Urban Metabolism as Framework for Circular Economy Design for Cities

Yuliya Kalmykova and Leonardo Rosado

Department of Civil and Environmental Engineering, Chalmers University of Technology, 412 96, Gothenburg, Sweden

Speaker: Yuliya Kalmykova and Leonardo Rosado

Corresponding author: Yuliya Kalmykova, yuliya@chalmers.se

Abstract

Circular economy (CE) principles can be applied at different scales: from materials to products, from individual supply chains to industries, from cities to national and transnational economies. In order to design a CE at any scale, a system approach is needed to describe and analyse the current situation and to model and implement the transformations required. In this paper we show how Urban Metabolism (UM) research can support the design of CE in cities. Urban metabolism considers resource consumption and environmental pressure of urban areas in a systemic way. The Urban Metabolism Group at Chalmers is developing three alleys of research: UM description, analysis and sustainable UM design. Findings from each of these may inform CE design by for example: quantifying resource flows at the product and material levels and with respect to industries and other sectors using them; identifying possible links between stakeholders with suitable materials and infrastructures; connecting material flows with life cycle impacts for multidimensional priority setting; depicting the drivers of material flows; and modelling policy effects on material flows. In this way, urban metabolism research can provide a comprehensive framework to investigate the pathways to circularity at both the urban and regional level.

Keywords: industrial symbiosis, material flow analysis, life cycle assessment, typology, policy.

1 Introduction

The vision of a sustainable city includes modern buildings and vehicles, a vibrant economy, urban ecosystems and healthy living. In addition, the city's pressure on the local and global hinterlands is expected to be minimized. In reality, the trend is towards growing pressure from urban areas on their hinterlands, as a result of an increase in resource intensity due to growing populations and an increasing affluence of urban dwellers. To control the resource consumption in cities, the Urban Metabolism (UM) must be managed, with the aim to reduce the pressure put on hinterlands, whilst still achieving the vision described above. Implementation of a Circular Economy (CE) at the urban level is one of the factors in a sustainable urban metabolism and could decrease the pressure caused by cities - through more efficient use and reuse of resources – while also supporting the economy. Knowledge about the UM also makes it possible to identify opportunities for CE design and for CE progress monitoring. To the best of our knowledge, the discourse of using an urban metabolism framework for CE design has not yet been discussed in the literature. Although numerous UM studies have been carried out (Kennedy et.al. 2007, Zhang 2013), very few have considered circular economy implementation. One exception is the CE promotion law in China (2009) where a Circular Economy is to be implemented at 3 functional levels of circular economic activities: firms/companies, eco-industrial parks and eco-city/municipality (Yung, 2006).

The Urban Metabolism group at Chalmers University of Technology, Sweden is developing methods and tools for three steps that will aid the decision-making process required to achieve a circular economy: description, analysis and circular economy design. This paper describes the Urban Metabolism group's vision for how UM knowledge can contribute to CE design, with examples of relevant findings within UM research.

2 Urban metabolism as framework for Circular economy design for cities

2.1 Urban metabolism description

Urban Metabolism is used as a metaphor for the resource consumption of cities, as it requires input of energy and materials to exist and grow just like a living organism, and also produces waste (Wolman, 1965). Urban metabolism research includes systematic studies of the inputs, outputs and storage of energy, water, nutrients, materials and wastes for an urban region.

This chapter describes UM research directions, including the description, analysis and design of a sustainable urban metabolism, and the contributions each of these could make to the design of a circular economy (see Figure 1 for the defined framework).

