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Reprint of: Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden

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A B S T R A C T

Knowledge about the characteristics and driving forces of material flows in urban areas is crucial, as the pathways towards sustainability depend on local conditions. Currently, Urban Metabolism research focuses on the analysis of trends and transitions in different stages of city development, on developing classification systems and identification of metabolism profiles for urban areas.

A novel framework for characterizing cities metabolism is provided using Urban Material Flow Accounting indicators as the basis. A Material Flow Accounting study is conducted for three cities in Sweden, from 1996 until 2011: Stockholm, Gothenburg and Malmo. Based on the urban metabolism characteristics framework, three distinct profiles are proposed: consumer-service; industrial; and transitioning.

Stockholm's material needs are mainly for final consumption. When compared with the other two cities, material flows follow a more stable trend and have lower dependency on external systems due to the marginal production and export of goods.

Gothenburg has the most resource intensive metabolism. It requires several times larger material inputs than the other two cities and produces much larger outputs, for benefit of the rest of the country and the world. Consequently, CO_2 emissions are higher in Gothenburg.

Malmo characteristics are more complex than Stockholm's with higher material needs in particular construction minerals. Its dependency on external flows is low, due to the fact that the economy and exports are based on domestically extracted Non-Metallic Minerals and Biomass.

1. Introduction

Urban areas are responsible for 75% of the global resource and energy consumption and 80% of the global CO_2 emissions (UNEP, 2012). The material flows consumed or extracted for consumption in urban areas represent potential ecosystem impacts on scales ranging from local through regional to global (Bai, 2007). At the same time, urbanization is expected to increase even further, from the current 54% to 75% in 2050 (United Nations, 2011). The decoupling of the economy from the material consumption has been described in the literature as a prerequisite for Sustainable Development (United Nations, 1992; von Weizsacker et al., 2009). Sustainability efforts in urban areas should therefore strive to reduce the metabolic flows (resource inputs and waste outputs) (Newman, 1999). Economic and Material Flow Accounting (MFA) indicators have already been used in economy-wide decoupling discussions, recently also for urban areas (Kalmykova et al., 2015b).

The study of the resource consumption and environmental pressure of urban areas in a systemic way falls within the scope of Urban Metabolism (UM). This field of research has become increasingly important in the last two decades, developing applications for Sustainability Indicators, Greenhouse Gas Accounting, Policy Analysis, Design and Material Flow Accounting. Kennedy et al. (2011) and Zhang (2013) provide reviews of the history, methodology and applications of Urban Metabolism.

The research focus is currently being shifted from methodology development and case-studies for different urban areas to the analysis of trends and transitions between stages of urban development (Kalmykova et al., 2015b; Bai et al., 2009; Schulz, 2007) and the development of classification systems for urban areas and their resource consumption profiles (Fernandez et al., 2013). The objective of such research is to go beyond simply describing the UM to the engineering and design of a sustainable UM. Kennedy et al.

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(2007) suggest that urban material flows may vary with age, stage of development and cultural factors, and that other differences can be associated with factors such as climate and population density. Fernandez et al. (2013) explore methods for classification of cities based on statistical analysis of urban resource use and socioeconomic data. Two preliminary typologies, of different degree of detail, are suggested after analysis of 155 cities worldwide. The typologies illustrate the main modes that cities fall into, but are also suggested to show a transition between one state and another. Weisz et al. (2006) also made an investigation about the relationship of overall and disaggregated Domestic Material Consumption in the EU-15 countries with several indicators, such as, percentage share of the tertiary sector in the overall GDP, population density, per capita GDP and final energy consumption. Another study, made by Kalmykova et al. (2015a) investigated the effect of the drivers of consumption such as, population density, educational level, income, car ownership, residential floor area and number of new constructions has on material consumption.

Knowledge about the resource consumption profiles of urban areas, and more importantly, the UM characteristics and driving forces resulting in different profiles, is crucial because the pathways toward urban sustainability are dependent on local traits and conditions (Ferrão and Fernández, 2013). Different types of urban areas may deploy different strategies for growth, and respond differently to material flow policies. It is possible that a reduction in material flows can undermine the resilience of an urban area dependent on material flows and affect its chances of persisting over time.

There is, however, a shortage of suitable data to inform material flows governance because the lack of detailed characterization of the urban metabolism of cities (Barles, 2010) that prevents us from benefiting from the identification of resource consumption profiles. Therefore, a systemic and detailed identification of interactions between society and the biosphere in urban areas (e.g. consumption of resources and emissions, and the depletion of non-renewable materials) is imperative to understand urban metabolism characteristics.

