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# Seeking Circularity: Circular Urban Metabolism in the Context of Industrial Symbiosis

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**Abstract:** Cities are leading in the implementation of circular economy (CE) principles and sustainable development due to the concentration of knowledge, resources and technology while remaining the highest consumers and producers of resources. CE, urban metabolism (UM) and industrial symbiosis (IS) offer a new more holistic approach based on material and energy flow analysis and materials recovery from waste by creating IS networks to support a new circular urban system (CUM) which contrast to the traditional linear extract-produce-use-dispose model of economic systems. In this paper, we present the concepts of CE, IS and CUM and how the new framework could improve cities transition to sustainability and CE, with detailed CE and IS indicators analysis. We introduce the relations between IS, CE and UM concepts, how they can be used and monitored in the CUM framework. CUM can help unite urban planners, the city's governance and the business sector to promote collaboration across the city to improve future sustainability and circularity by closing loops.

**Keywords:** circular economy; circular cities; urban metabolism; circular urban metabolism; industrial symbiosis

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## 1. Introduction

The circular cities concept is more relevant than ever in the context of growing problems caused by climate change, rapid urbanization, and growing demand for resources and services to maintain the same level of life quality. The recent publication of Bradshaw et al. [1] presents a ruthless analysis of the current environment by questioning governments' capacity to mitigate the erosion of ecosystem services, their ability to grasp the scale of threats to entire biosphere, humanity, and our well-being, and our efforts' effectiveness in improving future environmental conditions. Today's society focuses on meeting the rising average standard of living and short-term improvement by eliminating the need to restore biodiversity loss which now is recognized as one of the top global economic threats along with climate action failure, extreme weather, and natural disasters [1,2].

Today only 8.6% of the world economy is circular and this is 0.5% lower compared to 9.1% in 2018. This should arise politicians, society and business sector awareness, and concern about the success of reaching the 2030 Agenda for Sustainable Development Goals. The main reasons for this negative trend are: (1) high rates of extraction—over the past 50 years the global use of materials is more than 3.5 higher from 26.7 billion tonnes in 1970 to 92.0 billion tonnes in 2017; (2) growing urbanization and population concentration in the cities increase the demand for housing, which driving stock build-up dynamic to build-up utility infrastructure for energy, water, sanitation, communication and mobility services, short-lived material flows (e.g., clothes, electronics), and long-term stocks (building infrastructure and capital equipment); (3) processing and recycling are not sufficient to meet world economy demand [3].

While cities occupy only 3% of the world's surface, the concentration of the population in urban areas is about 55% and is expected to increase to 68% by 2050 [4]. Today urban areas consume about 75% of the world's resources and are responsible for 60–80% of the total greenhouse gas emissions [5]. Domestic materials consumption in the cities is predicted to grow faster than the urban population and it is projected to reach approximately 90 billion tonnes by 2050 [6]. The growing population in the cities will reshape the global economy and demand for resources. The importance to improve and optimize resources extraction, develop the use of renewable resource and optimize materials and energy recovery from the waste along with economic growth and reduced impact to environment are highlighted in the 2030 Agenda for Sustainable Development, and in the recent published Circular Economy Action Plan the European Green Deal. Sustainable Development Goal (SDG) 11 "Make cities and human settlements inclusive, safe, resilient and sustainable" materializes cities role to pursuit of sustainable development.

Cities and regions have a key role to play as promoters and enablers of the circular economy, because of their high concentration of knowledge, resources, and technology [7]. Cities are open systems depending on their hinterland for energy, water, food, goods, and other resource flows [8]. Cities see the circular economy as a tool to address many challenges: becoming more sustainable, ensure materials, and energy efficiency, resolving climate change and public health problems [9,10]. The implementation of the CE relies on the city, region, or even country political context, cultural norms, society participation, level of technology, and industrial development [7,8].

The CE refers to a new systematic approach that focuses on changes throughout value chains and wastes elimination by using new ways of turning waste into a resource and new models of consumer behavior [11,12] where different models such as UM and IS could be incorporated to close loops in the city perspective. In the context of cities' unsustainability patterns, rapid depletion of global resources, and cities' impact on global warming, UM model allows identification and spatialization of flows within cities' for resource consumption analysis, projection of future cities urbanization plans with the support of new technologies, and innovations [13]. UM material and energy flow analysis stimulate the transition from a linear perspective to a networked and cyclical perspective, turning waste into resources and energy, and reducing the city's dependence on the hinterland for resources [14]. In addition, IS as a business model relies on shared infrastructure and by-products to increase resource efficiency by creating value from waste [15].

The aim of this paper is to conceptualize the implementation of industrial symbiosis in the context of CUM by analyzing the concept of IS and CUM and how they can work together for sustainable implementation. Finally, we present the improved model of CUM with IS networks.

## 2. Materials and Methods

CE strategy or plan implementation cannot be successful without adequate indicators and integrated management models. It will allow efficiency changes in cities' urban planning towards the new sustainable and circular paradigm.

The European Commission [16] highlights the necessity to have a developed monitoring framework that aims to measure the performance of different areas directly or not directly contribute to the CE implementation.

The literature review helps to establish the research problem and identify the gaps in the theoretical framework. The research was conducted using literature review and the official documents and reports of circular cities to indicate CE indicators within the city and how IS with UM could be integrated with CUM framework (Figure 1).

The review of existing literature and publications was used to present the concepts of circular city, industrial symbiosis and circular urban metabolism, to map and assess how CE, IS and UM concepts correlate with each other. Scientific literature was collected from "Elsevier's Scopus", "Elsevier's ScienceDirect" databases, and Google Scholar using keywords "circular economy", "industrial symbiosis", "urban metabolism", and "circular urban metabolism" to investigate the relationship between those concepts and find common points. This was used to develop the theoretical framework of CUM in the context of industrial symbiosis.

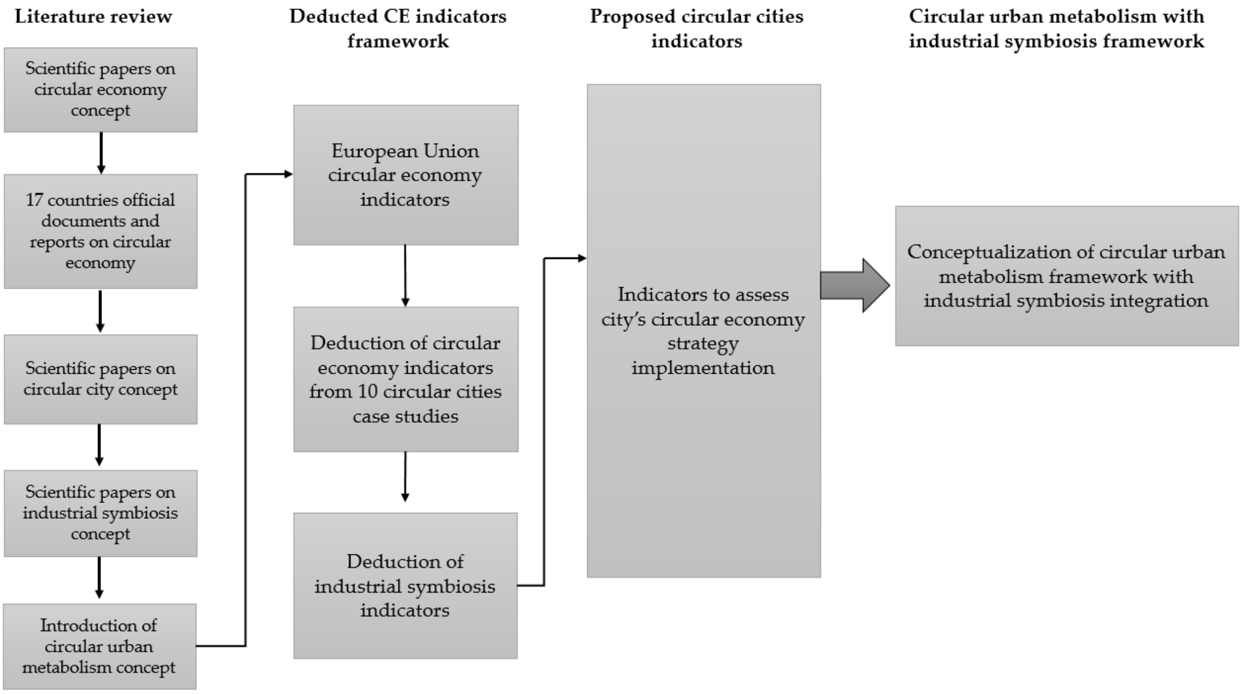


**Figure 1.** Methodology.

The criteria for selecting circular cities for CE indicators is presented in Table 1. The highest concentration of circular cities is in Europe. It can be explained by pro-circular EU policy and financial support transitioning to CE. In this study two criteria were applied selecting circular cities: published city's CE document (strategy, roadmap or plan) and officially identified CE indicators. The results of the inquiry on the presence of circular cities CE documents and indicators is presented in Table 1.

