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Methodological and Ideological Options

Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050

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ABSTRACT

Assessing progress towards environmental sustainability requires a robust and systematic knowledge base. Economy-wide material flow accounting (ew-MFA) is an established method to monitor resource use across scales and its headline indicators are widely used in policy. However, ew-MFA is currently limited by its empirical focus on annual flows of material and energy, because it neglects the pivotal role of in-use material stocks of manufactured capital. Explicitly integrating in-use stocks enables new insights into a range of Ecological Economics' topics, such as the biophysical assessment of socio-economic systems, the circular economy and stock-flow consistent scenarios.

Herein, we conceptually and practically expand the ew-MFA framework towards jointly addressing material flows, in-use stocks of manufactured capital and waste, using a fully consistent dynamic model of Material Inputs, Stocks and Outputs (MISO-model). We review the stock modelling literature, propose a novel distinction of stock-driven versus inflow-driven approaches and situate the MISO-model as the latter. We then investigate the global dynamics of socio-metabolic flows and in-use stocks from 1900 to 2014, explore model sensitivities and quantify and attribute uncertainty. Two exemplary scenarios are presented. Through these innovations for ew-MFA, we enable a dynamic and comprehensive assessment of resource use, stocks and all wastes in the socio-economic metabolism.

1. Introduction

Developing and monitoring policies for sustainable resource use requires a systems understanding about the dynamics of economy-wide material and energy use, in-use stocks of manufactured capital, and the resulting wastes and emissions (Bringezu et al., 2016; OECD, 2015; UNEP, 2016). The concept of socioeconomic metabolism has been developed to investigate the biophysical basis of society from a systems perspective (Ayres and Simonis, 1994; Brunner and Rechberger, 2017; Fischer-Kowalski and Weisz, 1999; Pauliuk and Hertwich, 2015). The framework of economy-wide material flow accounting (ew-MFA) is an operationalization of this concept and is widely used to monitor resource use, inform policy and to assess progress towards sustainability (Bringezu, 2015; Fischer-Kowalski et al., 2011; Haberl et al., 2004; OECD, 2015; UNEP, 2016).

Conceptually, ew-MFA systematically covers the extraction of primary raw materials of biomass, metals, non-metallic minerals, and fossil fuels, physical international trade, in-use stocks, and all resulting wastes and emissions in a mass-balanced approach. Aside from the pioneering proof-of-concept study "Weight of Nations" (Matthews et al., 2000), empirical efforts were focused so far mainly on implementing and harmonizing the ew-MFA framework for extraction, trade, apparent consumption and more recently, the so-called material footprint or raw material equivalents of consumption (Fischer-Kowalski et al., 2011; Martinico-Perez et al., 2018; Schandl et al., 2017; Wiedmann et al., 2015). Research on in-use stocks, flows of secondary recycled resources, and the systematic mass-balanced link to waste and emissions have gained significance only in recent years (Dombi et al., 2018; Fishman et al., 2014, 2016; Hashimoto et al., 2009; Kovanda et al., 2007; Krausmann et al., 2017b).

Indicators on yearly resource flows derived from ew-MFA are receiving widespread adoption into policy since the first multi-national studies were initiated by the World Resources Institute in the late 1990s (Adriaanse and World Resources Institute, 1997; Matthews et al., 2000). After a phase of methodological harmonization in the early 2000s (Eurostat, 2001; OECD, 2008), the framework was implemented into official statistical reporting of national and international organizations, among them the Japanese ministry of the environment, the EU,

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the OECD, and UNEP. Growing political awareness to environmental-economic interrelations and the usefulness of ew-MFA indicators are exemplified by, for example, the United Nations' Sustainable Development Goal 12 on ensuring sustainable consumption and production patterns (UN Economic and Social Council, 2016), OECD reporting on green growth and material productivity (OECD, 2015) and reports by the International Resource Panel of the United Nations Environment Program (UNEP, 2016, 2011). In a number of countries, ew-MFA indicators are also used in national policy formulation, such as the EU2020 Flagship Initiative for a Resource Efficient Europe (European Commission, 2011); the EU Circular Economy Action Plan (European Commission, 2018a); a large number of European countries (Bahn-Walkowiak and Steger, 2015); China's circular economy plans (Mathews and Tan, 2016; Su et al., 2013); and Japanese 3R policies (Ministry of the Environment Japan, 2016; Takiguchi and Takemoto, 2008).

However, it becomes increasingly clear that further advancements in ew-MFA research are necessary to improve its relevance for science and policy for a more sustainable resource use. This includes research on in-use stocks of manufactured capital, the role of secondary material flows within the socioeconomic metabolism, and the mass-balanced assessment of all resulting wastes and emissions (Fischer-Kowalski et al., 2011; Krausmann et al., 2017a). Such information will be useful for a number of important topics in ecological economics:

For example, properly understanding the dynamics of in-use stocks is crucial to provide meaningful and biophysically realistic pathways for dematerialization and decarbonization (Hertwich et al., 2015; Pauliuk et al., 2017) and efforts in developing ecologically grounded macro-economic models are increasingly building on systematic biophysical descriptions provided by ew-MFA based assessments (Dafermos et al., 2017; Haas et al., 2015). Assessing the societal outcomes of economic development and resource use also becomes much more robust when considering the specific history of societal resource use (Mayer et al., 2017) and the in-use stocks available to society (Lin et al., 2017; Müller et al., 2011). Conceptually, this relationship has been framed as in-use stocks providing services to society, for example shelter or mobility, and continuous flows of energy and materials are required to deliver these services (Haberl et al., 2017; Pauliuk and Müller, 2014). A sufficient and socially acceptable level of services provided by a steady-state or even shrinking resource use and stock patterns within ecological limits therefore constitutes an important research frontier (O'Neill, 2015; O'Neill et al., 2018). However, systematic theory and knowledge on the nexus between Stocks-Flows-Services is so far lacking (Haberl et al., 2017; O'Neill, 2015). Recently, the concept of a circular economy is becoming more popular, which makes a biophysical perspective on material and energy flows and in-use stocks of manufactured capital a crucial component towards a comprehensive assessment (Bruel et al., 2018; Geissdoerfer et al., 2017; Haas et al., 2015; Pauliuk, 2018). For this purpose, the dynamics of in-use stocks need to be explicitly addressed, because globally in-use stocks of manufactured capital already require about half of global resource use for their expansion and maintenance (Krausmann et al., 2017b). Furthermore, stocks also lock-in energy and emissions for their operation and their dynamics determine when and how much of the large amounts of materials accumulated as manufactured capital become available for re-use and recycling into secondary materials (Krausmann et al., 2017b; Pauliuk, 2018).

Research into in-use stocks has increased substantially in the last years, ranging from investigations of specific materials and substances, different types of in-use stocks and local to global scales (see reviews by Augiseau and Barles, 2016; Müller et al., 2014a; Tanikawa et al., 2015). Uncertainty and sensitivity assessments are also increasingly conducted (Džubur et al., 2016; Laner et al., 2014). However, for economy-wide MFA, empirically incorporating and investigating the dynamics of in-use stocks of manufactured capital is still in its infancy, where (some of) the authors so far provided a "proof-of-concept" (Fishman et al., 2014) and the first comprehensive investigation of the global dynamics of all in-use stocks in the socio-economic metabolism from 1900 to 2010 (Krausmann et al., 2017b). However, a proper conceptual and methodological extension of the economy-wide material flow accounting framework towards explicitly incorporating a dynamic modelling approach to investigating in-use stocks and all resulting wastes and recycling flows, including a comprehensive quantification and attribution of uncertainty, is still lacking.

Herein, we introduce the dynamic, inflow-driven, economy-wide model of Material Inputs, Stocks and Outputs (MISO-model, version 1.0), which is developed as a fully consistent extension of the economy-wide material flow accounting framework (ew-MFA), including systematic handling of uncertainty. In Section 2, we identify the research gaps in ew-MFA which we address with this modelling approach, while in Section 4 we review and evaluate available modelling strategies, suggest a new classification of modelling approaches and identify and situate the approach used for the MISO-model, which we then in Section 5 describe utilizing the "overview, design concepts, and details" (ODD) protocol for dynamic MFA (Müller et al., 2014a).

We showcase the MISO-model by applying it to the global scale from 1900 to 2014, covering all resource extraction and processing of materials into specific uses, tracing 14 stock-building materials accumulating in global in-use stocks of manufactured capital, and estimating all resulting end-of-life wastes and recycling into secondary stock-building materials (Section 6). Because validation and uncertainty are crucial topics for economy-wide and dynamic MFA, we extensively validate the MISO results against the literature and conduct various sensitivity tests (see also SI). In Section 7, we quantify and attribute sources of uncertainty to model results, utilizing the Spearman's rank correlation coefficient for a first-order Global Sensitivity Analysis, in order to identify the key parameters driving uncertainty and informing next steps towards more robust estimates. We then showcase the scenario capabilities of the MISO-model, by modelling some of the quantitative implications of a hypothetical global stabilization of resource use versus a sustainable circularity scenario until 2050 (Section 9). Finally, limitations and next steps in the further development of the MISO-model and ew-MFA, scenario efforts and improved uncertainty handling are discussed (Section 9) and final conclusions are drawn.

2. Linking Accounting with Modelling: Integrating in-Use Stocks into Ew-MFA

Ew-MFA has been designed to comprehensively account for material and energy flows based on information from standardized statistical reporting (e.g. agricultural, mining and energy statistics, trade statistics, waste and emission statistics), usually provided by national statistical offices and international organizations (e.g. International Energy Agency, Food and Agricultural Organization of the United Nations, UN-Comtrade). Material and energy flows are accounted by rigorously applying the mass-balance principle, to ensure a thermodynamically correct representation of socio-economic systems. Ew-MFA is designed to be part of the System of Economic Environmental Accounting, and is therefore aligned with various socio-economic and environmental indicators, most prominently with GDP (Eurostat, 2001; OECD, 2008; Fischer-Kowalski et al., 2011; Krausmann et al., 2017a). To allow for long-term and cross-sectional comparability of ew-MFA results at any spatial scale, system boundaries and all derived indicators have been clearly defined and internationally harmonized (Fischer-Kowalski et al., 2011; Schandl et al., 2017).

So far, in most empirical research of the socio-economic metabolism utilizing ew-MFA, the socio-economic system is simplified as a "black box", with a focus on flows into and out of the system, but neglecting processes within the system (Krausmann et al., 2017a). Full descriptions of materials' life stages have been developed for specific substances or materials, mainly for metals (Chen and Graedel, 2012; Müller et al., 2014a). Efforts are also ongoing which utilize physical (Altimiras-