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Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy

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ABSTRACT

The world's industrialised nations have accumulated a wealth of assets in the form of buildings, infrastructure and other durable goods. These assets constitute a valuable reservoir of secondary raw materials. This "anthropogenic material stock" should be understood as a future capital stock that must be systematically managed and exploited. Yet this capital stock has hitherto been largely ignored in discussions on resource efficiency, which instead have focused on inputs of primary raw materials. This is partly due to insufficient knowledge of the size and constitution of this material stock as well as its dynamics. Therefore, a project was set up by Germany's Federal Environment Agency to provide the missing information. Project results offer a comprehensive view of material stocks, inflows and outflows connected to durable goods. Thus we note an annual *per capita* growth in Germany's anthropogenic material stock of 10 t. In the last 50 years an estimated 42 billion tons of material has been added to the anthropogenic stock. Not all of this can be classified to primary groups of goods. Around 28 million tons of material has been consumed by buildings, infrastructure, building services as well as durable consumer goods. Of this figure, over 99% can be located in the built environment. This mass is approximately 79 times larger than the material mass currently consumed every year by these sectors. Annual outflow from the stock is around 0.8%. The annual rate of growth of the observed stock of goods is 0.5%. The various figures can be further broken down according to individual groups of goods and material groups. This knowledge provides the necessary foundation for the long-term monitoring of the anthropogenic stock and, moreover, is an important step in the evidence-based development of a model to incorporate and to improve closed-loop material flows as well as to support politics of securing supply of raw materials.

1. Introduction

1.1. *From a linear resource-intensive economy towards a circular economy*

"The circular economy is gaining increasing attention as a potential way for our society to increase prosperity, while reducing dependence on primary materials and energy" (SUN et al., 2015: 4). Initiatives to strengthen the circular economy are being pursued in many countries around the world (Moriguchi and Hashimoto, 2016). Under the German Resource Efficiency Programme, the role of the circular economy is promoted as one of four guiding principles (Federal Government, 2016a). Similarly, the EU Commission has drawn up a new Circular Economy Strategy, developed in the context of leading initiatives of the Europe 2020 growth strategy (European Commission, 2014, 2015). At an international level, the G7 group of leading industrialized nations has founded the Resource Efficiency Alliance, thereby committing to ambitious measures to protect natural resources and to improve resource efficiency. These efforts build on the Reduce-Reuse-Recycle framework of the Kobe 3R Action Plan as well as existing national initiatives (Federal Government, 2016b).

The transition to a circular economy necessitates fundamental changes to production-consumption systems. These challenges can only be overcome by greatly expanding our knowledge base and by developing a comprehensive analytical framework (Reichel et al., 2016).

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1.2. Relevance of the stock

The world's anthropogenic material stock grew continually throughout the 20th century. This trend continues until today (Krausmann et al., 2009; Haas et al., 2015). Whereas fossil fuels and biomass are largely consumed to produce energy or as foodstuffs/animal feed, the vast bulk of metals and mineral building materials is retained in the stock of durable goods such as buildings, infrastructure, consumer goods and capital goods for many decades (Gerst and Graedel, 2008; Müller et al., 2006). Such durable goods of the anthropogenic material stock provide services while also creating certain dependencies in regard to future raw material requirements. "Flows of resource inputs and waste outputs are driven by the need for services provided by stocks rather than the demand for flows themselves (Müller et al., 2004; Pauliuk and Müller, 2014)" (Baynes and Müller, 2016: 124). The basic strategy of managing and exploiting materials embedded in the anthropogenic stock is known as urban mining. Diverse authors understand this to be the integrated and interdisciplinary management of the stock in order to recover secondary raw materials from durable products, buildings and infrastructure that are no longer in use or will be retired from use in the near future, as well as from (also unmanaged) waste sites (Schebek, 2014; Rechberger, 2013; Brunner, 2011).

1.3. The metabolism framework

The notion of the "anthropogenic metabolism" was originally proposed by Baccini and Brunner (1991). They contrasted geogenic or natural fluxes of material and energy "run by solar energy and interactions of ecosystems" with anthropogenic fluxes "driven by man's biological and cultural needs" (Baccini and Brunner, 1991: 44). The concept of the anthropogenic metabolism encompasses all material and energy flows related to the production and consumption of goods. In addition, it considers stocks created through the accumulation of goods, which are viewed as resources to be exploited for future products (Baccini and Brunner, 1991: 112 ff.; Baccini and Brunner, 2012). Baynes and Müller (2016) describe man-made metabolisms using the concept of socio-economic metabolism. They interpret this term in "an inclusive sense that is synonymous with social (Fischer-Kowalski, 1998; Fischer-Kowalski and Weisz, 1999), industrial (Ayres, 1989) and anthropogenic metabolism (Baccini and Brunner, 1991)". Kennedy introduces an additional concept in the form of "urban metabolism" (Kennedy et al., 2007; Kennedy, 2016). According to Kennedy "urban metabolism can be seen as a scale-delineated component of socio-economic metabolism".