Understanding the UM characteristics is also important if we want to start studying the potential effects of material flows on the resilience of urban areas, and possibly determine if they can (Grimm and Wissel, 1997): remain essentially unchanged; return to the reference state (or dynamic) after a temporary disturbance; and persist through time.

The aim of this study is to contribute to the discourse on urban area typology as well as on identifying UM characteristics. The main objective is to identify those metabolic characteristics of urban areas that result in distinct resource use profiles by comparing three urban areas in Sweden. The study also wants to contribute to the discussion on how to evaluate the resilience of urban areas.

2. Method

In this article we present a methodological framework to identify urban metabolism characteristics based on the urban MFA indicators. The MFA indicators for the urban level are accounted using the UMAn model, created by adoption of Economy Wide MFA principles (Eurostat, 2001) to allow a standard detailed accounting of material flows at the urban level (Rosado et al., 2014). Energy carriers and materials are included in the accounting, but water is not considered in the method.

Eight UM characteristics were determined allowing the identification of distinctive urban metabolism profiles for the three metropolitan areas studied. Combining the MFA indicators makes it possible to begin to identify benchmarks for resource consumption and provides guidance as to the types of metabolism urban areas can have, based on generic information.

2.1. Urban material flow accounting

Material Flow Accounting (MFA) is a systematic assessment of materials, and their stocks and flows, over time and space, within a defined system (Brunner and Rechberger, 2004). To perform a MFA at urban level, all the Imports from the rest of the country (i.e. national) as well as from other countries (i.e. international), per means of transport (road, air, water and train) have to be accounted. The Imports, together with the Domestic Extraction within the studied territory (agriculture, fish, mining, etc.) will account for the total material Inputs. The Inputs can either be final products, or raw materials and intermediate products that will be used by the economic activities to produce final or intermediate products for the local consumption or export (Fig. 1). Materials that are imported being then exported, without being consumed or transformed are called crossing flows. The outputs are accounted including Exports to the rest of the country and other countries, wastes produced that leave the urban area, air emissions, in particular CO_2 emissions, dissipative flows and the solid part of the sludge. The net addition to stock is calculated using the lifespan of the products to predict if they stay accumulated in the urban area. For example, a product with more than one year of lifespan is considered to accumulate in the urban area. The described system can be simulated using the urban metabolism analyst (UMAn) Model (Rosado et al., 2014). With the exception of hidden flows, all Economy Wide MFA indicators were calculated using the UMAn model. The Material Flow Accounting (MFA) indicators considered are: Direct Material Input (DMI), Imports (Imp), Exports (Exp), Domestic Extraction (DE), Domestic Material Consumption (DMC), Net Addition to Stock (NAS), Industrial Production (IP), Domestic Processed Output (DPO), and Recovery.

All flows, except DPO and Recovery, have been accounted for 28 material types and aggregated into 6 broader material categories, using the ProdChar database (Rosado et al., 2014). The 6 broader categories are: Fossil Fuels, Metallic Minerals, Non-Metallic Minerals, Biomass, Chemicals and Fertilizers and Others, which include Non specified materials and Liquids. A comprehensive and rigorous quantitative analysis of the measurement errors and uncertainty associated with MFA data for the UMAn model was performed for the three metropolitan areas of Sweden (Patricio et al., 2015). DMC indicator has the highest uncertainty ranging from a minimum of 3.8% to a maximum of 22.6%, with a confidence interval with a probability of 0.68. Furthermore, the balance between inputs and outputs of the MFA for the three metropolitan areas ranges between 0.2% and 12.3%. for a detailed discussion on the causes for the unbalanced portion see the article by Patrício et al. (2015). The sources of data are provided in Supplementary Material I.

2.2. Urban metabolism characteristics framework

In this section the eight UM characteristics and the rationale for their construction are described. The characteristics are: Needs; Accumulation; Dependency; Support; Efficiency; Diversity of Processes; Self-Sufficiency; and Pressure on the environment. The MFA indicators used to describe the Urban Metabolism characteristics are summarized in Table 1.

(1) The Material Needs characteristic assesses the role of material flows in the economic development of an urban area. The indicators used for this characteristic are the DMI for the 6 materials – to understand the total needs of the urban area – and the DMC – to understand what proportion of the total needs goes to final consumption. It is important to highlight