Towards Urban Symbiosis of critical raw materials - a conceptual paper

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Abstract. Regions and national economies are facing several challenges regarding raw materials. As cities and metropolitan areas are increasingly becoming hubs of economic activity, they may also play a role in addressing raw material challenges. Many eco-industrial parks are not only found in industrial areas but also in urbanised areas the concept of *urban symbiosis* may offer viable solutions to those challenges. Urban symbiosis builds on urban and regional metabolism and industrial symbiosis, providing a concept and analytical toolkit that can serve to develop strategies to create the more efficient use and circulation of critical raw materials (CRM), enabled by the integration of different and complex systems. This paper aims to review how urban symbiosis of CRMs has been approached and defined in the prior literature and what are the closely related concepts. One of our key interest areas is to understand what kind of roles cities can have in the urban symbiosis. Based on the results, we suggest future research topics such as exploring concrete models of collaboration and new ways of joint value creation in urban symbiosis ecosystems.

Keywords: Urban Symbiosis, Critical Raw Materials, Circular Cities, Conceptual Paper

1 Introduction

There is a major need to find efficient and innovative solutions to stem the loss of resources, including critical raw materials (CRMs), in the future economy. CRMs can be broadly defined as raw materials that are economically and strategically important for an economy but have a high-risk associated with their supply, which can include, for example, metals (e.g., tungsten, cobalt, magnesium), minerals (e.g., phosphorus) and gasses (e.g., helium) [1]. Applications that include CRMs are widely used in society, and notably, as these materials are needed in buildings, infrastructure, and high technology products nations need to secure access to CRMs. High-tech products are not often used efficiently, and their lifetime can be relatively short. As they are used predominantly in cities, the urban scale is an underexplored domain through which the societal value CRMs can be retained.

One viable solution for simultaneously minimising resource use and reducing pollution is the transition towards a circular economy (see [2]) through implementing the practice of urban symbiosis [3]. Prior research has shown that the circularity rate is not a sufficient indicator for optimising resource use and footprint minimisation. Instead, there is a need to combine different indicators, including the costs of different solutions and the evaluation of trade-offs [3].

1.1 Methodology: Conceptual paper

The aim of the conceptual paper is to interlink and integrate existing theories and concepts, providing multidisciplinary insights into the phenomenon [9]. Thus, the focus is on creating a bridge between different theories, rather than creating a new theory. A conceptual paper is a relevant approach when exploring a new, complex multidimensional phenomenon. We start by describing the state-of-the-art and exploring relevant questions for further study [10].

This paper concentrates on creating an understanding of urban symbiosis for CRMs and the role of the cities. We acquired published empirical studies through Scopus, Web of Science, Science Direct, and Google Scholar using multiple keywords to identify relevant articles [11]. The keywords included “Urban symbiosis”, “Industrial symbiosis”, “Metabolism”, “Critical raw materials”, “Circular City” and their combinations.

We started with a systemic approach, encompassing the concepts in sustainability literature, which relate to urban symbiosis and what it makes part of. Figure 1 gives our understanding of the concepts. We included a special focus on the metabolism of CRMs, which can be embraced by both Industrial Symbiosis, Urban Symbiosis, and Urban Mining (Fig. 1).

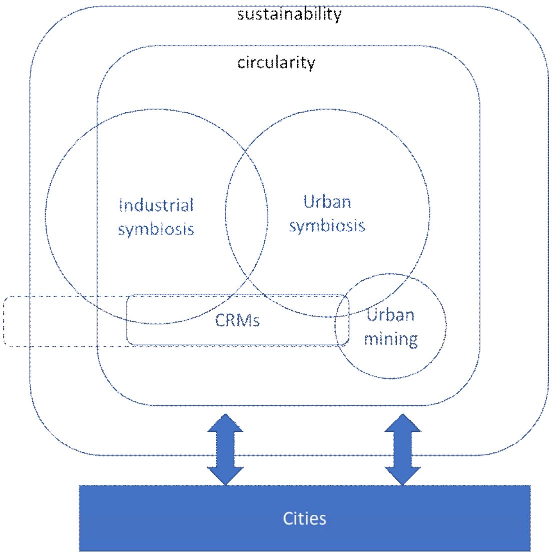

Fig. 1. Sustainability concepts relating to sustainable management of CRMs.