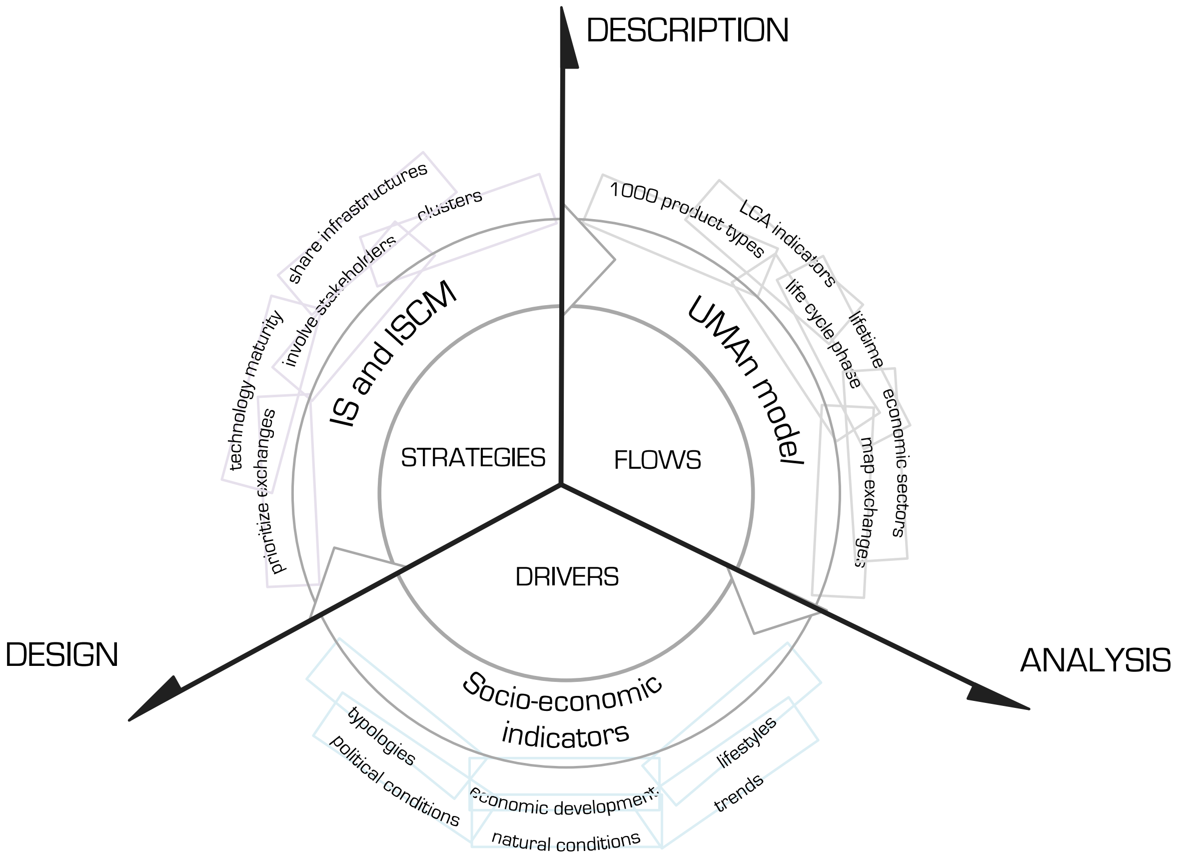

Figure 1: *Urban metabolism framework for Circular economy design*

Note: IS – Industrial Symbiosis, ISCM – Integrated Supply-Chain Management, UMAn – Urban Metabolism Analyst model, LCA – Life Cycle Analysis

2.1.1 Material Flow Analysis

Currently available urban metabolism research mostly involves systematic description of resource flows (Kennedy et. al. 2007, Kennedy et.al. 2011 and Zhang 2013). A commonly used method is Material Flow Analysis (MFA), which is a systematic assessment of materials, and their stocks and flows, over time and space, within a defined system (Brunner and Rechberger, 2004, Eurostat 2001, Kalmykova et.al. 2015A). Until recently, the quantification of urban material flows has been limited to the identification of highly aggregate indicators, such as Domestic Material Consumption[1] (DMC) and Domestic Material Input[2](DMI). These indicators represent high level material classes, commonly divided into 5 material types - Fossil Fuels, Biomass, Metals, Non-Metallic Minerals and Ores, and Chemicals and Fertilizers (Barles 2009, BFF 2002, Hammer and Giljum 2006). Domestic Material Consumption and DMI can be analysed in relation to GDP in order to investigate the resource-intensity of the economy, thereby helping to measure the overall effects of a circular economy (Kalmykova et.al. 2015B). However, using such aggregated data considerably limits its usefulness for decision-making processes, in particular processes related to CE design. For example, knowing the amount of metallic minerals imported to an urban area is not useful to decision-makers trying to determine whether to use local resources, as the stage the materials are in is not known; they may be entering as raw materials or embedded in products. The types of materials included are also unknown; this could be aluminium, steel or copper for example. With this in mind, the Urban Metabolism Analyst model (Rosado et al. 2014) was designed to enable approximately 1,000 different product types to be accounted, at all the different flow stages (inputs, stocks and outputs), thereby providing a solid basis for the design of interventions.