**Table 1.** Circular cities selection for CE indicator analysis (prepared by authors).

| Cities | CE Document | Established Indicators (Yes/No) |
|---|---|---|
| Amsterdam, The Netherlands [17] | Amsterdam Circular 2020–2025 Strategy | Yes |
| Rotterdam, The Netherlands [18] | Rotterdam for circular economy 2019–2023 | Yes |
| London, The United Kingdom [19] | London's circular economy route map<br>London—the circular economy capital | Yes |
| Glasgow, The United Kingdom [20] | Circular economy route map for Glasgow 2020–2030 | Yes |
| Peterborough, The United Kingdom [21] | Circular City Roadmap | Yes |
| Paris/France [22] | Paris Circular Economy Plan | Yes |
| Helsinki/Finland [23] | The City of Helsinki's Roadmap for Circular and Sharing Economy | Yes |
| Prague/Check Republic [24] | Strategy for the Transition of the Capital City of Prague to Circular Economy (project) | Yes |
| Maribor/Slovenia [25] | Strategy for the transition to circular economy in the municipality of Maribor | Yes |
| Brussel, Belgium [26] | Brussels Regional Program for a Circular Economy 2016–2020 | Yes |
| Copenhagen, Denmark [27] | Circular Copenhagen. Resource and Waste Management Plan 2024 | No |
| Vienna, Austria [28] | Smart city Wien Framework Strategy 2019–2050.<br>Vienna's strategy for Sustainable Development | No |

Cities which are moving towards implementing CE but not have produced CE documents are not included in CE indicators case study. The purpose is to capture a wide and varied set of metrics of circular economy cities through selected samples CE metrics review comparing with CE scopes identified in CE strategic documents. A total of 10 cities (see Table 1) have been selected according defined criteria.

The improved CUM framework with identified monitoring indicators was proposed based on the CE, IS, and UM literature review and circular cities indicators analysis results.

## 3. Results

### 3.1. Understanding Circular Economy Concept

CE is gaining momentum among politics, academia, industry, and society putting forward a number of environmental, economic, and climate-related benefits The CE concept as a political strategy was introduced by the EU in 2015 in the document called "Closing the loop—An EU action plan for the circular economy" and marks the beginning of EU's new international policy and efforts to encourage economy's transition from linear to circular. The presented CE concept focuses on solving socio-economic and environmental problems [29] proposing long term solution based on a closing-loops framework. CE implementation involves systematic change, technological innovations, and consumers' behavioral changes, so the concept itself is broader and covers not only resource extraction, production, and product use, but all business activities, consumption, and cultural changes reducing the use of primary resources [30].

The European Green Deal presented in 2019 presents an overarching aim to transfer Europe's economy into a modern, resource-efficient, and competitive economy, with a fair and prosperous society and make Europe a first climate-neutral continent by 2050. It is also set the direction of the EU's international policy where the EU takes the leading role building alliances with the like-minded. The Green Deal focuses on peoples, regions, industries and workers by encouraging closer collaboration with EU institutions and consultative bodies [31].

CE implementation highly depends on how the concept is understood and which line of implementation is selected. While EU's CE package defines CE as a transition "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized", there are a number of studies focusing on the CE concept definition. However, to get a broader understanding of CE and how it is implemented within cities, it is important to analyze countries' national documents and strategies and their understanding of the CE concepts. The definition of CE allows to understand the political direction and priorities in the circular transition process. Countries' CE definitions are presented in Table 2.

**Table 2.** Countries and CE definitions (prepared by authors).

| Country | Definition | Source |
|---|---|---|
| Belgium | CE is an economic system for exchange and production that aims to increase resource efficiency use and reduce environmental impact at all stages of the product life cycle, while developing the well-being of individuals. | [32] |
| Denmark | CE is a production and consumption approach where materials and products are recirculated, their value is fully utilized, and waste is minimized to improve the environment to the benefit of future generations. | [33] |
| Estonia | CE is businesses' ability to engage in research and development, to create innovations products and services addressing local socio-economic problems, creating innovative business models, with higher skilled jobs and increased productivity along with engagement of different stakeholders (businesses, policy makers, society as a whole). | [34] |
| Finland | CE is a new operating method for the economy that produces economic well-being within the limits of the planet's carrying capacity. In a CE, materials are utilized efficiently and sustainably, and they remain in circulation for a long time and safely. | [35] |

**Table 2.** *Cont.*

| Country | Definition | Source |
|---|---|---|
| France | The CE is about producing goods and services in a sustainable way by limiting the consumption and waste of resources and the production of waste. It is about moving from a completely disposable society to a more circular economic model. | [36] |
| Greece | CE is based on the rational use of resources, the concept of recycling-reuse and the IS model. It aims at and encourages the use of secondary materials and waste as productive resources and useful materials, attributing a sustainable dimension to the productive model. | [37] |
| Ireland | The CE concept encompasses a system that seeks to maintain and grow economic activity though at the same time reducing the extraction and consumption of virgin raw materials. It is based firmly on the waste hierarchy and the proposition that preventing waste in the first place is the most effective way to reduce consumption. Increased sharing of products both at personal level and through commercial product-as-a-service models allows greater usage of products without needing additional manufacturing. | [38] |
| Italy | CE is more rational and effective material and energy resources' management which requires a cultural and structural change with involvement of all stakeholders (business, public sector, consumer, citizens, and associations). | [39] |
| Latvia | CE is a sustainable development model which is essential for maintaining the value of products, materials and resources in the economy after longer, while reducing both consumption of raw materials and waste, as well as the impact on the environment | [40] |
| Luxembourg | The restorative use of materials and products in renewably powered cycles where everything is a resource for something else, generating positive economic, social and ecological impacts through improved quality and resource productivity | [41] |
| The Netherlands | CE is transition from "take, make and waste" to a system with preservation of natural capital by using renewable and generally available raw materials. Raw materials are optimally deployed and (re-)used without any risk for health and environment, and primary raw materials are extracted in a sustainable manner. | [42] |
| Portugal | CE is understood as an economy which actively promoted the efficient use and productivity of the resources it has harnessed, via products, processes and business models on the digitalization, reuse, recycling and recovery/regeneration of materials. It seeks to extract economic value and use from the materials, equipment and goods for as long as possible in cycles powered by renewable sources. | [43] |
| Slovakia | CE helps to maintain the value of products and materials as long as possible, thus waste and new resource utilization are minimized. | [44] |
| Slovenia | CE is a new paradigm that seeks to answer the changes that characterize the 21st century—changes that prove, in a material sense, that the exploitation of natural resources in the ways that were seemingly still acceptable in the 20th century can't allow for the quality survival of humanity or the other living creatures on this planet. | [45] |
| Spain | CE is a new production and consumption model in which the value of products, materials and resources are maintained within the economy for as long as possible, with minimal waste and reusing as much as possible the waste that cannot be avoided. | [46] |
| Sweden | CE is a tool to reduce resource use in society and the environmental impacts that follow from it. | [47] |
| The United Kingdom | CE allows keeping resources in use as long as possible, extracting maximum value from them, minimizing waste and promoting resource efficiency | [48] |

Authors were able to identify 17 Europe countries with national level documents where the approach of the CE was identified. By critically considering CE from sustainable development perspective and its three dimensions, economic, environmental, and social, the paper presents the key aspects of countries' CE concepts (Figure 2).

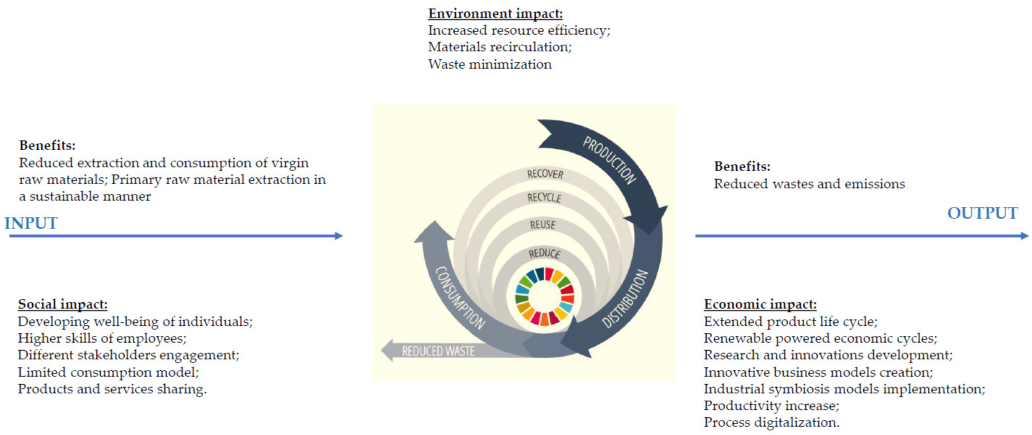


**Figure 2.** CE and its impact to sustainable development (prepared by authors using CE definitions presented in Table 1).