Taking a qualitative approach and using our prior knowledge, we selected the most relevant 33 articles. 28 were published in scientific journals (impact factor between 3-9), 3 in peer-reviewed books, and 2 in conference publications.

1.1 Aim of the study

Our objective is to study *how the urban symbiosis of critical materials has been approached and defined in the prior literature and what are the closely related concepts*. A key interest is to understand what roles cities can take in urban symbiosis. The role of cities as urban scale actors in retaining the value of CRMs is understudied and hence requires more investigation. The paper is structured as follows. Section 2 provides a brief literature review of industrial symbiosis, urban symbiosis, cities, and CRMs. Section 3 provides our synthesis and areas identified for future research.

2 Literature review

2.1 Industrial and urban symbiosis

Industrial symbiosis

Industrial Symbiosis (IS) has been studied over the last 25 years, yet during the last five-ten years, IS seems to have found a renewed impetus within the context of the Circular Economy (CE) [12]. The term "symbiosis" derives from the biology describing two different organisms living in a community that benefits both. Frosch and Gallopoulos [13] stated that an industrial ecosystem could operate analogously to a biological ecosystem. They suggested that in such an industrial system, the use of energy and materials are optimized, as the amount of waste and pollution is minimised. Based on this idea, industrial symbiosis (IS) has become a core part of the industrial ecology (IE) field [14]. Whilst IE takes a multi-level focus—on global, regional, local, and enterprise levels [15]—IS concentrates on enterprise linkages [16] One well-known example of such linkages is the Kalundborg IS, started in 1961 in Denmark [17].

Chertow [15] defines IS "as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity".

According to Chertow [15] input-output matching, stakeholder processes, and materials budgeting appear to be useful tools in advancing eco-industrial park development. Evolutionary approaches to industrial symbiosis are also found to be important in creating the level of cooperation needed for multi-party exchanges.

According to Momirski et al. [17], IS constitutes at minimum three companies that exchange at least two different sources creating a more circular than a linear process.

Similar to Chertow's [15] approach, the collaboration between different industry partners has been identified as an essential element for IS to create environmental and economic benefits [16]. Successful IS is often based on collaboration and synergies resulting from geographical proximity [15].

Laybourn [18], extends this definition by arguing that IS is not only for industries but also can include organisations such as research and government actors. Lombardi and Laybourn [19] highlight IS role as a business opportunity and tool for eco-innovation. IS operates in a network of eco-innovation-minded organisations that exchange knowledge, drive the process for cultural change and improve technical and business processes aiming to find joint value creation models. They suggest that geographic proximity might not play a crucial role in the exchange of physical resources [19]. Above all they see IS as a tool for innovative green growth and, ecological benefits should be seen as a result, not the driver. Summarising the discussion in the IS literature, IS becomes a model of sustainability when it manages four pillars: 1) eco-efficiency, 2) collaboration, 3) adaptability, and 4) Proximity [20].

Based on the barriers and enablers in IE literature Golev et al. [21] have identified seven enablers and enablers to industrial symbiosis: 1) organisational commitment to sustainability at the strategic level, 2), information (qualitative and quantitative) about waste streams and local industries' material/water/energy requirements to provide the starting point for the development of resource synergies, 3) cooperation and trust between key players for sharing of information and network development, 4) technical feasibility and knowledge, 5) understanding regulatory and legal frameworks are the drivers for synergy projects, 6) community awareness of the environmental and economic impacts that industries generate, and 7) both the positive economic outcome along with environmental benefits concretising as increased revenue, lower input costs, lower operational costs, and diversifying and/or securing water, energy, and material supplies. Yet, adding to Golev et al.'s [21] work, the development of industrial symbiosis may require significant investments in companies at the same time as the economic benefits will take time before materialising companies' financial performance. Table 1 summarizes the most important journal articles that were used in the literature review.