Different stakeholders in urban areas have different goals, and also different ways of influencing changes in the urban system. It is therefore vital that a proper quantitative description of the urban system takes this into account. The UMAn model also attributes quantities of products to different economic sectors, ranging from agricultural and forestry to industrial, construction, utilities and services, as well as final consumers, such as households and the public sector. This gives an understanding of who is responsible for the consumption of which products, and at what amounts, providing critical information for establishing appropriate goals for resource use reduction.

2.1.2 Life Cycle Assessment enhanced Material Flow Analysis

Material flow analysis indicators do not include upstream hidden flows related to imports, production and exports of raw materials and products. However, knowledge of hidden flows and their environmental impact in general is essential for correct priority setting in the management of material flows. For example, aggregate is, by mass, one of the most important resources consumed in a city, however, its environmental impact is much lower than that of the small flows of rare metals. It is therefore important to weight mass flows with their environmental impacts in order to identify correctly those products and materials that ought to be the focus for reduction, substitution and more effective use.

Environmental impact studies generally focus on prioritising materials and products using Economic Input-Output Life Cycle Assessment (EIO-LCA) (Tukker et.al., 2006). In particular, priority materials and products at the global level have been identified by the International Resource Panel of UNEP (UNEP, 2012) and for the EU by the Joint Research Centre (Tukker

---

[1] Direct Material Consumption (DMC) is defined as the total amount of material directly used in an economy, i.e. it equals domestic extraction plus imports minus exports (Eurostat, 2001).

[2] Domestic Material Input (DMI) summarizes domestic extraction and the imports, i.e. all materials that are used in production and consumption activities (Eurostat, 2001).

et.al., 2006). The EIO-LCA method has several limitations, such as being aggregated into a small number of sectors, for which the environmental impact is given as an average for the sector. In contrast, combining detailed MFA with LCA would allow evaluation of the environmental impact of specific materials and products. This type of MFA-LCA method is currently being developed by the Urban Metabolism Group at Chalmers in partnership with the IVL research institute, using the environmental impact of cities as a case study. In particular, an LCA database for products relevant to urban consumption, as defined by urban MFA results, is being compiled and the two datasets combined to generate weighted environmental impacts from consumption in individual cities. This provides a base scenario that can then be modified according to specific environmental measures with effects on consumption at the urban level allowing assessment of different measures.

This method has the potential to become important as there is a lack of methods for accounting the total environmental life cycle impacts of the metabolism of cities (Minx et.al. 2011). A small number of studies looking at CO_2 emissions caused by urban consumption use national average consumption data and EIO-LCA (Bolin, 2013). As a comparison, the developed MFA-LCA method is based on actual and detailed consumption at the city level and comprises five different environmental impact categories.

2.2 Urban metabolism analysis

The analysis of urban metabolism includes studies on how cities develop over time and how material flows are affected by different factors such as: lifestyles, economic and political conditions, as well as natural conditions. Urban metabolism analysis provides several ways to evaluate the effect of policies and to set priorities for policy development.

To begin with, potential pathways to decrease dependence on external inputs, non-renewable and virgin materials can be identified. For example, a study of Swedish cities found imbalances between the types of materials extracted, consumed and stocked, something that can make urban areas vulnerable to external changes in resource supplies (Rosado et. al. 2015). In order to increase the resilience of cities, the availability of domestic materials should be increased by, for example, circular economy strategies.

Additionally, using Sweden as an example, it has also been noted that policies implemented in the last two decades focused almost exclusively on energy and CO_2 emissions reduction, whereas the consumption of materials has been allowed to grow unchecked (Kalmykova et.al. 2015A). An increase in the material consumption also causes increased indirect (embodied) CO_2 emissions and additional waste. For this reason, it could be argued that it is time for both policy focus and investments to shift towards a reduction in the consumption of raw materials, and, in turn, indirect CO_2 emissions. In this respect, improved material recycling is a low-hanging fruit in the efforts to reduce the dependence of cities on external and non-renewable resources and decrease materials inputs. Currently, more than 80% of the consumed recourses are non-renewable and a circular use of materials is needed. In addition, urban waste, potentially a secondary resource, corresponds to 30% of the DMC, but only half of this is currently recycled to materials. However, instruments that limit consumer demand for new products must also be implemented, partly due to the fact that recycling rates are improving at a much slower pace than the growth in consumption. The demand may in part be satisfied by such CE strategies as reuse and remanufacturing, as well as by a sharing economy.