CE utilizes nature's cycle for preserving materials extraction and improving economic use. All countries do pay attention to resource-efficiency narratives relating to material and resource extraction and recovery optimization, waste management and environmental impact minimization along with changes in production and consumption. Estonia and Portugal highlight the importance of digitalization, innovations and support for sustainable business models towards economic growth in their CE concept. Only Greece in their national CE strategy identifies IS as one of the key elements on the circularity path. It is important to note that most of CE definitions neglect social aspects as a part of sustainable development and only five countries (Belgium, Estonia, Ireland, Italy, and Luxembourg) included socio-political considerations of circularity with terms related to human and society well-being, stakeholders' cooperation, and higher skills. On the other hand, the link between environmental and economic aspects is dominant in most of countries' CE definitions. Some countries such as Austria, Germany, Lithuania, Poland, Romania, and Bulgaria do not have national documents or strategies, where the CE concept could be clearly defined.

### *3.2. Circular Economy Implementation in Cities*

In the context of existing various definitions of CE, the concept itself can be understood as an "umbrella" [49,50] that is used to develop policies and strategies at different scales, from global production and international policies to cities and municipalities. Rapid growth of population in the cities causes environmental problems, increases resource consumption, energy use, and GHG emissions [51]. The rapidly urbanizing cities are the major engines of economic growth and can drive CE implementation gaining economic, environmental and social benefits. Ellen MacArthur Foundation [52] sees circular cities as systems that are constantly evolving, accessible and plentiful through waste elimination, high-value retention, and digitalization empowerment. Innovation and digitalization allow cities to use the most advanced technologies promoting economic growth, improving the quality and performance of city services [53] with reinforcement of sustainability.

Kirchherr et al. [54] in their analysis of 114 CE definitions suggest the application of CE where cities are introduced at the macro level as key players for the development of the CE framework. Prendeville et al. [55] define the circular city as "a city that practices CE principles to close resource loops, in partnership with the city's stakeholders (citizens, community, business and knowledge stakeholders), to realize its vision of a future-proof city". Their study focuses on geographically and administratively-bound cities' units, while the city has several other dimensions and characteristics. Paiho et al. [56] extend the concept of a circular city focusing on resource flows and how it could be closed, slowed and narrowed down. In their definition the circular city "is based on closing, slowing and narrowing the resource loops as far as possible after the potential for conservation, efficiency improvements, resource sharing, servitization and virtualization has been exhausted, with remaining needs for fresh material and energy being covered as far as possible based on local production using renewable natural resources".

A CE city seeks to create and ensure the well-being and resilience of itself and its citizens at the same time, separating value creation from the consumption of limited resources. Cities have well-developed infrastructure in different sectors with ongoing resource management efficiency projects that reduce the impact on the environment [57]. Cities' urban systems which include buildings, mobility, products, services and food systems are interconnected into networks and play an important role in a city's development [58]. Cities focus on smart products and production, more efficient use of materials and products with an extension of their life cycle [59].

Many cities today are strongly involved in CE activities. London, Paris, Amsterdam, Rotterdam, Prague, Helsinki have prepared city-level CE implementation strategies and plans [60]. Bernhardt et al. [61] presents 40 cases with city-level CE initiatives across the globe covering topics such as CE strategic documents, IS, public procurement, utilities, and municipal waste. Countries and cities, based on their government model choose different CE implementation approaches. CE can be implemented in two ways: bottom-up, when the business or interested parties play a key role encouraging CE development, or top-down where the government develops and design national or regional CE strategy [50,55]. Scientists analyzing CE implementation [50,55,62], noticed, that democratic countries in Europe or U.S. with strong business sectors and non-government organizations (NGOs), and social activists choose to implement CE from the bottom-up perspective. However, Amsterdam or Paris cities' CE case analysis shows, that CE could be implemented using both-way communication between the municipality and business sectors, NGOs [62,63]. Cities with a high density of population, knowledge, innovations, and resources cause major environmental problems and have a high level of resource demand. Additionally, they have the necessary resources, innovations, and knowledge for CE implementation.

### *3.3. Concept of Industrial Symbiosis*

IS can be understood as one of the approaches to realizing CE and one of the key strategies. Through symbiotic activities between different business sectors, IS improves CE by promoting sustainable resource use at the inter-firm level, minimizing input of virgin materials, and reducing waste [64,65]. The European Green Deal provides the action plan to transform the EU economy to resource-efficient and competitive moving to the CE [66] and IS is critical to Europe's CE transition and resource efficiency [67].

IS concept was first introduced in the late 1980s approaching industrial system from an integrated point of view—an industrial ecosystem for the necessity of increasing the recycling, reuse of materials and by-products [68] to new products. IS is more focused on the industrial processes in production stages allowing companies that traditionally execute individual activities, cooperate in the networks for resource sharing [64] ensuring a competitive advantage for each member of the network [65].

IS is based on the basic principle of CE—to move from linear extract-produce-use-dispose model to strategic partnership-based business cooperation transforming waste into resources and materials [69], exchanging one industry waste to resource for other industry [70] for economic, social, and environmental purposes [71,72]. IS can reduce the amount of wastes from producer perspective, primary inputs as raw materials, energy and water used in the production process, and GHG emissions [73]. IS can potentially have positive social impact by creating new jobs for highly qualified employees [74].

IS only focuses on the manufacturing sector, while the CE is a broader concept and covers the entire cycle from resource extraction, production, consumption to re-use, remanufacturing, refurbishing, and recycling into new products [75], making IS an integral part of the CE [30,76]. Recent publications focus on IS as the business model for CE [15,77,78]. Baldassare et al. [79] presented the visualization of the IS framework on the three pillars of circular business: technical innovations, collaboration, and sustainable business model innovation, where innovations promote partnership between the sectors' industries, capture the economic growth turning waste into value [15,80]. Sharing of knowledge and resources between network members boosts innovations, which leads to a competitive advantage over other businesses that are not a part of IS [81,82]. Over time, the concept of IS has expanded including services and infrastructure [83], social and knowledge-based inter-firm exchanges [84]. From an organizational perspective, IS can occur in a variety of ways through large-scale manufacturing firms (among production processes at the company), ecological or industrial clusters of companies located in the same or different areas (e.g., government plants, and business incubators) [65,85,86]. It means that geographical distance between companies might not be the main factor that determines the IS relationship, as long as synergy is convenient from an economic perspective [87]. Large-scale industries provide a critical mass of resources and by-products to develop IS in an eco-industrial cluster [65]. IS is understood as a network of business entities that may appear for different reasons, determined by existing infrastructure or come into being spontaneously [65], the form and participants of such network could change over time [65,82,88]. However, the concept of IS as an eco-industrial park is too narrow [89], in a broader context it may include a city or separate industrial sector [90] without limiting IS within a specific infrastructure or territory.

### *3.4. Concept of Circular Urban Metabolism*

In the concept of UM, the city is defined as a complex system with robust and adaptive nature, maintaining their long-term integrity. Today's cities are no longer appear to be static, isolated and disconnected. Now they interconnected in the network of exchange of goods, economies, work force and ideas with the surrounding environment that overcome regional, national and international boundaries [91,92]. Therefore, each investigation or research of the city must consider the network connecting all parts within the city and their links to the surrounding environment.

As a result of the growing concentration of population, production consumption, and amount of waste generated in the cities, urban systems are becoming more complex. Urban planning requires a more inclusive and sustainable approach in the cities for policymakers and urban planners to create a beautiful, healthy, and ecological environment to comply with the residents' needs [93]. Some scientists analyze CUM through urban-industrial symbiosis [94,95] (also called industrial and urban symbiosis in some literature). Sun et al.'s [95] case analysis on urban-industrial symbiosis proves that it able to reduce the resource exploration in upstream, resource processing and waste disposal in downstream from an environmental perspective. Other researchers focus on energy saving and resource conservation from municipal solid waste treatment and IS system perspective to improve the overall energy recovery efficiency of the city as a whole [96–98]. However, focusing on material, energy flows from UM perspective and waste treatment is too narrow and the concept of urban-industrial symbiosis is more complex. A more holistic approach in the context of CE and sustainable development is necessary.

Cities are an integrated part of the surrounding environment, where different units operate. Rapid urbanization and growth of cities outside the city's administrative boundaries links cities closely to surrounding regions, meaning city's UM analysis should be expanded outside geographic territorial of the city itself. Especially when city streams (material and energy flows, transport) cross the city's borders [56]. Scientist mostly focus on traditional and most visible physical (material and energy) flows that could be easily monitored and evaluated using local data [56,99,100]. However, other non-material flows, coexist and circulate inside and outside city. Bai [101] in his research expands the concept of material and energy flows by including capital and information as inputs supporting societal activities and urban functions, while knowledge and service as outputs.

CE and UM emphasize the importance of circularity in the context of sustainability implementation but neither of them applied separately effectively enough. UM is fundamental in developing sustainable cities and communities [99] based on material and energy flow analysis within the city and its hinterlands [100]. UM understands the city as an ecosystem in which the circularity of natural ecosystems should be restored [101]. Latest publications focus on cities as complex ecosystems analysis [102,103] and effectiveness [104], where urban material flows are defined in terms of exchange of material and energy between the urban system and surrounding ecosystems [105] and provide information on energy consumption, material cycles, waste management and social processes that determine the movement of these flows [99]. While the CE can improve the supply chain more efficiently with reduced amounts of generated waste.