Table 1. Definitions and perspectives on industrial symbiosis

Definitions and perspectives to industrial symbiosis (IS)	Author
IS, as part of the field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. IS engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to IS are collaboration and the synergistic possibilities offered by geographic proximity.	Chertow, 2000
IS constitutes at minimum three companies that exchange at least two different sources creating more circular than linear process.	Momirski et al., 2021
IS not only for industries but also can include organisations such as research and government actors.	Laybourn, 2006
IS can also be seen as a business opportunity and tool for eco-innovation: IS operates in a network of eco-innovation minded organisations who exchange knowledge, drive the process for cultural change and improve technical and business processes aiming to find joint value creation models. Geographic proximity might not play a crucial role in the exchange of physical resources.	Lombardi and Laybourn, 2012
IS becomes a model of sustainability when it managing four pillars: 1) eco-efficiency, 2) collaboration, 3) adaptability, 4) Proximity (Diemer, 2009).	Diemer, 2009
Seven barriers/enablers to industrial symbiosis: Commitment to sustainable development , information, cooperation, technical, regulatory, community, economic	Golev et al., 2015

Urban symbiosis

Industrial symbiosis has been extended to the urban level, focusing on the exchange of urban waste and energy (Urban symbiosis). The concept of urban symbiosis was introduced only in 2009 by Van Berkel et al. [22, 23]. Thus, there are many more studies concentrating on IS or integrating IS and urban symbiosis perspectives than solely focusing on urban symbiosis [17]. Yet, cities are facing several challenges regarding raw materials, and because many industrial parks are not only industrial areas but also part of an urbanized urban area where people live, urban symbiosis can offer viable solutions to those challenges [14].

Urban symbiosis can be seen as an extension of IS and is defined as “the use of by-products (wastes) from cities (or urban areas) as alternative raw materials or energy sources in industrial operations” [17]. Much of the urban symbiosis emanates from Japan, where solid waste source separation systems are well established in municipal systems and uniquely suited to the Japanese core eco-urban program [24]. Van Berkel et al. [22] stress geographical location in their definition of urban symbiosis: “(it) covers specific possibilities arising from geographic proximity of urban and industrial areas to use physical resources discarded in urban areas (“wastes”) as alternative raw material or energy source for industrial operations”.

Both IS and urban symbiosis aims for waste recycling and a network of symbioses through feedstock savings and/or emissions reductions that provide obvious benefits to society as a whole [25]. The main difference between IS and urban symbiosis can be seen in the following way: as IS recognizes the exchange of waste resources and by-products between enterprises that do not normally cooperate in resource exchange; urban symbiosis recognizes the use of solid waste in cities as input sources for industries that do not normally accept these sources [25]. Urban symbiosis can be seen as a network of communities, in which industrial actors integrate the local needs to improve resource utilisation by exploring synergies in urban and industrial areas [26, 27]. Often the public sector facilitates the waste exchanges and firm/community interaction [28, 29].

Urban symbiosis is seen as a strategy toward more efficient metabolism of cities. To achieve urban symbiosis, the integration of several systems is needed, which often sets major challenges for renewing pre-existing systems and building new joint systems connecting novel areas. It can be stated that urban symbiosis is a physical, economic, and political challenge, but it also faces several other challenges including the complexity of managing the interests of all stakeholders involved [30]. Therefore, similar to IS, the collaboration between stakeholders plays a crucial role in enabling the transition towards urban symbiosis [7].