1.4. Methods to analyze stocks and flows at national level

Stocks and flows can be investigated using various methods of material flow analysis. These methods aim to quantify the material and energy flows of a particular socioeconomic system by examining the material inputs, stocks and outputs. One wide-ranging approach is that of economy-wide material flow accounting (ew-MFA). In its original design this simply relates imports and resources extracted domestically with outputs in terms of export flows from the system into other economies as well as emissions and waste flows back to nature (Fig. 1). Economy-wide MFA is employed at the macro-level, for example to investigate the connection between changing economic parameters and the consumption of physical resources as well as to allow international comparison (OECD, 2012). Eurostat has published methodological guidebooks and compilation guides to promote the standardization of economy-wide material flow accounts (Eurostat, 2001, 2013). Moreover, this approach has been conceptualized within OECD and UN Frameworks (OECD, 2007; UN, 2014).

Economy-wide MFA has been criticized for its limitations particularly in respect to the lack of material flow information within national economies (Giljum and Hubacek, 2010: 62). These weaknesses can be reduced by combining ew-MFA with environmentally extended input-output analysis (EE-IOA). Input-output tables take the form of so-called supply and use tables of economic activities, disaggregated by sector in order to analyze economy-environment relationships from a meso perspective (Giljum and Hubacek, 2010: 63). The resulting physical-monetary IO models allow the input of individual raw materials to be tracked through the entire production chain to the final product (Schoer and Schweinert, 2005).

Meanwhile, so-called 'Multi-regional Environmentally Extended Supply and Use/Input-Output Tables' (MR EE SUT/IOT) are now widely seen as a promising approach towards creating such an international accounting system by systematically linking national accounts (UN, 2014; Tukker et al., 2014; Wiedmann et al., 2013). While multiregional input-output analysis captures imports more precisely and better models interrelations and impacts at a global level, at the same time it offers significantly lower product detail with regard to the interrelations between production and consumption.

All of the methods discussed consider material flow volumes at various resolutions for a defined time-period, generally calendar years. Thus changes to the material stock can only be calculated at a fixed periodicity. Using conventional ew-MFA, it is possible to indirectly calculate balances or residuals such as the domestic material consumption (DMC) or net additions to stock (NAS). In theory, these parameters should specify the amounts of material consumed by the domestic economy or material that is accumulated and which can later usually be reused in some form. In view of the fact that the underlying variables for NAS and DMC (extraction, import, export, emissions) encompass a highly diverse range of materials in various compositions and types of processing, it is practically impossible to distinguish individual materials and goods. However, ew-MFA can be used to indirectly estimate the total material stock of system such as a national economy, supposing data from a sufficiently long time series is available. The more sophisticated approach of the EE-IOA offers improved analysis of the first, intermediate and final categories of use (Schoer et al., 2012). In particular, it can be used to classify resource consumption along the productive chain up to goods of final use (private consumption, investment in equipment, infrastructure, buildings, etc. as well as exports). However, until now these methods have either neglected the question of waste material or only integrated this in rudimentary form. Thus while material inflows into the stock can in principle be captured, outflows resulting from renovation, demolition or waste disposal are ignored.

The model limitations of the top-down MFA approaches can be considerably expanded by combining these with quantitative models that make use of coefficients. These bottom-up methods gather information on stock variables to estimate in-use stock and to infer the behavior of flows. These follow the principle: quantity of final good i in-use at time $t \times$ specific material content = material stock of a specific material (UNEP, 2010).

Coefficient-based bottom-up analytical methods have generally been applied to small spatial units to determine diverse stocks of goods and materials. The bottom-up approach offers a high degree of flexibility, whether for the description of flows or the analysis of material stocks. The precision of this method is determined by the particular stock of goods under investigation, the groups of goods chosen as representatives as well as knowledge of material compositions. As a great deal of work is required to investigate comprehensive baskets of goods, calculations are generally not exhaustive. For a recent overview see Ortlepp et al.