The concept of CUM is briefly scientifically analyzed [105–109] focusing on local material and energy cycles. Aguledo-Vera et al. [110] briefly discussed the CUM concept, but they conceptualized the main framework of the CUM in the context of the city—low consumption rate, recycling and reuse of the different urban flows, with less impact on hinterlands and other cities. A recent publication of Lucertini and Musco [111] presents a framework of CUM by integrating CE and UM principles to simplify the complexity of the city to facilitate the assessment of urban complexity and the implementation of a sustainable urban vision [111]. In other words, CUM could be explained as a recognition of the city's material and energy outputs as recycled inputs [105,112], while city's relationship with his hinterlands and other cities was excluded. The CUM is based on the idea of closed loops of inputs of resources and outputs of waste when urban areas can be developed with less impact on the environment and more balanced with the natural ecosystem on which the city depends [105], along with the reduced need for natural resources and reduced wastes [110].

Lucertini and Musco [111] proposed CUM framework builds on the combination of the 3R framework developed by CE and UM as an urban ecosystem. CUM framework helps to understand, how urban flows interact with the environment and ecosystems within and outside the city. The principles of CE can be seen as a starting point for a more sustainable UM by analyzing a city's input-output relationships and the relationship between a city's and its hinterlands, helping assess the consequences and relations between dependence and causes for future urban planning and the ability to adapt to environmental change. CUM has the potential to maximize co-benefits, evaluate the effectiveness of land use, re-project infrastructure use, and improve cities' ability to respond to climate change. CUM implies CE principles in the city level with the connection of flows, rethinking urban activities, redesign social and urban infrastructure, reduction and recovery of resources [111]. However, Lucertini and Musco [111] proposed CUM framework, which does not include hidden flows impact analysis to urban ecosystems. Hidden flows can be understood as flows included in goods and services city consume or produce [101,113] and are not visible in economic records, trade and production statistics. It reflects that modern cities can significantly reduce the direct material and energy flows, but can remain intensively dependent on material and energy intensive processes and services elsewhere [111,113]. Generally, hidden flows consist of secondary energy consumption in processing products or services. A modified CUM framework with hidden flows is presented in Figure 3.

Lucertini and Musco [111] in their research don't go into details about inputs and outputs within the urban-rural spaces and only identifies material and energy flows, economic and social flows as such within urban areas. The framework does not provide detailed flows and specific indicators to monitor CUM as well as inputs and outputs of the framework. It is important to develop an indicator system to assess, monitor and compare different circular initiatives across rural-urban spaces.

The formation and development of CUM in the city is a complicated process that depends on the local cultural and political environment, social and economic relations. CUM requires an extended collaborative design, decision-making, and synergies between stakeholders from urban and rural systems for successful sustainable development. Flows analysis in, within and out the city can help to understand relations between different stakeholders in rural and urban areas and how social-economic relations can re-shape transition to circularity. Today's cities' UM analysis is based on the historical material and energy flows data. Cities are constantly changing due to rapid urbanization, technologies, innovations, and digitalization processes. UM analysis results can be misleading in today's situation and create uncertainty when urban planners have to make city's strategic decisions. EU in "A New Industrial Strategy for Europe" [114] aims to promote digital transition in economy enhancing digital infrastructure can be useful for cities' urban planning measuring UM.

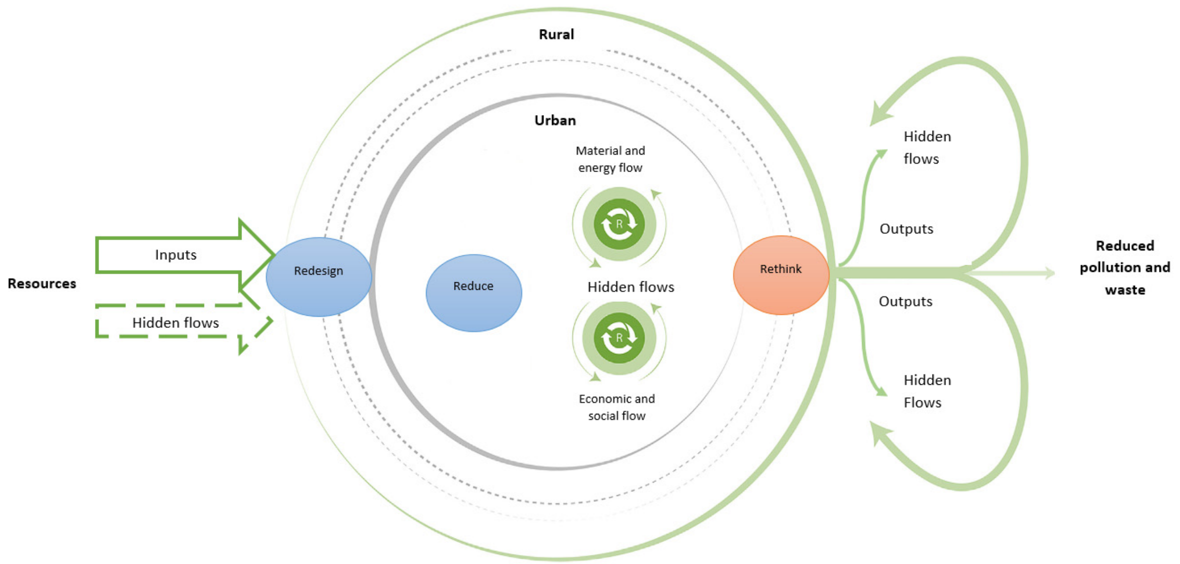


**Figure 3.** Circular Urban Metabolism Framework (Lucertini and Musco, 2020; Bai, 2016) (modified by authors).

## 4. Measuring Circular Economy Implementation

### *4.1. European Union Circular Economy Indicators Framework*

To track the circularity transition, the European Commission has established the set of indicators in COM(2018)29 "a monitoring framework for the circular economy" [115]. The monitoring framework is structured in four broad areas which consist of 10 indicators and sub-indicators (see Table 3).

The CE indicators framework can guide cities to develop their own CE indicators. However, there are some considerations:

- It might be difficult for countries, regions or cities to understand or use indicators in practice.
- Green public procurement indicator is still under development and specific data are not provided.
- EU's CE indicators framework shows one-dimensional view of CE and indicates the progress of waste policy, while water use, energy, emission indicators are out of scope.
- From the framework of indicators chosen by the EU to measure circularity transition, only one of them related to social dimension of sustainable development (number of persons employed).
- Not all developed indicators can be relevant at the city level or there might be no data at city level (e.g., EU self-sufficiency on raw materials, trade in recyclable raw materials) or high cost to undertake collection.
- Another issue that can be targeted here that Circular material use rate is too general to measure EU's economy transition from linear to circular and does not include specific targets for the re-use of secondary raw materials and upcycling.
- The CE monitoring framework also lack indicators on emissions, circular business models, life cycle indicators, and IS.

**Table 3.** EU CE indicators framework.

| Area | Indicator | Sub-Indicator | Unit(s) |
|---|---|---|---|
| Production and consumption | EU self-sufficiency for raw materials | | % |
| | Green public procurement | | Number, % GDP |
| | Waste generation | Generation of municipal waste | kg per capita |
| | | Generation of waste excluding major mineral wastes, per GDP unit | kg per thousand euros, chain linked volumes (2010) |
| | | Generation of waste excluding major mineral wastes, per domestic material consumption | % |
| | Food waste | | tonne |
| Waste management | Recycling rates | Recycling rate of municipal waste | % |
| | | Recycling rate of all waste excluding major mineral waste | % |
| | Recycling/recovery for specific waste streams | Recycling rate for overall packaging | % |
| | | Recycling rate of plastic packaging | % |
| | | Recycling rate of wooden packaging | % |
| | | Recycling rate of e-waste | % |
| | | Recycling of bio-waste | kg per capita |
| | | Recovery rate of construction and demolition waste | % |
| Secondary raw materials | Contribution of recycled materials to raw materials demand | End-of-life recycling input rates for raw materials | % |
| | | Circular material use rate | % |
| | Trade in recyclable raw materials | Imports from non-EU countries | tonne/thousand euros |
| | | Exports to non-EU countries | |
| | | Intra EU trade | |
| Competitiveness and innovation | Private investment, jobs and gross value added related to circular economy sectors | Gross investment in tangible goods | million euros, %GDP |
| | | Number of persons employed | Number, % employment |
| | | Value added at factor cost | million euros, % GDP |
| | Number of patents related to recycling and secondary raw materials | | Number, % world |

A number of publications have a critical approach on the EU's CE indicators. On the latest publication Friant et al. [57], it is concluded that CE indicators are lacking the holistic view of circularity not including mandatory socio-economic targets such as job generation, investments in the social and solidarity economy, number of cooperatives and social enterprises working on circularity, wealth and income Gini indexes, and percentage of consumption of products. Indicators should provide overall progress. The relationship between different metrics to avoid unintended side effects should also be taken into consideration.