Reviewing sustainable urban development strategies for eleven cities, Momirski et al. [17] show that the awareness of IS and urban symbiosis is rising, and there already exists legislative support that is aligned with EU legislation. However, they show the reuse of by-products either for energy or new products is almost totally missing or plays a trivial role. Table 2 summarises the discussion and perspectives on urban symbiosis.

Table 2. Definitions and perspectives on urban symbiosis

Definitions and perspectives to Urban Symbiosis	Author
Urban symbiosis can be seen as an extension of IS and is defined as the "the use of byproducts (wastes) from cities (or urban areas) as alternative raw materials or energy sources in industrial operations"	Dong, 2014
The term urban symbiosis covers specific possibilities arising from geographic proximity of urban and industrial areas to use physical resources discarded in urban areas ("wastes") as alternative raw material or energy source for industrial operations.	Berkel et al., 2008
Both IS and urban symbiosis aim for waste recycling and a network of symbioses through feedstock savings and/or emissions reductions that provide obvious benefits to society as a whole. The main difference between IS and urban symbiosis is that as IS recognizes the exchange of waste resources and by-products between enterprises that do not normally cooperate in resource exchange; urban symbiosis recognizes the use of solid waste in cities as input sources for industries that do not normally accept these sources.	Chen et al., 2011
Urban symbiosis is seen as a strategy towards more efficient metabolism of cities. In order to reach urban symbiosis, integration of several systems is needed, which often sets major challenges for renewing pre-existing systems and start building new joint systems connecting novel areas. Urban symbiosis not only sets physical, economic, and political challenges, but it also faces several other challenges including the complexity of managing the interests of all stakeholders involved.	Mulder, 2017

2.2 Urban Symbiosis and cities

The circular city

While industrial symbiosis is seen as a business-focused collaborative approach, the circular city plays a key role in evolving urban symbiosis systems. Cities consume about 75 % of global resources, emit 50-70 % of all greenhouse gases and generate 50-70 % of global waste [31, 32]. Cities are, thus, a potential source of secondary materials and can play a significant role in recirculating critical resources, thereby supporting the resilience of societies and diminishing the extraction of virgin sources. Indeed, the EU Urban Agenda presents 12 priority themes concerning the crucial in the development of cities, one of which is circular economy (CE). City-level actions are seen as essential in encouraging businesses and consumers in adopting circular modes of thinking and doing, putting local governments in a unique position in facilitating a transition from a traditional linear economy to a more sustainable circular one (European Commission, 2021). Cities have a density and concentration of producing businesses and consuming citizens that generate material and resource flows with circular potential. Moreover, many cities also have a scale that, on the one hand, enables quick decisions, having the power to regulate and incentivise, and, on the other hand, is large enough to enable the establishment of new circular city functions and services, and circular business models [32]. However, cities often tend to view themselves as facilitators, disinclined to risk the investment into new circular infrastructure themselves and provide little funding for CE initiatives [33].

Paiho et al. [34] pointed out in their conceptual work the lack of a single definition of a 'circular city', but several components of urban circularity have been proposed. The European Investment Bank has described a circular city as one that conserves and reuses resources and products, shares and increases the use and utility of all assets, and minimises resource consumption and wastage in all forms [32].

The International Council for Local Environmental Initiatives [35] defines a circular city as one that promotes a just transition from a linear to a circular economy across the urban space, through multiple city functions and departments and in collaboration with residents, businesses, and the research community. Moreover, Williams [36] highlighted seven circular strategies – looping, localisation, substitution of resource-intensive materials and products, adaptation, sharing, optimising, and regenerating natural capital to operate together to deliver the circular city.

Cities' role in urban symbiosis

With the increased resources being concentrated in cities, they can be seen as urban mines. With the increasing amount of waste generated within cities, the city as an urban mine creates the market potential for recovered materials. Moreover, considering the metal criticality, the importance of extending the lifetime of products containing CRMs, and recovering and recycling CRMs containing waste gathered in urban mines is increasing [37]. In this context, the collection of waste electrical and electronic equipment (WEEE), the main urban flow containing critical metals, has achieved much attention lately. The significance of this potential resource will also likely increase with shifts concerning energy production and consumption.