UM studies, on the other hand, point to resources and materials that could be used more effectively in a circular economy. For instance, the consumption of construction materials has been shown to grow exponentially in Swedish cities. Moreover, construction materials contribute up to 75% of the materials throughput, and are mostly of a non-renewable nature. UM findings suggest that construction materials is a potential focus area in order to reduce materials throughput and increase materials cycling. In fact, economically viable technologies exist for reuse, remanufacturing and recycling of construction materials. In addition, construction materials can be supplied from industrial residues of different kinds, for example through industrial symbiosis schemes. More efficient and multiple-purpose use of the existing building stock should be developed.

Another example that requires attention is the observed exponential growth in the consumption of new electronics (Kalmykova et.al. 2015A,B). This consumption may also be reduced by CE and in particular by promoting repairs of electronics (Extended Use), the second-hand market (Reuse), and Remanufacturing. The consumption of Textiles is also growing steadily and should be a focus for Reuse and Recycling.

2.3 Circular economy design

Based on the Circular Economy concept, as defined by for example the Ellen MacArthur Foundation (2012), it can be suggested that the underlying key concept for Circular economy design relies on the application of strategies that induce changes in the system, towards reducing the needs for materials from outside the technosystem in question. There is a significant number of strategies that could be applied, but if they are selected disjointly from each other, negative feedback effects may occur and a seemingly good strategy could end up being a poor choice, due to increased impacts on the overall system and unwanted effects on another existing group of processes. It is therefore essential that a holistic approach is taken, which is quantifiable and able to trace not only the direct benefits of putting a strategy in place, but also the overall effects on the system as a whole. Material flow analysis, and UM studies in particular, offer such a holistic and quantitative approach for the design of a circular economy. As already explained in the Analysis chapter, urban metabolism can be used as a tool for identifying opportunities for a circular economy.

Our current work considers the identification and evaluation of Industrial Symbiosis (IS) opportunities at the urban and regional levels, using urban and regional MFA. One project identifies the potential clusters for CO_2 reuse in the Gothenburg Metropolitan area. The overall objectives are to: i) Locate and quantify CO_2 emissions from stationary sources; ii) Characterize and evaluate the CO_2 containing flue gases; iii) Quantify the current CO_2 use; iv) Identify new opportunities for CO_2 reuse; v) Prioritize technologies with more potential to be implemented in the region; vi) Identify clusters for CO_2 exchange, and; vii) Identify missed opportunities. Another study, for the Gothenburg North East case, focuses on the development of circularity for farming activities. The main stakeholders of four product supply chains have been mapped and links established between producers, distributers and consumers. Five resources were identified as having the greatest potential for sharing, which would involve six different stakeholders. In another study for Sotenäs municipality, where an IS plan is currently being implemented, the method allowed mapping of the planned symbiosis from the perspective of the entire supply chains. This provided valuable information for a second development stage that involves the expansion of symbiosis to distribution and consumption stakeholders. Furthermore, it also allowed the compilation of CO_2 savings.

3 Conclusions

Resources will be required to refurbish existing and construct new cities, as well as to meet the needs of a growing urban population. To reduce the ever increasing resource flows to cities and the corresponding environmental impacts, sophisticated management of the urban metabolism is required. A circular economy, which would reduce the need for materials from the hinterland, is one of the most promising approaches to UM management. In addition, as discussed in this paper, UM knowledge can inform circular economy design in many ways.

In particular, UM description studies, which involve MFA as well as assessment of the embedded flows and impacts, could contribute by: i) Quantification of the flows of resources at the product and material levels, which are basic units for CE design; ii) Looking at the distribution of flows to different economic sectors, including specific industries and other users. This allows identification both of the entities responsible for the flows and of the contributions they can make to the CE. In addition, the flows from different entities can be matched and linked to enable increased resource circularity and sharing and iii) Understanding the environmental impacts of flows from an LCA perspective, which enables multi-target prioritizing.

Urban metabolism analysis, which considers trends in resource consumption and differences between cities, and evaluates the impacts of different factors on the metabolism, could contribute by: iv) Identification of the most important drivers for resource flows; v) Analysis of trends in flows and vi) Assessment of the effects of CE implementation, by, for example, indicators measuring total and specific resource consumption and by resource productivity (DMC/GDP) – total, by sector and by specific industries.