### *4.2. Measuring Circular Economy Implementation in Cities*

The question how to measure circular cities transition is rapidly evolving in the literature [116–119]. CE operates on three systematic levels (micro, meso, macro) tools and indicators differ depending on the level of CE application [120]. Several cities in EU have CE strategies (Amsterdam, Prague, Maribor), roadmaps or city plans but lacking when it comes toa management system to evaluate the progress. Some EU's identified CE indicators are bottlenecked for cities implementing and measuring CE strategy.

The highest concentration of CE cities is in Europe because of EU's CE oriented policy implementation. The CE is not a new phenomenon and some of its elements (e.g., waste recycling) have been included in cities' strategies and plans. However, the EU notes that in many CE project cases implemented in cities there is a lack of an integrated and comprehensive approach to urban development and decision-making processes [61]. Review of scientific articles and selected cities' circularity reports [116,121] confirm that some indicators are not fully clear and it might be difficult to monitor their implementation without agreed units of measurement. Recent publication of Girard and Nocca [116] present analysis of 14 circular cities (13 European cities and one from Japan) deducted 180 CE indicators from official documents and reports. Identified indicators was grouped into environmental dimension with 98 indicators, economic and financial dimension with 35 indicators, social and cultural dimensions with 47 indicators. Authors agree that cities mostly focus on technical flows and material cycles related to production chains because it easier to understand and measure. The units of measure or how to estimate the data is not fully clear for some of indicators. However, the authors' proposed indicators in the circular city framework also lacks identified units of measure and raise reasonable doubts about adequacy of some proposed indicators to measure community well-being and health in circular city. Although Girard and Nocca [116] presented a deducted matrix of indicators is very rich, it is lacking when it comes to indicators referring to circular strategy implementation or specific CE scope (agriculture, construction, food, consumption, health sector, and etc.) identified in those documents.

Table 4 presents the summary of CE scope on city level and identified CE indicators for each Europe's city, if a published CE strategy, roadmap or map was presented. Only cities with officially published CE indicators was used in this analysis.

Each city in their strategy, roadmap or plan identifies strategic scopes (areas), where city focuses on transitioning to CE. Five key scopes were identified within circular cities after strategic documentation review: construction, consumption, economy, environment and material and energy flows (see Figure 4).

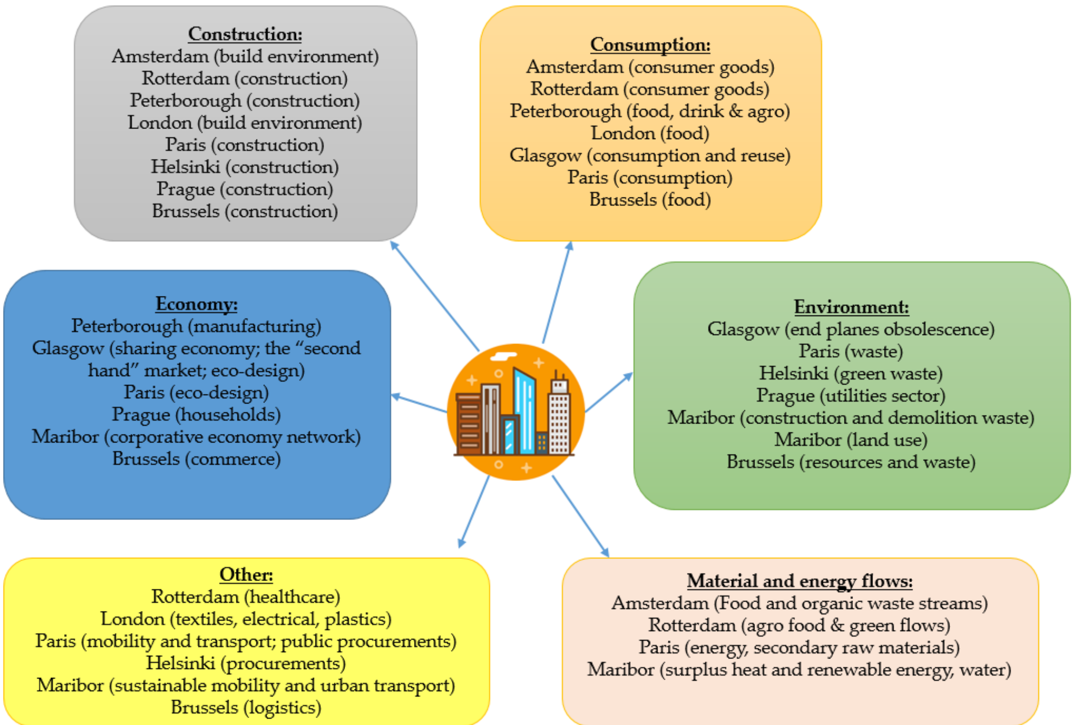


**Figure 4.** Circular cities scopes (prepared by authors).

**Table 4.** CE scope and indicators of circular cities deducted from cities' official reports.

| City/Country | CE Documents | CE Scope on City Level | CE Indicators | Source |
|---|---|---|---|---|
| **Amsterdam/The Netherlands** | Amsterdam Circular 2020–2025 Strategy | Food and organic waste streams<br>Consumer goods<br>Built environment | *Environment:*<br>Raw material efficiency<br>Use of renewable resources<br>Environmental costs<br>$CO_2$ emissions<br>*Economic:*<br>Gross value added<br>*Social:*<br>Circular services | City of Amsterdam [17]<br>Amsterdam Circle Economy [122] |
| **Rotterdam/The Netherlands** | Rotterdam for circular economy 2019–2023 | Construction<br>Agro-food and green flows<br>Consumer goodsHealthcare | *Environment:*<br>Total raw material productivity<br>Primary raw material productivity<br>Raw material demand per capita<br>Primary raw material demand per capita<br>% renewable material used<br>Waste generated/capita<br>% solid material applied to high-value and low-value re-use<br>% solid waste to landfill and incineration without energy recovery<br>% high/scarce materials recovered at high value<br>Potentially toxic material flows<br>Energy requirements per capita<br>GDP per energy requirement<br>Supply renewable energy<br>$CO_2$ intensity<br>Embedded water use/land use/energy use<br>Embedded $CO_2$ emissions<br>Raw materials with high risk for impact on biodiversity<br>*Society, health and culture:*<br>Social cohesion<br>Health good/very good<br>Population with middle or high education<br>Annual average air quality particulate matter<br>Percentage of population dying from diseases of the respiratory system<br>*Economic:*<br>Unemployment<br>Average households income<br>Change in GDP through Circular activities<br>Share of Circular jobs<br>Change in circular jobs<br>Population below poverty line | Rotterdam Circular [18]<br>Rotterdam Circle Economy [121] |

**Table 4.** *Cont.*

| City/Country | CE Documents | CE Scope on City Level | CE Indicators | Source |
| --- | --- | --- | --- | --- |
| **Peterborough/The United Kingdom** | Circular City Roadmap | Food, Drink and Agri<br>Manufacturing<br>Construction | *Economy*:<br>% circular jobs<br>% circular businesses<br>Number of shares on Share Peterbotough<br>*Environmental:*<br>% adults cycling and walking (>3 times per week)<br>$CO_2$ emissions per capita<br>Amount of renewable electricity available to each household<br>% non household waste recycled<br>% household waste recycled | Circular Peterborough [21,123] |
| **London/The United Kingdom** | London's circular economy route map<br>London—the circular economy capital | Built environment<br>Food<br>Textiles<br>Electrical<br>Plastics | *Consumption:*<br>Circularity of Industry consumption (ratio of spending on services to spending on goods)<br>Circularity of Household Consumption (ration of spending on services to spending on goods)<br>*Material intensity and carbon intensity indicators:*<br>Material intensity per unit of GVA<br>Emissions<br>*Municipal waste:*<br>Waste intensity per household<br>Management of local authority waste, share of waste to the following categories: landfill, incinerated, recycled, other<br>*Industry waste:*<br>All waste for all industrial sectors<br>*Jobs and GVA:*<br>Direct jobs in the CE<br>Indirect jobs in the CE<br>Share of London's GVA for CE activity<br>*Enabling metrics:*<br>CE procurements<br>Number of business supported<br>Number of demonstration projects<br>Number of CE courses PhDs/university courses, patents | Circular London [19,124]<br>European Commission [125] |