With the regeneration of cities, acceleration of renewable energy production technologies, including wind and solar technologies, has taken place, and, related to this trend, new technologies for more efficient electricity consumption patterns have emerged [38]. With increasing smartness, relating i.e. to energy use, cities are also becoming more reliant on the use of critical raw material [39].

2.3 Critical raw materials

Ensuring a sufficient raw material supply to meet demand is seen as economically important in many countries and regions. In Europe, EU level CRM listing arises from the growing concern of securing valuable raw materials for the EU economy. The actions taken to support raw materials supply, the European Raw Materials Initiative was launched in 2008, followed by establishment of a list of CRMs at the EU level.

The needs, economic importance, and geopolitical relations evolve, leading to updates. The current (fourth) list (2020) contains 30 CRMs that are particularly important for high-tech products and emerging innovations and therefore of high economic concern [40]. For example, transitioning to a low carbon society with low carbon technologies and to a data economy with increased digitalization will entail an increased use in CRMs containing components such as batteries, magnets, PCBs, etc.

The EU methodology for CRMs relies on a criticality assessment of raw materials. In this assessment, supply risk is considered to be related to recycling (End-of-Life Recycling Input Rate), substitutability (Substitution Index), and the Herfindahl Hirschman Index [41]. Actions minimizing supply risk taken through secondary raw materials and substitution are widely used and actions to increase the overall circularity of CRMs may substantially reduce supply risk. Actions taken to support life-time extension through circular economy business models would both decrease the need for new products, and CRMs and support the collection and proper cycling of CRMs.

3 Conclusions and future research areas

The literature review highlighted several perspectives on urban symbiosis. Urban symbiosis is a strategy toward a more efficient metabolism of cities and, thus, can offer significant sustainability improvements. However, significant challenges (such as physical, ecological, political challenges, and stakeholder involvement) must be overcome (e.g. [42]).

Our proposition for urban symbiosis builds on urban and regional metabolism (see [4, 5]) and industrial symbiosis [6], serving as a concept and analytical toolkit to develop strategies for the efficient use and circulation of CRMs enabled by the integration of different and complex systems (cf. [7]). Urban symbiosis starts with understanding the metabolism of CRMs—how CRMs flow through cities and their different systems—and moves beyond an empirical exercise, analysing CRMs flows through cities wealth-creating subsystems to develop novel business ecosystems. Urban symbiosis emphasises the disruptive value-adding collaborative models, and resource dependencies between businesses, organisations, and consumers within cities.

For CRMs in high technology products, the urban symbiosis approach starts with understanding the metabolism of CRMs and the actors involved in their governance (public, private, and consumers) and then developing business ecosystems, circular supply chains, and city-level policy strategies that are tailored to their institutional context. Urban symbiosis emphasises the resource dependencies between actors within a city and, thus, a need for the co-evolution of institutionally embedded value co-creation and policy process [8]. Urban symbiosis would offer a possibility to increase the sustainable circularity of CRMs through city-level actions, notwithstanding the global nature of supply chains and the systemic changes required.

There are several barriers and enablers identified in the IS context, and many of them also apply to the urban symbiosis context (e.g. [21]). For example, the role of collaboration between different stakeholders is highlighted in both IS and urban symbiosis contexts and CE in general. Thus, the concrete models of collaboration to accelerate the urban symbiosis of CRMs requires further research area. The role of the city in accelerating the transition towards circularity and models for collaboration and common interests of private companies and public organisations also requires investigation. Understanding of different value creation models for different actors as well as the sustainable value in general in urban symbiosis-based ecosystems would be needed to accelerate the transition process. Furthermore, more research and understanding, in general, is needed on the real cases, barriers, and enablers in implementing urban symbiosis of CRMs to create a concrete understanding of the phenomenon.

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