability *11*, 2101.

McDonough, W., and Braungart, M. (2002). Cradle to Cradle: Remaking the Way We Make Things (North Point Press).

Merli, R., Preziosi, M., and Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. *178*, 703–722.

Thomson, G., and Newman, P. (2018). Urban fabrics and urban metabolism–from sustainable to regenerative cities. Resour. Conserv. Recycling *132*, 218–229.

World Commission on Environment and Development (1987). Our Common Future (Oxford Univeristy Press).