**Table 4.** *Cont.*

| City/Country | CE Documents | CE Scope on City Level | CE Indicators | Source |
|---|---|---|---|---|
| **Glasgow, The United Kingdom** | Circular economy route map for Glasgow 2020–2030 | Sharing economy<br>Consumption and reuse<br>The "second hand" market<br>Eco-design<br>End planet obsolescence | *Material flows*<br>Raw material consumption<br>Domestic material extraction<br>Material productivity<br>Material footprint<br>Waste arisings<br>Recycling and recovery<br>Circular material rate<br>Energy efficiency<br>Capture rates of key materials<br>Utilization rate of Industrial solid waste<br>Major pollutants emissions<br>*Economic:*<br>Household spending on product repair and maintenance<br>Environmentally adjusted net domestic product (EDP)<br>Circular employment opportunities<br>£ generated per land use area<br>Patents delivered in CE products and services<br>Private sector investment in CE<br>Circular public procurement<br>Public R&D spending to support CE innovation<br>*Environmental:*<br>Socioeconomic resilience to ecological risks<br>Carbon emissions<br>Carbon emissions per capita<br>Carbon emissions per typical basket of goods and services<br>Carbon emissions per £ of economic value<br>Carbon emissions generated per land use area<br>Nature resource stocks (natural capital)<br>Value generated by CE sector<br>Water efficiency per £GDP<br>One planet development | Glasgow city council [20]<br>Zero Waste Scotland [126] |
| **Paris/France** | Paris Circular Economy Plan | Waste<br>Consumption<br>Mobility and transport<br>EnergyEco-design<br>Secondary raw materials<br>Construction<br>Public procurements | Domestic material consumption per capita<br>Resource productivity<br>Ecolabel holders<br>Number of industrial and territorial ecology projects<br>Car-sharing frequency rates<br>Food waste<br>Quantities of waste sent to landfill<br>Use of recycled raw materials in production processes<br>Household spending on product repair and maintenance<br>Employment in the circular economy | Mairie de Paris [22]<br>DATALAB [127] |

**Table 4.** *Cont.*

| City/Country | CE Documents | CE Scope on City Level | CE Indicators | Source |
|---|---|---|---|---|
| **Helsinki/Finland** | The City of Helsinki's Roadmap for Circular and Sharing Economy | Construction<br>Procurements<br>Green waste<br>Sharing economy | *Design:*<br>Patents related to the circular economy<br>*Material extraction:*<br>Consumption of domestic materials<br>Material intensity<br>*Production:*<br>Number, turnover and personnel of circular economy establishments<br>Circular economy business activity by region<br>Pay level in circular economy industries<br>Persons employed in circular economy industries by level of education<br>*Logistics*(*No current indicator*)<br>*Trade and services:*<br>Share of service industries<br>*Consumption:*<br>Sharing economy<br>Flea market trade<br>Flea market trade by region<br>*Waste:*<br>Recovery of municipal waste<br>Total amount of waste and waste intensity<br>Production and utilization of biogas<br>*Reuse and recycling:*<br>Circular material use rate<br>Circulation of materials<br>Remanufacturing and reuse | Helsinki [23]<br>Statistic Finland [128] |
| **Prague/Check Republic** | Strategy for the Transition of the Capital City of Prague to Circular Economy (project) | Construction<br>Households<br>Utilities sector | *Economy:*<br>Employment<br>Gross value added<br>GHG emissions<br>Average households' consumption<br>*Environment:*<br>Total quantities of minerals recovered<br>Total revenue from the sale/leasing of reused objects<br>Annual number of visitors to ReUse hubs<br>Total quantities of bio-waste processed in biogas facility<br>Percentage of MSW collection fleet powered by BioCNG<br>Total share of separately collected bio-waste | Circle Economy [129]<br>Kongres [24] |

**Table 4.** *Cont.*

| City/Country | CE Documents | CE Scope on City Level | CE Indicators | Source |
| --- | --- | --- | --- | --- |
| **Maribor/Slovenia** | Strategy for the transition to circular economy in the municipality of Maribor | Construction and demolition waste<br>Surplus heat and renewable energy<br>Sustainable mobility and urban transport<br>Land use<br>Water<br>Cooperative economy network | *Production and consumption:*<br>Self-sufficiency raw materials<br>Green public procurement (under development)<br>Waste generation:<br>Generated municipal waste<br>Generation of waste excluding major mineral wastes per GDP<br>Generation of waste excluding major mineral wastes per DMC<br>Food waste generated<br>*Waste management:*<br>Recycling rate of MSW<br>Recycling rate of all waste excluding major mineral waste<br>Recycling rate of overall packaging/plastic packaging/wooden packaging<br>Recycling rate of e-waste<br>Recycling of biowaste<br>Recovery rate of construction and demolition waste<br>*Secondary raw materials:*<br>End-of-life recycling input rates<br>Circular material use rate<br>Imports from non-EU countries<br>Exports to non-EU countries<br>Imports from EU countries<br>*Competitiveness and innovation:*<br>Gross investment in tangible goods<br>Persons employed<br>Value added at factor cost<br>Number of patents related to recycling and secondary raw materials | Wcycle Institute Maribor [25]<br>Statistični Urad [130] |

**Table 4.** *Cont.*

| City/Country | CE Documents | CE Scope on City Level | CE Indicators | Source |
|---|---|---|---|---|
| **Brussels, Belgium** | Brussels Regional Program for a Circular Economy 2016–2020 | Construction<br>Logistics<br>Resources and waste<br>Commerce<br>Food | *Social*:<br>Share of existing CE jobs<br>New created CE jobs<br>% of local GDP allocated to CE activities<br>City's unemployment rate<br>% of persons in full-time employment<br>City product per capita<br>Number of businesses per 100K population<br>Distribution of CE jobs by population strata<br>*Environmental:*<br>Total electrical energy per capita<br>% of total energy use derived from renewable sources<br>Total water consumption per capita<br>% of water loss<br>Per capita generation of municipal solid waste (MSW)<br>Recycling rate<br>Per capita demand for imported construction materials<br>Per capita generation of construction and demolition waste<br>Ecological health of the main waterways and ponds<br>Per capita GHG emissions | Be circular [26]<br>UN [131] |

London's circular economy route map focus on key products value chains (textiles, electrical, plastics, build environment, and food) as it is defined in (COM 2020)98) "A new Circular Economy Action Plan for a cleaner and more competitive Europe" [132] published by European Commission as part of the Green Deal package. CE can be used as a tool to resolve public health problems [9,10]. However, Rotterdam was the only city who identified healthcare as one of the key scopes of the city in the circular transition process. Transport sector and mobility was mentioned in three cities' circular documentation (Paris, Maribor, and Brussels). Paris and Helsinki included public procurements in their strategic CE documentation. Cities show a narrow view on environmental challenges, mostly focusing on waste management and only Amsterdam, Rotterdam, Paris, and Maribor included material and energy flows as key areas in their CE documentation.

Belmonte-Ureña et al. [133] finds that CE theorization how to address challenges on the ongoing use of natural resources and physical boundaries of circular flows is weak and does not accept boundaries for the application of the concept. Cities' circular scope results confirms (see Table 4) that cities do not have holistic circularity approach with 3 of 10 cities not including economy as one of the strategic areas in circular transition.

Indicators are critical for CE strategic document implementation, help monitor and measure city's transition, and provide the basis on which critical urban decisions are taken. As emerged from Table 4, cities assessing CE models focus on technical flows and material cycles, because they are easier to understand. Material and energy flows indicators are mainly specific for industries and production chains (as emerged from Rotterdam, Glasgow, Paris, and Maribor). Cities' CE indicators do not correlate with identified key circular areas (scopes). For example, Amsterdam uses six indicators measuring circularity and only one circular services indicator was defined measuring consumer goods area. Maribor city identifies "surplus heath and renewable energy", "sustainable mobility and urban transport", "corporative economy network" as key areas in CE strategy but does not present any indicators to monitor any of them. As cities follow EU's CE indicator framework and include public procurement as a focus area in circular documents (Helsinki and Paris) but indicators to measure or how to estimate the data are not provided.

All indicators have to be measurable and understood by different stakeholders. Helsinki and Maribor cities do not have own identified indicators and instead use national CE indicators. However, for some indicators as "imports from non-EU countries", "exports to non-EU countries", "imports from EU countries", and "social cohesion" can be difficult to obtain data and measure on city level. Rotterdam city has identified 37 indicators to measure circular transition divided into 4 groups: resource usage, environmental impact, society, health and culture and economic performance. However, eight of them need further research how to calculate them [121].

Clear definition and understanding of indicators are fundamental for making data comparable among cities and evaluating circular strategy/roadmap/plan implementation and monitoring the progress. In this way, it is impossible to understand if city's strategy implementation is going in the right direction or if additional measures need to be taken.

### *4.3. Industrial Symbiosis Indicators*

Data are important in cities development and urban planning processes. IS indicators can be useful for monitoring, evaluation, and can support decision making at both city or company level. [91]. There are a wide number of IS indicators available in the literature. For example, Valenzuela-Venegas et al. [134] have identified 249 sustainability indicators classified in environmental, economic and social dimension which can be used to assess eco-industrial parks. Additionally, there are few studies aimed at classifying IS indicators in groups (see Table 5).