Current studies on CE design and implementation in cities explore industrial symbiosis (IS) application at the urban and regional scales. Two different approaches are being developed in parallel: 1) a top-down approach that identifies opportunities for IS based on clusters of industries with suitable material flows and 2) a bottom-up approach originating from the interest of certain industries in implementing IS and seeking to identify relevant stakeholders and resources.

References

Barles, S. 2009. Urban metabolism of Paris and its region. Journal of Industrial Ecology, 13 (6): 898-913.

BFF (Best Foot Forward) 2002. City Limits. A resource flow and ecological footprint analysis of Greater London. http://www.citylimitslondon.com. Accessed March 2007.

Bolin, L., Larsson, J., Sinclair, R., Hellström, P., Palmestål, K., Svensson, I.-L. and Mattsson, B. (2013) Klimatomställning Göteborg. Tekniska möjligheter och livsstilsförändringar. Mistra Urban Futures Reports URL

Brunner, P. H., Rechberger, H. (2004). Practical handbook of material flow analysis. The International Journal of Life Cycle Assessment, 9(5), 337-338.

Ellen MacArthur Foundation (2012): Towards the Circular Economy (1) – Economic and business rationale for an accelerated transition

Eurostat, 2001 " Economy-wide material flow accounts and derived indicators - A methodological guide", Eurostat, http://ec.europa.eu/eurostat/documents/3859598/5855193/KS-34-00-536-EN.PDF/411cd453-6d11-40a0-b65a-a33805327616

Hammer, M. and Giljum, S., 2006. Materialflussanalysen der Regionen Hamburg, Wien und Leipzig. (Material flow analysis of the regions of Hamburg, Vienna and Leipzig) NEDS Working Papers #6 (08/2006), Hamburg, Germany.

Kalmykova, Y., Rosado, L., Patrício, J. (2015A) Urban economies resource productivity and decoupling: metabolism trends 1996-2011 in Sweden, Stockholm and Gothenburg. Environmental Science & Technology. http://dx.doi.org/10.1021/acs.est.5b01431

Kalmykova, Y.; Rosado, L.; Patrício, J., (2015B) Resource consumption drivers and pathways to reduction: economy, policy and lifestyle impact on material flows at the national and urban level. J Clean Prod **2015,** doi:10.1016/j.jclepro.2015.02.027

Kalmykova, Y.; Patrício, J., Rosado, L. and Ber P.EO. (2015C) Out with the old, out with the new–The effect of transitions in TVs and monitors technology on consumption and WEEE generation in Sweden 1996–2014, Waste Management, doi:10.1016/j.wasman.2015.08.034

Kennedy, C.; Cuddihy, J.; Engel-Yan, J., The changing metabolism of cities. J Ind Ecol 2007, 11 (2), 43-59.

Kennedy, C.; Pincetl, S.; Bunje, P., The study of urban metabolism and its applications to urban planning and design. Environ Pollut 2011, 159, (8-9), 1965-1973.

Minx, J.; Creutzig, F.; Medinger, V.; Ziegler, T.; Owen, A.; Vbaiocchi, G. (2011) Developing a pragmatic approach to assessing urban metabolism in Europe: A Report to the Environment Agency.

Rosado, L., Kalmykova, Y., Patrício, J. (2015) Establishing differences and similarities for three different urban typologies in Sweden using MFA indicators to describe urban metabolism properties. Under review.

Rosado, L., Niza, S., Ferrão, P. (2014) A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model. Journal of Industrial Ecology 18 (1): 84-101

Tukker, A.; Huppes, G.; Guinée, J.; Heijungs, R.; de Koning, A.; van Oers, L.; Suh, S.;Geerken, T.; Van Holderbeke, M.; Jansen, B.; Nielsen, P. (2006) Environmental Impact of Products (EIPRO). Analysis of the Life Cycle environmental impacts related to the final consumption of the EU-25

UNEP (2012) Responsible Resource Management for a Sustainable World: Findings from the

Wolman, A., The Metabolism of Cities. Scientific American 1965, 213, 179.

Zhang, Y. 2013. Urban metabolism: A review of research methodologies. Environmental Pollution 178(0): 463-473.

Yuan, Z., Bi, J. and Moriguichi, Y. 2006. The Circular Economy: A New Development Strategy in China. Journal of Industrial Ecology, 10: 4–8.