**Table 5.** Summary of the review of IS methodologies and indicators.

| IS Methodologies and Indicators | Source |
|---|---|
| *Eco-efficiency indicators:* | Park and Behera [135] |
| *Economic indicators:* | |
| Product or service costs | |
| Net economic benefit | |
| *Environmental indicators:* | |
| Raw material consumption | |
| Energy consumption | |
| $CO_2$ emissions | |
| *Flow analysis:* | Fraccascia and Giannoccaro [87] |
| *Material flow analysis (MFA):* | |
| Material and energy inputs and outputs | |
| Waste outputs | |
| GHG emissions | |
| *Substance flow analysis (SFA):* | |
| Carbon emissions | |
| Enterprise Input-Output approach (for single production unit): | |
| Physical flows | |
| Monetary flows | |
| Logistic flows | |
| *Thermodynamics:* | |
| *Emergy analysis:* | |
| Percent renewable | |
| Nonrenewable to renewable ratio | |
| Emergy yield ratio | |
| Unit emergy value of economic output, | |
| Environmental loading ratio | |
| Emergy lost percent | |
| Emergy investment ratio | |
| Recycling and reuse benefit ratio | |
| Improved emergy sustainable index | |
| *Exergy analysis:* | |
| Exergetic sustainability index | |
| *Life cycle analysis* | |
| *Network analysis:* | |
| Social network analysis: | |
| Number of companies in IS | |
| Centrality of companies in IS | |
| *Stakeholder value network approach:* | |
| Utilities flows | |
| *Ecological network analysis:* | |
| Amount of waste exchanged | |
| *Food web analysis:* | |
| The ratio between the amounts of waste producers and waste users | |
| The number of waste producers interacted per waste receiver | |
| The number of waste flows implemented compared to the theoretically possible flows | |

**Table 5.** *Cont.*

| IS Methodologies and Indicators | Source |
|---|---|
| *General IS indicators:*<br>Number of companies in IS<br>Activity degree in resource changes<br>Number of exchanged resources<br>Investments in IS<br>*Environmental IS indicators:*<br>Saved primary resources<br>Recycled resources<br>Material recovery rate<br>Renewable energy produced in the IS system<br>Reduced emissions<br>*Economic IS indicators:*<br>Cost savings of materials and human resources<br>Production-cost-specific IS cost savings<br>Emdollar value of Total Emergy Savings (ETS)<br>Specific resource productivity<br>Yield-specific IS cost savings<br>Specific area-related IS value-added ratio<br>*Social IS indicators:*<br>Created number of jobs<br>Number of joint organized social/charity events/activities/infrastructure projects<br>Improved environmental, health, and safety (EHS) aspects/working conditions | Lütje and Wohlgemuth [136] |
| *Environmental Impact Momentum (EIM):*<br>EIM Inbound (EIMi)<br>EIM Outbound | Felicio et al. [137] |
| *Environmental:*<br>Material consumption<br>Energy consumption<br>Exergy<br>Air emissions<br>Solid waste generation<br>By-products<br>Life cycle indicators (resource depletion, footprints, life cycle costs, cumulative energy and exergy demand)<br>*Economic:*<br>Product quantity<br>Turnover<br>Net value added<br>OPEX<br>CAPEX<br>*Social:*<br>Job creation and retention<br>Creation of IS<br>Social responsibility<br>Life longing learning<br>Health and safety at work<br>Rate of community participation<br>Level of social acceptance<br>Community development<br>Innovation and investment in R&D<br>*Circularity:*<br>Environmental impact momentum<br>Utility (lifetime and function served)<br>Environmental cost effectiveness<br>NSA:<br>Betweenness and closeness<br>Reciprocity<br>Intensity | EU [138] |

Park and Behera [135] use eco-efficiency indicators to evaluate symbiotic transactions. Authors eco-efficiency indicators divide into two groups: economic and environmental. Environmental performance is measured using raw material consumption, energy consumption and $CO_2$ emissions indicators. Fraccascia and Giannoccaro [87] in their publication discuss four groups of IS analysis methodologies: flow analysis (which can be divided in three methodologies: material flow analysis (MFA), substance flow analysis (SFA), enterprise Input-Output approach), thermodynamics (emergy and exergy methodologies), life cycle assessment (LCA), and network analysis. Lütje and Wohlgemuth [136] divide IS indicators into four groups: general, environmental, economic, and social. General indicators present the specific aspects of IS structure, activity, and knowledge to generate an overview of the current state and activity level in the IS network. Felicio et al. [137] in the research developed Environmental Impact Momentum (EIM) which can be further divided into Inbound ("the total sum of the amount of materials exchanged between the companies within an IS") and Outbound ("he materials that are not re-used by the companies and which, therefore, exit the IS") and the rate between these two variables determine the symbiosis level. EU [139] with the project named "FISSAC" proposed 27 indicators for monitoring IS initiatives with sub-indicators. Indicators were divided into five groups: environmental, economic, social, circularity and NSA.

However, too many indicators without critical analysis and classification, create confusion and gives different IS analysis results. In some cases, companies or government might have limited tools and infrastructure to track and measure some of the IS indicators. Considering that IS provides environmental, economic and social benefits, the analysis of IS performance should be based on the evaluation of these natures. While some of the structural indicators such as (use of land, territory, quantity match between demand and supply) can be used to compare different IS networks across the country/region.

## 5. Industrial Symbiosis Integration into the Circular Urban Metabolism

Historically industrial zones were built in the suburbs outside of the central main city with limited living facilities and the residents remained concentrated in the city center [139]. In recent years, population in the suburbs is growing and industrial sites become a part of the city. Today, shrinking distance between industrial districts and cities incorporate industrial districts in cities material and energy flows by withdrawing the exclusion of industrial districts and cities frames.

IS incorporation in the CUM allows it to contribute economic growth and environmental benefits from reduced consumption of primary resources, reduced amounts of waste and emissions [140] in the city's systems. IS success is based on the mutual beneficial relationship of industrial entities where the city can be incorporated as a resource of knowledge, waste, infrastructure with coordination function for better improvement of IS and CUM. Close geographical proximity is a strong enabler of the physical position of entities [64,65,141] for IS. Cities have to deal with multiple challenges and develop sustainable measures [108] and with developed infrastructure and knowledge could gain mutual benefits from IS networks. Figure 5 illustrates the identified, structured, and mutually combined framework of IS networks and CUM in the city.

In this framework, IS is incorporated in CUM framework and helps improve cities and industry circularity by closing the urban loops. The CUM can help to understand the relations between urban and rural ecosystems along with IS networks and their urban flows interact within the spaces over time. Giving scientists and urban planners an understanding of how flows between ecosystems and IS networks have to be redesigned in a more sustainable way by using the CE model at the city and industry level, indicating less pressure on the local ecosystems, optimizing the supply chain demand, developing the connections between local supply chains to close loops.

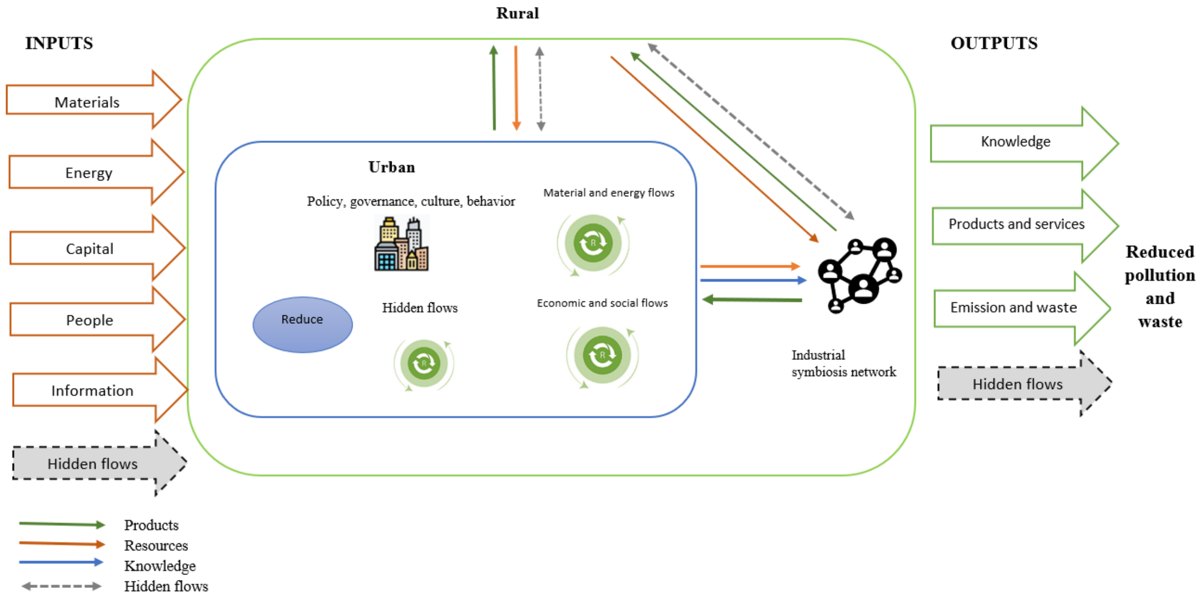


**Figure 5.** Circular urban metabolism framework in the context of industrial symbiosis (modified by authors [101,111,140]).

The indicators emerged from the analysis of circular cities and IS in Tables 4 and 5 neglected some strategic scopes identified in cities' circular documents. Considering the proposed framework of CUM with IS integration and identified main inputs and outputs, some indicators of CUM are proposed below (see Table 6). Some of these indicators have already been deducted from the CE and IS literature analysis, and from previously analyzed selected circular cities cases studies.

**Table 6.** Proposed indicators for CUM framework (prepared by authors).

| Type | Indicator |
|---|---|
| **Inputs** | *Materials and energy:*<br>Raw material demand per capita<br>Energy from renewable sources<br>Renewable resource demand per capita<br>Share of renewable sources<br>Energy imports<br>Energy consumption<br>Biofuel demand<br>Diesel demand<br>Gasoline demand |
| | *Products:*<br>Imported food<br>Imported agriculture goods<br>Imported woods<br>Imported sub-products<br>Imported e-products |
| | *Capital:*<br>Foreign direct investment<br>Investment in research and development<br>Investments in CE related projects<br>Government support to CE initiatives |

**Table 6.** *Cont.*

| Type | Indicator |
| --- | --- |
| | *People:*<br>Number of people working in city<br>Number of tourists<br>Number of immigrants from EU countries<br>Number of immigrants from non-EU countries |
| | *Information:*<br>Imports of IT equipment |
| | *Hidden flows:*<br>Energy used in imported products<br>Energy used in imported services<br>Water used in imported products<br>Renewable energy % in imported products<br>Renewable energy % in imported services |
| **Within city** | *Production:*<br>Used raw materials in production process<br>Regenerated water use in the production<br>Raw material productivity<br>Recycled material productivity<br>Used recycled materials<br>Material recovery rate |
| | *Consumption:*<br>Consumption of non-recyclable plastic in food packaging<br>Food consumption<br>Sales of organic and local food products<br>Domestic material consumption<br>Water consumption<br>Heat consumption (fossil fuels, biofuels, biomass, renewable sources) |
| | *Economy:*<br>Employment<br>Gross value added<br>Number of CE companies<br>Private investments to CE<br>Number of CE initiatives<br>Number of CE related start-ups<br>Community engagement to CE initiatives<br>Average household income<br>Population below poverty line<br>Household spending on product repair and maintenance<br>Number of patents<br>Number of patents related to recycling and secondary raw materials |
| | *Social:*<br>Population with middle or high education<br>Circular economy employment<br>Number of circular jobs<br>Number of jobs created from re-use activities<br>Number of CE programs in universities<br>Number of students trained in education field |

**Table 6.** *Cont.*

| Type | Indicator |
|---|---|
| | *Construction and building environment:*<br>Construction and demolition waste usage rate<br>Reused materials and products from construction and demolition waste<br>Recovery rate of construction waste as material<br>Number of projects incorporating smart design<br>Number of started buildings renovation projects<br>Number of ongoing renovation projects<br>Number of finished building renovation projects<br>Number of abandoned houses |
| | *Mobility and transport:*<br>Number of private cars in city<br>Number of electric private cars in city<br>Number of hybrid private cars in city<br>Number of diesel private cars in city<br>Number of gasoline private cars in city<br>Number of trucks in city<br>Number of population using public transport<br>Using of car sharing services |
| | *Industrial symbiosis:*<br>Number of IS networks<br>Number of companies participating in IS networks<br>Investments to IS networks<br>Number of persons employed<br>Saved primary resources<br>Reduced emissions<br>Recycled resources<br>Material recovery rate<br>Renewable energy produced in the IS system<br>GDP per capita generation |
| | *Environmental:*<br>Energy efficiency<br>Share of renewable energy in the city heating<br>Household water use<br>Household energy use<br>Households use of energy from renewable sources |
| **Outputs** | *Knowledge:*<br>Number of habitants working in another city<br>Total value of sold technologies and patents |
| | *Products and services:*<br>Objects collected and diverted for reuse<br>Objects recovered in reuse centers<br>Objects repaired<br>Repaired e-waste<br>Clothing recycling |

**Table 6.** *Cont.*

| Type | Indicator |
|---|---|
| | *Emissions and waste:*<br>$CO_2$ emissions<br>$CO_2$ emissions per capita<br>Carbon impact of waste<br>Annual average air quality particulate matter<br>Water lost<br>Energy lost<br>Wastewater<br>MSW generation<br>Recycling rate of MSW<br>Recycling rate of plastic packages<br>Recycling rate of glass packages<br>Recycling rate of metal packages<br>Recycling rate of e-waste<br>Recycling rate of construction waste<br>Recycling rate of bio-waste<br>Quantities of waste sent to landfill<br>Quantities of waste sent to incineration<br>Amounts of illegal dumping |
| | *Hidden flows:*<br>Energy used for exported products<br>Energy used for exported services<br>Water used in exported products<br>Renewable energy % in exported products<br>Renewable energy % in exported services |

Using knowledge from circular cities indicators cases analysis and lows identified in CUM framework, proposed CUM indicators are divided into three groups: inputs, indicators of flows existing within city and outputs and with further grouping inside inputs, outputs and within city. The city's indicators are grouped into: production, consumption, economy, social, construction and building environment, mobility and transport, IS and environmental groups. The main aim of indicators deduction—to propose easily understandable and measurable indicators considering different stakeholders within city, upcoming regulations from the Green Deal documentation package. Scientific literature proposes various lists of detailed indicators related to material and energy flows, waste generation. This paper focuses on presenting the main indicators related to flows inside and outside city and leaves the decision up to the cities when it comes to creating a more detailed indicator list according to their needs and specifics.

## 6. Empirical Support for Our Framework

In many studies, empirical evidence of the CE, UM, and IS described above are touched upon. Major factors having impact to CUM framework development are listed below:

- Policy programs from the EU and the national government are major conditioning factors. European Circular Economy Action Plan was adopted in 2015 and 2020 as a part of the new industrial strategy [11,31,67] to influence IS development. EU has an ambitious aim to become world's first climate-neutral continent by 2050 and cities will take the major role in this process because of the high concentration of resources, knowledge, and innovations in cities and their financial capabilities to implement drastic environmental changes in the urban planning process.
- Today, some countries and cities (the United Kingdom, Belgium, Sweden, Denmark, Spain, Netherlands) have already taken a leading role implementing public policies and initiatives for IS development [47,60,63,142–144].

- Some cities already measure the impact on the environment [102,145,146], metabolic relations between cities and rural regions [103] to model future metabolism under certain conditions and policies [103,147,148].
- Strategic partnership examples between industrial sectors and cities along with social and knowledge exchanges supporting CE implementation can be found in recent published studies. [15,71,78,84]. Numerous cases of IS can be found in Europe across different countries with planned and facilitated IS initiatives in the United Kingdom, Ireland, Netherlands, traditional manufacturing clusters with IS activities in Spain [75]. Haq et al. [71] discuss the synergy relationship between the regional municipality and the industrial and agricultural companies in the IS network in the Sodankylä region (Finland).
- IS, UM, and CE are often addressed in isolation in the context of sustainable urban planning, but the specific conclusions from various studies allow to combine those elements in CUM framework.
- CE, IS indicators analysis confirms that some cities (Rotterdam, Glasgow, Maribor) are taking first steps integrating IS indicators into CE framework. However, it is necessary to have integrated approach to consider the relationship between different metrics to avoid unintended side effects.

## 7. Discussion and Conclusions

Scientific literature review of CE, UM, and IS was used to identify key pillars and build the CUM framework. EU documents review on CE and IS, circular cities cases analysis was used to identify circular cities scope, indicators and main gaps measuring cities' circular transition. Circular cities analysis only confirms that cities are lacking common monitoring framework which not always address in the strategic documentation identified circular scope.

The CUM framework is quite new and lacks well-established scientific field of its own. While separate components of the CUM framework are widely discussed and analyzed from various perspectives, the CUM framework itself requires broader research and deeper data-based analysis. Future research will help to clarify these framework components and their inter-relations.

Resource management is the critical factor for sustainable development in cities in today's context and it will not lose the importance in the future. Cities must manage resources in a sustainable way to improve their economic development along with minimizing their environmental impact. Cities are not isolated, they are connected to other systems, their rural areas, and industry sector for resources, products, and services exchange. However, concentration to one system will simplify the analysis, but it can give misleading conclusions in the circularity and sustainability context. Resource weight and volume is not sufficient information to apply proper urban policy and take effective urban planning decisions, and social-economic indicators should be taken into consideration. Sustainable urban planning requires deeper analysis of resource location and flows (including hidden flows), their transition directions in the real-time perspective, how flows are connected. While UM focus on flow analysis for critical point identification for future improvement in cities, IS—on industrial sector cooperation opportunities for materials exchange to improve waste use, integrated framework of CE, UM, and IS could improve mutual relations of rural, urban systems and industrial sector. The ability to provide dynamic data for future urban planning scenarios will be an essential factor.

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